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1 **A tipping point in West Antarctica in 2023's circumpolar 5-sigma event? a glimpse from the**
2 **emperor penguin's perspective**

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18

19 **Abstract.** Emperor penguins are one of the seabird species most vulnerable to climate change in
20 Antarctica, as they depend on stable sea ice for breeding and molting. Recent extremes of warming
21 have taken to the lowest records of sea ice in West Antarctica in 2022 and 2023, raising concerns to
22 the extent that emperor penguins have been affected. We evaluated historical satellite data (1985-
23 2022) of sea ice around the 10 emperor penguin breeding colonies, identified so far along the coast
24 of the Amundsen and Bellingshausen Seas, and compared them to recent sea ice cover (2022-2023)
25 to identify where and when critical thresholds of sea ice cover have been crossed. We found that
26 the sea ice retreated below the critical thresholds in 2022-2023 during the chick-rearing and in some
27 cases failed to return at the start of the following breeding season, hence likely affecting 9 of the 10
28 emperor penguin colonies in the region. This is an unprecedented climatic phenomena affecting
29 breeding habitat of emperor penguin colonies over a large area, potentially affecting numerically
30 important colonies in West Antarctica.

31

32

33 **Keywords.** Antarctic - Amundsen Sea, *Aptenodytes forsteri*, Belingshausen Sea, Seabirds, Sea Ice

34

35

36 Introduction

37 Antarctic sea ice has been following a downward trend that started about one decade ago (Eayrs et
38 al. 2021) due to warming and the increased frequency of intense heat waves or warm atmospheric
39 rivers (Turner et al. 2021; Hepworth et al. 2022; Wille et al. 2022). As a consequence, Antarctic sea
40 ice cover in 2022 and even more so in 2023, with the below 5-sigma threshold, has been at its lowest
41 since the start of measurements, particularly in West Antarctica (Yadav et al. 2022; Liu et al. 2023;
42 Scott and Scambos 2023).

43 Emperor penguins have been identified as one of the most vulnerable species under the projected
44 climate change scenarios in Antarctica (Lee et al. 2022). Critical months for the breeding season of
45 emperor penguins include August to mid-December (Handley et al. 2021). Population dynamics of
46 this species are heavily linked to sea ice (Croxall 2002; Jenouvrier et al. 2014), as they are dependent
47 on stable sea (fast) ice or ice shelves for breeding and molting (Kooyman et al. 2000, 2004; Fretwell
48 et al. 2014; Zitterbart et al. 2014). Collapse of sea ice during late crèche stage (October to December)
49 have resulted in high mortality in some colonies, with posterior slow recovery (Croxall 2002; Trathan
50 et al. 2011). As a consequence, breeding sites seem to have been abandoned after consecutive years
51 of unsuitable conditions (Trathan et al. 2011; Fretwell and Trathan 2019).

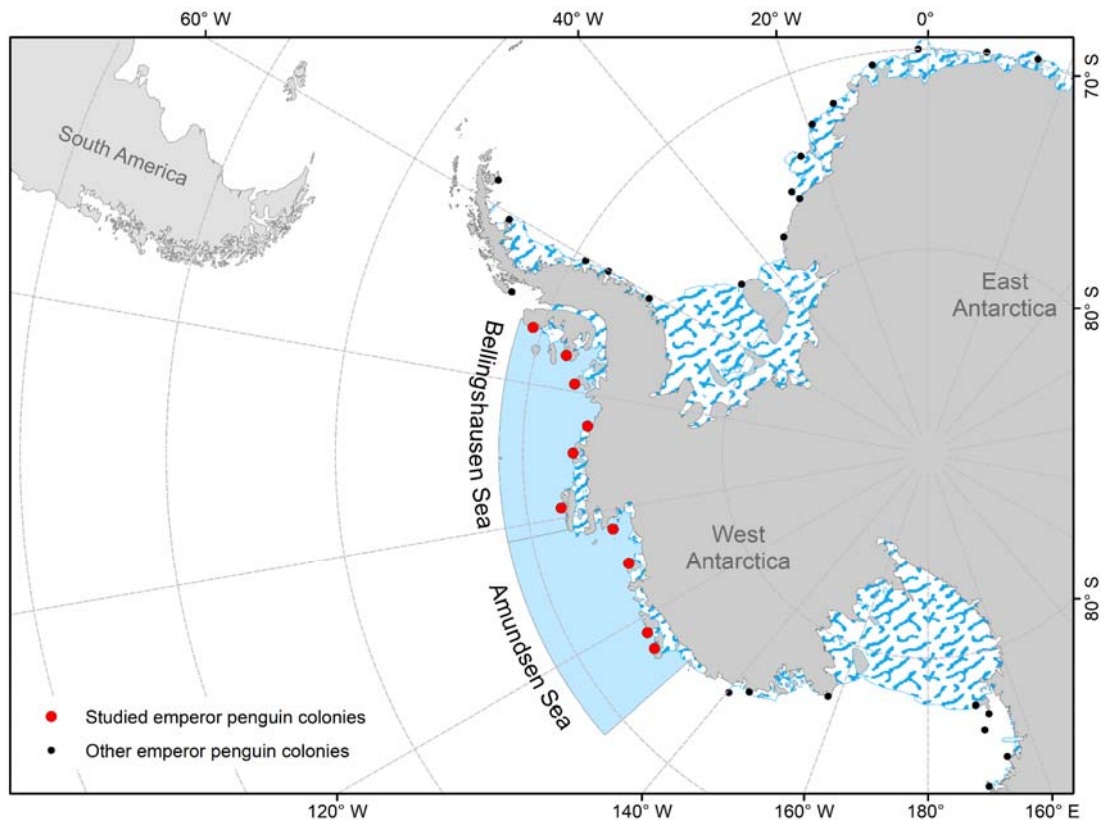
52 The recent records of low sea ice cover in west Antarctica during summer (Liu et al. 2023) poses a
53 serious concern for emperor penguins (Fretwell et al. 2023). Rapid increase in loss rate of stable sea
54 ice could represent a substantial decrease in the availability of suitable breeding habitats (Trathan et
55 al. 2020). Emperor penguin colonies in the Bellingshausen and Amundsen seas have been forecasted
56 to experience steep decreases within a period of a few decades (Jenouvrier et al. 2021), and it is
57 possible that 2022 and 2023 events mark a quickening of that process (Fretwell et al. 2023). With the
58 recent reports of intense warming taking to the lower levels of sea ice ever recorded in the
59 Amundsen and Bellingshausen Sea regions, we evaluated here the condition of sea ice at emperor
60 penguin colony sites by using a 39-years interval to calculate local sea ice daily means and identifying
61 periods between January 2022 and June 2023 when sea ice was below the historical 20th percentile.
62 We then checked from Sentinel-2 optical images for the conditions in each site where Emperor
63 penguin guano can be detected (Fretwell and Trathan 2020).

64 Methods

65 Geographic position of emperor penguin colonies from West Antarctica were downloaded from the
66 Mapping Applying for Penguin Populations and Projected Dynamics (MAPPPD ; Humphries et al.
67 2017; Lynch et al. 2022). A 50 km buffer around each of the 10 colonies (the minimum rounded
68 distance between any of the colonies was ~95km, therefore a 50km radius minimized buffer zone
69 overlap) identified in the regions of the Amundsen and Bellingshausen Seas (between 70°W and
70 130°W ; Fig. 1), was used to download daily optimum interpolation of sea ice cover (SIC) data from
71 ERDDAP server (Huang et al. 2023) between January 1, 1985 and June 20, 2023. Using the approach
72 described in (Mora-Soto et al. 2022; Schlegel and Smit 2023), a past average SIC was calculated for
73 each day of the year, using data from January 1, 1985 to December 31, 2022. Anomalies between
74 daily observations and the 38-year SIC average were calculated between January 1, 2022 and June
75 20, 2023, and periods when SIC anomalies exceeded a value below the 25th percentile of the past
76 average SIC for more than three consecutive days were identified as periods of extreme low sea ice
77 cover. Events were classified as moderate (1 time below threshold) and strong (two times below
78 threshold). Code for the analysis can be found at (Krüger 2023).

79

80 Using the methods proposed in (Fretwell and Trathan 2020), freely available Sentinel-2 optical
81 images (Sentinel-2 2023) were inspected using a cloud cover threshold of 50% and a custom
82 rendering of bands that highlights penguin guano on the surface of the sea ice
83 ([B08*0.8,B04*0.8,B03*0.8] Fretwell and Trathan 2020), between October and March of 2021/22
84 and 2022/23 breeding seasons. L1C or L2A (29 m x 29 m pixel size) images were downloaded. Guano
85 stains were identified using an unsupervised classification algorithm in ArcMap.



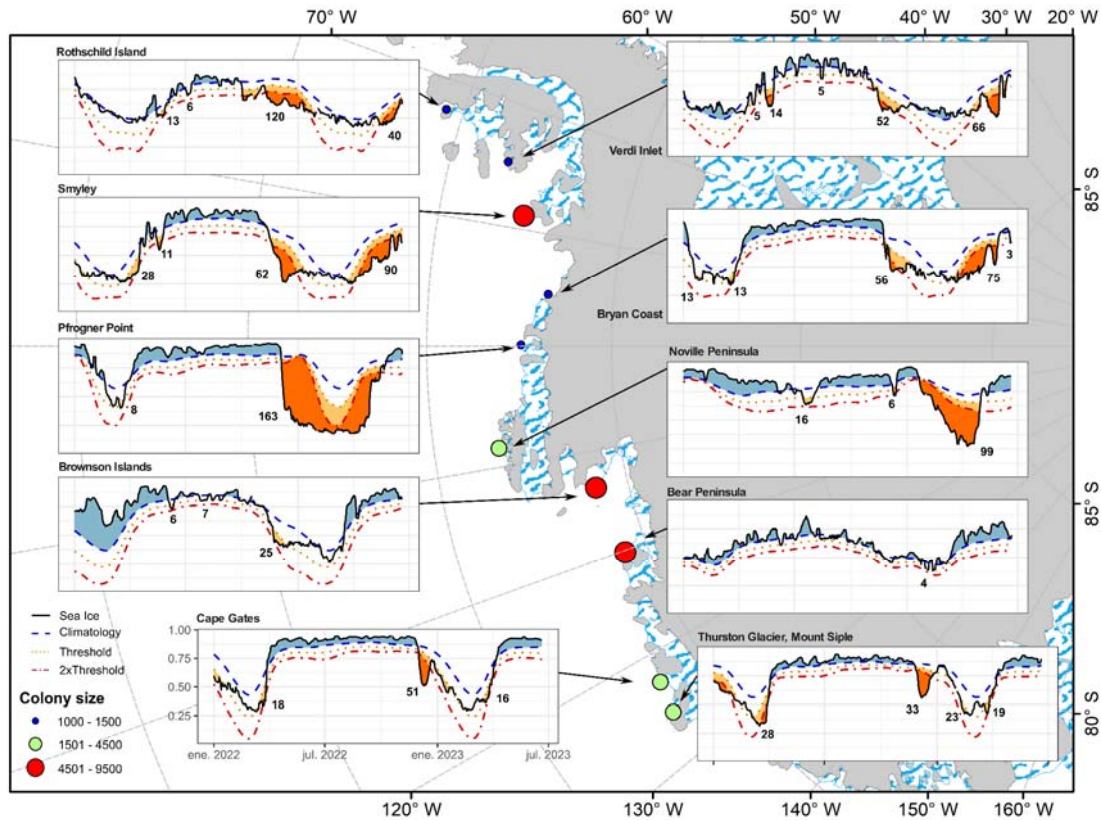
86

87 **Fig. 1** Location of studied emperor penguin colonies in the Bellingshausen and Amundsen Seas, West
88 Antarctica. The geographic position of emperor penguin colonies was downloaded from the
89 Mapping Application for Penguin Populations and Projected Dynamics (Humphries et al. 2017, Lynch
90 et al. 2023). Limits of the Bellingshausen and Amundsen Seas adapted from (Larter et al. 2014;
91 Christie et al. 2023).

92 Results

93 The three colonies to the east of 80°W, in the Bellingshausen Sea (Rothschild Island, Verdi Inlet,
94 Smyley Island), experienced short events (less than 15 days) of low sea ice cover between 2022
95 March and August, followed by longer events in October and November 2022 that persisted for over
96 30 days, and again in March to May 2023 (Fig. 2). The three colonies to the west of 80°W, in the
97 Bellingshausen Sea (Bryan Coast, Pfrogner Point and Noville Peninsula), experienced strong and long
98 events of low sea ice between November 2002 and January 2023 that persisted until middle
99 May/early June (Fig. 2). For three colonies in the Amundsen Sea (west of 100°W; Brownson Island,
100 Cape Gates, and Thurston Glacier), low sea ice events occurred in November and December 2022,

101 January, February and March 2023, with two short low sea ice events at Brownson Island in June and
 102 July 2022 (Fig. 2). The colony at Bear Peninsula had a single short, low-intensity event in February
 103 2023(Fig. 2).
 104
 105



106
 107

108 **Fig. 2** Emperor penguin colony sites (circles) in the Bellingshausen and Amundsen Sea region with
 109 estimated number of penguins (colony size) from the Mapping Application for Penguin Populations
 110 and Projected Dynamics (Humphries et al. 2017, Lynch et al. 2023). Daily sea ice cover within a 50
 111 km radius around each colony, between January 1, 2022 and June 20, 2023 (solid black line in
 112 panels), is plotted against the 38-year SIC average (dashed blue line in panels), the 25th percentile
 113 critical threshold (dotted orange line in panels) and two times the threshold (dot-dash red line in
 114 panels) to identify low sea ice anomalies compared to historical values. Blue areas show periods
 115 when average sea ice cover was above the 38-year SIC average; orange areas show periods when
 116 average sea ice cover was below the critical (25th percentile) thresholds; and red areas show periods
 117 when negative anomalies were below 2x the critical thresholds. Numbers indicate days when sea ice
 118 cover remained below the critical threshold.

119 These episodes of low sea ice cover have affected the availability of sea-ice habitat at colony site
 120 upon the return of penguins to the breeding colonies in 2023 in 9 sites (Fig 3a-j) and during chick
 121 rearing of 2022 in 6 of the 10 sites (Fig3 a,b,c,d,e,g). In Brownson Islands (Fig 3g), it was possible to
 122 see the sea ice receding substantially around the crèches between November 20 and 30, 2022,

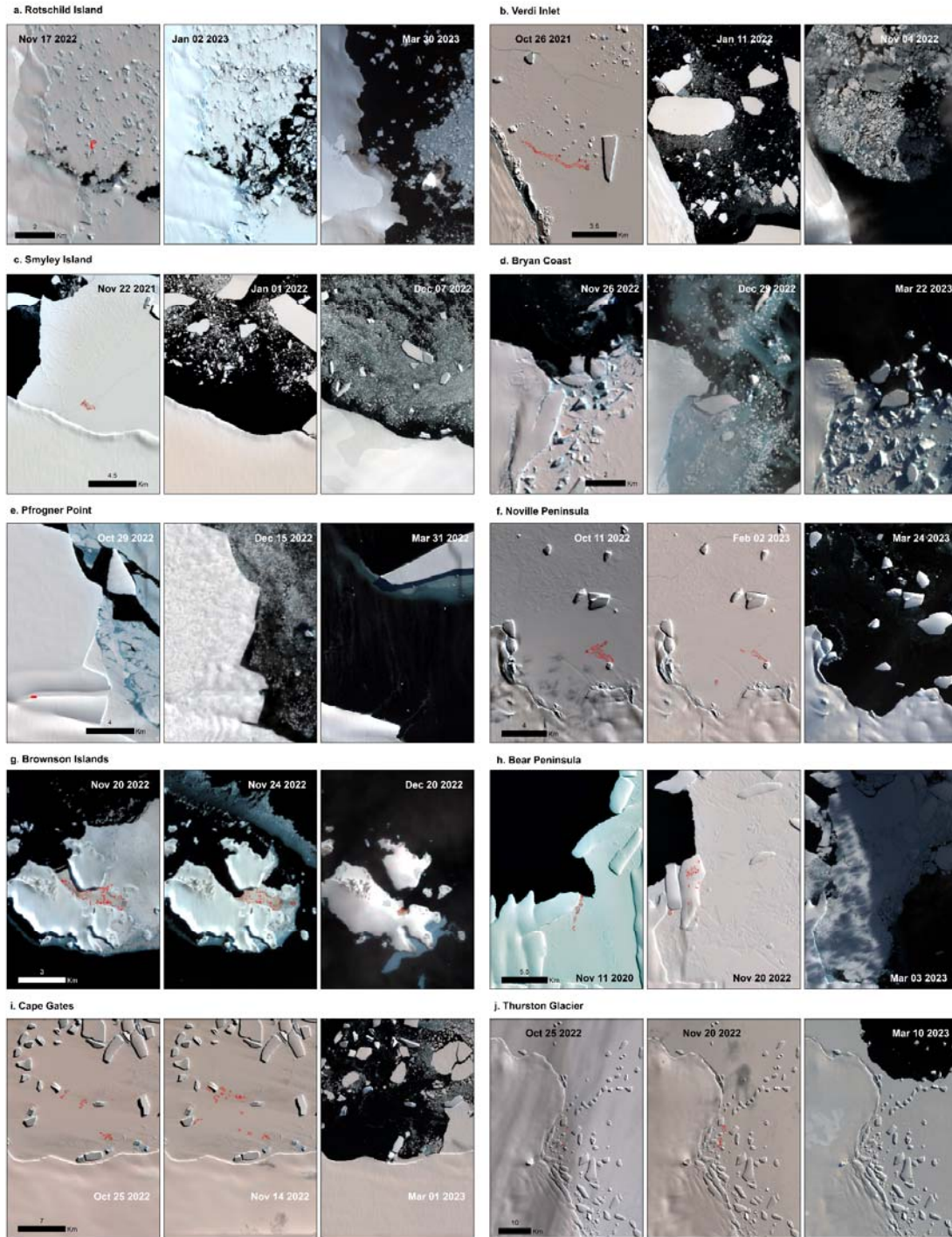
123 which were then “trapped” in a small bay when there was no more sea ice on December 20, 2022.
124 In Bear Peninsula (Fig 3h) the colony that was previously located over fast ice in 2020 moved into the
125 sea shelf in 2022, and that shelf completely collapsed by March 2023. Thurston Glacier colony (Fig
126 3j) was the only site to have stable ice throughout 2022 and 2023.

127 **Discussion**

128 Recent levels of sea ice cover in West Antarctica during key periods of emperor penguin breeding
129 activity (the late chick-rearing period and the start of the breeding season) over the past two years
130 have been lower than the 25th percentile of the last 38 years. For colonies in which satellite optical
131 images were available for these periods, sea ice within the 50 km radius turned out to be critical at
132 the breeding site.

133 While it is not possible to ascertain whether there has been breeding failure due to early sea ice
134 retreats, sea ice losses prior to mid-December can result in complete breeding failure (Fretwell and
135 Trathan 2019). There are examples of colonies that disappeared or reduced substantially in numbers
136 after years of unsuitable breeding conditions, such as in Marguerite Bay, in the West Antarctic
137 Peninsula (Trathan et al. 2011), and Halley Bay, east of the Weddell Sea (Fretwell and Trathan 2019).
138 In addition, since the satellite imagery investigations began, several colonies have been known to
139 “blink”, meaning that they disappear in some years, only to reappear in others (see Fig. 1 in
140 Jenouvrier et al. 2021). It has been suggested that this could be a result of birds’ decision to move
141 elsewhere after multiple consecutive failures or due to consecutive absence of optimal sea ice prior
142 to arrival at the colony.

143 In the 2022/2023 season, sea ice extent was substantially low at most of the studied colonies in the
144 Bellingshausen and Amundsen Seas in mid- to late-March (Fretwell et al. 2023, this study), when
145 adults start returning to the colony to breed (Stonenhouse 1953; Prévost 1958). Adults may decide
146 to skip breeding after arriving in suboptimal sea ice conditions (Kooyman and Ponganis 2017;
147 Garnier et al. 2023), and there are examples of colonies that relocated to nearby ice shelves, as
148 occurred for the colonies at Pfrogner Point (Trathan et al. 2020), Bear Peninsula (this study) , Jason
149 Peninsula and Atka Bay in the Weddell Sea (Fretwell et al. 2014; Zitterbart et al. 2014) or on the
150 mainland for the Pointe Géologie colony (during the last 2022 and 2023 breeding seasons, Le Bohec
151 unpublished observations). However, successive years of poor sea ice conditions can lead to site
152 abandonment, as is assumed to have happened to colonies in Marguerite Bay, on the western
153 Antarctic Peninsula (Trathan et al. 2011) and Halley Bay, on the eastern Weddell Sea (Fretwell and
154 Trathan 2019).



155

156 **Fig. 3** Sentinel-2 (2023) optical images at eight emperor penguin colonies from West Antarctica.
157 Images used in the analyses consisted of recent images with less than 50% of cloud coverage in late
158 crèche stage (October/November), during chick fledging period (December/January), and at the start
159 of the breeding season (March/April), during episodes of low sea ice cover in 2022 and 2023. Red
160 polygons (colony contours) were identified by unsupervised classification as penguin guano. The
161 locations of the colonies presented here can be seen in Fig. 1.

162

163

164

165 Enhanced monitoring of emperor penguin colonies in the West Antarctic is paramount to assess,
166 over the coming seasons, whether poor sea ice conditions persist and whether breeding colonies
167 continue to occupy the areas. Satellite data with better resolution could be combined with field
168 research (see Winterl et al. 2023) to assess the mortality associated with these events and its
169 consequences on population trends.

170 **Conservation considerations**

171 Recent studies have identified 29 Important Bird and Biodiversity Areas (IBAs) for emperor penguins
172 distributed along the Antarctic coast, of which around 6 are located in the Bellingshausen and
173 Amundsen Sea regions (Handley et al. 2021). Four of them (Smyley Island, Noville Peninsula,
174 Brownson Island and Cape Gates) experienced sea ice loss during chick rearing or when adults
175 returned to start a new breeding season, which likely represents a substantial proportion of the
176 region's breeding population.

177 Persistence of these colonies under expected changes in sea ice (Eayrs et al. 2021; Casagrande et al.
178 2023), depends on seabirds' ability to disperse to new breeding sites. Garnier et al. (2023) suggested
179 that emigration rates of emperor penguins are low and that their dispersal distance is short when
180 compared to their post- and pre-breeding movements. They also suggested that the establishment
181 in a new colony is random and that, when moving to a new colony, penguins may have limited
182 knowledge of the sea ice conditions at the new site. Given the levels of similarity and spatial scales
183 found in this study, even if emigration occurs in the Bellingshausen and Amundsen Sea regions, it
184 will most likely be to sites with similar sea ice conditions. At-sea tracking data (non-existent for these
185 colonies, see Houstin et al. 2022) combined with molecular techniques (i.e. Cristofari et al. 2016;
186 Garnier et al. 2023) will be crucial for understanding the process of breeding site selection by new
187 breeders and dispersal of adults under changing conditions.

188 Risks of local extinction for colonies in the Bellingshausen and Amundsen Sea region have been
189 predicted to be high in the future, even with a forecasted 1.5°C increase in global temperature
190 (Jenouvrier et al. 2021). The next few years will be of crucial importance in verifying whether
191 emperor penguins will have the ability to persist in the region.

192 **Acknowledgments**

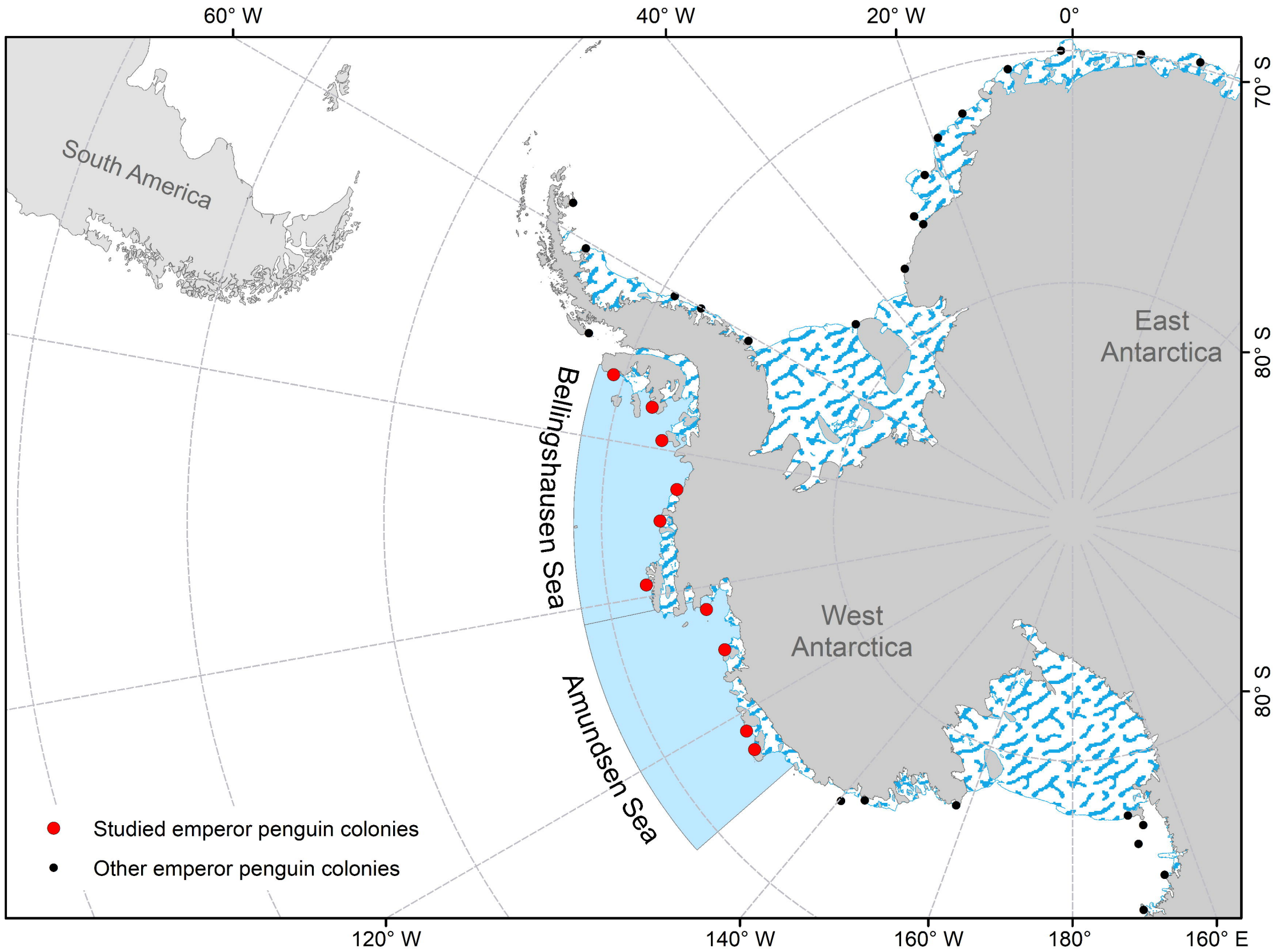
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70° W

60° W

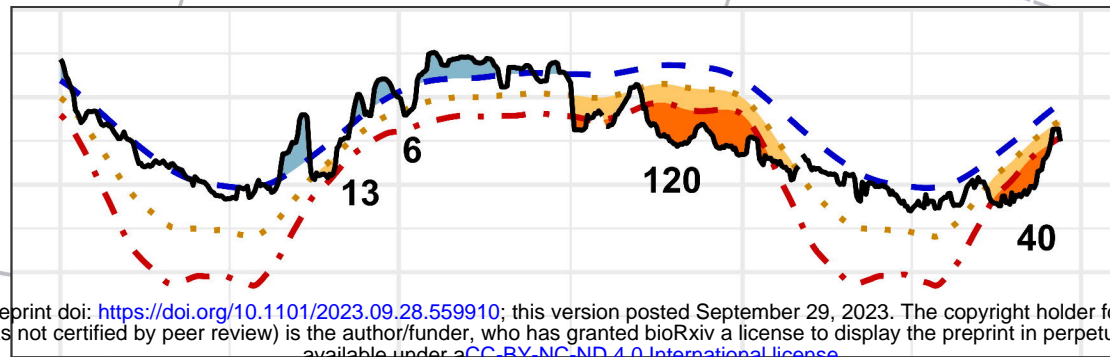
50° W

40° W

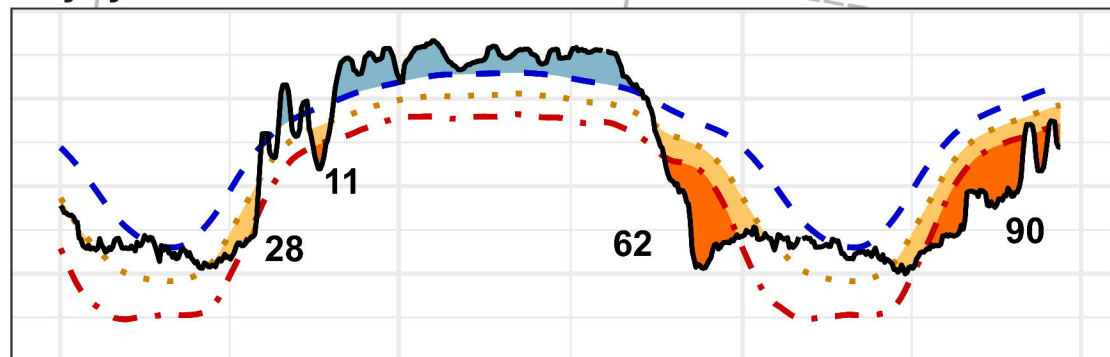
30° W

20° W

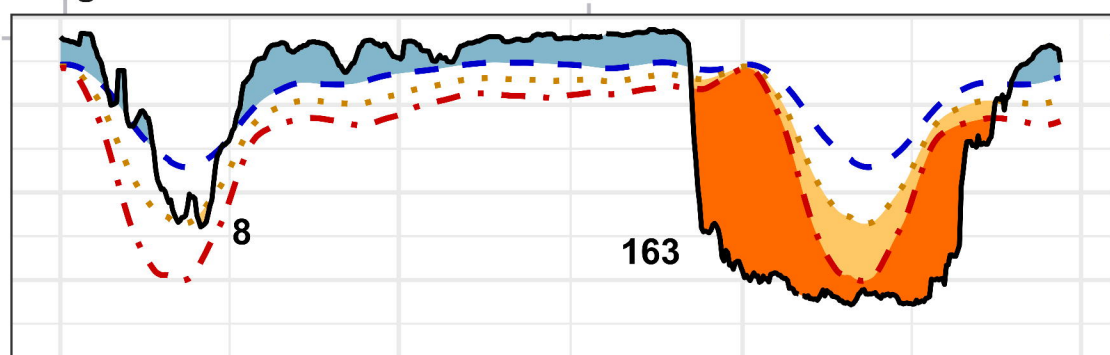
Rothschild Island



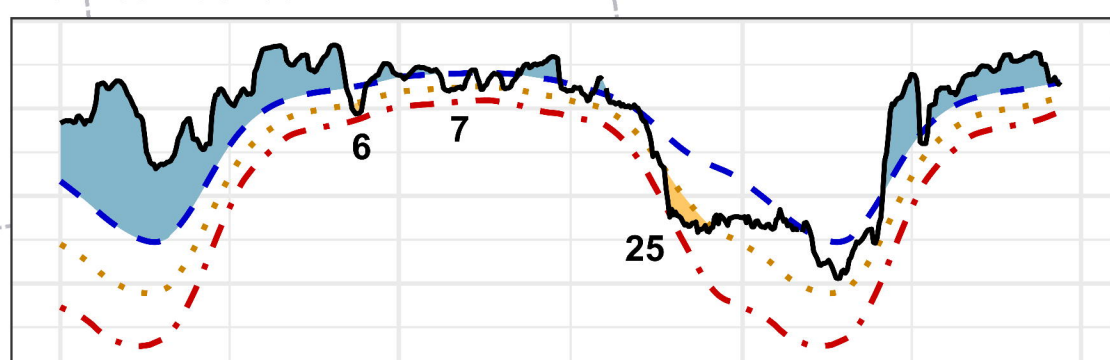
Smyley



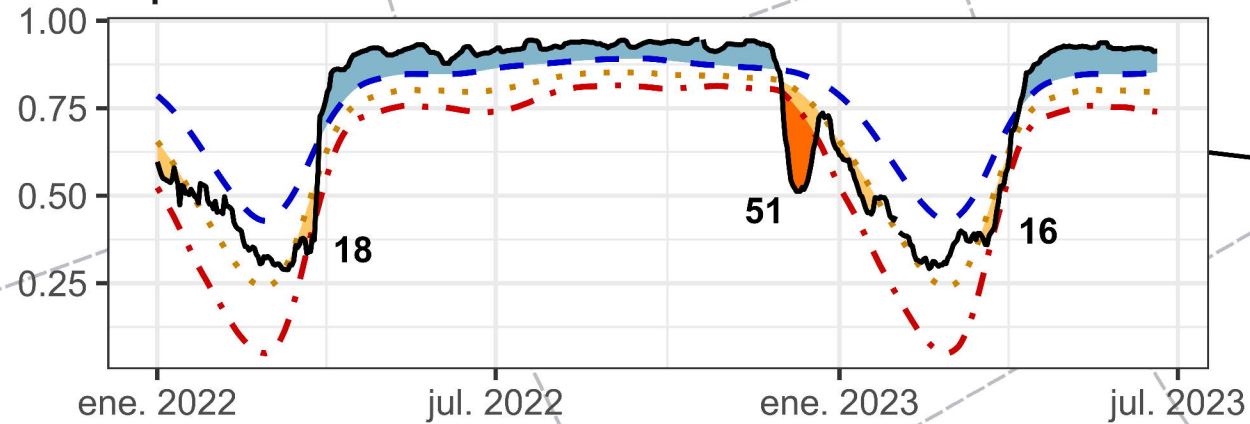
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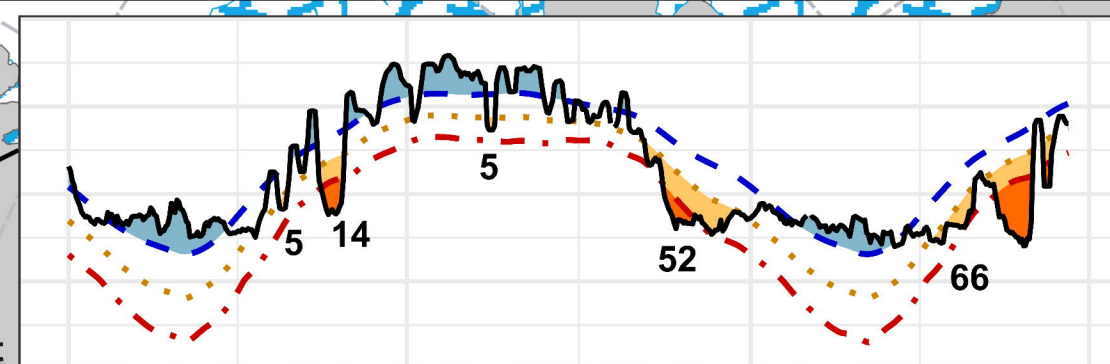
Brownson Islands



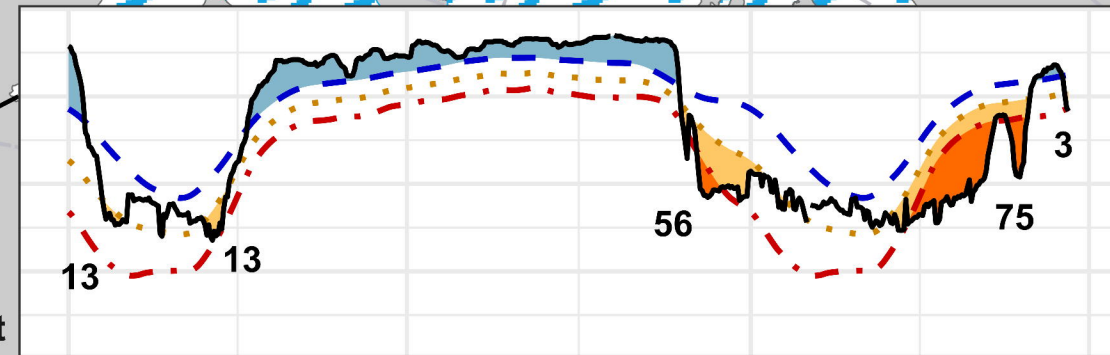
Cape Gates



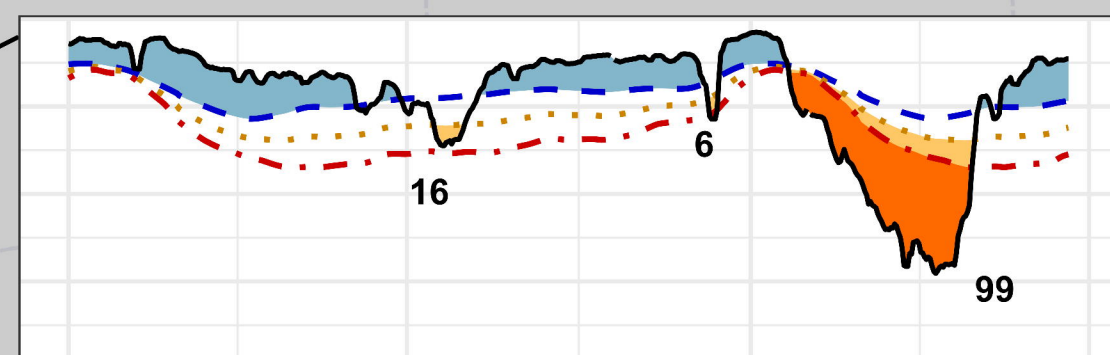
Verdi Inlet



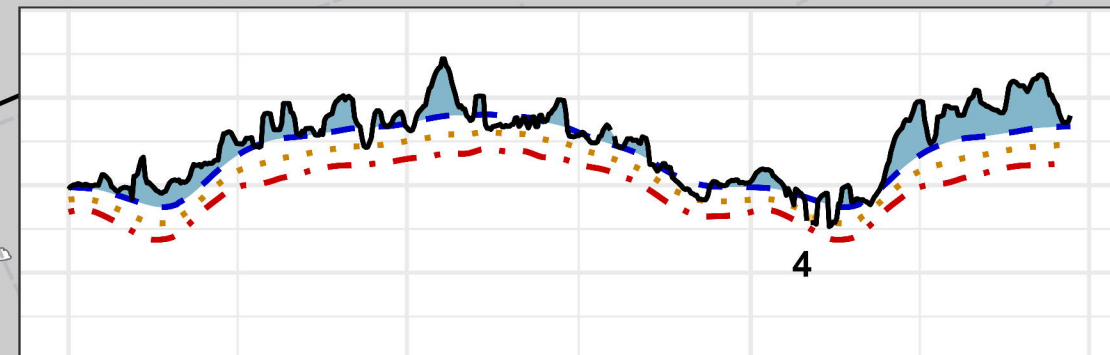
Bryan Coast



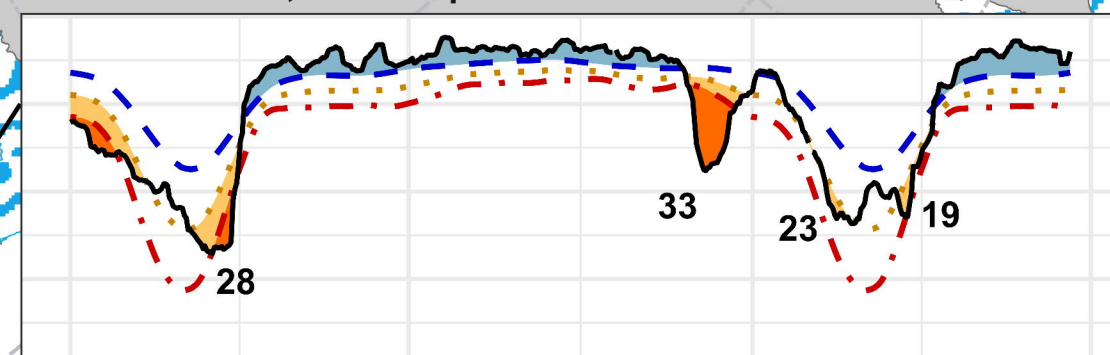
Noville Peninsula



Bear Peninsula



Thurston Glacier, Mount Siple



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- Sea Ice
 - - - Climatology
 - ... Threshold
 - - - 2xThreshold
- Colony size**
- 1000 - 1500
 - 1501 - 4500
 - 4501 - 9500

120° W

130° W

140° W

150° W

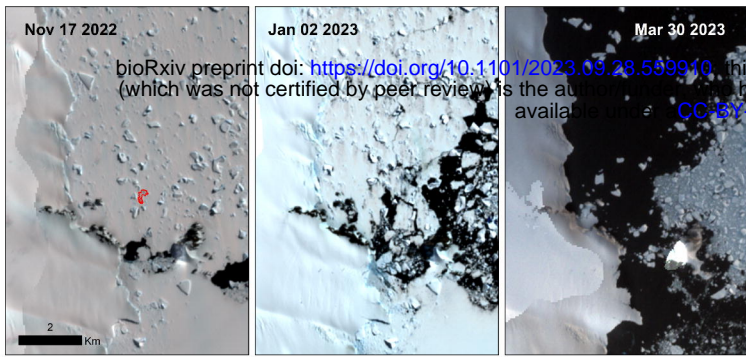
160° W

85° S

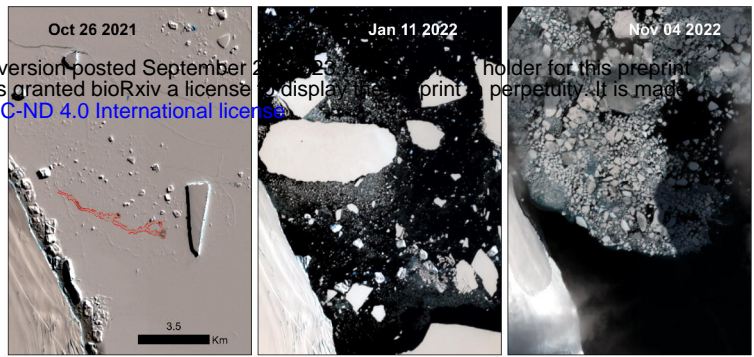
85° S

80° S

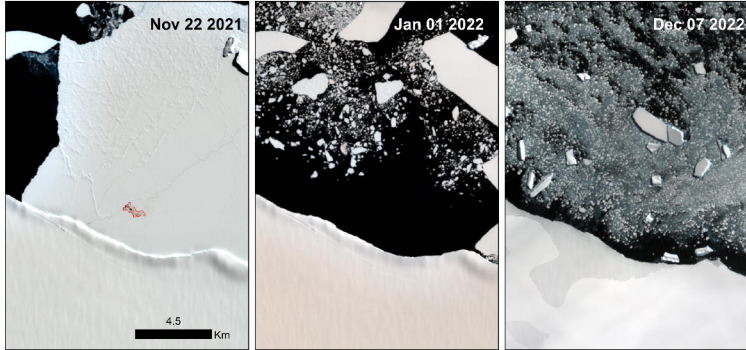
a. Rotschild Island



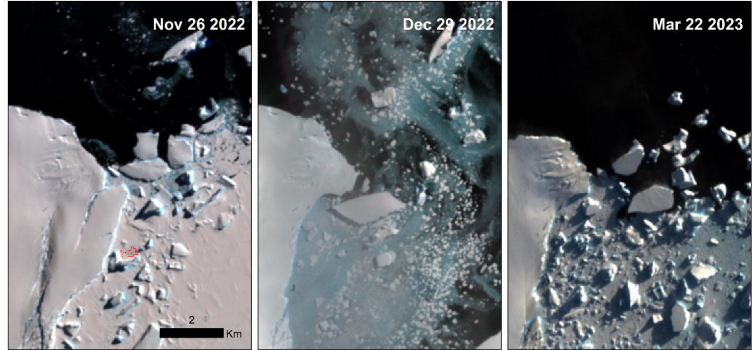
b. Verdi Inlet



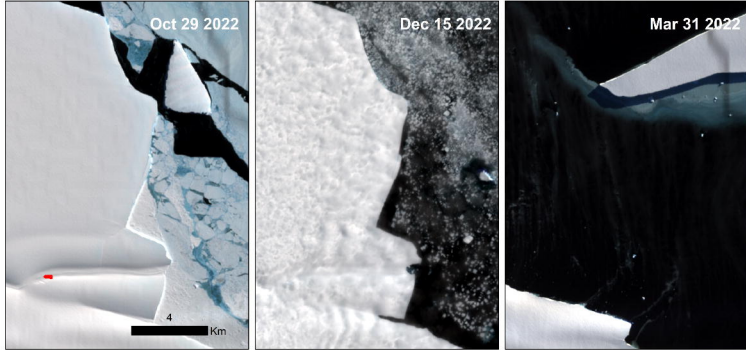
c. Smyley Island



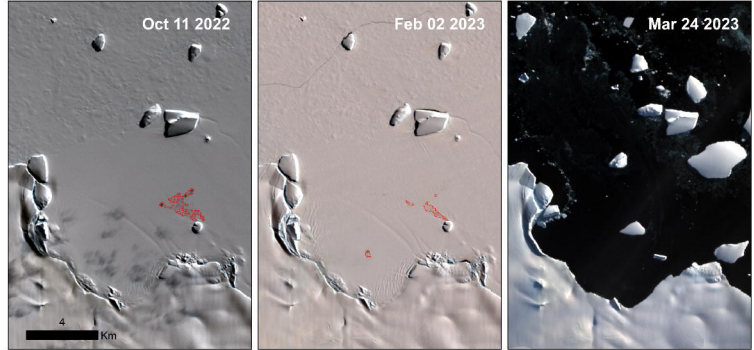
d. Bryan Coast



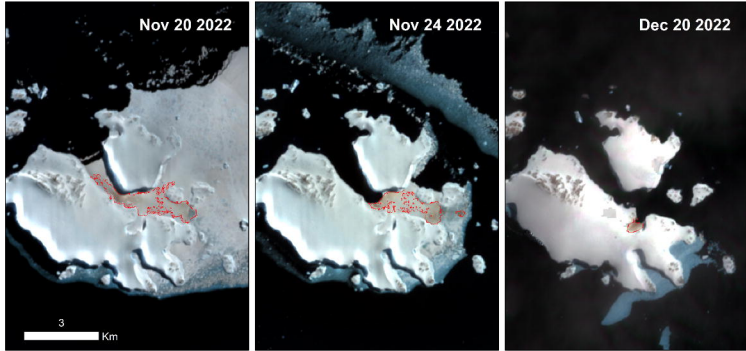
e. Pfrogner Point



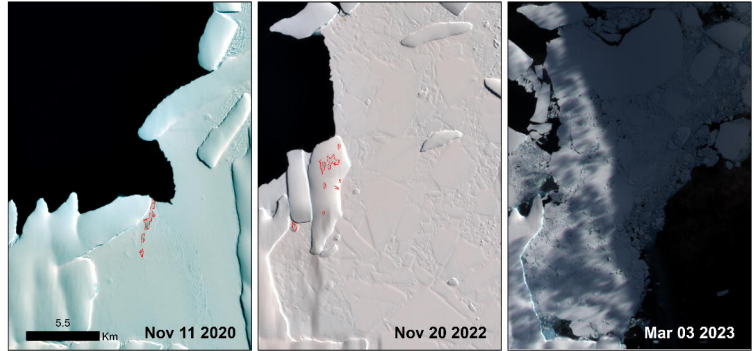
f. Noville Peninsula



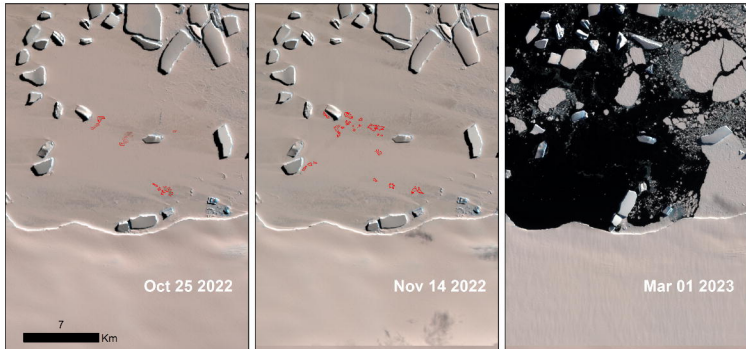
g. Brownson Islands



h. Bear Peninsula



i. Cape Gates



j. Thurston Glacier

