

## ORIGINAL RESEARCH

# Discovery of new colonies by Sentinel2 reveals good and bad news for emperor penguins

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**Keywords**

Breeding colonies, climate change, penguins, Satellite remote sensing, Sentinel2

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Editor: Kylie Scales

Associate Editor: Phil Bouchet

Received: 28 January 2020; Revised: 10 June 2020; Accepted: 10 July 2020

doi: 10.1002/rse2.176

**Abstract**

The distribution of emperor penguins is circumpolar, with 54 colony locations currently reported of which 50 are currently extant as of 2019. Here we report on eight newly discovered colonies and confirm the rediscovery of three breeding sites, only previously reported in the era before Very High Resolution satellite imagery was available, making a total of 61 breeding locations. This represents an increase of ~20% in the number of breeding sites, but, as most of the colonies appear to be small, they may only increase the total population by around 5–10%. The discoveries have been facilitated by the use of Sentinel2 satellite imagery, which has a higher resolution and more efficient search mechanism than the Landsat data previously used to search for colonies. The small size of these new colonies indicates that considerations of reproductive output in relation to metabolic rate during huddling is likely to be of interest. Some of the colonies exist in offshore habitats, something not previously reported for emperor penguins. Comparison with recent modelling results show that the geographic locations of all the newly found colonies are in areas likely to be highly vulnerable under business-as-usual greenhouse gas emissions scenarios, suggesting that population decreases for the species will be greater than previously thought.

**Introduction**

Emperor penguins *Aptenodytes forsteri* are a high latitude, ice obligate seabird that breeds during the austral winter; they are highly adapted to cold conditions and spend their entire lives in the Antarctic (see recent review by Trathan et al. 2019). Almost all colonies depend upon stable land-fast sea ice, which they use as breeding habitat. They arrive at their preferred breeding sites in late March–April, and lay eggs from May to June. Eggs hatch after 65 days and chicks fledge from December to January. Thus their breeding habitat, land-fast ice, must remain stable for approximately 9 months. In February to March, adults haul out to moult, possibly travelling long distances (up to 1200 km) from their breeding sites (Kooyman et al. 2000) to areas of seasonally persistent pack ice where they may remain for several weeks. Emperor penguins feed mainly upon fish, krill and cephalopods, mainly within the pack ice, in leads or polynyas.

Breeding emperor penguins are colonial, returning to discrete locations each year and huddling for protection

from the wind and cold, especially during incubation, which occurs during the coldest part of the year (July–August), when temperatures at breeding sites may drop below  $-40^{\circ}\text{C}$ . Their need for stable fast ice renders emperor penguins vulnerable to altered wind regimes, rising temperatures and reduced sea ice extent and persistence, as many recent studies have highlighted (Ainley et al. 2010; Jenouvrier et al. 2014; Jenouvrier et al. 2017; Jenouvrier et al. 2019). All such studies project that a large percentage of the emperor penguin population will be lost by the end of this century. Under a business-as-usual scenario, with unmitigated greenhouse gas (GHG) emissions, Jenouvrier et al. (2019) estimated that by the end of this century all colonies will decrease in size, with 43 of the 54 (80%) colonies decreasing by more than 90%, and thus quasi-extinct. Under this scenario, annual mean Antarctic sea ice extent will decrease by 48%, and breeding habitat for the most endangered colonies, in the north of the range, will probably be lost during the egg-laying season as sea ice formation is delayed by warmer temperatures. Globally, projections of abundance show a

decrease of 86%, relative to the current population size, if colonies cannot relocate to more suitable breeding habitat. Even under the best-case scenario with a global temperature increase of 1.5°C, the population will decrease by at least 31% over the next three generations (Jenouvrier et al. 2019).

Emperor penguins occupy an ecological niche dependent upon Antarctic sea ice, an ecosystem that is dynamic, at risk and extremely difficult to study. Predictions of sea ice loss (Turner et al. 2013) and other impacts of climate change, such as increases in temperature, fluctuations in precipitation, variation in ocean circulation and increased wind speed and storminess are likely to impact the whole sea ice ecosystem (Cavanagh et al. 2017). Climate model simulations project sea ice retreat over the latter part of this century, but the amount and pattern of retreat remains difficult to assess (Holmes et al. 2019). Regardless of GHG emissions scenario, there is therefore an ongoing need to monitor the population size and distribution of this sentinel species. Four years of unprecedented record Antarctic sea ice minima have occurred since 2015 (Parkinson 2019), and are likely to have impacted on breeding success at some emperor colonies and for other ice-dependent species (Fretwell and Trathan 2019). Continued and expanded systematic monitoring of emperor breeding sites is therefore essential to establish population trajectories and ecosystem impacts (Trathan et al. 2019).

A decade ago, the population size and distribution of emperor penguins remained poorly described. Wienecke (2009, 2010) reviewed historically available information and recorded 34 sites of which six were thought not to exist or had not been confirmed although a number of plausible sites remained as unconfirmed sightings, with some such sites possibly being moulting aggregations. In 2009, the realization that colonies could be identified from their guano stains on sea ice, visible in freely available Landsat7 imagery (Fretwell and Trathan 2009) initiated a complete re-appraisal of the number and distribution of colonies. Subsequent use of satellite imagery (Landsat8 and DigitalGlobe (now Maxar)) and aerial survey resulted in the discovery of 25 colony locations and verification of one of the unconfirmed sites (Shackleton Ice Shelf). At present, the total number of known colony locations is 54 (Trathan et al. 2019). Maxar are now acquiring imagery of every known colony to track long-term population change (Fretwell et al. 2012; LaRue et al. 2015; Fretwell and Trathan 2019).

Low-resolution Landsat imagery has been the most cost effective means for discovering new colonies. However, Landsat 7/8 colour pixels are 30m, meaning that guano stains from small colonies of just a few hundred individuals will be missed (Fretwell and Trathan 2009). In

contrast, 30–50 cm VHR imagery can be prohibitively expensive for searching the entire margin of the Antarctic continent. However, searching within the gaps identified in the geographic distribution (Ancel et al. 2017) reduces the need to search the entire coastline. The Sentinel2 sensor, part of the European Space Agency's (ESA) Copernicus Mission, collects data from two identical satellites, Sentinel 2A and Sentinel 2B. The satellites take optical imagery with varying spatial resolution depending upon the spectral band ([https://sentinel.esa.int/documents/247904/685211/Sentinel-2\\_User\\_Handbook](https://sentinel.esa.int/documents/247904/685211/Sentinel-2_User_Handbook)). The visible/near infrared pixels have a ground sample resolution of 10 m, while short wave infrared pixels have a resolution of 20–60 m. The satellites are sun-synchronous and have a revisit time of 5 days, giving a potentially high temporal resolution. The Copernicus mission does not target all parts of the globe, and initially there was no collection of imagery over Antarctica. However, in 2016, the SCAR Action Group on Remote Sensing (<https://www.scar.org/science/remotesensing/home/>) requested ESA to collect Antarctic data, recognizing the need for remote sensing of birds and mammals. ESA now undertakes high frequency data collection around the margins of the continent, with data collected in 2016, 2018 and 2019.

Recognizing that there may still be a number of undiscovered colonies (Ancel et al. 2017), we used the increased spatial and temporal resolution of Sentinel2 satellite imagery to search for undiscovered emperor penguin colonies.

The aim of this paper is therefore twofold;

- 1 To assess the usefulness of Sentinel2 for finding and monitoring emperor penguin colonies.
- 2 Using the distribution of the newly found colonies, discuss the biogeography and implications for future projects of emperor penguin populations.

## Materials and Methods

### Satellite imagery

We used Sentinel2 imagery which, for Antarctica, is currently available for 3 years (2016, 2018 and 2019). We used ESA's Sentinel Playground (<https://www.sentinel-hub.com/explore/sentinel-playground>) for access to freely available Sentinel2 imagery. This platform facilitates review of large amounts of imagery in various image band combinations. The platform is internet cloud-based, therefore removing the need for time-consuming and inefficient data download. Sentinel Playground has greatly streamlined the process of searching for emperor penguin colonies.

We reviewed images manually searching for small areas of brown pixels representing the guano staining of the

penguin colonies, generally at a scale of 1:50,000 (the 500 m scale in the Sentinel Playground). We viewed imagery in the Colour Infrared (8, 3, 2) band combination in the Sentinel Playground as this was found to have the highest contrast between guano and sea ice. In the default settings, ice and snow appear overexposed, so we changed the settings (custom setting 'return [B08\*0.8,B04\*0.8,B03\*0.8]') to give better contrast with ice. Additionally, we used the SWIR band combination (12, 8A, 4) to confirm guano, as guano is highly reflective in short-wave infrared (Schwaller et al. 1984; Fretwell et al. 2015; Rees et al. 2017). At targeted locations (see section on targets search parameters) we viewed every available image with less than 50% cloud cover in the months between August and December. At un-targeted locations a search was undertaken using a lower number of images. If a suspected colony was found, we used other images from the archive to confirm its presence.

### Targeted search parameters

Previously known colony locations are approximately regularly spaced around the continent, with a mean separation distance of 311 km (Ancel et al. 2017). Gaps in this distribution suggest that undiscovered colonies may exist. We therefore used three parameters to target our search:

1 Distance from other known colonies: Ancel et al. (2017) hypothesized that there are gaps in the circum-polar distribution of emperors where undiscovered colonies might exist. The largest gaps between colonies coincides with the coastlines of the three largest ice shelves (the Ross, Ronne-Filchner and the Larsen B), and on the northern Antarctic Peninsula where land-fast sea ice cover is much reduced. These habitats are unsuitable as colony locations. As such, we searched within the other large gaps (over 500 km); these exist between Mertz (67.24°S, 145.53°E) and Davies Bay (69.34°S, 158.49°E) (543 km), between Davies Bay and Cape Roget (71.98°S, 170.59°E) (509 km), and between the Sabrina Coast (66.17°S, 121.058°E) and Dibble Glacier (66.00°S, 134.80°E) (618 km). In addition, we also focused upon gaps that were greater than 400 km; these included those between Ragnhild (69.90°S, 27.15°E) and Gunnerus Bank (68.76°S, 34.38°E) (443 km), Peterson Bank (65.91°S, 110.23°E) and the Sabrina Coast (490 km), Cape Colbeck (77.13°S, 157.73°W) and Rupert Coast (75.38°S, 143.30°W) (446 km), Thurston Glacier (73.49°S, 125.62°W) and Bear Peninsula (74.35°S, 110.23°W) (471 km), Noville Peninsula (71.76°S, 98.44°W) and the Bryan Coast (73.25°S, 85.35°W) (450 km), Smyley Island (72.30°S, 78.82°W) and Rothschild Island (69.52°S, 72.23°W) (401 km) and between Dolleman Island (70.61°S,

60.42°W) and Smith Peninsula (74.37°S, 60.82°W) (418 km).

2 Previous records: Several suspected colonies have been reported (Woehler and Johnstone 1991, Woehler 1993 and references therein, Wienecke 2010), but have never been confirmed, possibly because they were too small to be identified using 30 m pixel Landsat imagery (Fretwell and Trathan 2009). However, a number of colonies, including Shackleton Ice Shelf (65.10°S, 96.02°E), Jason Peninsula (66.10°S, 60.67°W) and Bowman Island (65.16°S, 103.07°E) have now been confirmed (Ancel et al. 2014; LaRue et al. 2015; Trathan et al. 2019) from VHR satellite imagery. It is possible that others of the previously unconfirmed colonies exist, including at Casey Bay (67.50°S, 48.00°E) recorded in 1961 and not seen since (Budd 1962), Yule Bay (70.73° S, 166.83° E) recorded as breeding in 1980 (Wilson and Taylor 1984) and Karelin Bay (66°50 S, 85°50 E) in 1958 (Korotkevich 1964). The improved resolution of Sentinel2 may facilitate detection of these smaller colonies.

3 Breeding habitat: Emperor penguin breeding locations can be classed into four groups based on geographic features (Table 1), we targeted:

- A The windward side of bays, headlands, glacier tongues and ice shelves. This is the most common location for colonies. Over half of all known colony (30 of 54) show this preference.
- B Land-fast ice within small island archipelagos. Five colonies, with a further two that also conform with group A, have this characteristic.
- C Semi-permanent ice creeks. Five colonies, mostly around Dronning Maud Land, share this trait.
- D Offshore on fast ice amongst icebergs trapped by shallow shoals. Seven colonies have this location preference. Two such colonies in the eastern Weddell Sea are less than 10 km offshore, but two such colonies in East Antarctica: Burton Ice Shelf and Sabrina Coast are over 50 km from land.

Some colonies use geographic features that are more challenging to search, these include:

- E Ice shelf breeders. Four colonies have regularly been located on ice shelves (Fretwell et al. 2014).
- F Land. One colony breeds entirely on land (Robertson et al. 2014), another has been found on a frozen lake, but whether this is the regular location of the breeding colony is difficult to assess due to lack of ground survey (Kato 1999).

Resulting sites were also checked using DigitalGlobe (Maxar) Search and Discovery tool (<https://discovery.digitalglobe.com/>) to confirm the existence and to assess if the colony existed before the onset of Sentinel2 collection in Antarctica (2016). This tool shows reduced resolution

**Table 1.** The locations of newly discovered and rediscovered colony found in this analysis. Habitat refers to the habitat types in the Target Parameters section of the methodology

ID	Name	Latitude	Longitude	Example Image date	Habitat	Known?	No.
1	Yule Bay	−70.7161	166.4777	23/11/2016	A	Rediscovered	29
2	Karelin Bay	−66.4118	85.38361	9/10/2018	A	Rediscovered	3
3	Casey Bay	−67.312	46.957	17/10/2018	A	Rediscovered	23
4	Verdi Inlet	−71.5559	−74.7603	30/10/2019	A	Discovered	9
5	Cape Gates	−73.6609	−122.697	7/11/2016	A	Discovered	8
6	Cruzen Island	−74.7235	−140.357	3/12/2018	A	Discovered	12
7	Ninnis Bank	−66.7229	149.677	26/8/2018	D	Discovered	13
8	Porpoise Bay	−66.3204	129.7496	15/10/2017	A	Discovered	8
9	Cape Darlington	−71.8872	−60.1338	23/10/2019	E	Discovered	14
10	Cape Poinsett	−65.7817	113.2351	19/11/2019	A	Discovered	16
11	Pfrogner Point	−72.5687	−89.9058	7/11/2019	E	Discovered	18

The No. column refers to the number of Sentinel2 images in which the colony could be identified.

versions of VHR satellite imagery at approximately 12 m resolution.

The population size of each colony is very difficult to assess using single Sentinel2 imagery and several images were used to assess variability and the extent of the guano stain associated with the penguins. Remote sensing has proved a valuable tool for assessing populations of emperor penguins in remote areas, but these studies have utilized VHR satellite imagery and even then have large variance in count quality (Barber-Meyer et al. 2007; Fretwell et al. 2012). This variance in the VHR estimates is often due to variable image quality, sun angle, cloud and atmospheric phenomenon, shadows from icebergs or ice walls, variation in huddle density and distribution and the amount of guano staining. These factors will also influence medium resolution imagery such as Sentinel2. Here we use the comparative sizes of previously known colony populations to make a first-order assessment of populations. As no quantitative assessment of the accuracy of estimating colony size by Sentinel2 imagery has been made, the estimates given in Table 2 should be viewed as only approximate, and as colonies have inherent annual variability, several years of VHR satellite analysis may be needed to assess the new populations (Barber-Meyer et al. 2007; Fretwell et al. 2012; Fretwell and Trathan 2019). These estimates should provide a guide until other higher resolution surveys can be conducted.

## Results

Our search revealed 11 colonies not identified in the latest satellite imagery inventory (Fig. 1 and Table 1) (Trathan et al. 2019); two in the Peninsula Region, three in West Antarctica and the remaining six in East Antarctica (Table 2). These sites included two new sites breeding on ice shelves (Fretwell et al. 2014), and two off-shore sites.

We identified three previously unconfirmed locations close to those reported by Budd (1962), Wilson and Taylor (1984) and Korotkevich (1964). All three were several kilometres from the reported locations: Yule Bay was 13 km west of the previously recorded position, Karelin Bay was 11 km farther north and Casey Bay was 50 km northwest, but still within Casey Bay. Each of these colonies were small and indistinct, with only a small number (>20) of brown pixels, and Yule and Karelin Bay required multiple images to confirm their presence. We estimate that these rediscovered sites all have small populations, probably only a few hundred birds, or less per location. Examples of these colonies in Sentinel2 imagery are shown in Figure 2.

We discovered a new colony in the Verdi Inlet, on the Beethoven Peninsula, Alexander Island. The guano stain, evident in the imagery at this site was generally small to moderate in size, probably a few thousand pairs.

The largest of the new colonies found was at Cape Gates. This colony consists of several groups of penguins and is likely to comprise many thousand pairs. Over the 3 years of Sentinel2 satellite acquisition, the location and grouping of this colony has been variable, with subgroups forming in each year. In 2018, one small subgroup relocated some 15 km to the east of the main colony site.

We found a new 'offshore' colony near Cruzen Island, a small isolated island 40–50 km offshore from the Rupert Coast. Like the Franklin Island and Beaufort Island colonies in the Ross Sea, this colony must rely on stable fast ice forming around the island, although it is in a more exposed location than those breeding sites.

We also found another new offshore colony close to Ninnis Bank. The colony was ~ 180 km offshore, over a shallow area of bathymetry where large grounded icebergs facilitate the formation of stable fast ice. Previously, groups of emperors were recorded near Ninnis Glacier, 198 km to the south (Wilson and Taylor 1984); it is

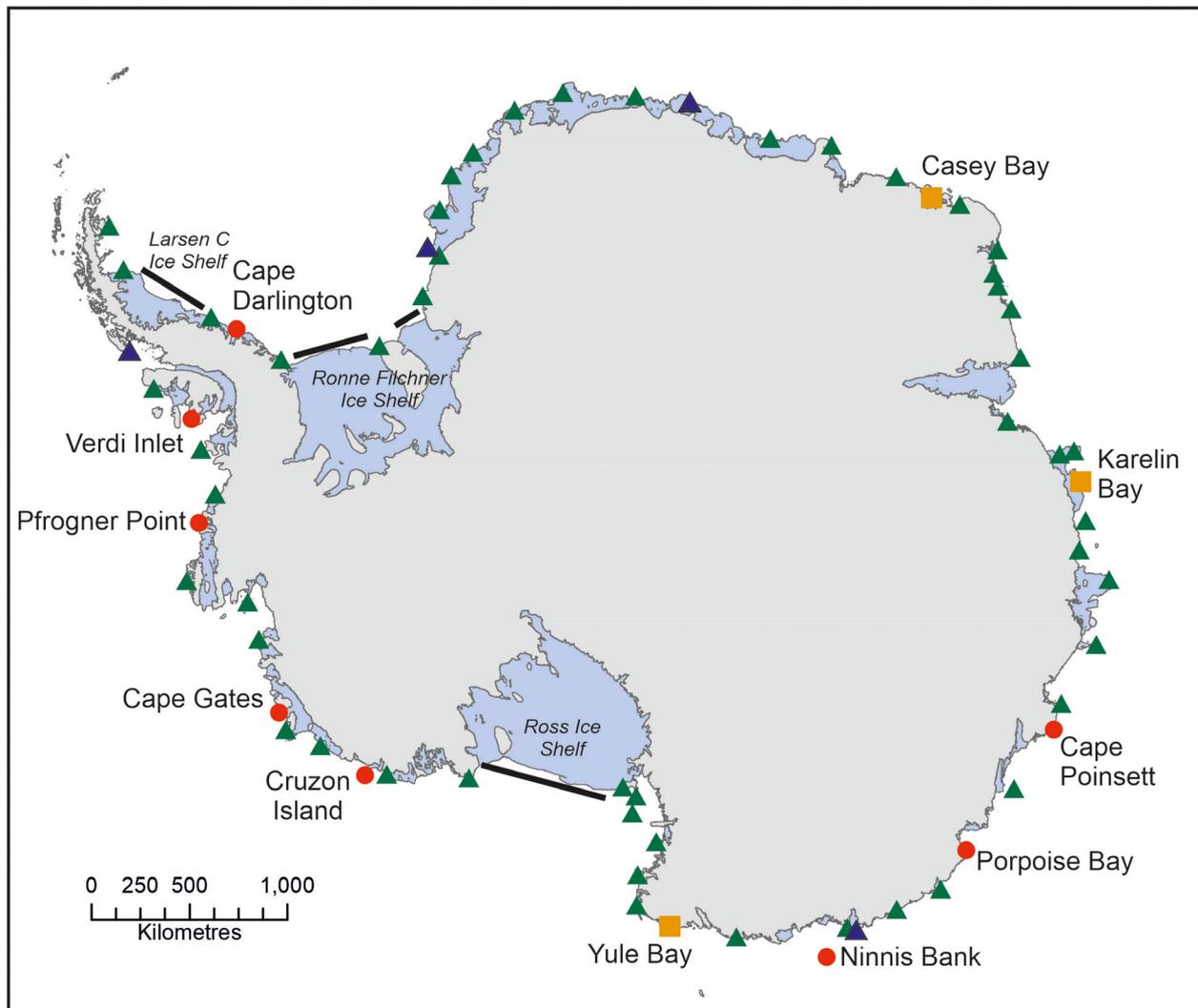
**Table 2.** Indicating the discovery of emperor penguin colonies and the estimated population size of the newly found colonies. Note that of the 65 locations only 61 are currently occupied. Of these around half (30) have been discovered by satellite and several more have been rediscovered, confirmed or relocated by satellite imagery

Name	Latitude	Longitude	Habitat	New pairs		Discovered	By satellite?	Discovered by	Published by	Notes
				(1000s)	Discovered					
Cape Colbeck	-77.135	-157.730	a		1993	N		T. Kooyman	Kooyman (1993)	
Rupert Coast	-75.382	-143.308	e		2012	Y		Fretwell	Fretwell et al. (2012)	
Cruzen Island	-74.724	-140.357	a	1	2019	Y		Fretwell	this paper	
Ledda Bay	-74.272	-131.243	a	>1	2009	Y		Fretwell	Fretwell et al. (2009)	continues to form but during most years is subject to early sea ice break-up
Thurston Glacier	-73.498	-125.620	a		2004	N		Lea and Soper	Lea and Soper (2005)	Sometimes referred to as Mt Siple
Cape Gates	-73.661	-122.697	a	3-6	2019	Y		Fretwell	this paper	
Bear Peninsula	-74.350	-110.239	a		2009	Y		Fretwell	Fretwell and Trathan (2009)	
Brownson Islands	-74.351	-103.631	b		2012	Y		Fretwell	Fretwell et al. (2012)	
Noville Peninsula	-71.769	-98.447	a		2009	Y		Fretwell	Fretwell and Trathan (2009)	
Pflogner Point	-72.569	-89.906	e	1-2	2019	Y		Fretwell	this paper	On Wienecke Ice Tongue
Bryan Coast	-73.249	-85.348	a	1-2	2014	Y		Fretwell	LaRue et al. (2015)	
Smyley Island	-72.302	-78.819	a		2009	Y		Fretwell	Fretwell and Trathan (2009)	
Verdi Inlet	-71.556	-74.760	a	1-2	2019	Y		Fretwell	this paper	thought to be extinct but recently 2-3 chicks have been reported
Rothschild Island	-69.521	-72.229	ab	>1	2014	Y		LaRue	LaRue et al. (2015)	
Dion Islands	-67.866	-68.704		0.01	1947	N		Dalglish	Stonehouse (1953)	
Smith Peninsula	-74.369	-60.827	a		2009	Y		Fretwell	Fretwell et al. (2014)	
Jason Peninsula	-66.100	-60.674	e	1-2	2012	Y		Fretwell	Fretwell et al. (2014)	Also referred to as Clarke Bay
Dolleman Island	-70.611	-60.421	a		2012	Y		Fretwell	Fretwell and Trathan (2009)	after suggested sightings from Larsen 1893
Cape Darlington	-71.887	-60.134	e	1	2019	Y		Fretwell	this paper	
Snow Hill	-64.524	-57.445	a		1997	N		Coria and Montalti	Coria and Montalti (2000)	
Gould Bay	-77.710	-47.656	a		1957	N		Malville	Neuburg et al. (1959)	ship visit Kapitan Khelbnikov no longer in Gould Bay
Luitpold Coast	-77.271	-33.552	d		2009	Y		Fretwell	Fretwell and Trathan (2009)	
Halley Bay	-75.555	-27.423	a		1956	N		Novatti	Novatti (1959)	declining since 2015, not extant in 2019
Dawson Lambton	-76.014	-26.648	a		1986	N			Hempel and Stonehouse (1987)	
Ice Tongue	-74.120	-23.087	a		1986	N			Hempel and Stonehouse (1987)	
Stancomb Wills Glacier	-72.826	-19.326	c		1985	N		Dubbels	Dubbels et al. (1985)	
Drescher Inlet	-72.124	-15.106	d		1986	N			Hempel and Stonehouse (1987)	
Riser Larsen Ice Shelf	-70.614	-8.132	a		1981	N		Drescher	Drescher (1982)	
Atka Bay	-69.999	-1.413	c		1979	Y		Fretwell/Condy	Fretwell and Trathan/Condy (1979/2009)	rediscovered by satellite in new position
Sanae									Fretwell and Trathan (2009)	
Astrid Ice Tongue	-69.948	8.318	a		2009	Y		Fretwell		

(Continued)

Table 2. Continued.

Name	Latitude	Longitude	Habitat	New pairs (1000s)	Discovered	By satellite?	Discovered by	Published by	Notes
Lazarev Ice Shelf	-69.750	15.549	a		1959	N	unknown	Ledenev (1965)	has not reformed since 2014
Ragnhild Coast	-69.908	27.155	c		2009	Y	Fretwell	Fretwell and Trathan (2009)	
Gunnerus Peninsula	-68.762	34.382	a		1964	N	Japanese Antarctic Research Expedition	Hoshiai and Chujo (1976)	Also known as Risser Larsen Peninsula
Umbeashi	-68.046	43.017	a		1984	N	unknown	Kato et al. (2004)	extremely small not visible in 2019
Casey Bay	-67.312	46.597	b	>1	2019	Y	Fretwell	this paper	previous local sightings by unknown recorders
Amundsen Bay	-66.783	50.544	f		1996	N	Kato and Ichikawa	Kato and Ichikawa (1999)	Small but obvious in imagery - breeds on ice shelf
Kloa Point	-66.641	57.278	a		1957	N	Clemence	Willing (1958)	
Fold Island	-67.324	59.316	b		1956	N	Downie and Seaton	Willing (1958)	
Taylor Glacier	-67.454	60.878	f		1954	N	Dovers and Schwartz	Willing (1958)	
Auster	-67.397	63.974	d		1957	N	Johnston	Willing (1958)	
Cape Darnley	-67.887	69.696	a		1958	N	Clemence	Willing (1958)	
Amanda Bay	-69.271	76.835	ab		1956	N	Korotkevich	Korotkevich (1964)	
Barrier Bay	-66.550	81.818	e	0.2	2012	N	Wienecke	Wienecke (2012)	
West Ice Shelf	-67.225	81.931	a	4	1997	N	Spletstoesser	Spletstoesser et al. (2000)	rediscovered 2012
Karelin Bay	-66.412	85.384	a	>1	1958	N	Korotkevich	Korotkevich (1964)	rediscovered 2019
Burton Ice Shelf	-66.272	89.695	d	1	2014	Y	Fretwell	LaRue et al. (2015)	
Haswell Island	-66.531	93.008	b		1912	N	Jone and Hoadley	Mawson (1915)	Possibly the same colony as Korotkevich record 85 km east
Shackleton Ice Shelf	-65.089	96.020	e		2012	Y	Fretwell	Fretwell et al. (2012)	
Bowman Island	-65.161	103.067	d		1960	N	Korotkevich	Korotkevich (1964)	
Peterson Bank	-65.918	110.235	d	1-2	1994	N	Melick and Bremmers	Melick and Bremmers (1995)	Rediscovered by satellite 2012
Cape Poinsett	-65.782	113.235	a	1-2	2019	Y	Fretwell	this paper	
Sabrina Coast	-66.177	121.058	d	1-2	2014	Y	Fretwell	Trathan et al. (2019)	
Porpoise Bay	-66.320	129.750	a	>1	2019	Y	Fretwell	this paper	
Dibble Glacier	-66.000	134.800	a		2012	Y	Fretwell	Fretwell et al. (2012)	
Point Geologie	-66.674	140.005	b		1950	N	Sapin-Jaloustre	Cendron (1952)	
Mertz Glacier	-67.240	145.535	c		2009	Y	Fretwell	Fretwell and Trathan (2009)	
Mertz break off	-67.366	145.834	b		2014	N	Ance	Ance et al. (2014)	no longer extant – reunited with larger colony at Mertz in 2017
Ninnis Bank	-66.723	149.677	d	2-4	2019	Y	Fretwell	this paper	
Davis Bay	-69.348	158.492	a		2019	Y	Fretwell	Fretwell and Trathan 2009	
Cape Washington	-74.637	165.382	a		1965	N	Cranfield	Cranfield (1966)	
Yule Bay	-70.716	166.478	a	>1	2019	Y	Fretwell	this paper	unconfirmed local sighting by unknown observers at Yule Bay in 1982
Beaufort Island	-76.925	167.043	a		1962	N	Stonehouse	Stonehouse (1966)	
Franklin Island	-76.187	168.440	a		1964	N	Stonehouse	Stonehouse (1969)	
Cape Crozier	-77.465	169.329	c		1902	N	Skelton	Wilson (1907)	
Coulman Island	-73.348	169.624	a		1958	N	Dearborn and Dewitt	Harrington (1959)	
Cape Roget	-71.988	170.597	a		1964	N	Cranfield	Anon	



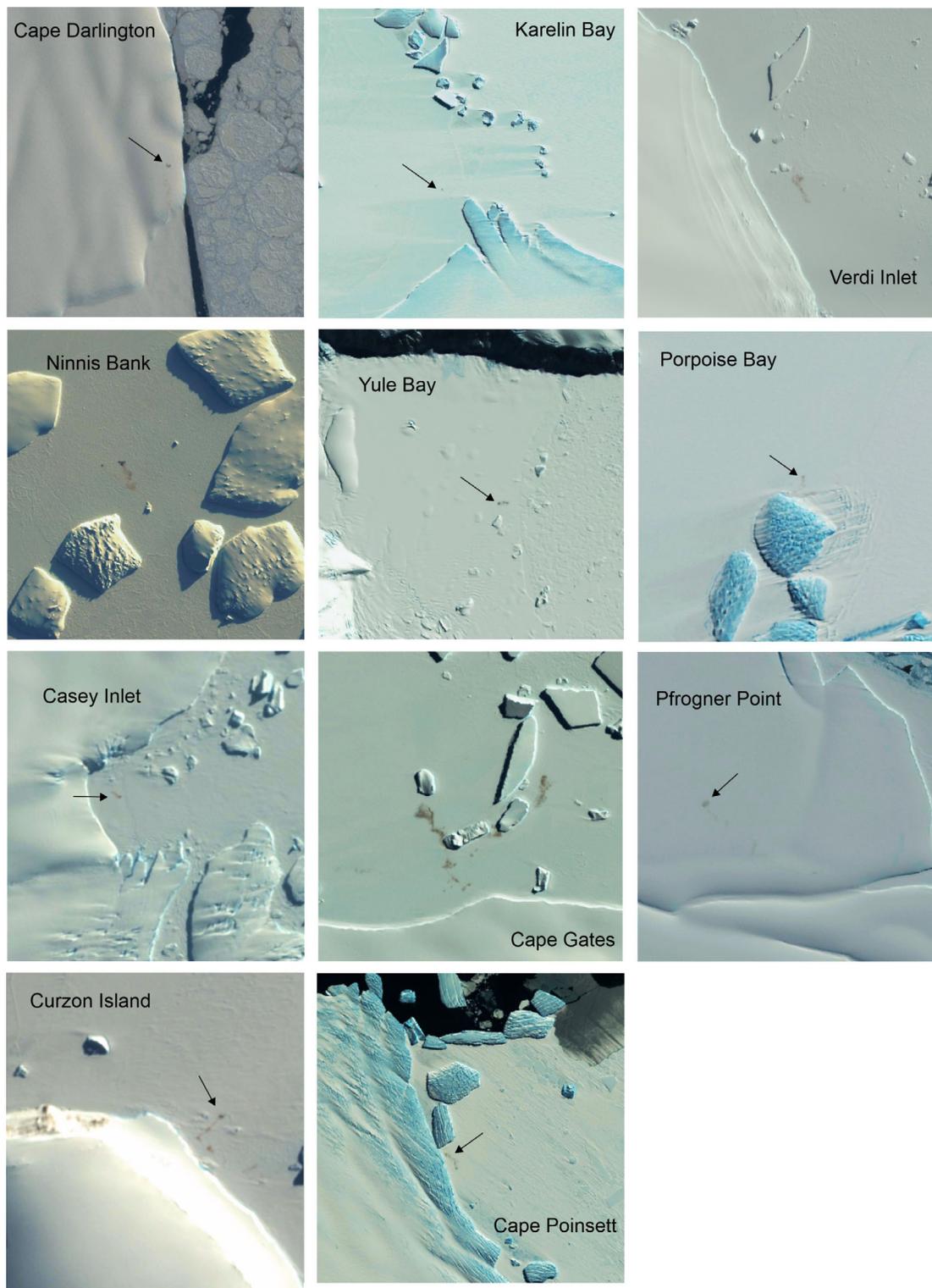
**Figure 1.** Newly discovered and rediscovered colonies found using Sentinel2. Newly discovered (red circles) and re-discovered colonies (yellow squares), in relation to previously known colony locations (green triangles). The dark blue triangles are site thought to be no longer extant. Note the regular spacing of colony locations around the coast as predicted by Ancel et al. 2017. The only gaps in the distribution that are over 400 km are in front of the largest three ice-shelves (Ross, Ronne-Filchner and Larsen C), marked as thick black lines on the map, which are probably unsuitable habitat.

plausible that this new colony is the origin of those groups of penguins. If a colony still exists at the original site, it must be extremely small. As such, we consider that the new Ninnis Bank colony is a separate record. This colony is extant in all years within the Sentinel2 archive, and is probably several thousand pairs, based on the size of the colony in the imagery.

We found a new colony on the eastern side of Porpoise Bay in Wilkes Land. It is adjacent to the eastern coast of the bay near to a small unnamed glacier tongue. It is visible in all years of the Sentinel2 record (and several years in the DigitalGlobe record), but not in all images due to

its very small size, which is probably just a few hundred pairs.

A colony was found on the Larsen D Ice Shelf, 142 km south of the Dolleman Colony. This is one of a number of colonies now known to occur at times on ice shelves (Fretwell et al. 2014). The area is often cloudy and cloud-free Sentinel2 imagery was only available in 2018 and 2019. In both these years the colony was located on the shelf rather than the sea ice, which here is composed of a floating ice tongue coming out of Hilton Inlet. The available imagery suggests that the colony is small, probably only around 1000 pairs or less. The site is unnamed, but



**Figure 2.** Sentinel2 satellite imagery of the eleven newly discovered or rediscovered colonies. Example of colour corrected imagery from Sentinel2 at 1:50 000 scale of the newly discovered or rediscovered sites.

**Table 3.** Distance between colonies.

Name	Latitude	Longitude	Distance (km)	name	Latitude	Longitude
Cape Colbeck	-77.135	-157.730	429	Rupert Coast	-75.382	-143.308
Rupert Coast	-75.382	-143.308	112	Cruzen Island	-74.723	-140.357
Cruzen Island	-74.723	-140.357	276	Ledda Bay	-74.272	-131.243
Ledda Bay	-74.272	-131.243	194	Thurston Glacier	-73.497	-125.620
Thurston Glacier	-73.497	-125.62	94	Cape Gates	-73.660	-122.697
Cape Gates	-73.660	-122.697	390	Bear Peninsula	-74.349	-110.239
Bear Peninsula	-74.349	-110.239	199	Brownson Islands	-74.351	-103.631
Brownson Islands	-74.351	-103.631	333	Noville Peninsula	-71.769	-98.446
Noville Peninsula	-71.769	-98.446	305	Pfrogner Point	-72.568	-89.905
Pfrogner Point	-72.568	-89.905	167	Bryan Coast	-73.249	-85.347
Bryan Coast	-73.249	-85.347	240	Smyley Island	-72.301	-78.819
Smyley Island	-72.301	-78.819	163	Verdi Inlet	-71.555	-74.760
Verdi Inlet	-71.555	-74.7603	245	Rothschild	-69.520	-72.229
Rothschild Island	-69.520	-72.229	233	Dion Islands	-67.865	-68.703
Dion Islands	-67.865	-68.703	628	Snow Hill	-64.523	-57.444
Snow Hill	-74.369	-60.827	513	Jason Peninsula	-77.709	-47.656
Jason Peninsula	-66.099	-60.673	503	Dolleman Island	-70.610	-60.420
Dolleman Island	-70.610	-60.420	142	Cape Darlington	-71.887	-60.133
Cape Darlington	-71.887	-60.1338	277	Smith Peninsula	-74.369	-60.827
Smith Peninsula	-64.523	-57.444	231	Gould Bay	-66.099	-60.673
Gould Bay	-77.709	-47.656	344	Luitpold	-77.271	-33.552
Luitpold Coast	-77.271	-33.552	226	Halley Bay	-75.555	-27.422
Halley Bay	-75.555	-27.422	55	Dawson Lambton	-76.014	-26.647
Dawson Lambton	-76.014	-26.647	204	Stancomb Wills	-74.120	-23.086
Stancomb Wills	-74.120	-23.086	187	Drescher	-72.825	-19.326
Drescher Inlet	-72.825	-19.326	162	Riiser Larsen Ice Shelf	-72.124	-15.106
Riiser Larsen Ice Shelf	-72.124	-15.106	300	Atka Bay	-70.614	-8.131
Atka Bay	-70.614	-8.1316	261	Sanae	-69.999	-1.412
Sanae	-69.999	-1.4128	372	Astrid	-69.948	8.3176
Astrid	-69.948	8.3176	279	Lazarev Ice Shelf	-69.750	15.549
Lazarev Ice Shelf	-69.750	15.549	447	Ragnhild	-69.908	27.154
Ragnhild Coast	-69.908	27.154	312	Gunnerus Bank (Riiser Larsen Peninsula)	-68.762	34.381
Gunnerus Bank (Riiser Larsen Peninsula)	-68.762	34.381	363	Urnebosi	-68.045	43.017
Urnebosi Rock	-68.045	43.017	198	Casey Bay	-67.312	46.957
Casey Bay	-67.312	46.957	174	Amundsen Bay	-66.786	50.555
Amundsen Bay	-66.786	50.555	444	Kloa Point	-66.640	57.277
Kloa Point	-66.640	57.277	117	Fold Island	-67.323	59.315
Fold Island	-67.323	59.315	68	Taylor Glacier	-67.454	60.877
Taylor Glacier	-67.454	60.877	132	Auster	-67.396	63.974
Auster	-67.396	63.974	249	Cape Darnley	-67.887	69.695
Cape Darnley	-67.887	69.695	329	Amanda Bay	-69.271	76.834
Amanda Bay	-69.271	76.834	310	Barrier Bay	-66.549	81.817
Barrier Bay	-66.549	81.8175	75	West Ice Shelf	-67.225	81.930
West Ice Shelf	-67.225	81.9308	159	Karelin Bay	-66.411	85.383
Karelin Bay	-66.411	85.3836	193	Burton Ice Shelf	-66.271	89.695
Burton Ice Shelf	-66.271	89.6954	150	Haswell Island	-66.530	93.007
Haswell Island	-66.530	93.0078	211	Shackleton Ice Shelf	-65.088	96.02
Shackleton Ice Shelf	-65.088	96.020	331	Bowman Island	-65.161	103.067
Bowman Island	-65.161	103.067	341	Peterson Bank	-65.917	110.235
Peterson Bank	-65.917	110.235	137	Cape Poinsett	-65.781	113.235
Cape Poinsett	-65.781	113.235	358	Sabrina Coast	-66.177	121.057
Sabrina Coast	-66.177	121.057	391	Porpoise Bay	-66.320	129.75
Porpoise Bay	-66.32	129.75	230	Dibble Glacier	-65.999	134.799

(Continued)

**Table 3.** Continued.

Name	Latitude	Longitude	Distance (km)	name	Latitude	Longitude
Dibble Glacier	−65.999	134.799	245	Point Geologie	−66.674	140.005
Point Geologie	−66.674	140.005	249	Mertz Glacier	−67.240	145.535
Mertz Glacier	−67.240	145.535	19	Mertz break off	−67.365	145.833
Mertz break off	−67.365	145.83	182	Ninnis Bank	−66.722	149.677
Ninnis Bank	−66.722	149.677	470	Davies Bay	−69.348	158.492
Davies Bay	−69.348	158.492	340	Yule Bay	−70.716	166.477
Cape Washington	−74.637	165.382	193	Franklin Island	−76.187	168.440
Yule Bay	−70.716	166.477	204	Cape Roget	−71.988	170.597
Beaufort Island	−76.925	167.043	82	Cape Crozier	−77.465	169.329
Franklin Island	−76.187	168.440	90	Beaufort Island	−76.92	167.043
Cape Crozier	−77.465	169.329	786	Cape Colbeck	−77.135	−157.73
Coulman Island	−73.348	169.624	194	Cape Washington	−74.637	165.382
Cape Roget	−71.988	170.597	155	Coulman Island	−73.348	169.624

Showing the loxodromic distance between neighbouring colonies. The distances shown in grey are considered to be in areas of unsuitable habitat: (a) large calving ice shelves, and (b) the northern Antarctic Peninsula where year-round sea ice does not occur at the coast. The table shows that there are no gaps of over 500 km with suitable habitat between known colonies.

we here call it Cape Darlington, after the nearest named feature some 23 km west of the site.

Extensive searching of the Abbott Ice Shelf area revealed a second ice-shelf breeding colony. The site is 4 km inland of the shelf front, close to an ice creek on an unnamed ice tongue between Pfrogner Point and Farwell Island. It is visible in 2016, 2018 and 2019, and in all years is initially located on the ice tongue although there is some evidence that in 2017 it moved into the creek later in the season.

The final new colony is at Cape Poinsett, on the eastern side of Law Dome, 140 km east of Peterson Bank. This colony is probably over 1000 pairs. It is present every year of the Sentinel2 record, but has a tendency to hug the ice cliffs early in the season (before October), which may be a contributing factor to why it has not been discovered until now.

## Discussion

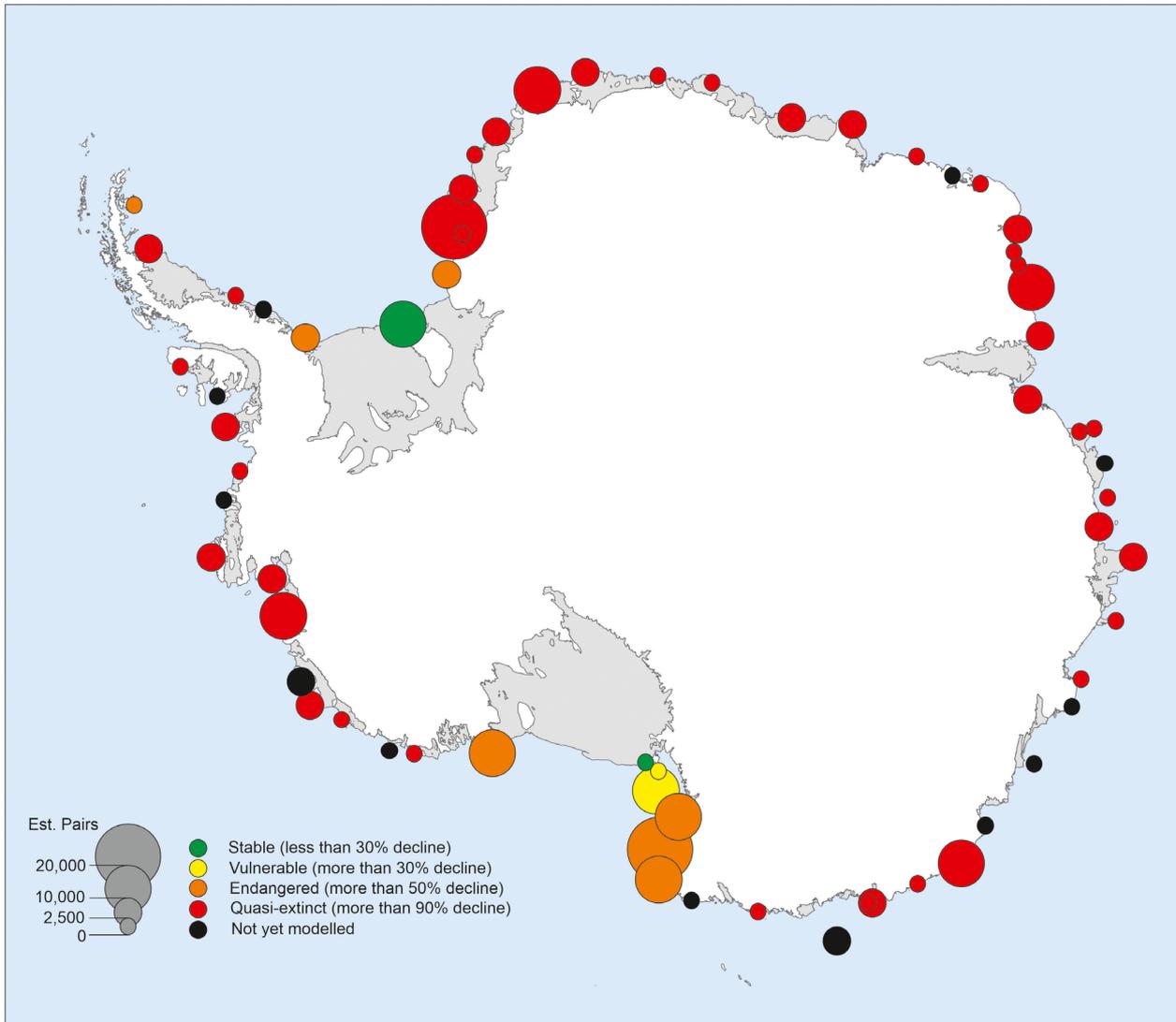
Although an extra 11 colonies represent an increase of almost 20% in the number of breeding sites, the numbers of penguins at each site are likely to be small (Table 2). Based on the approximate size of these 11 newly reported colonies, we believe that, providing that all colonies we detect are breeding colonies and have always been present in these locations, these extra 11 locations may increase the global estimate by 5–10% (approximately 25,000–55,000 (10,000–22,000 breeding pairs) greater than the population size used in the Jenouvrier et al. (2019)). There must be some consideration as to whether all these new sites represent breeding locations or moulting sites, or even small groups of

non-breeders. As the imagery shows that all the sites were in existence throughout the chick rearing period (August–December), well before the moulting season (February/March for breeding emperors), it seems highly likely that these are breeding sites. In some cases, small groups of non-breeding (probably juveniles) penguins have been recorded at separate locations in the breeding season (M. LaRue pers coms.). However, as all these new sites are persistent throughout the breeding season, and are visible in approximately the same place in multiple years, the current evidence suggests that these will be breeding sites.

The new sites occur in gaps in the known distribution of colonies (Ancel et al. 2017). This reinforces the hypothesis that emperor penguin colonies occur at regular intervals around the continent. All new sites are more than 94 km from the closest previously known colony. Distance to the nearest colony on either side of the coast varies between 94 and 470 km (mean 229 km, SD 96 km). Our survey shows that there are no gaps > 500 km between emperor penguin colonies (Table 3), except in front of large ice shelf fronts, that is, areas that are probably unsuitable habitats given the disturbance associated with iceberg calving.

Most of the colonies we report here are so small that they required multiple images to confirm their existence (Fig. 2) and it could be that yet smaller colonies also exist. If other smaller colonies occurred elsewhere, they would be unlikely to contribute greatly to the global population of the species, given that they could not be resolved using the 10 m pixels of Sentinel2.

We identified a number of offshore colonies (>30 km from the coast). The Ninnis Bank colony was

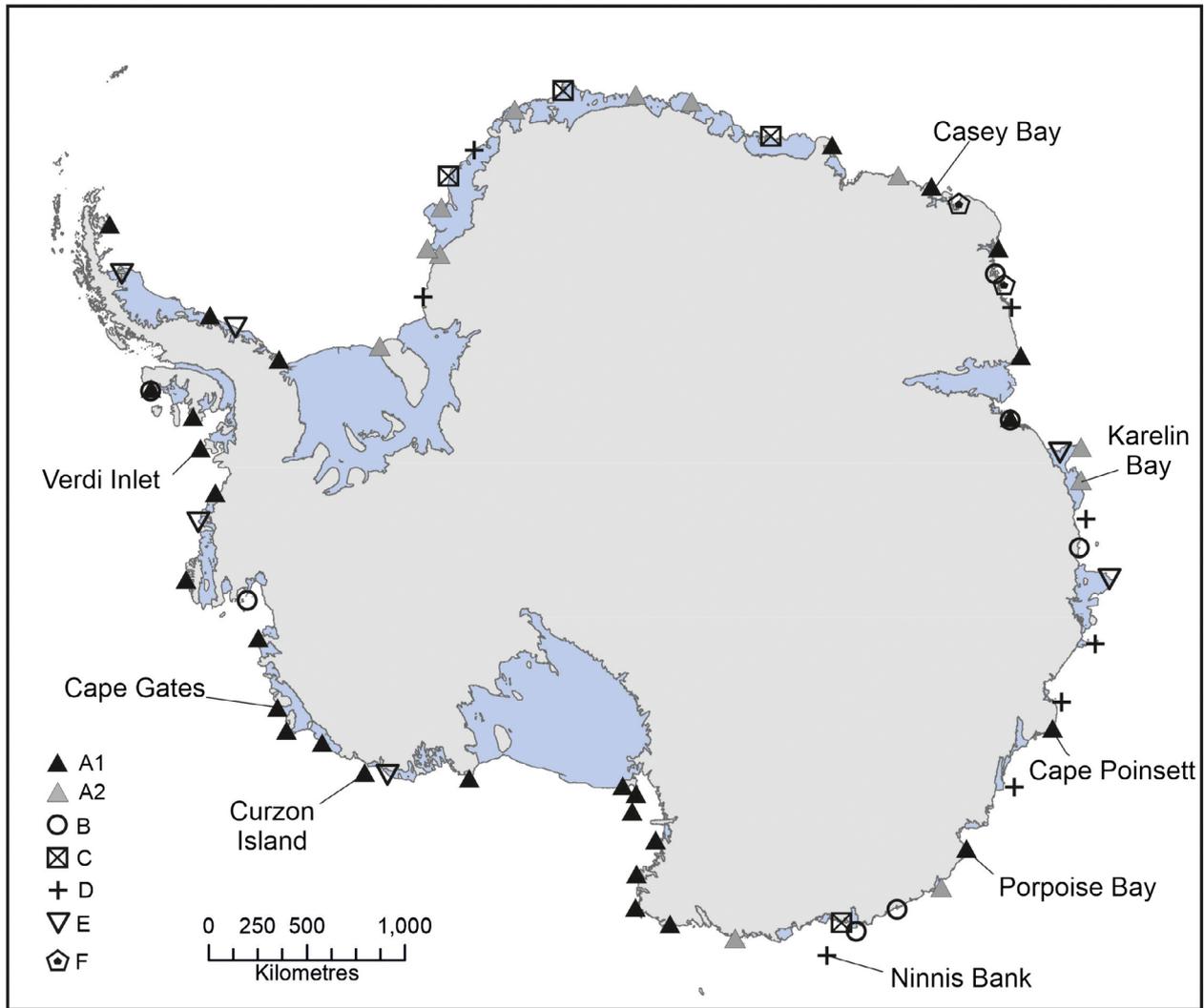


**Figure 3.** Colony distribution, size and vulnerability. Based on the business-as-usual scenario of Jenouvrier et al. (2019); quasi-extinct (red), endangered (orange), vulnerable (yellow) or stable (green) by the end of this century. The eight newly discovered or rediscovered colonies are shown in black; the other colony not modeled by Jenouvrier et al. (2019) on the Sabrina Coast (Trathan et al. 2019) is also shown in black. Geographically, all these newly discovered or rediscovered colonies are in regions that will become extinct or quasi-extinct by the end of this century under current rates of carbon emissions.

located ~ 180 km from land; since it persisted for at least 2 years, it is unlikely to be a moulting site or small aggregation of non-breeders. This is the farthest from shore of any known colony, although other offshore colonies were previously known at Burton Ice Shelf colony (58 km offshore), Sabrina Coast (56 km) and Peterson Bank (34 km). This potentially important breeding trait has not yet been considered. Recognition that emperor penguins can breed a long way from the coast is important; it confirms that potential breeding habitat exists in areas not previously documented. However, as these areas away from the coast are more northerly, they will be in warmer

areas and therefore will be more likely to be susceptible to early sea ice loss (Ainley et al. 2010).

Jenouvrier et al. (2019) identified colonies that are projected to be either quasi-extinct, endangered, vulnerable or stable by the end of this century assuming a business-as-usual GHG emissions scenario and a climate-dependent-meta-population model. The revised map of emperor penguin distribution (Fig. 3) shows that all 11 newly reported colonies, plus the new colony on the Sabrina Coast reported by Trathan et al. (2019), are not in areas that have been identified as possible climate refugia, either in the Ross Sea or Weddell Sea (Jenouvrier et al.



**Figure 4.** Habitat types by location. (A) The windward side of bays, headlands, glacier tongues and ice shelves. A1 refers to land features such as bays and headlands, A2 indicates colonies associated with glacier tongues and ice shelves, which by nature have to be more mobile than those near land features. (B) Land-fast ice within small island archipelagos. (C) Semi-permanent ice creeks. (D) Offshore on fast ice amongst icebergs trapped by shallow shoals. (E) Ice shelf colonies. (F) Colonies located on land.

2019). The 12 colonies are all in areas where colonies are expected to become extinct or quasi-extinct by the end of the century (Jenouvrier et al. 2019).

Some of the newly reported colonies are very small. The energetic basis of these small colonies is therefore likely to be of considerable interest. The metabolic rate of emperors able to huddle is on average lower than that of loosely grouped birds or isolated birds unable to huddle effectively (Gilbert et al. 2008). For some of these colonies, exposure to wind is likely to be significant, given that they are in exposed locations. The minimum size of emperor penguin huddles in the winter deserves further consideration, given small colony size may be detrimental to colony persistence and survival.

With regard to the use of satellite imagery, Sentinel2 has been useful in finding new colonies. It can be used to efficiently check the position and existence of existing colonies, a requirement for accurate VHR satellite imagery collection. A check of all known colony sites suggests the absence of penguins at Dion Islands (Trathan et al. 2011) and Halley Bay (Fretwell and Trathan 2019) and, that the recently reported colony that separated from the main colony where the Mertz Ice Tongue calved (Ancel et al. 2014), has now rejoined with the main group (since 2017). One colony, Lazarev Ice Shelf, discovered in 1959 (Ledenev 1965) is not evident in the Sentinel2 record and is absent from other satellite records since 2014. Further investigation reveals that the

sea ice broke up early in the 2014 season and the colony has not reformed since, a situation similar to the Halley Bay site (Fretwell and Trathan 2019). The Lazarev Ice Shelf colony had been sighted in the 2009 (Fretwell and Trathan 2019) and 2012 (Fretwell et al. 2012) satellite surveys; it was a small colony comprising about 820 pairs. Whether those birds have moved to another colony, or have moved to a new, as yet, undiscovered site is unknown.

## Conclusion

Sentinel2 is a powerful tool for discovering and monitoring the distribution of emperor penguin colonies. The spatial resolution, combined with high temporal resolution of satellite revisit time, and the ease of access through the Sentinel Playground has allowed us to rapidly review new habitats (Fig. 4), allowing us to report seven additional colonies and confirm the presence of three colonies reported prior to the era of VHR satellite imagery. These findings bring the total number of known sites to 65 of which 61 are still extant; 30 of these breeding locations have been discovered using satellite imagery (Table 2). The newly reported colonies also highlight the presence of offshore breeding habitat for emperor penguins.

After consideration of the distribution of the newly reported colony locations, it is evident that future climate change is likely to affect them, based on projections for nearby colonies (Jenouvrier et al. 2019). Our findings therefore suggest the possibility of an even greater proportion of the global population will be vulnerable to climate change, than previously considered.

## Acknowledgments

This work was funded as part of British Antarctic Survey's Wildlife from Space project. British Antarctic Survey is part of the UK's Natural Environment Research Council. We would also like to acknowledge the impetus given to the project by Dr Andrew McDonald and the pupils of Stirling High School whose initial experiments with Sentinel2 and penguins inspired PTF to use the higher resolution satellite to find emperor penguin colonies.

We are also extremely grateful and would like to thank the reviewers for their extremely detailed and helpful comments that have improved the manuscript.

## Author Contributions

PTF Conceived the project, designed the survey and analysed the data, PTF and PNT wrote the manuscript.

## Conflict of Interest

The authors know of no competing interests for this study.

## Data Availability Statement

Sentinel2 data are freely available for searching from <https://www.sentinel-hub.com/explore/sentinel-playground> and can be freely downloaded from <https://www.sentinel-hub.com/>

Locations of colonies are available as an ESRI Shapefile or GoogleEarth KMZ format at <ftp://ftp.nerc-bas.ac.uk/pub/ptf/emperors>.

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