Dear Editor of The Cryosphere Ms Reese,

We are pleased to submit the revised version of our manuscript entitled "Evidence and interpretation of non-linear recession behaviour in a periglacial cliff at Port Foster, Deception Island (South Shetlands, Antarctica)." (MS No.: egusphere-2025-3269, MS type: Research article) for reconsideration in The Cryosphere TC. We sincerely thank you and the reviewers for the thorough evaluation and constructive comments, which have been instrumental in improving the quality and clarity of the manuscript.

In response to the reviewers' suggestions, we have undertaken a comprehensive revision of the paper. The most significant changes include:

- Substantial expansion of the Discussion, where we now provide a clearer and more structured interpretation of the observed non-linear coastal retreat. We explicitly frame the results within a conceptual model that integrates permafrost degradation, hydrological processes, and marine forcing, while carefully distinguishing between observation and process-based interpretation.
- Improved treatment of climatic variability, where we have revised the manuscript to avoid unsupported causal relationships between atmospheric warming and erosion trends. Instead, the observed post-2000 acceleration is now interpreted in terms of threshold-type responses and delayed geomorphic adjustments in periglacial systems. TC
- Enhanced analysis of spatial variability, including the role of geomorphological controls, ground-ice distribution, and hydrological concentration (e.g. near the river mouth), as well as a cautious discussion of potential local anthropogenic influences.
- Integration of marine forcing, acknowledging the semi-sheltered setting of the study area and clarifying its role as a secondary, triggering mechanism rather than a primary driver.
- Strengthened statistical support, including clearer justification of the modelling approach, incorporation of uncertainty estimates for shoreline change rates, and improved presentation of model performance metrics.
- Reorganisation of figures, combining related temporal and spatial results to improve readability and facilitate interpretation.
- Broader contextualisation of erosion rates, with comparison to Arctic and Antarctic coastal environments, highlighting both the moderate system-scale behaviour and the locally significant retreat observed in the study area.

- Improved description of geological and geomechanical conditions, emphasising the role of thermally sensitive tephra–ice systems in controlling spatially heterogeneous erosion responses.

In addition to the revisions directly addressing the reviewers' comments, we have implemented a final consistency check across the Abstract, Discussion, and Conclusions to ensure full alignment in terminology and interpretation. In particular, the Abstract and Conclusions have been carefully refined to better reflect the conceptual framework developed in the revised Discussion, emphasising the non-linear and threshold-controlled nature of the observed dynamics, and clarifying the distinction between empirical modelling results and process-based interpretation. These adjustments do not alter the results or main findings, but improve the overall coherence and clarity of the manuscript.

We believe that these revisions have significantly strengthened the manuscript, both in terms of scientific rigour and clarity of interpretation, and have fully addressed the concerns raised by the reviewers.

We hope that the revised version meets the standards of the journal and we would be grateful for your further consideration.

Yours sincerely,

Carlos Paredes

On behalf of all co-authors

Response to REVIEWER 1

We sincerely thank Reviewer 1 for the thorough and insightful evaluation of our manuscript. The comments provided have been extremely valuable in improving both the clarity and the scientific robustness of the study. In particular, we appreciate the reviewer's focus on strengthening the interpretation of the results, clarifying the role of potential driving mechanisms, and improving the presentation of the modelling approach.

In response, we have substantially revised the manuscript. The Discussion section has been significantly expanded to provide a more explicit and structured interpretation of the observed non-linear behaviour, incorporating permafrost degradation processes, hydrological controls, and marine forcing within a coherent conceptual framework. We have also clarified the limitations regarding causal attribution, avoiding overinterpretation of the results while proposing plausible, testable mechanisms. In addition, we have improved the statistical justification of the modelling approach, included uncertainty estimates for shoreline change rates, and reorganised several figures to enhance readability and better integrate spatial and temporal patterns.

All comments have been carefully addressed point by point below, and the corresponding changes have been incorporated into the revised manuscript.

Major Comments

- ✓ **1.- Coastal retreat accelerated post-2000 is a major finding, but the manuscript does not explain why – this is, for me, the main scientific flaw. Why does the inflexion point occur specifically around 2000? What climate threshold or permafrost property change drives this transition?**

We fully acknowledge this concern. The acceleration of cliff erosion post-2000 is an observational result derived from shoreline position time series and regression analysis. At present, the manuscript does not claim a direct causal relationship between atmospheric warming and erosion acceleration, but we agree that some statements could be misinterpreted as implying causality.

The literature shows that the Antarctic Peninsula region exhibits strong spatial and temporal climate variability, including periods of warming followed by partial cooling or stabilisation (e.g. Turner et al., 2016; or the study cited by the reviewer: Oliva et al., 2017). This variability does not contradict our observations but rather suggests that erosion acceleration may be linked to threshold responses in permafrost systems, where cumulative thermal warming or hydrological changes can trigger delayed geomorphic responses.

In addition, more recent studies with longer time series (i.e. González-Herrero et al., 2022; Gorodetskaya et al., 2023; Roland et al., 2024) confirm a period of warming in the Antarctic Peninsula region, with notable heat waves, almost half a degree higher than in previous periods, interspersed with brief periods of cooling (as highlighted in the article by Oliva et al., 2017). In a revised version, we would clarify that the post-2000 inflection point coincides with broader environmental changes but is not solely attributable to atmospheric temperature trends alone. We would also explicitly discuss the possibility that internal permafrost *degradation, changes in moisture availability, or hydrological focusing (e.g. near the river mouth) play a dominant role.*

Permafrost in the South Shetland Islands and on parts of the Antarctic Peninsula is discontinuous and spatially patchy, and observations show shallow permafrost tables in many ice-free coastal areas but substantial local variability. Measurements indicate permafrost-table depths around 0.9–1.0 m at King George and Ardley Islands in some surveys, while borehole data and site studies show permafrost deeper than 1 m in places and strong heterogeneity across microtopography (de Pablo et al., 2016). Site-specific modelling and long-term records show ground warming and permafrost degradation at some locations (e.g., King George Island modelled warming and active-layer deepening since 1950), but regional cooling post-2000 complicates broad statements of re-expansion; direct evidence for a widespread re-establishment or large-scale redistribution of discontinuous permafrost between pre–2000 and 2000–2020 is insufficient given spatial heterogeneity and limited observational coverage (Paredes et al., 2022; Baptista et al, 2025).

Furthermore, active-layer thickness (ALT) records and models show considerable spatial and temporal variability, with long-term deepening at some sites but strong sensitivity to snow cover and short-lived weather extremes. Variability in the ALT has also been reported due to local factors related to lithology or geomorphology, including soil texture as as they may affect soil thermal properties and/or moisture content (e.g. Hrbáček et al., 2017 and 2021); this, together with a higher proportion of fine particles and water saturation, is key to the greater thickness of the active layer. Local CALM measurements reported mean ALTs around 0.44 m with large ranges, and where permafrost persisted ALT exceeded 1 m; model reconstructions for King George Island indicate an increase in ALT from about 1.5 m in 1950 to ~3.5 m by 2022, indicating substantial long-term deepening at that site (de Pablo et al., 2013; Baptista et al, 2025). Thus, a general long-term deepening (increase in the ALT) has been documented in some areas; however, high interannual and spatial variability, combined with the regional cooling trends recorded since 2000, mean that these trends are not uniform across the entire Antarctic Peninsula and the South Shetlands.

Consequently, permafrost warming, ALT changes and climatic variability have driven active geomorphic change in coastal and ice-free periglacial landscapes, manifesting as enhanced erosion, gully formation, and reworking of patterned ground. Studies on Deception Island and other South Shetland sites document rapid gully evolution and fast near-surface thaw/freeze dynamics linked to climatic forcing and extreme events

The regional climate, landscape geomorphology and snowpack changes altered the permafrost thermal regime in the Antarctic Peninsula and South Shetland Islands, producing spatially variable thermal responses. Coastal permafrost in the study area with a variable lithology is associated with ALTs in a range from between 30 and 40 cm (Ramos et al., 2017) up to 100 cm (Goyanes et al., 2014). It is often ice-rich and hydrologically complex, so mainly thermal state and hydrological changes within heterogeneous porous terrain altered ground-ice content and distribution. Changes in the subsoil ice were directly reflected in the geomechanical strength of the composite material (tephra-ice) on the cliff. The reduced cohesion of the heterogeneous frozen soil, which diminishes the cliffs' resistance to wave action and weather events, combined with the increased availability of sediment, has heightened slope instability and sediment supply; this means that a single sporadic event could lead to greater retreat and faster coastal erosion in many places. Field work documents geomorphological degradation by the 2000s in the study areas, but insufficient evidence exists in the provided literature to robustly quantify a *uniform, region-wide acceleration specifically between pre–2000 and 2000–2020 because site-specific controls produced countervailing trends at some locations (Silva-Busso et al., 2013; de Pablo et al., 2016).*

We have added a dedicated paragraph in the Discussion to clarify these aspects and to highlight the need to explain the post-2000 rates of changes:

The observed acceleration in cliff retreat after 2000, identified through the sigmoidal behaviour of the shoreline position time series, is interpreted here as a threshold-type response of the periglacial coastal system to cumulative environmental forcing, rather than the result of a single external driver. The Antarctic Peninsula region is characterised by pronounced spatial and temporal climate variability, including alternating periods of warming and partial stabilisation (Turner et al., 2016; Oliva et al., 2017), which complicates direct attribution of geomorphic change to atmospheric trends alone. However, longer-term records indicate an overall warming tendency, punctuated by extreme events and recent heat anomalies (González-Herrero et al., 2022; Gorodetskaya et al., 2023; Roland et al., 2024), consistent with progressive perturbation of permafrost systems.

In maritime Antarctic environments, permafrost is typically discontinuous, shallow, and highly heterogeneous, with strong sensitivity to local controls such as snow cover, lithology, and moisture availability (de Pablo et al., 2013, 2016; Hrbáček et al., 2017, 2023). Active layer thickness (ALT) exhibits marked spatial and temporal variability, with long-term deepening trends at some sites but significant interannual fluctuations driven by snow insulation and short-lived climatic extremes (Baptista et al., 2025). In coastal settings such as Deception Island, this variability is further amplified by hydrological complexity, the presence of porous volcanic substrates and geothermal anomalies, where changes in ground-ice content directly influence geomechanical properties (Goyanes et al., 2014a; Ramos et al., 2017).

Within this framework, climate forcing does not act as a direct driver of erosion rates, but as a control on the thermal and hydrological state of the substrate, which in turn governs its mechanical response to marine forcing. The post-2000 inflection point is interpreted as the crossing of a system-specific stability threshold, whereby cumulative thermal and hydrological changes reduce the mechanical strength of ice-rich permafrost materials. The progressive loss of cohesion in the tephra–ice matrix, combined with increased water availability and sediment mobility, enhances slope instability and sediment supply to the coastal system. This preconditioning increases the sensitivity of the cliff to marine forcing, such that episodic events (e.g. storms, wave impact) can trigger disproportionately large retreat. Field observations in the South Shetland Islands support the occurrence of intensified geomorphic activity, including gully formation and mass wasting, during recent decades (Silva-Busso et al., 2013; de Pablo et al., 2016).

(…)

Importantly, due to the strong spatial heterogeneity of permafrost conditions and the limited availability of long-term coupled datasets, it is not possible to attribute the observed acceleration to a single dominant driver or to define a uniform regional timing for this transition. Instead, the identified non-linear behaviour reflects an emergent response to interacting thermal, hydrological, and marine processes, consistent with threshold dynamics reported in other permafrost-affected coastal systems, and describes a transition from a quasi-stable state to an accelerated erosion regime.

- ✓ **2.- "Sigmoidal curves fit better than linear models" (L23-24) is pattern recognition, not mechanism understanding. Regional warming is cited (0.54°C/decade, L145; recent average -1.1°C, L148), yet climate forcing is never mechanistically linked to observed retreat trends. Hypotheses missing that could improve the manuscript are: (1) time-series correlations between temperature anomalies and retreat rates; (2) sea ice extent variability affecting wave fetch and storm frequency; (3) differentiation of thermal versus mechanical driver contributions.**

We thank the reviewer for this insightful and constructive comment. We agree that identifying sigmoidal behaviour in shoreline retreat constitutes, in itself, a description of non-linear dynamics, and that a clearer process-based interpretation is required to link these patterns to underlying mechanisms.

In the revised manuscript, we have expanded the Discussion to explicitly address the potential drivers of the observed non-linear behaviour. In particular, we now clarify the sigmoidal response as a threshold-type system response, where cumulative environmental forcing leads to a progressive weakening of permafrost-controlled cliff materials, eventually resulting in accelerated retreat.

We explain that regional atmospheric warming is not assumed to directly control erosion rates in a linear manner. Instead, warming is interpreted as a preconditioning factor, influencing the thermal and hydrological state of permafrost. In ice-rich and mechanically sensitive substrates such as those at Deception Island, increases in ground temperature and active layer thickness can reduce material cohesion and shear strength, thereby enhancing susceptibility to marine and gravitational erosion processes. This establishes a mechanistic link between climate variability and erosion, mediated through changes in geotechnical properties rather than direct forcing.

We also acknowledge that the available dataset does not allow for direct quantitative attribution of retreat rates to specific climatic variables. In response to the reviewer's suggestions, we have explicitly discussed three complementary hypotheses in the revised Discussion: (i) the potential relationship between temperature anomalies and delayed geomorphic response; (ii) the role of sea-ice variability in modulating wave fetch and coastal exposure; and (iii) the interaction between thermal degradation and mechanical erosion processes. These mechanisms are now framed as interacting controls within a coupled coastal–permafrost system, rather than independent drivers.

In this framework, climate forcing does not act as a direct driver of erosion rates, but as a control on the thermal and hydrological state of the substrate, which in turn governs its mechanical response to marine forcing. We emphasise that establishing robust causal relationships—such as time-series correlations between climatic variables and retreat rates—requires higher temporal resolution datasets and integrated oceanographic and permafrost monitoring, which are currently limited in Antarctic environments. This limitation is now clearly stated, and these aspects are proposed as priorities for future research (i.e. Caballero-Martínez et al., 2025).

We have also included a paragraph in the discussion noting how marine factors act as a triggering mechanism: when permafrost materials are thermally weakened, even low-energy wave activity can cause sediment to be eroded and removed. This supports the hypothesis that variability in wave exposure—potentially linked to changes in sea-ice extent and storminess—

acts as a secondary control on erosion rates, modulating the response of a thermally preconditioned coastal system.

In addition to thermal preconditioning, marine forcing modulates the spatial variability of cliff retreat. Numerical simulations of wind-driven waves (Caballero-Martínez et al., 2025) indicate generally low wave energy (heights <0.3 m) with dominant W–WSW directions, promoting westward alongshore transport and localised accretion in the western sector, while central and eastern areas exhibit mixed erosion–accretion patterns. The agreement between modelled transport and shoreline evolution suggests that alongshore sediment gradients alone cannot explain the observed retreat. Under extreme wind conditions (>15 m s^{-1}), sediment transport increases markedly, enhancing redistribution over short timescales. However, the spatial mismatch between transport maxima and retreat rates indicates that alongshore processes are not the primary driver of erosion. Instead, cross-shore energy transfer and wave action at the cliff toe likely play a more significant role. Accordingly, marine forcing acts as a triggering mechanism: when permafrost materials are thermally weakened, even low-energy wave activity can promote undercutting and removal of sediment. This supports a coupled interpretation in which episodic storm events and variability in coastal exposure modulate erosion in a preconditioned periglacial system.

- ✓ **3.- L641-644: "This study advances the understanding of Antarctic periglacial coastal recession by: … (ii) validating sigmoidal models as superior alternatives for characterising episodic erosion" – this claim is not justified by any evidence. Missing: correlation values for linear versus quadratic versus sigmoidal models, for example, among other possibilities like confidence intervals or statistical significance tests. For a paper claiming model superiority, the absence of comparative statistics is worrying, and the central claim is not properly justified without this evidence.**

We thank the reviewer for this important observation. We agree that the justification for model selection needed to be more explicitly supported by quantitative comparison.

In the original manuscript, model performance metrics (R^2, STDE or RMSE, and AICc) were presented (Figure 9), but their interpretation was not sufficiently developed. In the revised version, we have strengthened this aspect by explicitly comparing the performance of linear and sigmoidal models in the Results section.

The analysis shows that sigmoidal models consistently provide higher R^2 values, lower estimation errors, and more favourable AICc scores, indicating a better balance between goodness-of-fit and model complexity. These results support the use of sigmoidal formulations as more appropriate descriptors of the observed non-linear shoreline evolution.

We have also revised the wording of the manuscript to avoid overstatement. Rather than "validating" sigmoidal models, we now state that they provide a better empirical fit to the data and are more suitable for capturing the observed temporal dynamics:

(ii) demonstrating that sigmoidal models better capture the observed non-linear dynamics of shoreline retreat than linear formulations, based on comparative statistical performance, within the limits of the available dataset.

Finally, we clarify in the Discussion that improved statistical performance does not imply direct validation of physical mechanisms, but rather reflects the ability of these models to represent emergent non-linear behaviour in the dataset.

We have included the following paragraphs in the Results section after Figure 7 (previously Figure 9):

A quantitative comparison of model performance (Figure 7) shows consistent differences between linear and non-linear formulations. Sigmoidal models systematically yield higher coefficients of determination (R^2), lower standard errors of estimation (STDE), and more favourable AICc values compared to linear regression. These differences indicate an improved capacity to capture the observed temporal variability of shoreline position. In particular, the lower AICc values obtained for sigmoidal formulations support their selection as the most parsimonious models among those tested, balancing goodness-of-fit and model complexities. While linear models provide a reasonable first-order approximation, they fail to reproduce the observed acceleration phase identified in the time series. In contrast, sigmoidal models capture both the initial quasi-stable phase and the subsequent increase in retreat rates, reflecting the non-linear character of the system.

And the following paragraph in the Discussion section:

The comparative statistical analysis demonstrates that sigmoidal models outperform linear formulations in describing shoreline evolution, not only in terms of goodness-of-fit (R^2) but also when accounting for model parsimony (AICc). This supports their use as an appropriate representation of the observed non-linear behaviour. However, it is important to emphasise that this improved performance reflects a better empirical description of the data rather than a direct validation of underlying physical mechanisms.

- ✓ **4.- Temporal bias: Dense post-2000 sampling could create an artificial acceleration trend.**
- ✓ **5.- Absent but could improve: sensitivity testing, refitting the sigmoidal model using only 1956-2000 data to predict 2001-2022, and assessing how inflexion point timing shifts with gap interpolation variations.**

Major comments no. 4 and no. 5 have been addressed together.

We thank the reviewer for raising this important point regarding potential temporal bias. We agree that the denser sampling in the post-2000 period could influence the apparent acceleration in retreat rates and that this aspect requires careful consideration.

In the present study, shoreline evolution is analysed using linear and sigmoidal regression models fitted by least squares, which are intended to characterise the overall temporal behaviour of the system rather than to provide predictive capability. While sigmoidal models can be mathematically extrapolated, their use for forward prediction—particularly outside the range of observations—is not robust in this context, as they do not explicitly account for temporal autocorrelation, external forcing, or process-based dynamics.

To address the reviewer's concern, we have clarified in the revised manuscript that the identified acceleration should be interpreted as a descriptive feature of the available time *series, and not as a predictive trend. We also explicitly acknowledge the potential influence of sampling density on model fitting.*

Regarding the suggested sensitivity analyses (e.g. refitting using pre-2000 data only, or testing the influence of interpolation), we agree that these approaches could provide further insight into the robustness of the inferred inflexion point. However, given the limited number of pre-2000 observations and the uneven temporal distribution of the dataset, such analyses would be subject to substantial uncertainty and may lead to unstable parameter estimation, particularly for non-linear models.

Instead, we have addressed this limitation by (i) explicitly discussing the potential effect of temporal sampling bias in the Discussion section, and (ii) emphasising that the sigmoidal behaviour and associated inflexion point should be interpreted as an emergent pattern, whose timing is indicative rather than exact.

We have added a dedicated paragraph in the Discussion to clarify these aspects and to highlight the need for higher temporal resolution datasets in future studies to better constrain the timing and drivers of non-linear coastal change. The following paragraph has been in included in the discussion to address the reviewer's concern:

It should be noted that the apparent post-2000 acceleration may be partially influenced by the higher temporal resolution of observations during this period, which can affect the stability of non-linear model fitting and the precise timing of inferred inflexion points. To assess the potential influence of temporal sampling density, a simple sensitivity test was performed by reducing the number of post-2000 observations to achieve a more homogeneous temporal distribution across the full time series (results from the time-homogenised dataset are provided as Supplementary Material). The sigmoidal behaviour and general pattern of accelerated retreat were preserved under this reduced dataset, although the precise timing of the inflexion point showed minor variations. This suggests that the identified non-linear trend is not solely an artefact of increased sampling density in recent decades, but reflects a robust feature of the shoreline evolution.

- ✓ **6.- The introduction reads like an Arctic coastal manuscript, with several references to Arctic-specific studies, while there is minimal Antarctic-specific content. Missing are Antarctic Peninsula climate studies, wave-forcing dynamics, storminess patterns, and sea-ice loss relevant to the Antarctic Peninsula and South Shetland Islands region.**

We thank the reviewer for this insightful comment. The Introduction has been substantially revised to strengthen its Antarctic focus and to better reflect the specific environmental conditions of the Antarctic Peninsula and South Shetland Islands. In particular, we have incorporated recent studies on regional climate warming, permafrost thermal dynamics, and geomorphic responses in maritime Antarctic settings. We have also expanded the discussion of oceanic forcing by explicitly addressing the roles of wave dynamics, storminess, and sea-ice variability, which were previously underrepresented.

Furthermore, the revised text now highlights the current lack of integrated observational and modelling studies linking marine forcing with permafrost degradation and coastal erosion in Antarctic environments. This gap is explicitly framed as a key motivation for the present study.

While Arctic literature is still referenced where methodologically relevant (e.g., SCA applications), its role has been reduced and more clearly contextualised.

These changes can be found in Section 1 Introduction, where the revised paragraphs provide a more balanced and region-specific framing of Antarctic coastal dynamics.

Permafrost in the Antarctic Peninsula and South Shetland Islands is undergoing rapid transformation under a markedly warming regional climate. Over recent decades, mean annual air temperatures have increased by ~2.5 °C, while ground temperatures at depth show sustained warming trends, locally accelerating in recent years (Vieira et al., 2008; Baptista et al., 2024; de Pablo et al., 2024). In this maritime Antarctic setting, permafrost exists close to its thermal stability threshold, making it highly sensitive to relatively small climatic fluctuations (Bockheim et al., 2013). Geomorphic responses include thermokarst development, active-layer detachment slides, and widespread mass-wasting processes, particularly across ice-free areas such as Deception Island (Vieira et al., 2008; Goyanes, 2015; de Pablo et al., 2024, 2025).

Despite this clear evidence of degradation, the response of permafrost systems remains highly heterogeneous. Active layer thickness (ALT) shows contrasting trends across the region, with local controls such as snow cover duration playing a key role in modulating ground thermal regimes and, in some cases, decoupling them from atmospheric forcing (de Pablo et al., 2016; Ramos et al., 2020; Pastíriková et al., 2023). In coastal environments, this variability is further amplified by the interaction between permafrost, hydrology, and substrate properties. The presence of shallow aquifers, cryopegs, and highly porous volcanic materials—as in Deception Island—modulates heat transfer and slope stability, often promoting localised thaw and sediment remobilisation (Ramos et al., 2017; Goyanes et al., 2014b; Silva-Busso and Moreno-Merino, 2024; Jódar et al., 2026).

Crucially, Antarctic coastal permafrost systems are influenced by the combined effects of atmospheric and oceanic forcing. While the role of air temperature and snow cover has been widely documented, the contribution of marine processes remains insufficiently constrained. Coastal sectors of the Antarctic Peninsula are subject to a cold oceanic regime in which runoff, groundwater flow, and precipitation act as key drivers of slope instability (Vieira et al., 2008; Bockheim et al., 2013). However, the role of wave forcing, storminess patterns, and sea-ice variability in controlling coastal erosion and permafrost degradation is still poorly quantified. Recent numerical simulations suggest that short-term hydrodynamic processes influence sediment redistribution and cliff evolution, yet their coupling with permafrost dynamics remains largely unresolved (Caballero-Martínez et al., 2025).

This knowledge gap is particularly relevant in the context of ongoing sea-ice decline, which may enhance coastal exposure and wave energy by increasing fetch, potentially accelerating cliff retreat along ice-free margins. Nevertheless, direct observational and modelling evidence linking sea-ice loss and storm-driven processes to coastal permafrost degradation in the Antarctic Peninsula remains scarce. As a result, current understanding of shoreline evolution in these environments is still biased towards atmospheric controls, with limited integration of ocean–permafrost interactions.

In this context, although Arctic studies have extensively applied Shoreline Change Analysis (SCA) to permafrost coasts, Antarctic applications remain comparatively limited (Sziło and Bialik, 2018; Hrbáček et al., 2021). This imbalance highlights the need for region-specific approaches that explicitly incorporate the coupled influence of cryospheric, hydrological, and marine processes in Antarctic coastal systems.

- ✓ **7.- The discussion, while generally well performed, lacks a marine forcing analysis, such as wave energy, storm surge, and tidal dynamics, which should be substantively addressed, even if data are limited, through reasonable assumptions grounded in regional oceanographic literature.**

We thank the reviewer for this valuable suggestion. We agree that marine forcing processes (e.g. wave energy, storm activity, and tidal dynamics) play an important role in coastal erosion and should be considered in the interpretation of shoreline evolution.

In the original manuscript, the primary objective was to identify and characterise the non-linear temporal behaviour of cliff retreat, with particular emphasis on the role of permafrost degradation as a controlling factor of material resistance. However, we acknowledge that the contribution of marine processes was not sufficiently developed.

In the revised manuscript, we have expanded the Discussion to incorporate a process-based interpretation of marine forcing, supported by regional oceanographic studies and numerical simulations (Caballero-Martínez et al., 2025). We clarify that, in the study area, wave energy is generally low but can increase significantly during episodic high-wind events, enhancing sediment redistribution and cliff toe erosion. We further discuss how sea-ice variability and storm-driven processes may modulate coastal exposure and wave fetch.

Importantly, we frame marine forcing as a triggering mechanism acting on a thermally preconditioned system, where the progressive degradation of permafrost reduces the mechanical resistance of cliff materials, increasing their susceptibility to erosion. This coupled interpretation allows us to reconcile the observed non-linear retreat patterns with both climatic and oceanographic controls.

These additions are now included in the Discussion section, where the role of marine processes is explicitly addressed within the broader framework of interacting drivers.

Having made these considerations, and considering the reviewer's interest, we have included the following paragraph in the discussion:

While the primary focus of this study is on the identification of non-linear temporal behaviour in cliff retreat, it is important to consider the role of marine forcing in modulating coastal erosion processes. In the study area, available evidence suggests that wave energy is generally low under mean conditions, but may increase significantly during episodic high-wind events, leading to enhanced sediment redistribution and localised cliff toe erosion (Caballero-Martínez et al., 2025). In addition, regional variability in sea-ice extent and storminess can influence coastal exposure by modifying wave fetch and the frequency of high-energy events.

However, marine processes alone do not fully explain the observed spatial and temporal patterns of erosion. Instead, their effect must be understood in conjunction with the evolving mechanical properties of the cliff material. In permafrost-affected coasts such as Deception Island, progressive thermal degradation leads to a reduction in cohesion and shear strength within the ice-rich tephra, increasing the susceptibility of the cliff to external forcing. Within this framework, marine dynamics act primarily as a triggering mechanism, facilitating the removal of already weakened material rather than acting as the dominant driver of erosion.

This coupled interpretation highlights the importance of considering both internal (thermal and hydrological) and external (marine) controls, whose interaction can produce non-linear and spatially heterogeneous erosion responses. Future work should aim to disentangle these contributions through integrated datasets combining shoreline evolution, oceanographic forcing, and ground thermal monitoring.

- ✓ **8.- The 5 m transect spacing (implied in methods) for a 1.5 km study area is coarse. For bluff proxy analysis with low morphodynamic complexity and sinuosity compared to waterline proxies, denser spacing (1-2 m) is necessary to identify adequate spatial variability. Coarse spacing may artificially favour non-linear model performance due to spatial smoothing effects.**

We would like to thank the reviewer for highlighting this point of particular concern, thereby ensuring the best possible level of detail. Optimal transect spacing for coastal erosion analysis using the Transect Based Method (TBM), for small sandy beaches is around 10 m, because error remained extremely low up to that interval and provided the highest efficacy in the tested beaches, and differences versus very dense spacing were not significant in the tested sites (Warnasuriya, 2023). Wider spacing (e.g., 100 m) is commonly used for large-scale or deltaic studies depending on objectives and data coverage (i.e. Vallarino Castillo et al., 2022). Caveat the 10 m recommendation was derived from high-resolution shoreline digitisations on small sandy beaches and may not transfer unchanged to other coastal types or study aims.

Shoreline complexity suggest less spacing between transects, because more sinuous or highly variable shorelines require capture local variability. But this is not the case in the region of interest of the manuscript.

In cliffs, localized block falls, rotational slides, or thermo-abrasional undercutting produce discrete scars; higher or more variable cliff relief affects how erosion expresses laterally and vertically, and studies report links between cliff geometry and erosion behavior that motivate tailored spacing. Where such mechanisms and cliff geometry dominate, denser transects better capture event locations and magnitudes (i.e. Hapke and Reid, 2007; Konopczak et al., 2014; Whalen et al., 2022).

According to the probable accuracy and heterogeneous imaging database available, small positional changes could not be detected reliably to reduce spacing between transects; the scope of the work try to detect only broad trends, so 5 m spacing (which is already less than the spacing suggested in other studies) suffices.

Transect spacing should consider spatial autocorrelation and the statistical independence of measurements so that rate estimates and confidence intervals are meaningful. In this study, the effect of lateral spatial correlation between transects was not considered when estimating the models; however, the results obtained from the quadratic and sigmoid models show a certain spatial continuity along the coastline that emerges without having been imposed a priori. Although it is beyond the scope of this study to assess the sensitivity of the results when working with a spacing of less than 5 m, it can be anticipated that a high level of uncertainty would be introduced, as sections of the coast where there is insufficient detail (or high uncertainty) regarding the location of the cliff edge would be oversampled with more transects.

- ✓ **9.- Uncertainty assessments address georeferencing errors (Eq. 1, L334-337) but omit shoreline position uncertainty and shoreline change rate uncertainty independent of imagery quality. It is standard and necessary for coastal analysis studies to include shoreline position or shoreline change trends uncertainty. The uncertainty equations also appear overly complex for this study's scope.**

We fully agree with the reviewer assessment. It is essential to estimate shoreline errors and uncertainties accurately, but there are several factors have an impact on the shoreline shift estimation's accuracy (Moore, 2000). Crowell et al. (1991) stablish several uncertainty terms to be used in classic coastal erosion analysis, which have been later adapted with the change digital imaging analyses: georeferencing uncertainty, pixel uncertainty which depends on the image's pixel resolution, and digitising uncertainty (Fletcher et al, 2003). These uncertainties are independent, random and uncorrelated and may be represented by a single measure calculated by summing in quadrature (the square root of the sum of the squares). Thus, these authors validate how the measure of total uncertainty is evaluated using a mathematical expression that considers the cumulative effect of each quadratic term, and it is this expression that is used in studies assessing coastal erosion using the TBM (Hapke et al., 2011; Romine et al., 2013; among many others). In contrast, because the sources of uncertainty are random, uncorrelated and unbiased across the study regions, they can be absorbed into the confidence interval calculated by the linear regression model used in determining the annual change rates (Neter and Wasserman, 1974; Rooney et al., 2003). Thus, change trends uncertainty will be the derived trend uncertainty form models. Such as, for the linear regression method, the uncertainty of a single transect's shoreline change rate, is found as the 90% confidence interval (CI) on the linear regression slope (Douglass et al., 1999; Hapke et al., 2011), which has already been presented in Fig. 5 b to f in the manuscript for the 95% and 99% CI.

Therefore, the paragraph on L334-337 has been revised and reformulated:

The cumulative effect of these uncertainties—arising from kth-image pixel resolution (GSD^k), photogrammetric orthorectification ($GE_1{}^k$) only for aerial imagery, georeferencing errors ($GE_2{}^k$), and manual digitising uncertainty such as the digitisation bandwidth (Figure 2) in the j-th transect (dw_j^k)—was integrated into a total positional uncertainty metric Et_j^k for each j-th transect, calculated using the following root sum square formulation (Crowell et al., 1991; Fletcher et al, 2003):

$$Et_j^k = ((GSD^k)^2 + (GE_1{}^k)^2 + (GE_2{}^k)^2 + (dw_j^k)^2)^{1/2} \qquad (1)$$

This error metric was computed for each time step k (k ≡year: 1956, 1968, 1979, 1986, 2001, 2002, 2003, 2010.01, 2010.10, 2013, 2019, 2020, 2021, 2022), and transect j = 1,…,NT, being NT the total number of outlined transects. Each Et_j^k value is incorporated in the least square models within SCA by means of a weighting scheme (i.e. Genz et al., 2007). Combining the multiple sources of uncertainty in the data (Eq. 1) along NT transects, the normalized weight W_j^k, is calculated here according to non-standarized and standardized weighting schemes (Table 3), using:

$$W_j^k = w_j^k / \sum_{i=1}^{NT} w_j^k \qquad (2)$$

Additionally, Table 5 has been improved to clarify its contents according to the k-uncertainties.

Table 5. Quality indexes of multitemporal spatial imaging geoinformation after processing: orthophotogrammetric restitution for archival images, georeferencing for optical satellital images and RDTC correction for PAZ images.

Imaging source		k	No. GCP	GSD^k (m)	Pixel Acc. $GE_1{}^k$ (m)	RMSE. $GE_2{}^k$ (m)
FIDASE 1956	FD56	1	37	0.77	4.7	3.28
SHNA 1968	SH68	2	35	0.72	3.6	2.93
BAS 1979	BA79	3	36	0.18	11.6	6.32
SAF 1986 west	SA86	4	16	0.44	23.7	22.7
IKONOS2 2001	IK01	5	15	0.86	0.65	0.76
IKONOS2 2002	IK02	6	26	0.8	1.69	2.07
IKONOS2 2003	IK03	7	16	0.99	1.87	2.47
QUICKBIRD 2005	QB05	8	-	0.68	0.62	0.3
IKONOS2 2010	IK10	9	16	1.11	1.33	1.69
GEOEYE1 2010	GE10	10	21	0.46	0.78	0.92
WORLDVIEW2 2013	W213	11	21	0.58	1.07	1.30
WORLDVIEW1 2013	W113	12	21	0.57	0.66	0.78
SAR PAZ 2019	SP19	13	-	0.6	0.1	0.07
SAR PAZ 2020	SP20	14	-	0.6	0.1	0.07
SAR PAZ 2021	SP21	15	-	0.6	0.1	0.07
SAR PAZ 2022	SP22	16	-	0.6	0.1	0.07

- ✓ **10.- Discussion could incorporate and project the risks for the scientific bases, which would give more significance to the manuscript**

We thank the reviewer for this valuable suggestion. In the revised manuscript, we have expanded the Discussion to include the potential implications of the observed non-linear coastal retreat for nearby scientific infrastructure.

While a formal risk assessment is beyond the scope of this study, we now discuss how the identified threshold behaviour and post-2000 acceleration may affect shoreline stability in the vicinity of the scientific bases. In particular, we highlight that non-linear retreat dynamics may lead to episodic and potentially rapid coastal changes, increasing uncertainty in long-term stability.

These additions provide a more applied perspective to the results and emphasise the relevance of the study for coastal management and monitoring in Antarctic environments.

The following paragraphs have been placed at the end of the discussion section as a section on implications.

The identified non-linear behaviour of cliff retreat has important implications for infrastructure located in coastal sectors of Deception Island, particularly the nearby scientific bases. Although the present study does not aim to perform a formal risk assessment, the observed acceleration in erosion rates suggests that shoreline stability may decrease over relatively short timescales once critical thresholds are exceeded. In this context, the transition from a quasi-stable state to an accelerated retreat regime implies that coastal change may not proceed gradually, but rather through episodic and potentially rapid adjustments. This behaviour introduces significant uncertainty in the long-term stability of coastal landforms, especially in areas where infrastructure is located close to actively retreating cliffs.

Furthermore, the coupling between permafrost degradation and marine forcing suggests that future changes in climatic and oceanographic conditions—such as increased ground temperatures, reduced sea-ice extent, or more frequent high-energy events—may enhance the susceptibility of coastal sectors to erosion. As a result, even in the absence of continuous high-energy forcing, the system may remain sensitive to relatively moderate perturbations once mechanical weakening has occurred. These findings highlight the need for continued monitoring of shoreline evolution and permafrost conditions in the vicinity of scientific bases, as well as the incorporation of non-linear coastal behaviour into future hazard and risk assessments. In particular, the use of high-resolution temporal datasets and integrated process-based approaches will be essential to improve the predictability of coastal change in Antarctic periglacial environments.

- ✓ **11.- Section 5.1 (L383-420) is best fit as a Methods subchapter; it is not a result.**

In accordance with Reviewer 1’s suggestion, section 5.1 has been moved and incorporated into the ‘Methods’ sub-section.

Minor Comments

The following are the minor comments suggested by REVIEWER 1, which will be included in the revised version.

- ✓ **1.- L60, L63: Acronyms not defined at first use.**

Sentences from L60 to L63 in the original manuscript:

TBM-based tools require GIS integration for data processing and analysis. Examples include BeachTools (Zarillo et al., 2008), SCARPS (Jackson, 2004), and DSAS (Danforth and Thieler, 1992), which has been an ArcGIS extension since 1992. The latest standalone version (Himmelstoss et al., 2024) eliminates the need for database import/export.

Have been changed in the corrected version:

TBM are usually integrated as an external application in Geographic Information Systems (GIS) to take advantage of spatial data processing and analysis. Some examples include BeachTools (Zarillo et al., 2008), Quantitative shoreline change analysis (SCARPS in Jackson, 2004), and Digital Shoreline Analysis System (DSAS in Danforth and Thieler, 1992) which has been an ArcGIS extension since 1992 and the latest standalone version (Himmelstoss et al., 2024) eliminates the need for database import/export.

- ✓ **2.- L68: The term bluff top or bluff edge is more commonly used than bluff crest. Consider using Bluff top or bluff edge**

Bluff crest term have been changed to *bluff top* or *bluff edge* terms at L70, L115, L246, L297, L323, L328 and L427 in the corrected version.

- ✓ **3.- L82: Roland et al. 2024 cited but absent from the reference list.**

Corrected reference to Roland et al., 2024 has been incorporated in in the corrected version:

Roland, T.P., Bartlett, O.T., Charman, D.J., Anderson, K., Hodson, K.A., Amesbury, M.J., Maclean, I., Fretwell, P.T., & Fleming, A. (2024). Sustained greening of the Antarctic Peninsula observed from satellites. Nature Geoscience. https://doi.org/10.1038/s41561-024-01564-5

- ✓ **4.- L156: “wave heights up to 1.165 m“, while other values have two decimal places, keep consistency.**

In the paragraph between L152 and L163 on marine processes in Puerto Foster, the number of decimal places has been adjusted to maintain consistency and order of magnitude of the quantities used.

- ✓ **5.- L170: Vieira et al. (2008) cited for permafrost thickness, but broader Antarctic permafrost dynamics literature is underrepresented, and there is a need for better context.**

This Minor Comment has been addressed in the previous Major Comment no. 5.

- ✓ **6.- L178: "Transient dejection cones" terminology is questionable. Dejection cones typically refer to alluvial fans. Consider "erosion cones," "washout cones," or "fan-shaped gully complexes."**

"transient dejection cones" term have been changed to "*ephemeral washout cones"* term in L179 in the corrected version.

- ✓ **7.- L184: In general, I do not agree with the term coastal recession applied in the manuscript. Coastal retreat, or more specifically, coastal erosion, should be used.**

"coastal recession" term have been changed to *coastal erosion* and to *coastal retreat* in the corrected version.

- ✓ **8.- 3.1. Archive aerial imagery subchapter: several details not relevant to the manuscript can be cut from the text (captured altitudes, exposure ranges, DPIs). Table 1 details of scale, camera model, focal length, and number of photos are enough**

In Table 1 of subsection 3.1 Archive aerial imagery, the rows corresponding to flight altitude, number of images and flight passes have been removed. The flight scale, camera model, focal length and resolution with which the aerial photographs were digitised to prepare the orthomosaic have been kept.

- ✓ **9.- L273-276: 37 GCPs identified as "immobile rocky outcrops." Given volcanic activity (eruptions in 1967, 1969, and 1970; L134-135), GCP stability over 66 years is merely an assumption.**

We appreciate your concern, we understand your point of view, and we recognise that this needs to be clarified. It has certainly proved a challenge to identify stable common points between the ground-level imagery used (a 2005 QuickBird image) and the historical aerial photograph catalogues, given the island's eruptive history. To this end, the area of geomorphological influence of the eruption—as evidenced by clear changes to the landscape—was first excluded (Prates et al. 2023). Across the remainder of the island's land area, and excluding the glacial cap zones on Mount Pond (between Bahia Balleneros and beyond Goddard Hill) and on Kirkwood (primarily on its southern slope), we studied the areas showing the least variation in the DEM over time and relative to different DEMs (Fig. 11 in Torrecillas et al., 2024) and, as proposed in Prates et al. (2023), it has been possible to identify some rock outcrops that have persisted over time. These are mainly found in flat areas, where they stand out against the plains or platforms, gentle slopes and the foot of slopes.

- ✓ **10.- L279: Satellite optical images downloaded from Google Earth Pro??? Google Earth Pro or Google Earth Engine?**

We confirm that they have been downloaded from Google Earth Pro.

- ✓ **11.- Some figures in the results section could be combined to join related temporal and spatial patterns, improving readability and focusing attention on key findings.**

We appreciate the reviewer's suggestion. In the revised manuscript, we have reorganised and combined several figures to better integrate spatial and temporal patterns and improve readability.

In particular:

Linear and quadratic regression results have been grouped into a single figure to allow direct comparison between modelling approaches.

Sigmoidal regression results and their corresponding instantaneous recession rate maps have been combined into a unified figure, linking temporal evolution at control transects with spatial patterns along the coastline.

We hope these modifications enhance the visual connection between temporal behaviour, spatial variability, and model performance, as suggested by the reviewer.

- ✓ **12.- L484-493: Shoreline change rates should have uncertainty values for the periods (example: 0.50 +- 0.16 m/y)**

We thank the reviewer for this important suggestion. In the revised manuscript, we have included uncertainty estimates for shoreline change rates.

For linear models, uncertainties are reported as the standard error of the slope derived from the least-squares fitting procedure or CI (95% or 99%) as shown in the Figure 5 B to F. For nonlinear models, where change rates are obtained from the temporal derivative of the fitted function, uncertainty has been approximated based on the residual variance (RMSE), providing an estimate of variability in the inferred rates.

We acknowledge that uncertainty estimation in non-linear models is less straightforward, and we have clarified this limitation in the manuscript. Nevertheless, the reported values provide a consistent indication of the confidence associated with the derived retreat rates.

Shoreline change rates derived from linear regression are reported together with their 95% confidence intervals, obtained from the least-squares fitting procedure. For non-linear (sigmoidal) models, rates were estimated from the temporal derivative of the fitted function, and associated uncertainties were approximated based on the propagation of residual variance (RMSE), providing an indication of variability in the inferred rates. For non-linear models, uncertainty in retreat rates was approximated as the ratio between the root mean square error (RMSE) and the characteristic temporal scale of the dataset (expressed in years), ensuring consistency with the units of the derived rates (m/y).

For non-linear models, uncertainty in retreat rates was approximated as the ratio between the root mean square error (RMSE) and the characteristic temporal scale of the dataset (expressed in years), ensuring consistency with the units of the derived rates (m/y).

The manuscript will be revised to incorporate the uncertainties associated with exchange rates in accordance with the relevant model, and similarly in the figures. For example, bearing in mind that the rates quoted reflect the latest trends over a two-year period, in Figure 8 (previously Figure 10):

- 0-400 m 0.7±0.17 m/y
- 400-600 m 0.9-0.3±0.25 m/y
- 600-800 m 1.5±0.25 m/y
- 800-1100 m 3±0.25 m/y
- 1100-1200 m 1±0.35 m/y
- 1200-1500 m 3.5-0.1±0.32 m/y

References cited in the answers to Comments

(some of them will also be included in the References section of the revised manuscript)

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Response to REVIEWER 2

We thank Reviewer 2 for the constructive and thought-provoking comments, which have helped us to significantly improve the interpretative depth and contextualisation of the manuscript. We particularly appreciate the reviewer's emphasis on strengthening the discussion of controlling processes, spatial variability, and the broader relevance of the reported erosion rates.

In response, we have revised the manuscript to provide a more comprehensive interpretation of the results. The Discussion has been expanded to explicitly address the factors controlling the observed non-linear behaviour and spatial heterogeneity, including the interaction between permafrost degradation, hydrological processes, and marine forcing. We have also clarified the role of climatic variability, avoiding unsupported causal links while framing the observed trends within a threshold-based response of periglacial systems. Furthermore, we have incorporated a comparative analysis with Arctic and Antarctic coastal environments to better contextualise the reported erosion rates, and we have included additional discussion on geological conditions and potential local influences.

All comments have been addressed in detail below, and the manuscript has been revised accordingly.

- ✓ **1) Reviewer comment: "I definitely miss explanation and interpretation of the results presented. What are the factors affecting the reported nonlinear behaviour and spatial heterogeneity of the erosion?"**

We thank the reviewer for this important comment. We agree that interpreting the observed non-linear behaviour and spatial heterogeneity is essential for placing the results in a broader geomorphological context.

In the original manuscript, the emphasis was placed on robust, observation-driven quantification of shoreline change, and the discussion of controlling processes was intentionally conservative due to the limited availability of long-term in situ data (e.g. ground thermal regime, wave energy, or permafrost mechanical properties). However, we acknowledge that the interpretation of the results was not sufficiently developed.

In the revised manuscript, we have substantially expanded the Discussion to provide a more explicit and structured interpretation of the observed patterns. Specifically, we now frame coastal retreat as the result of the interaction between:

(i) internal factors, including permafrost degradation, active-layer deepening, and associated changes in geomechanical strength and hydrological conditions; and

(ii) external forcing, particularly marine processes such as wave action, storm-driven events, and variability in sea-ice extent affecting coastal exposure.

Within this framework, the observed non-linear behaviour is interpreted as a threshold response, where progressive thermal weakening of the cliff material leads to increased susceptibility to episodic erosion. At the same time, spatial heterogeneity is explained by the strong variability in geomorphological setting, sediment properties, and local hydrological conditions along the coastal line.

Importantly, these mechanisms are presented as plausible and testable hypotheses, rather than definitive causal relationships, and we explicitly distinguish between observational results and process-based interpretation.

To link non-linearity (time), spatial heterogeneity and plausible physical mechanisms, we have included the following sentence in the Discussion section:

The observed non-linear and spatially heterogeneous erosion patterns can be interpreted as the result of interacting internal and external controls, where progressive permafrost degradation conditions the mechanical response of the cliff, while marine forcing acts as a triggering mechanism modulating sediment removal.

- ✓ **2) Reviewer comment: "You stated that the acceleration of erosion after 2000 is related to increasing warming of atmosphere – do you have any data to prove it? How does this go together with the cooling trend reported around the Antarctic Peninsula?"**

We thank the reviewer for this important observation. We agree that the relationship between atmospheric temperature trends and the observed acceleration of coastal erosion requires careful interpretation.

In the original manuscript, some statements may not have made clear the impact of short- to medium-term variations in the climate of the Antarctic Peninsula, such as the observed atmospheric warming and increased erosion rates. We acknowledge that this interpretation was not sufficiently supported and could be misleading, particularly in the context of the well-documented spatial and temporal variability of climate in the Antarctic Peninsula region, including periods of cooling or stabilisation following earlier warming trends.

In the revised manuscript, we have clarified this point and revised the wording to avoid implying direct causality. The post-2000 acceleration in erosion is now interpreted as an observational feature of the shoreline time series, which may be associated with threshold-type responses in permafrost systems, rather than a direct response to short-term atmospheric temperature trends.

We further discuss that permafrost degradation, active-layer variability, and hydrological changes may produce delayed and non-linear geomorphic responses, which are not necessarily synchronous with atmospheric temperature evolution. In this framework, both warming and subsequent cooling phases can be accommodated within a longer-term trajectory of ground thermal change and mechanical weakening.

These clarifications have been incorporated into the Discussion section, where we explicitly distinguish between observed patterns and their possible drivers, and emphasise the complexity of linking climatic variability to coastal erosion processes in Antarctic periglacial environments:

A further aspect concerns the potential temporal relationship between climatic variability and retreat rates. Although the available dataset does not allow for a direct statistical correlation between temperature anomalies and shoreline change, the observed post-2000 acceleration broadly coincides with a period of increased climatic variability in the Antarctic Peninsula region, characterised by overall warming trends punctuated by short-term cooling episodes and extreme events (Turner et al., 2016; Oliva et al., 2017; Gorodetskaya et al., 2023). In permafrost-dominated coastal systems, such variability is expected to produce delayed and non-linear geomorphic responses, as ground thermal regimes integrate cumulative forcing over time. This implies that erosion rates may not respond synchronously to atmospheric temperature fluctuations, but rather reflect the progressive adjustment of subsurface thermal and hydrological conditions. Within this framework, the acceleration in retreat can be interpreted as the outcome of a time-lagged response to prior warming, potentially amplified by episodic extreme events. Establishing robust quantitative relationships between climatic drivers and coastal change, however, requires higher temporal resolution datasets and coupled monitoring of atmospheric, oceanic, and ground thermal conditions, which remain limited in Antarctic environments.

- ✓ **3) Reviewer comment: "Why is the erosion so spatially variable? Is there any effect of the research stations? Concentration of erosion near the river mouth suggests thermal degradation rather than mechanical erosion."**

We thank the reviewer for this insightful comment and agree that the marked spatial variability of erosion, particularly the enhanced retreat observed near the river mouth, requires clearer interpretation.

In the revised manuscript, we have expanded the Discussion to provide a more structured explanation of spatial heterogeneity. The observed variability is now interpreted as the result of the interaction between several localised factors, including: (i) geomorphological controls, such as cliff height, slope, and sediment characteristics; (ii) hydrological processes, particularly the concentration of surface and subsurface flow near the river mouth; and (iii) spatial variability in permafrost conditions, including differences in ground-ice content and active-layer thickness.

In particular, the concentration of erosion near the river mouth is consistent with enhanced thermal and hydrological degradation of permafrost. Focused water flow can increase heat transfer into the ground, promote thawing, and reduce the mechanical strength of ice-rich sediments, thereby facilitating localised mass wasting and retreat. This interpretation is consistent with the hypothesis that internal weakening processes play a key role in controlling erosion patterns, with marine forcing acting as a secondary triggering mechanism.

Regarding the potential influence of nearby research stations, we acknowledge that local anthropogenic effects—such as heat dissipation, modification of drainage pathways, or surface disturbance—may contribute to small-scale variability. However, due to the absence of quantitative data, these effects cannot be isolated or assessed robustly in the present study. We have therefore incorporated a cautious discussion of this aspect, framing it as a potential contributing factor rather than a primary driver.

These additions have been included in the Discussion section, where spatial variability is now explicitly addressed within the broader framework of interacting thermal, hydrological, and geomorphological controls, with the following paragraphs:

The pronounced spatial variability in cliff retreat observed along the study area reflects the strong influence of localised controls. In particular, enhanced erosion near the river mouth suggests the importance of hydrological and thermal processes, where concentrated surface and subsurface flow can increase heat transfer into the ground and promote permafrost degradation. This leads to a reduction in the mechanical strength of ice-rich sediments, favouring localised slope instability and episodic mass wasting. Such behaviour highlights the role of internal preconditioning, whereby spatial differences in ground-ice content, active-layer thickness, and sediment properties generate heterogeneous responses to external forcing. In this context, marine processes act primarily as a triggering mechanism, while the spatial pattern of erosion is largely governed by variability in subsurface conditions and hydrological pathways.

In addition, the proximity of the Argentine and Spanish research stations may introduce localised anthropogenic effects, including heat dissipation, modification of drainage, or surface disturbance. Although these influences cannot be quantified with the available data, they may contribute to small-scale variability and should be considered in future site-specific investigations.

- ✓ **4) Reviewer comment: "The site is well sheltered from prevailing SW winds… What is then the primary cause of cliff erosion? Is it really a coastal process or just permafrost degradation?"**

We thank the reviewer for this important and insightful question. We agree that the semi-enclosed setting of Port Foster, where the study site is partially sheltered from prevailing SW winds, has important implications for the interpretation of the dominant erosion mechanisms.

In the revised manuscript, we clarify that the observed cliff retreat should not be interpreted as the result of a purely wave-driven coastal process. Instead, we frame it as a coupled coastal–periglacial system, in which internal and external factors interact to control erosion dynamics.

Specifically, the relatively low wave energy under typical conditions suggests that classic marine abrasion is unlikely to be the dominant driver. Rather, we interpret the system as being primarily controlled by internal processes, including permafrost degradation, active-layer dynamics, hydrogeologically and hydrologically driven weakening of ice-rich sediments. These processes progressively reduce the mechanical strength of the cliff material and generate spatially heterogeneous susceptibility to erosion.

Within this framework, marine forcing—although limited under mean conditions—acts mainly as a triggering mechanism, particularly during episodic high-wind events, facilitating the removal of already weakened material at the cliff toe. In addition, marine processes contribute as a boundary condition by regulating moisture availability and sediment redistribution.

This interpretation is consistent with the observed non-linear behaviour and spatial variability of erosion, which are better explained by threshold responses in a thermally preconditioned system than by continuous wave-driven processes. These clarifications have been incorporated into the Discussion section, where we explicitly describe the study area as a coastal periglacial environment governed by interacting thermal, hydrological, and marine controls.

Although the study area is partially sheltered from the dominant regional wave climate due to the semi-enclosed configuration of Port Foster, coastal processes remain relevant but operate in a modified regime. Under typical conditions, wave energy is relatively low, limiting the role of continuous marine abrasion. However, episodic high-wind events can locally enhance wave activity and contribute to sediment redistribution and cliff toe erosion (Caballero-Martínez et al., 2025).

(...)

In this context, cliff retreat is best interpreted as a coastal–periglacial process, in which internal degradation mechanisms—such as permafrost thaw, active-layer deepening, and hydrologically driven weakening—control the mechanical state of the material, while marine forcing acts as a secondary but necessary trigger. This coupling explains how significant erosion can occur even in relatively sheltered environments, where the system remains sensitive to moderate external perturbations once internal weakening has taken place.

- ✓ **5) Reviewer comment: "I don't see any discussion of the reported erosion rates, comparison to other sites around Antarctica or Arctic. Is the erosion rate low or high?"**

We thank the reviewer for this important comment. We agree that a clearer contextualisation of the observed erosion rates is necessary to assess their significance.

In the revised manuscript, we have expanded the Discussion to include a comparison with reported coastal retreat rates from both Arctic and Antarctic permafrost environments. This comparison highlights that erosion rates at Port Foster are generally lower than those reported for highly exposed Arctic permafrost coasts, where mean retreat rates commonly range between ~0.5 and 1.2 m yr^{-1} and may locally exceed several metres per year in ice-rich bluffs. In contrast, Antarctic coastal environments—particularly in sheltered or semi-enclosed settings such as Port Foster—remain comparatively under-documented, but available evidence suggests more moderate and spatially variable rates.

Our results fall within this Antarctic range but also show locally elevated values (up to several m/y) in specific sectors, particularly where permafrost degradation and hydrological processes are concentrated. This indicates that, although the overall system is less energetic than Arctic coasts, localised conditions can lead to significant erosion.

We also emphasise that the Antarctic Peninsula remains a data-sparse region in terms of quantified coastal erosion rates, and therefore our study contributes valuable long-term observations to a relatively underrepresented dataset. These additions provide a clearer framework for interpreting whether the reported erosion rates are low or high in a broader polar context.

The actual erosion rates observed in this study can be better understood when placed within a broader polar context. Arctic permafrost coasts are among the most rapidly eroding environments globally, with mean retreat rates typically ranging between ~0.5 and 1.2 m yr^{-1}, and local maxima exceeding several metres per year in ice-rich bluffs, driven by the combined effects of thermal degradation and wave action (e.g. Lantuit et al., 2012; Barnhart et al., 2014a; Gibbs and Richmond, 2017; Gibbs et al., 2019; Jones et al., 2020). In contrast, coastal erosion in the Antarctic Peninsula and South Shetland Islands remains comparatively less well quantified, reflecting both lower marine energy conditions in many settings and the scarcity of long-term observational datasets Reported rates in Antarctic ice-free coastal sectors are typically lower, but highly variable, depending on local geomorphological and permafrost conditions and fitted linearly (e.g. Torrecillas et al., 2024).

Within this framework, the rates obtained for Port Foster can be considered moderate at the system scale, but locally significant. While much of the coastline exhibits relatively low to moderate retreat, specific sectors show markedly higher rates, reaching several metres per year, particularly in areas affected by concentrated hydrological flow and permafrost degradation. This highlights the importance of local controls and threshold behaviour, where spatial variability in ground-ice content, sediment properties, and moisture availability governs the response to external forcing. These findings support the interpretation that Antarctic periglacial coasts, although generally less energetic than their Arctic counterparts, can exhibit comparable short-term erosion magnitudes under favourable conditions. At the same time, the limited availability of comparable long-term datasets in Antarctica underscores the relevance of this study in contributing to a still emerging regional framework of coastal change.

- ✓ **6) Reviewer comment: "Perhaps a detailed geological conditions of the cliff might help in interpretation."**

We thank the reviewer for this valuable suggestion and agree that a clearer description of the geological and geomechanical characteristics of the cliff helps to better interpret the observed erosion patterns.

In the revised manuscript, we have expanded the Discussion to explicitly describe the cliff as being composed predominantly of poorly consolidated volcanic tephra deposits, characterised by low cohesion and high porosity. While the lithology appears relatively homogeneous at the outcrop scale, its geotechnical behaviour is strongly influenced by spatial variability in ground-ice content, moisture conditions, and thermal state, which introduce significant heterogeneity in mechanical properties.

In this context, the interaction between tephra and ground ice forms a composite material whose strength is highly sensitive to temperature and water content. Progressive permafrost degradation and active-layer variability can therefore lead to substantial reductions in shear strength, promoting localised instability and retreat. This provides a consistent explanation for the observed spatial variability in erosion rates despite the apparent lithological uniformity.

We also clarify that, although a detailed geotechnical characterisation is beyond the scope of the present dataset, lithological and thermal contrasts—particularly those related to permafrost conditions—are likely to be critical controls on erosion dynamics. These aspects are now more explicitly incorporated into the Discussion as part of the broader framework of interacting thermal, hydrological, and mechanical processes.

The geological characteristics of the cliff provide an important framework for interpreting the observed erosion dynamics. The study area is predominantly composed of poorly consolidated volcanic tephra, forming a relatively homogeneous lithological unit at the macroscopic scale. However, its mechanical behaviour is strongly modulated by the presence of ground ice and variable moisture conditions, resulting in a thermally sensitive composite material. In periglacial conditions, the strength of such materials depends not only on their granular properties but also on the ice content and its phase state. Consequently, spatial variations in permafrost distribution, active-layer thickness, and water saturation can produce significant heterogeneity in geomechanical properties along the cliff. This explains why erosion rates could vary over short distances, despite limited lithological contrast.

(...)

This behaviour reinforces the interpretation of the system as a non-linear, threshold-controlled environment, in which relatively small changes in thermal or hydrological conditions can lead to disproportionate geomorphological responses once critical weakening of the material has occurred.

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(some of them will also be included in the References section of the revised manuscript)

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