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Assessing the degree of impact from iceberg activities on penguin colonies of Clarence Island

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Abstract

During August and September 2023, three giant icebergs, each bigger than Paris, successively grazed Clarence Island in the northeast of the Antarctic Peninsula, a home to a population of over 100 000 penguins. This incident may serve as a clarion call for the increasing iceberg calving due to global warming and its subsequent impact on the Antarctic ecosystem. Here we investigate this unexpected event and employ historical records and probabilistic analyses of iceberg grounding to assess the degree of impact on penguin colonies of Clarence Island. Among the eleven colonies, there is one with low impact, eight with medium impact, and two with high impact. The low-impact colony, Cape Lloyd, is located in the northern part of the island, while the high-impact colonies, False Ridge and Pink Pool, are in the southeast. The eight medium-impact colonies are distributed along both the eastern and western coasts of the island. This study provides essential support for evaluating the impact of iceberg activity on penguin colonies. We argue that penguin colonies located in areas prone to iceberg drift, such as Clarence Island, may become more vulnerable to the heightened risk of iceberg collisions or groundings in the warming future. Therefore, we hope the public will become more aware of the grave impacts of climate change on penguins and underscore the urgent need for effective conservation strategies.

Key words: iceberg, penguin, remote sensing, extreme events, climate change

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1 Introduction

Clarence Island encountered three giant icebergs over a month (August–September 2023). Icebergs D29B and D30A grazed Clarence Island on August 3 and September 8, respectively, while Iceberg D28 approached about 10 km of the island on August 15 before swiftly departing after skimming the northeastern region of the island on August 17. Luckily, Clarence Island was spared any catastrophic impact. This was partly due to the timing of annual nesting and breeding season for these penguins, which typically spans from October to February (Sladen, 1953). A few months' delay in the arrival of the icebergs, accompanied by grounding, could have dire consequences on the nesting penguins, potentially resulting in a total breeding failure for the year (NASA Earth Observatory).

Clarence Island is located approximately 200 km from the northern tip of the Antarctic Peninsula, part of the South Shetland Islands. The island is home to eleven distinct penguin colonies, including those of the Adélie penguins (*Pygoscelis adeliae*), Chinstrap penguins (*Pygoscelis antarcticus*), and Macaroni penguins (*Eudyptes chrysolophus*). These penguins are pivotal to the ecosystem of the island and are also regarded as sentinels of Antarctic climate change (Lynch and LaRue, 2014). These birds subsist mainly on krill and fish; they engage in reproductive activities during the austral summer (Lynnes et al., 2004). Historical records reveal breeding pair counts of 2 206 for Adélie penguins (in 2006) and 87 370 for Chinstrap penguins (in 2011), while the Macaroni penguin population had 4 142 breeding pairs in 1977 (Humphries et al., 2017). The leeward, flat terrain on the eastern side of the island offers favorable conditions for penguin nesting and account for 78% of the total penguin population on the island. An abundance of nearby krill bases in the eastern waters substantially enriches the food resources available to penguins (Fig. 1).

Historically, there have been catastrophic events caused by grounded icebergs that threatened penguin survival. For instance, in 2001, the giant iceberg B15A invaded the Cape Crozier colony in the southwestern Ross Sea, destroying nests and crushing penguins, resulting in a complete breeding failure for that year. The chick count in Cape Crozier in 2002 reduced by 954 compared to the year 2000, a decline of 79% (Kooyman et al., 2007). Indeed, the impacts of icebergs on penguin colonies are both substantial and complex: besides immediate colony

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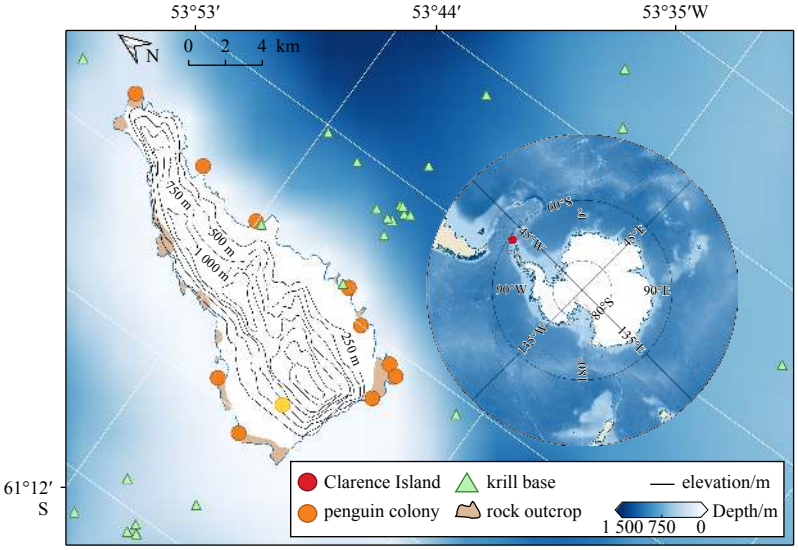

Fig. 1. Clarence Island and penguin colonies. Orange dots and green triangles represent penguin colonies and krill bases, respectively. Black closed lines indicate contour lines, and the brown regions depict the exposed rock areas on the island. The base map shows the bathymetric features. An inset on the right demonstrates the location of Clarence Island.

destruction, long-term grounding can compel penguins to alter their foraging routes, and hinder population growth (Arrigo et al., 2002; Dugger et al., 2010). However, icebergs can offer benefits. Shorter, smaller icebergs may serve as temporary habitats for penguins (Fretwell et al., 2023). Additionally, the fertilization effect of giant icebergs can stimulate productivity (Duprat et al., 2016). Deep water and minerals entrained by the meltwater plumes can enhance krill reproduction, thereby enriching the food supply for the penguins. Nevertheless, the adverse impacts are more pronounced when giant icebergs become grounded near or within penguin colonies (Kooyman et al., 2007).

Clarence Island, as one of the important penguin colonies, experienced three iceberg grazing events over a month. Such events provide us with excellent case studies to understand the activities of giant icebergs near penguin colonies and to evaluate the impact of iceberg on these colonies under a changing climate. To this end, we utilized satellite imagery to track the icebergs, analyzing seafloor topography, ocean currents, wind speeds to comprehend the behavior of the icebergs. Furthermore, we employed historical iceberg activity data and the probability of iceberg grounding to assess the degree of impact from iceberg on penguin colonies.

2 Materials and methods

2.1 *Iceberg tracking*

We employed Sentinel-1, Sentinel-2, and Moderate Resolution Imaging Spectroradiometer (MODIS) datasets on the Google Earth Engine (GEE) platform to monitor iceberg trajectories. SAR imagery from Sentinel-1 served as our primary data for delineating the trajectories of the three icebergs. During intervals of Sentinel-1 data unavailability, we relied on the daily temporal resolution of MOD09GA imagery to examine iceberg activity. Sentinel-2 data were specifically deployed to assess the impact on the island during iceberg encounters. Monthly mean wind speed data from July to September 2023 were extracted from the ERA5 dataset, while monthly mean ocean current velocities from 0 m to 400 m depth for the same period were computed using Ocean Reanalysis System 5 (ORAS5) data.

2.2 *Quantifying iceberg passage near penguin colonies*

Iceberg trajectory records sourced from Brigham Young University (BYU) (Budge and Long, 2018) were used in this study. We established a 10 km buffer zone around each penguin colony and counted the number of icebergs that passed through these zones from 1978 to 2023. The lower quartile (Q_1) and upper quartile (Q_3) of iceberg counts were calculated, and the frequencies were categorized as high, medium, or low. Counts below Q_1 are designated as low, counts above Q_3 as high, and those falling between Q_1 and Q_3 as medium.

2.3 *Evaluating iceberg grounding probability near penguin colonies*

We leveraged the Radarsat Antarctic Mapping Project Digital Elevation Model (Version 2), integrated in Quantarctica, to ascertain the average seabed depth within a 10 km buffer around the eleven colonies. Iceberg grounding probabilities were categorized based on bathymetric conditions into high risk (0–400 m), medium risk (400–800 m), and low risk (800–2 000 m) zones (Li et al., 2017).

2.4 *Assessing degree of impact from icebergs on penguin colonies*

We employed a dual-factor approach to comprehensively assess the degree of impact from iceberg activities on the eleven penguin colonies of the island. The factors include historical data on iceberg passages near Clarence Island and the probability of iceberg grounding near the colonies. For each colony, we obtained three categories of iceberg passage frequency: low frequency, medium frequency, and high frequency (Section 2.2), as well as three categories of iceberg grounding probability: low risk, medium risk, and high risk (Section 2.3). Then, we used a matrix evaluation approach to synergistically utilize iceberg passage and grounding probability (Fig. 2). For instance, colonies were flagged for the high impact when they experienced high iceberg passage and were in a high-risk grounding zone. Conversely, colonies were marked for the low impact when they had low iceberg passage and were in a low-risk grounding zone. The degrees of iceberg impact for other scenarios are illustrated in Fig. 2. This

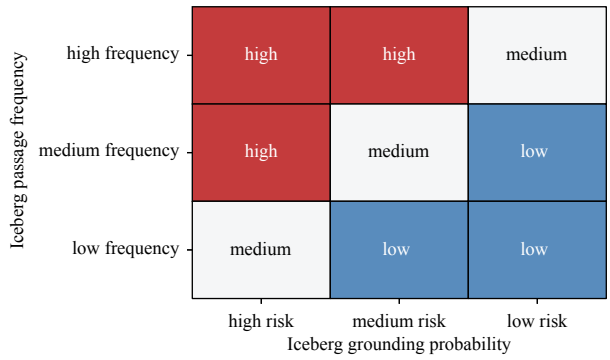

Fig. 2. Heatmap of the iceberg impact on penguin colonies. The iceberg impact is categorized into three levels: low, medium, and high, corresponding to the blue, gray, and red blocks in the heatmap, respectively. The degree of iceberg impact on penguin colonies is determined by both the iceberg passage frequency (vertical axis) and the iceberg grounding probability (horizontal axis).

classification was corroborated by empirical observations that suggest a significant impact on penguin viability when giant icebergs approach their colonies (Wilson et al., 2016).

The evaluation of iceberg impact in this study is qualitative due to the lack of ground assessments. Currently, the scarcity of data coverage in penguin populations over time (Humphries et al., 2017) and the challenges associated with timely monitoring limit quantitative studies of penguin population dynamics in response to icebergs and other climate factors. Enhancing the density of the penguin population time series through remote sensing (Larue et al., 2024) would facilitate updating this study to a quantitative assessment to explore how penguin breeding and population respond to iceberg activity.

3 Results and discussion

3.1 *Analysis of iceberg movement*

Among the three icebergs, D28 has the highest freeboard at approximately 45 m, exceeding the others by 10–15 m. D30A possesses the longest axis, approximately 72 km, which is three times longer than that of D29B. All three icebergs skimmed past the eastern part of the island (Figs 3a–d). Trajectories derived from Sentinel-1 imagery indicate that D29B and D30A displayed similar behavioral patterns as they grazed the island (Fig. 3e). Initially rotating counterclockwise upon approach, they made contact with the southeastern part of the island, continued their counterclockwise rotation, and glided northward while in close proximity to the island before eventually departing. Such rotational grazing by giant icebergs will have palpable ecological impacts, particularly on the southeastern side of Clarence Island. Sentinel-2 image on September 8 reveals a sea surface between D30A and the eastern coast of the island cluttered with brash ice induced by collision (Fig. 3e inset). Complementary examinations using MODIS imagery indicate that the island-grazing event of D29B was ephemeral, relocating northward without contact by August 5, whereas the grazing of D30A spanned an entire week. If the D30A had arrive a few months later, its sojourn could not only endanger colony safety but also force penguins to take longer foraging routes, incurring additional energy expenditure and reducing feeding frequency for chicks, thereby reducing adult survival and breeding success (Jenouvrier et al., 2014). D28 was observed to be mobile off the eastern coast of the island during July and August, and was at a distance slightly greater than 10 km from the island on August 15. MODIS imagery from August 17 shows the tail end of D28 grazing past Clarence Island, after which it rapidly departed and lost all contact within a day. The respective draft depths for D28, D29B, and D30A are approximately 372 m, 289 m, and 248 m. Given that most of the sea depths in the iceberg-adjacent areas exceed 300 m, grounding is unlikely for D29B and D30A. D28 drifted in deeper waters without colliding the island, thus avoiding grounding. Wind data from the ERA5 reanalysis during July–September indicate an average wind speed of 3.6 m/s in the eastward direction, facilitating the departure of the icebergs from the island (Fig. 3e). Ocean reanalysis system data during this period reveal a northward current near Clarence Island, also favoring the departure of the icebergs.

Further, we analyzed the trajectory data of icebergs provided by BYU to assess the iceberg passages and origins within a 10 km radius of Clarence Island. Our analysis reveals that from 1978 to 2023, Clarence Island has been situated in a hotspot for Antarctic iceberg drift (Fig. 3f). Over the past 46 years, a total of nine recorded icebergs have passed by Clarence Island, remarkably, with three of these incidents occurring just in 2023 (up until October 2023). Of all these events, the most frequent are from Area B with four occurrences, followed by Area D with three. Notably, no icebergs from Area C have been recorded passing through the island. Given its location in an iceberg drift hotspot, the ecological impact of icebergs on Clarence Island should not be underestimated.

3.2 *Degree of impact from icebergs on penguin colonies*

Our findings indicate that among the eleven colonies, only Cape Lloyd in the northern part is categorized as low impact. Two colonies exhibiting high impact are located in the southeastern part of Clarence Island, namely False Ridge and Pink Pool Point (Fig. 3g). The remaining eight colonies are of medium impact. Colony 1 in the north has a water depth nearing 700 m but has seen fewer historical iceberg passages. Colonies 4–7 in the east have average water depths exceeding 700 m and a medium-to-high frequency of historical iceberg passages, with up to nine recorded events. Compared to Colony 7, Colonies 5 and 6 experienced a higher frequency of iceberg passages, totaling eight times. Although the number of iceberg passages at Colony 4 is equal to that at Colonies 5 and 6, its average water depth (812 m) is deeper than that at Colonies 5 and 6 (719–725 m). Therefore, despite the proximity of Colonies 4–7, only Colonies 5 and 6 are classified as high impact. From the iceberg trajectories in Fig. 3e and satellite imagery we utilized, it is evident that the southeastern part of Clarence Island is indeed the area most likely to be initially impacted when icebergs approach. Therefore, the southeastern part of the island is more prone to iceberg activity. Colonies 2 and 3 have mean depths of 604 m and 685 m, respectively, shallower than the southeastern part. However, it is noteworthy that Colonies 2 and 3 are located in a concave coastline. It indicates that when large icebergs with a long axis exceeding 20 km slide along the eastern side of the island, they are less likely to directly collide with Colonies 2 and 3. This can be observed in Fig. 3e when icebergs D30A and D29B grazed the island. Colonies 9–11 on the western side of the island have average depths less than 200 m and are thus prone to grounding, although they have experienced fewer historical iceberg visits. Data from Mapping Application for Penguin Populations and Projected Dynam-

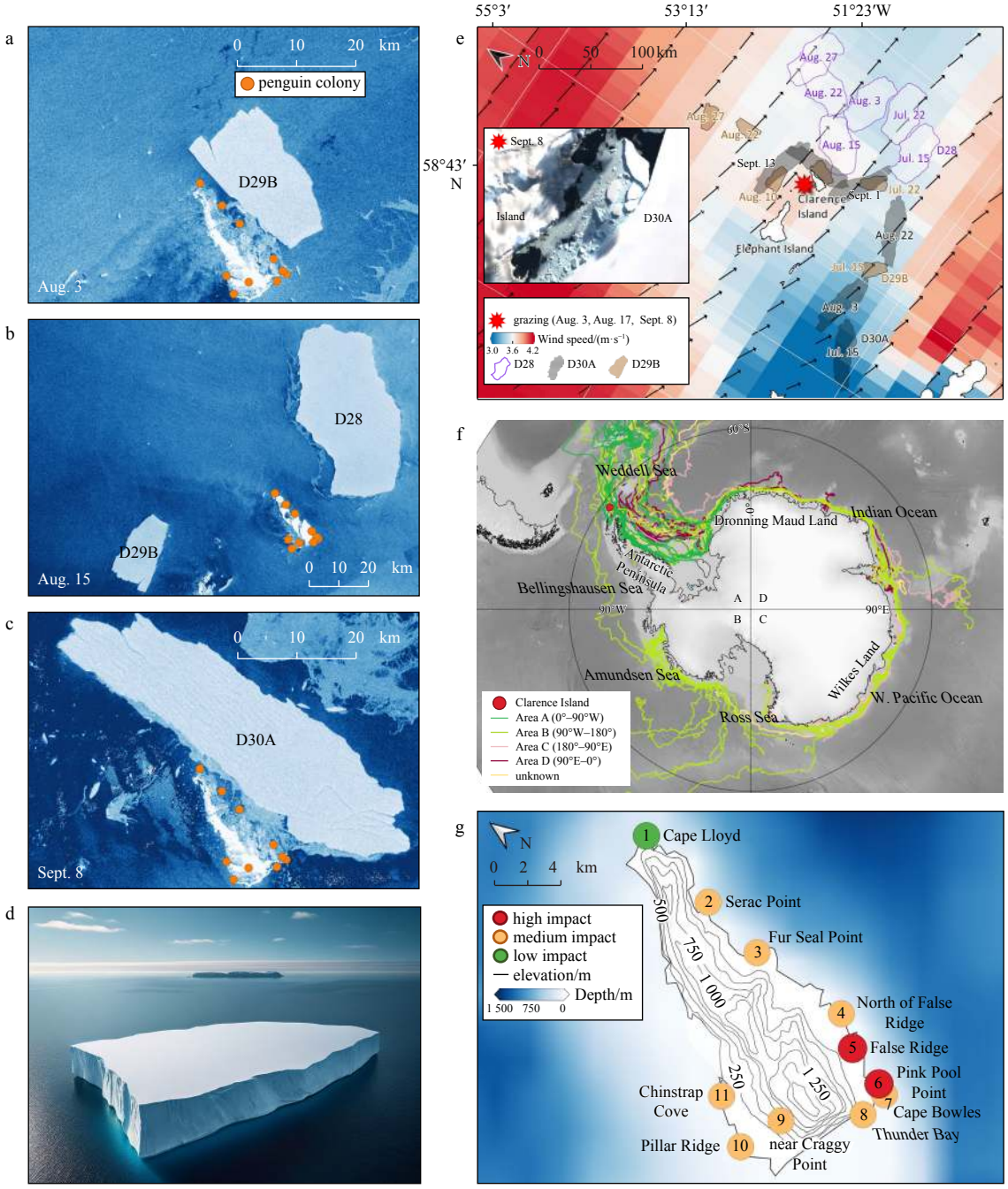

Fig. 3. Iceberg grazing events, trajectories, and assessment of impact on penguin colonies. a. Iceberg D29B grazes the island on August 3, 2023. b. Iceberg D28 nears the island on August 15, 2023. c. Iceberg D30A grazes the island on September 8, 2023. d. Schematic of a flat iceberg nearing the island. e. Trajectories of the three icebergs from July to September 2023 and average wind speeds for the period. Inset on the left features a Sentinel-2 image from September 8, 2023, showing abundant sea ice fragments. f. Trajectories and origins of icebergs from 1978 to 2023. Iceberg nomenclature is based on the Antarctic quadrant where they were first identified, with sectors delineated counterclockwise as: Area A (0°–90°W), dark green lines; Area B (90°W–180°), light green lines; Area C (180°–90°E), pink lines; Area D (90°E–0°), deep red lines. Light yellow lines indicate icebergs of unknown origin. g. Iceberg impact levels on eleven penguin colonies: red for high impact, yellow for medium impact, and green for low impact. The background displays bathymetric features.

ics (MAPPPD) on penguin populations show that over the past 36 years (1976–2011), the breeding pairs at Cape Lloyd have increased by 300 pairs, whereas those at high-impact colonies False Ridge and Pink Pool Point have decreased by 3 000 and 38 500 pairs, respectively, a decline exceeding 60%. Although various factors and mechanisms affect penguin populations, the alignment of population trends with our impact assessment suggests that our metric may offer a reasonable measure of vulnerability to penguin colonies to some extent.

3.3 *Potential impact of increased iceberg activity on penguins*

Climate warming has led to a significant increase in the incid-

ence of Antarctic iceberg calving events. Particularly during 2015–2020, the annual average number of such events escalated to 203, far surpassing the average of 97 observed in the previous decade (Qi et al., 2021). It remains unclear whether the three giant iceberg grazing events that occurred between August and September 2023 are part of a natural cycle or are directly attributed to climate change. However, with the increasing production of icebergs, this incident may potentially herald the advent of more frequent iceberg grazing. While this grazing event posed a narrow escape for Clarence Island, future episodes may not be as fortuitous, particularly for the high-impact colonies in the southeastern part of the island. Previous studies have suggested that climate warming could render penguins a vulnerable species (Jenouvrier et al., 2014; Trathan et al., 2020). Facing an escalating threat of iceberg collisions or groundings, penguin colonies, like Clarence Island, situated within iceberg drift hotspots could be more vulnerable in the future.

4 Conclusions

This study utilized satellite remote sensing data to track three giant iceberg grazing events near Clarence Island during August and September 2023, employing wind speed, ocean currents, and seabed topography data to understand the behavior of the icebergs. During the study period, eastward winds and northward currents favored the drift of icebergs away from the island, and the deeper waters off the east coast reduced the probability of iceberg grounding. Nevertheless, iceberg D30A still left a significant amount of floating ice during its grazing passage. Moreover, we integrated historical iceberg activity data and iceberg grounding probabilities to assess the degree of impact from iceberg activities on the eleven penguin colonies of Clarence Island. The results indicated that only Cape Lloyd in the north experienced low impact, while False Ridge and Pink Pool Point in the southeast were highly impacted, with other colonies facing medium impact. In a warming future, with an increase in iceberg calving events, penguin colonies located in iceberg drift hotspots are likely to experience greater impacts from iceberg activities. Hence, we call upon the public to pay heed to climate warming and implement measures such as mitigating anthropogenic greenhouse gas emissions (Trathan et al., 2020), implementing support for floating shelves, and other geoengineering methods to alleviate ice shelf collapse (Moore et al., 2018). These measures will be beneficial in mitigating threats to penguin ecosystems.

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