Sea Ice Examination for Ice Class Ships visiting Horseshoe Island, Antarctica, Using MODIS in 2000-2022

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Sea ice has a significant impact on numerous areas, ranging from the reflection of the sun rays back on the albedo scale, to spurring intense phytoplankton blooms that help maintain the marine ecosystem and making the navigation of some maritime routes challenging. The formation of sea ice in the Southern Ocean affects maritime logistics and scientific operations on Antarctica, especially on the Antarctic Peninsula, which hosts half of the scientific stations. Ships needed to supply British and Turkish scientific bases on Horseshoe Island in the southernmost part of the Antarctic Peninsula are in high demand. Therefore, the analysis of the oldest trends of sea ice that affect maritime operations is crucial. The goal of the study was to examine the formation of sea ice, and especially ice-free days, by using images collected between 2000 and 2022 by over 8000 NASA's Terra/MODIS Moderate Resolution Imaging Spectroradiometer instruments (MODIS). An analysis of maritime traffic gives a better understanding of maritime operation needs and usage of natural ports, including bays within the research area. Therefore, the study focused on four sites: western approach to Horseshoe Island, Sally Cove (hosting a British station), Lystad Bay (hosting a Turkish station) and Gaul Cove. The results indicate that there has been no multiyear sea ice around Horseshoe Island. The most suitable months for the safe navigation of any type of ship in the area, due to the greatest number of ice-free days, are March, February, April and January. The study reveals that, in accordance with the Polar Code, lower ice class ships are required for safe navigation during scientific expeditions to Horseshoe Island. Also, as the average number of days with clear skies was 38, and average cloudiness very high, the use of optical satellites for long-term monitoring studies on Horseshoe Island is not recommended.

KEY WORDS

~ Antarctic Peninsula,
~ Remote sensing,
~ Polar Code,
~ Maritime safety

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1. INTRODUCTION

Sea ice, which has an important role in heat balance maintenance, supports a wide range of living ecosystems from sea to air in the polar areas, affects maritime operations and many other sectors, has faced high rates of melting after industrialization (Newman et al., 2019, Anisimov et. al., 2001). Sea ice is a natural phenomenon that occurs when seawater temperature drops below -1.5°C and freezes, forming a dense layer of ice. It is a thriving ecosystem that covers the surface greater than 18 million km^2 in both polar oceans during the winter (Sandven and Johannessen, 2006). Global warming has caused record temperatures above 20^0C on Antarctica, which is warmer than its average (NOAA, 2022; Gonzalez et. al., 2022).

The Southern Ocean Observing System (SOOS) aims to provide strategic and sustainable observation of the region. The Scientific Committee on Antarctic Research (SCAR) adopted the Antarctic Sea-ice Processes and Climate protocol that enables ongoing terrestrial observation programs, remote sensing studies and numerical models to use a common language, used widely in a number of studies (Worby and Comiso, 2004; aspect: 2023). Furthermore, numerous sea ice research projects have been carried out using sea vehicles, aircraft, remote sensing satellites, buoy systems, underwater and aerial unmanned technologies, etc. (Newman et al., 2019). The development of satellite technology caused a proliferation of sea ice research using various sensors and remote sensing methods. However, the extreme characteristics of polar regions, such as unpredictable conditions, distance, size and dynamic structure, inspire scientists to continue conducting both field and remote sensing studies.

The importance of using sea ice conditions and forecasts in maritime operations, such as logistics and navigation routes, has been demonstrated in Wagner et al., 2020. Owing to the development of the shipbuilding industry, ice class ships and icebreakers are being built by various countries and used in polar waters (Sandven and Johannessen, 2006). The Polar Code came into force in 2017 to prepare vessels for changing sea ice conditions in the Arctic and Southern Oceans (Karahalil et al., 2020).

Satellite remote sensing of sea ice is important for understanding overall sea ice conditions and improving ship navigation safety (Hui et al., 2017; Yu et al., 2023). Moderate Resolution Imaging Spectroradiometer Instrument (MODIS) is a frequently used sensor in polar region sea ice studies with its 36 different spectral bands (Drüe and Heinemann, 2005; Fraser et al., 2010; Fan et al., 2020). It provides daily data in a sun-synchronous near-polar orbit with a one-day revisiting period (Rösel and Kaleschke, 2011; Feng et al., 2022). Many researchers have used MODIS for long-term sea ice observations, in spite of choosing different approaches (Lopez-Acosta et al., 2019; Shi et al., 2020).

The examination of sea ice concentrations around the entire Antarctic Peninsula revealed that the western coasts of the Antarctic Peninsula have the lowest rate of sea ice (Holland and Kimura, 2016). Although the Antarctic Peninsula is one of the places most affected by global climate change, sea ice formation changes in the Southern Ocean also have a dynamic role in this change, as an important element in all other scientific measurements and ecosystems. Many formations and objects, such as polar ports and scientific stations, have been studied in an attempt to determine their efficiency, depending on whether sea routes are obstructed by ice. More research is needed to understand sea ice.

Various sea ice related studies in Marguerite Bay appear to have been conducted on plankton varieties. Rozema et al., 2017 research on the relationship between phytoplankton biomass and winter sea ice in the region is also important. According to the research and observations made in Marguerite Bay in the 1960s, sea ice was present from late April to January, with the first annual sea ice reaching the thickness of 0.5 meters (Heap, 1963). The paper by Perovich et al, 2004, looked into the morphological features, development processes and permeability of winter sea ice in the bay. An extensive literature review reveals that the above-mentioned data have been collected and that further research into sea ice is in progress. However, it is evident that the latest studies conducted in the Marguerite Bay, i.e. the area of this study, are not available and cannot be based on local data. The review paper by Yirmibesoglu et al., 2022, gives a detailed literature review of the scientific studies conducted on Horseshoe Island.

This study examines the surroundings of Horseshoe Island, located in the southernmost part of the Antarctic Peninsula. Nearly half of all Antarctic scientific bases, including depots, airways, etc. are located on the Antarctic Peninsula (COMNAP, 2017). Having reviewed the data from studies carried out after 2017, Turkish scientists intensified their research especially on Horseshoe Island in Marguerite Bay (Yavasoglu et al., 2019). Research in the area can be considered to have started with the scientific research and establishment of a British station in the 1950s. Although the majority of studies focused on the main topics, such as earth sciences and meteorology, a variety of studies are envisaged to be conducted in the Turkish scientific base in Marguerite Bay, which the Turks plan to establish in the 2020s. The environmental assessment report in this direction was shared in early 2021 (TARS, 2021). Only a few stations and ships operating in the vicinity of Horseshoe Island conduct different scientific research. Marguerite Bay has four scientific stations known as Carvajal (Chilean), Rothera station which includes the Dutch Dirck Gerritsz Lab (British), the San Martin station (Argentinean), and the Turkish Camp Site (COMNAP, 2017).

This study examines sea ice conditions around Horseshoe Island based on various satellite data obtained by using remote sensing technology in recent years to contribute to the field studies of ship logistics and scientific research. Remote sensing satellite images obtained from NASA's Terra satellite equipped with MODIS, have been used to improve our understanding of sea ice conditions (Riggs et. al., 2006; Fraser et. al., 2009; Zeng et. al., 2016). The purpose of the research was an analysis of future maritime operations by ice class vessels to reveal the condition of sea ice in the Marguerite Bay and determine a safer navigation route to Horseshoe Island. In the light of these developments, it is expected that the maritime activities and scientific research in the region will gain great momentum in the upcoming years.

2. STUDY AREA

Antarctica remains a continent where new studies, coordinated by the Scientific Committee on Antarctic Research (SCAR), can be conducted frequently (Florindo et. al., 2022). Horseshoe Island, having the surface of 78 km^2, has three main sea access points. The first is Sally Cove in the North which hosts Base Y, a former British scientific base from the 1950s, that is now listed in the Historic Sites and Monuments of the Antarctic Treaty (AT-Measure 19). The other site is Lystad Bay, located on the west side of the Island, currently hosting the Turkish Scientific Research Camp Site and the future location of the Turkish Antarctic Research Station (TARS, 2021). The third location is Gaul Cove in the East, containing no scientific equipment or stations.

Horseshoe Island is located in Marguerite Bay at 67°49''26' South and 067°12''16' West, within the Antarctic Circle (66°33'39'' South). Figure 1 shows the exact location of Horseshoe Island, which is located just between Pourquoi Pas Island and the Antarctic Peninsula on Antarctica. Furthermore, the map was created by Quantarctica program and does not depict any sea ice to better understand seaareas (Matsuoka et al., 2021).

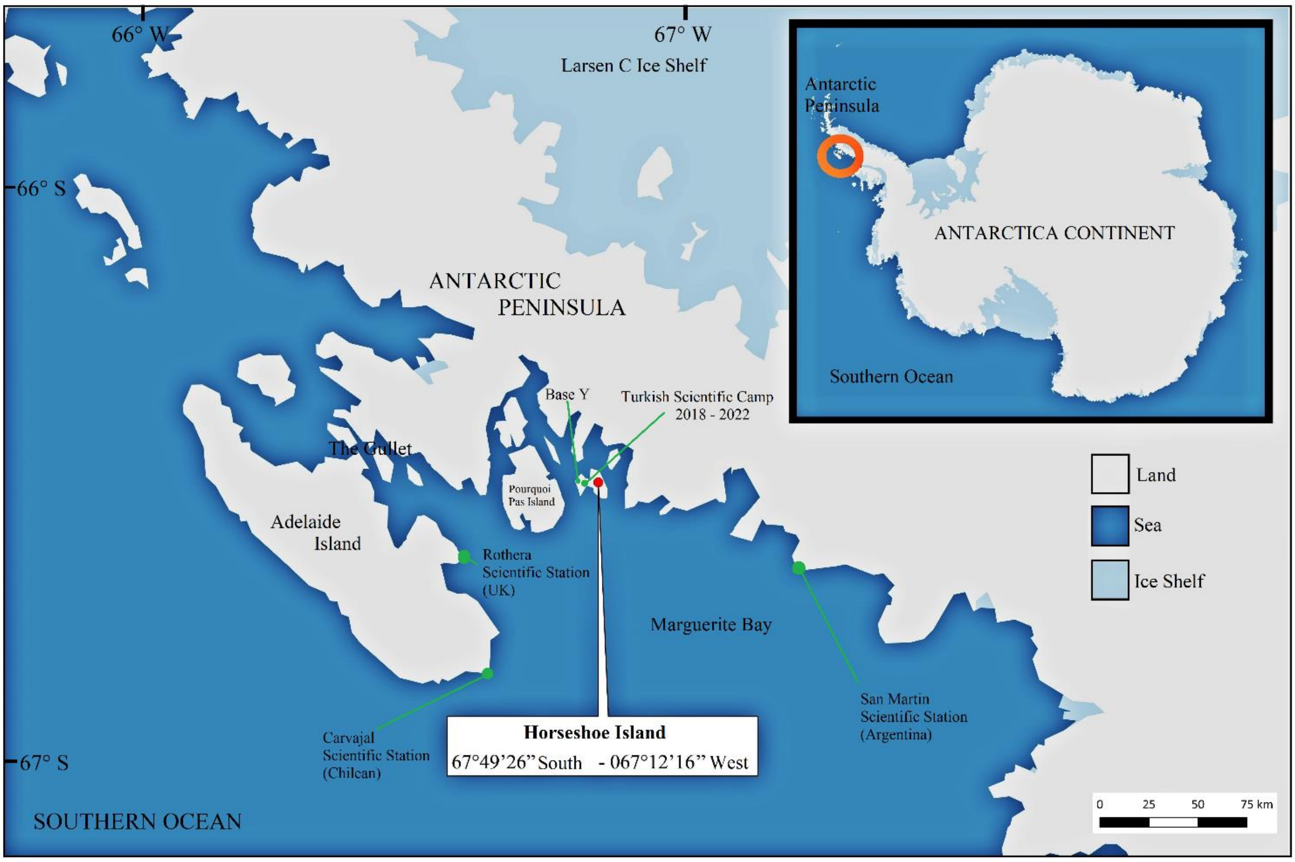


Figure 1. The location of Horseshoe Island (Source: edited in Quantarctica)

Figure 1 shows other scientific research stations in the vicinity of Horseshoe Island and conducting different scientific studies in Marguerite Bay. There are four scientific research stations in the bay, namely Carvajal and Rothera on Adelaide Island, San Martin Station on Barry Island, and the Turkish Camp Site on Horseshoe Island (SCAR Bulletin, 2003). The air distance between these scientific stations and Horseshoe Island is 71 km for Carvajal Station, 47 km for Rothera Station and 33 km for San Martin Station, respectively. Apart from sea routes, the stations are also connected to each other by air facilities, such as helipad and airstrip at Rothera and San Martin, helipad at Carvajal and the Turkish Camp Site (COMNAP, 2017).

2.1. Maritime perspective for Horseshoe Island in Marguerite Bay

Owing to increasing ship traffic in the polar regions over the past decade, the International Maritime Organization (IMO) put the Polar Code into force on 1 January 2017 (Chaure and Gudmestad, 2020). The mapping limits and practices applied to the Southern Ocean are based on winter sea ice conditions. Updating the Polar Code with changing sea ice conditions will help prevent ice class ships from harming the environment and the sea ice ecosystem. The Polar Code introduces new maritime regulations to ensure maritime safety and environmental protection in the polar region, such as the Polar Water Operational Manual (PWOM), the new SOLAS Chapter XIV, the MARPOL Amendments in Annexes I, II, IV, V and the Basic – Advanced Trainings to STCW 78 (Brigham, 2018).

The comparison of the two polar regions reveals they have different sea ice thickness distribution. While average sea ice thickness on Antarctica is between 1 and 1.5 meters, it is almost 3 meters in the Arctic. Consequently, ships break up ice in the Southern Ocean more easily (Sandven and Johannessen, 2006). These circumstances are crucial for ships navigating in polar waters. The Polar Code defines three main categories of vessels, each capable of dealing with specific sea ice types. The term “Category A” refers to vessels operating in at least medium first year sea ice, and are also known as Polar Class (PC) 1 to 5. The term “Category B” means vessels capable of navigating in at least thin first year sea ice, but excluding category A ships. PC 6 and PC 7 ships could be considered Category B ships. The term “Category C” includes other vessels capable of navigating in less severe sea ice conditions and not included in A and B categories (Polar Code, 2017).

Logistics are the primary strategic component on both scientific and tourist Antarctic expeditions (Hughes et. Al., 2020). Given that extreme weather conditions make flight operations difficult, shipping plays an important rule in all aspects (Nicol, 2015). Many ships navigate the Antarctic Peninsula in every summer season (McCarthy et. al., 2021), some of which head to Horseshoe Island in Marguerite Bay. The island has no airport runways nor human-made vessel docks, but its three bays serve as natural ports for many vessels, with a draft limitation. The island is mostly visited by scientists who conduct multidisciplinary research and supply stations (EIES, 2022).

Many types of vessels, such as sailing, yacht, icebreaker, and scientific research ships, visit the area, especially on ice-free days in the summer to supply the stations, conduct scientific research and engage in tourism (Marine Traffic, 2022). As of 2017, the Turkish Antarctic Expedition (TAE) has followed the round-trip route on the western coasts of the Antarctic Peninsula between King George Island and Horseshoe Island. The first TAE conducted sea ice studies and looked for a safer sea route to Horseshoe Island (Yirmibesoglu, 2018). The following TAE expeditions encountered different sea ice conditions, such as the fourth expedition when Antarctica broke the temperature record due to the effects of anthropogenic climate change in February 2020 (Gonzalez et. al., 2022).

3. METHODS AND DATA (SEA ICE CONDITIONS AROUND HORSESHOE ISLAND)

The research consisted of several steps - finding updated shipping routes and ports of interest to minimize the research area, collecting available satellite imagery for Horseshoe Island, analyzing data on Quantarctica software, checking maximum and minimum sea ice extent days on Horseshoe Island, and identifying sea ice free days since 2000. The ice-free days are days where sea ice concentration is lower than 1% and waters are navigable.

Vessel traffic data for Marguerite Bay for the last two years have been taken from Marine Traffic database to better understand the latest shipping interests in Horseshoe Island. Figure 2 gives an overview of maritime shipping routes taken by various vessels to reach Horseshoe Island and other scientific stations in Marguerite Bay: the data for 2020 given in (a) and for 2021 in (b) (Marine Traffic, 2022).

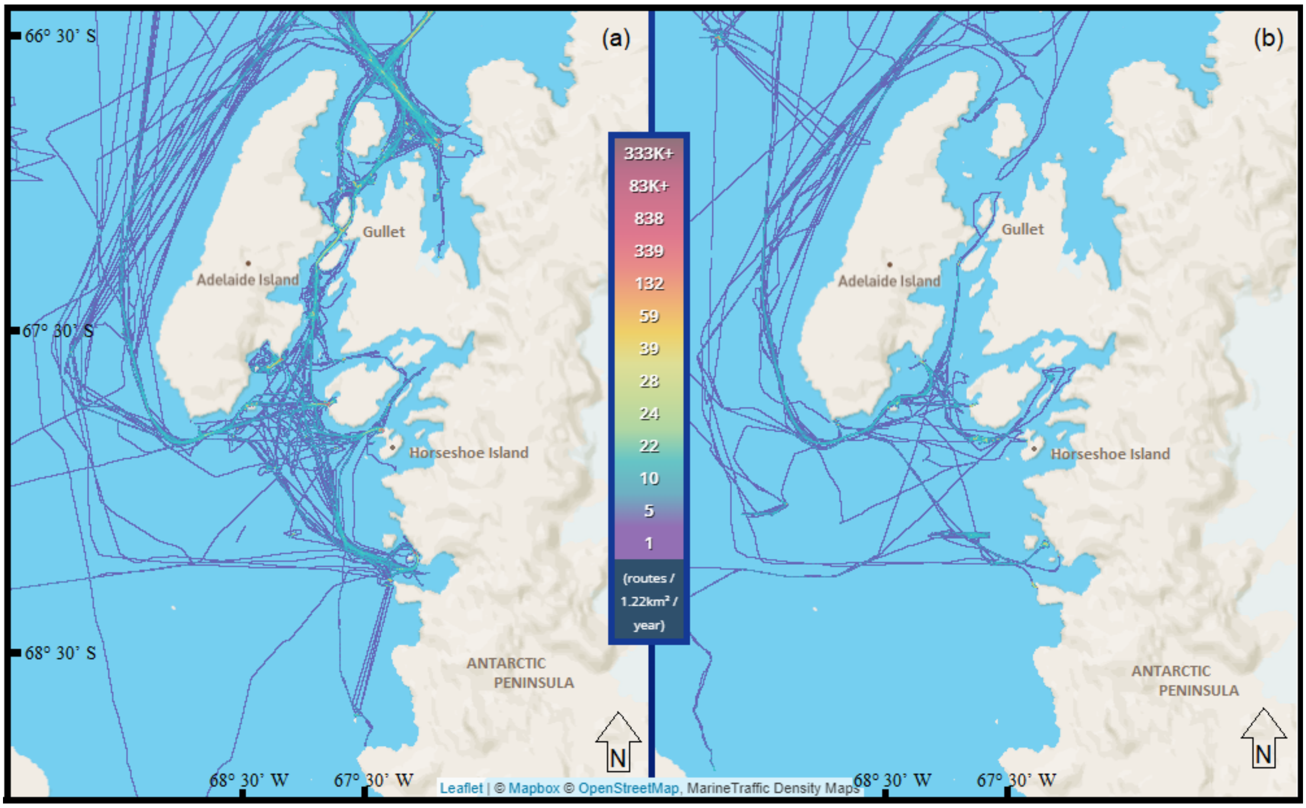


Figure 2. Shipping routes to Horseshoe Island in Marguerite Bay (Source: Marine Traffic)

In addition, maritime traffic routes in Figure 2 combined with Table 1 and the Antarctic Treaty's electronic information exchange system (EISS) give an overview of maritime scientific expeditions to the area (EIES, 2022).

Operating country	Ship name	Ice classification	Logistic purpose	Voyage details	Date
USA	R/V Nathaniel B. Palmer	A - A2 - PC3	Scientific	Punta Arenas - Rothera	Jan 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Punta Arenas - Rothera	Jan 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - Stanley	Jan 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Punta Arenas - Rothera	Feb 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - Signy	Feb 20
USA	R/V Nathaniel B. Palmer	A - A2 - PC3	Scientific	Punta Arenas - Rothera	Mar 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Signy - Rothera	Apr 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - Stanley	Apr 20
UK	MV Billesborg	C - Ice Class IA - PC7	Construction	Teesport - Rothera	Apr 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - Stanley	May 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Signy - Rothera	Dec 20
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - Falkland	Jan 21
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Signy - Rothera	Feb 21
UK	RRS James Clark Ross	A - Icebreaker - PC1	Scientific	Rothera - King Edward	Feb 21
Türkiye	S/Y Australis	C	Scientific	King George - Horseshoe	May 21
Türkiye	M/V Betanzos	C	Scientific	King George - Horseshoe	Feb 22

Table 1. Shipping activity in Marguerite Bay in the last two years based on EIES reports

Using the density map, the research area was divided into four main areas and satellite image examination focused mostly on the west side of Horseshoe Island, as shown in Figure 3.

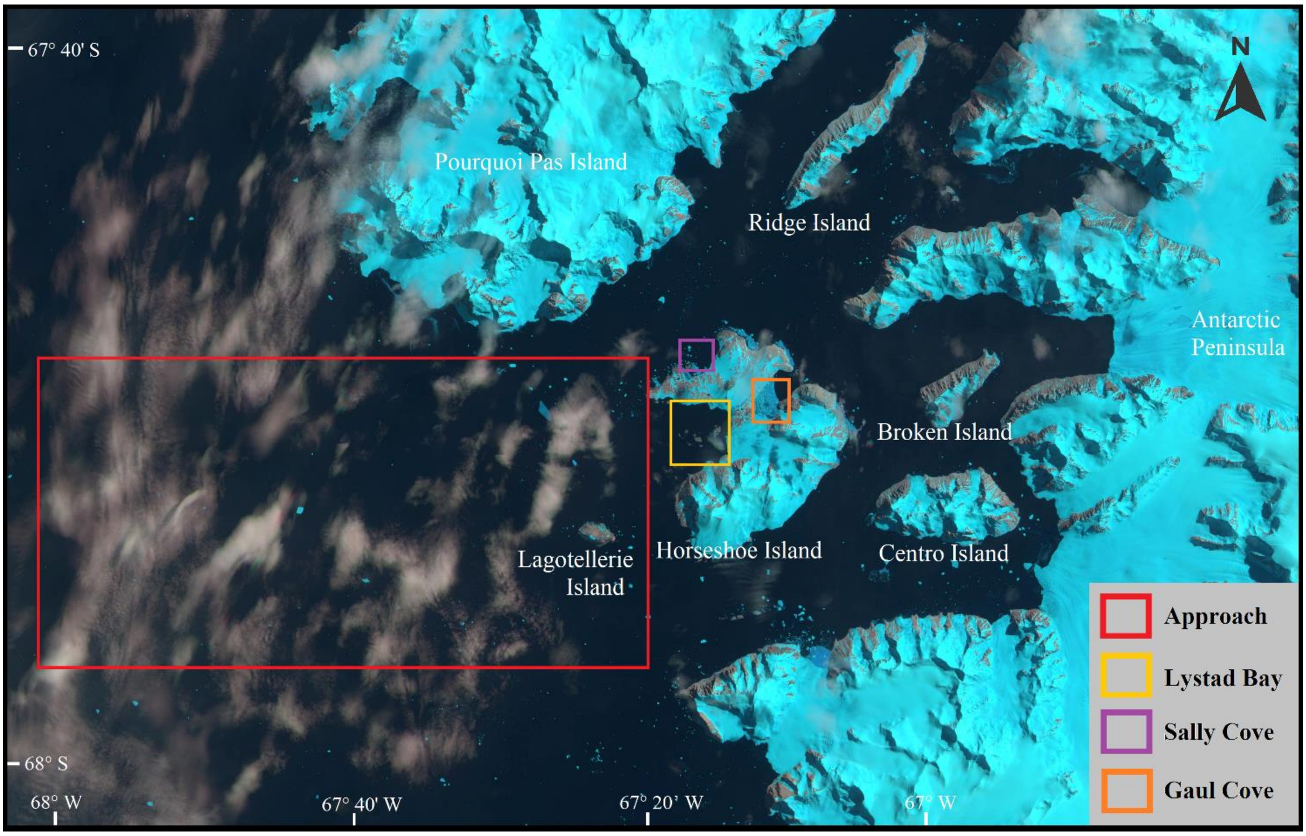


Figure 3. Area of interest for research (Source: Sentinel 2, date: 14/01/2018)

Dominant navigation route area has been marked with red color, Lystad Bay with yellow, Sally Cove with purple, and Gaul Cove with orange. These areas have also been chosen due to having different sea ice conditions in the melting period. The image above is a Sentinel 2 satellite image from January 14, 2018, which shows sea ice accumulating at Gaul Cove and the northern coasts, as well as small icebergs dispersed throughout the area (Copernicus, 2022).

Figure 4 presents research steps in flowchart form. After identifying key locations for maritime operations around Horseshoe Island, appropriate satellite images were gathered, minimum and maximum sea ice extents determined, sea ice was classified by melting seasons, sea ice-free areas were identified and appropriate ice class ship type determined.

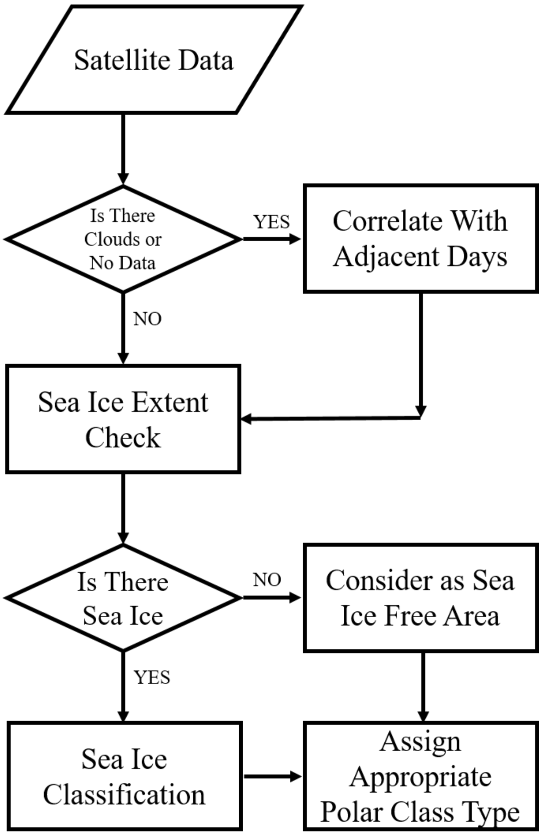


Figure 4. Appropriate ice class type identification process in flowchart form

Sea Ice Index passive microwave satellite data, with 25 km x 25 km spatial resolution, give a quick overview of sea ice changes in the Southern Ocean since 1979 (Fetterer, et al., 2016). These monthly data are used for long-term trend analysis. The annual Southern Ocean Sea Ice extent limits on minimum and maximum days have been obtained from the archives of the National Snow and Ice Data Center (NSIDC) and compared in Table 2. The minimum extent represents record melting of sea ice, while the maximum extent represents the largest water surface area reached within a year. On such days, sea ice conditions in Marguerite Bay should be a close reflection of the overall situation, improving the ability of the study to identify multiyear sea ice occurrence in the research area.

Years	Min date	Min extent ($x10^6$ km^2)	Max date	Max extent ($x10^6$ km^2)
2022	**25 Feb**	**1.920**	16 Sep	18.189
2021	22 Feb	2.680	30 Aug	18.893
2020	19 Feb	2.711	25 Sep	19.062
2019	28 Feb	2.427	26 Sep	18.489
2018	18 Feb	2.200	30 Aug	18.315
2017	1 Mar	2.080	9 Oct	18.145
2016	17 Feb	2.616	29 Aug	18.581
2015	18 Feb	3.544	2 Oct	18.912
2014	21 Feb	3.548	**20 Sep**	**20.201**
2013	19 Feb	3.679	1 Oct	19.608
2012	23 Feb	3.111	22 Sep	19.478
2011	22 Feb	2.319	23 Sep	18.954
2010	16 Feb	2.842	6 Sep	18.998
2009	22 Feb	2.671	24 Sep	19.299

2008	20 Feb	3.692	3 Sep	18.298
2007	19 Feb	2.723	29 Sep	19.086
2006	20 Feb	2.487	21 Sep	19.360
2005	18 Feb	2.804	29 Sep	19.295
2004	20 Feb	3.259	08 Sep	19.124
2003	17 Feb	3.626	25 Sep	18.680
2002	20 Feb	2.697	9 Sep	18.116
2001	19 Feb	3.441	28 Sep	18.494
2000	18 Feb	2.582	28 Sep	19.159
1999	20 Feb	2.707	30 Sep	18.981
1998	25 Feb	2.772	15 Sep	19.244
1997	27 Feb	2.264	22 Sep	18.792
1996	25 Feb	2.597	23 Sep	18.831
1995	24 Feb	3.330	26 Sep	18.762
1994	12 Feb	3.083	31 Aug	18.827
1993	19 Feb	2.281	20 Sep	18.710
1992	23 Feb	2.492	11 Sep	18.467
1991	27 Feb	2.554	30 Sep	18.671
1990	22 Feb	2.784	30 Sep	18.379
1989	20 Feb	2.723	23 Sep	18.274
1988	24 Feb	2.639	3 Oct	18.785
1987	21 Feb	3.010	15 Sep	18.524
1986	6 Mar	2.953	18 Sep	18.027
1985	19 Feb	2.602	11 Sep	18.931
1984	27 Feb	2.382	22 Sep	18.370
1982	23 Feb	2.843	3 Sep	18.811
1981	20 Feb	2.890	18 Sep	18.550
1980	26 Feb	2.694	23 Sep	18.856
1979	17 Feb	2.521	13 Sep	19.092

Table 2. Minimum and maximum sea ice extents (source: NSIDC, 2022)

Terra satellite using MODIS imagery has been in operation since 2000. Its wavelengths are blue, green, and red, creating natural colored images of land and ocean surfaces for the human eye (Xiong et al., 2005; Terra/MODIS, 2022). MODIS has 36 different spectral bands overall, with resolution between 250 m and 1 km (Drüe and Heinemann, 2005). First, all available Terra/MODIS satellite images for the area around Horseshoe Island were examined to identify maximum and minimum sea ice extent days and the highest and lowest sea ice limits. Then, available corrected Terra/MODIS images downloaded from NASA Worldview were used to examine sea ice conditions in the study area (NASA, 2022). Different remote sensing satellites and their sensor data were also checked and used to understand the sea ice situation in Marguerite Bay. Specifically, ice-free days were used to identify most suitable months for the safe navigation of all types of ice class vessels. Finally, a detailed study was conducted to determine which ice class ships can navigate around Horseshoe Island depending on sea ice thickness, based on monthly averages over the last twenty years.

The Antarctica package of professional open-source Geographical Information System (GIS) software, known as ‘Quantarctica’, produced by the Norwegian Polar Institute, was used in this research to visualize, import and explore the area with satellite images (Matsuoka et al., 2021). While preparing working ground, a detailed base map, taken from the SCAR Antarctic Digital Database, which included land, ocean, ice shelf, sea mask, cloud mask, and coastline features was used. The validation of images was completed by comparing the sea ice situation on cloudless days with the images from satellites equipped with optical sensors, such as Sentinel – 2, Landsat 8, Göktürk-2, RASAT. In addition, in situ sea ice observation was conducted around Horseshoe Island every summer season since 2017.

4. RESULTS

Vessel traffic density in 2020 and 2021 is shown in Figure 2, where shipping routes taken by various vessels were taken from the Marine Traffic database. This information was used to understand the latest logistical operations in the area and the need to determine sea ice condition relevant for shipping operations. Potential destinations for visitors were identified as Sally Cove and Lystad Bay on Horseshoe Island. Based on available data, vessel traffic density appears to have been lower in the research area in 2020, due to the Covid-19 pandemic and research by Hughes and Convey from 2020 confirms this result for the entire continent. To understand the density map accuracy, voyage purposes and vessel numbers were cross-checked against EIES data and presented in Table 1. The data indicate that 11 voyages were undertaken in 2020, compared to only 4 in the following year. It appears that six disparate ships from all polar code vessel classes visited the area to meet the scientific, construction and logistic needs of Rothera Research Station and the Turkish Camp Site in the summer months.

The NSIDC Sea Ice Index data presented in Table 2 indicate that, on average, September has had the maximum and February the minimum sea ice extent in the Southern Ocean since 1979 (Fetterer, et al., 2016). The lowest sea ice extent since the start of satellite data collection in 1979 was recorded in 2022. In the meantime, according to satellite data in Table 2, the record maximum sea ice extent was observed on September 20, 2014 (Comiso et al., 2017). Minimum sea ice extent dates have significant implications for understanding the differences between the occurrence of first-year sea ice and multiyear sea ice in the area. 84 Terra/MODIS images from 2000 on were examined and no sea ice was observed in the research area on record minimum sea ice extent dates except in 2002-2006, 2009, 2012, and 2014-2017. Nevertheless, the western approach to Horseshoe Island has seen completely sea ice free on more than half of the minimum extent dates for Antarctica.

By contrast, Horseshoe Island was almost completely surrounded by first year sea ice on maximum sea ice extent dates on 97 Terra/MODIS images. The approach route to Horseshoe Island was covered with sea ice ranging from 5 to 10 and Lystad Bay from 2 to 10 on maximum extent days. However, Gaul cove was always covered in sea ice on maximum extent dates. This difference suggests that the currents have a greater impact on sea ice drift on the island’s west coasts.

8376 Terra/MODIS images were analyzed to identify ice-free days and sea ice conditions suitable for maritime operation around Horseshoe Island. Sea ice average for specified areas for the last twenty years was calculated and is given in Figure 5.

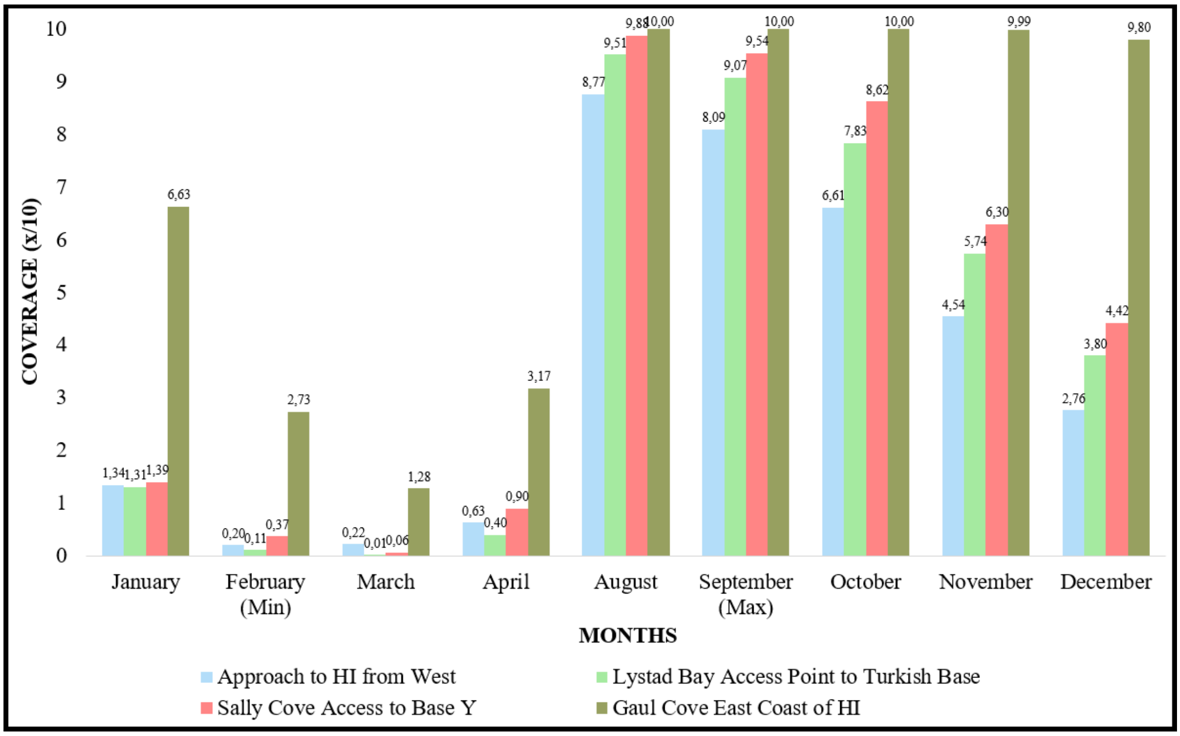


Figure 5. Average monthly sea ice coverage 2000 - 2022

Figure 5 shows that especially the east side of Horseshoe Island experiences heavier sea ice conditions than the western side due to meteorological differences, as well as many other parameters, such as high mountains, less interaction with open water, and the prevailing NE wind blowing directly towards Gaul Cove. Ice formation was the fastest in Gaul Cove, followed by Sally Cove and Lystad Bay. The wind aids in the opening of polynyas in Lystad Bay. That's why icy conditions are more frequent in Gaul Cove than in other areas. Due to the lowest sea ice coverage, the area is most easily accessible in February and March.

Figure 6 shows examples of the most characteristic minimum and maximum sea ice occurrence in the research. The upper image shows an ice-free day on 24 February 2020, while the bottom image illustrates full sea ice coverage in the research area on 1 September 2005.

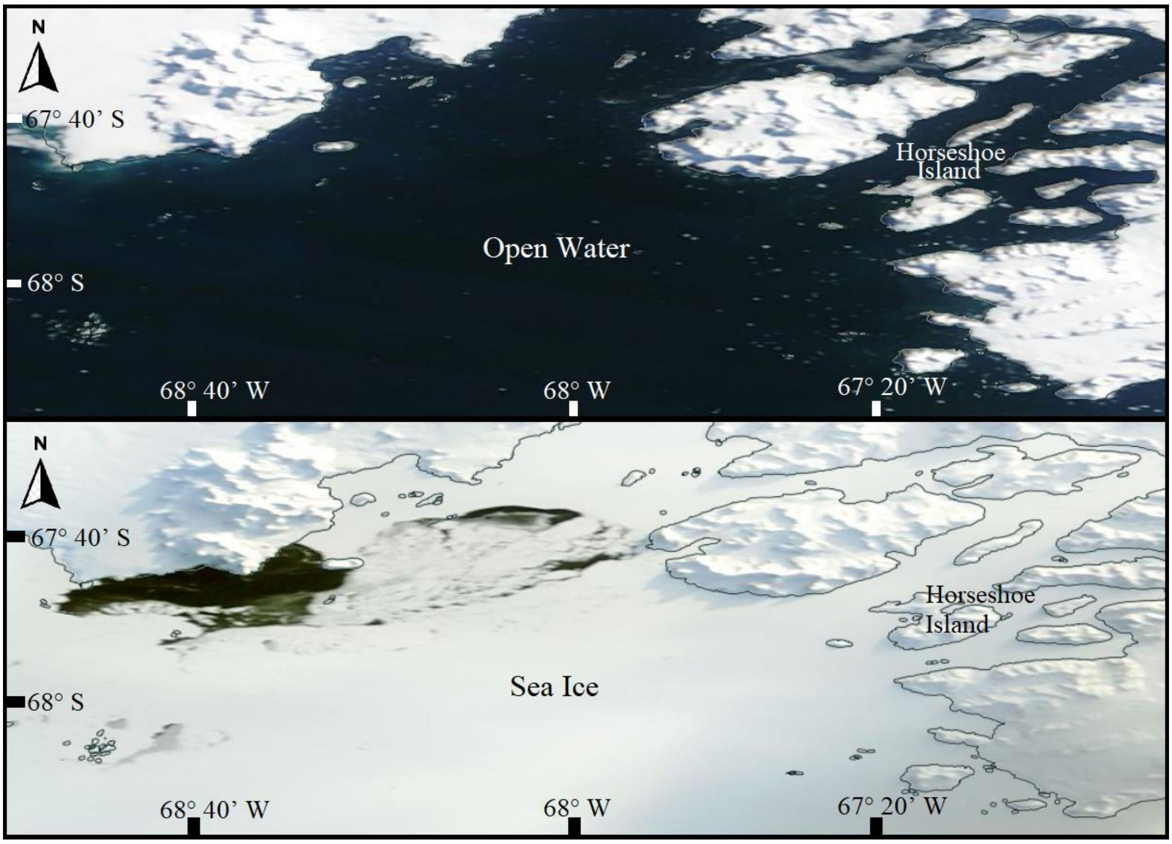
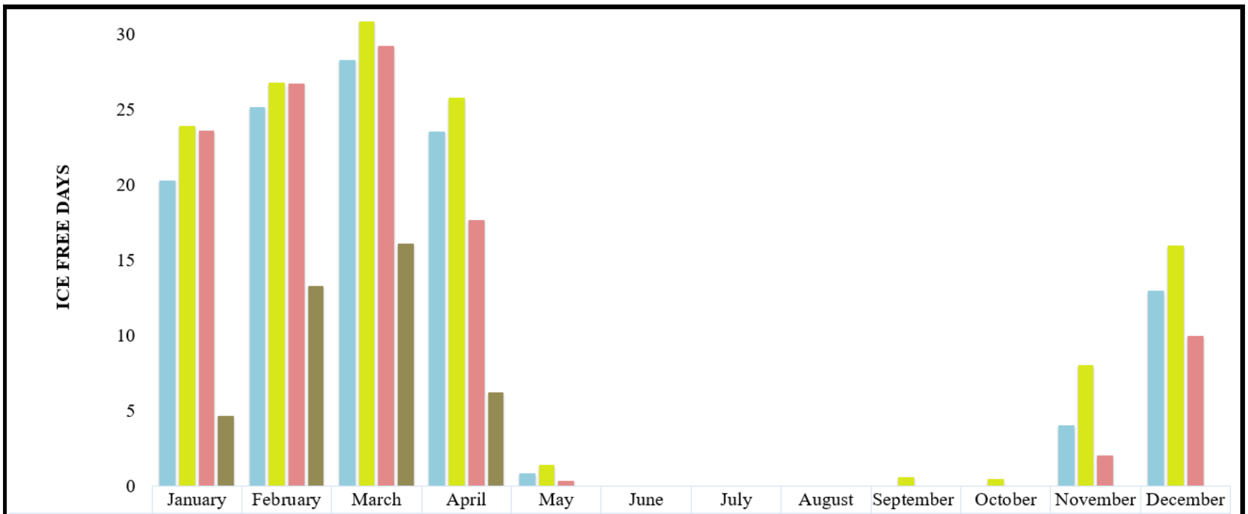


Figure 6. Examples of minimum and maximum sea ice coverage (Source: NASA)

Average ice-free days by months are given in Figure 7, based on calculations for 2000-2022.



	January	February	March	April	May	June	July	August	September	October	November	December
Approach to HI	20	25	28	24	1	0	0	0	0	0	4	13
Lystad Bay	24	27	31	26	1	0	0	0	1	0	8	16
Sally Cove	24	27	29	18	0	0	0	0	0	0	2	10
Gaul Cove	5	13	16	6	0	0	0	0	0	0	0	0

MONTHS

Figure 7. Average sea ice free days by month in 2000 - 2022

Satellite images show that four research areas experienced ice-free conditions mostly in March, followed by February, April, and January. With the exception of Gaul Cove, there were also ice-free days in December and November. There were almost no ice-free areas in May, June, July, August, September, and October. Area with the most ice-free days was Lystad Bay, followed by the western approach, Sally Cove and Gaul Cove. The number of ice-free days suggests there are better options for all vessel types to navigate in Antarctica than stipulated in the Polar Code.

Figure 8 gives a clear and comprehensive overview of the atmospheric conditions during Horseshoe Island observations.

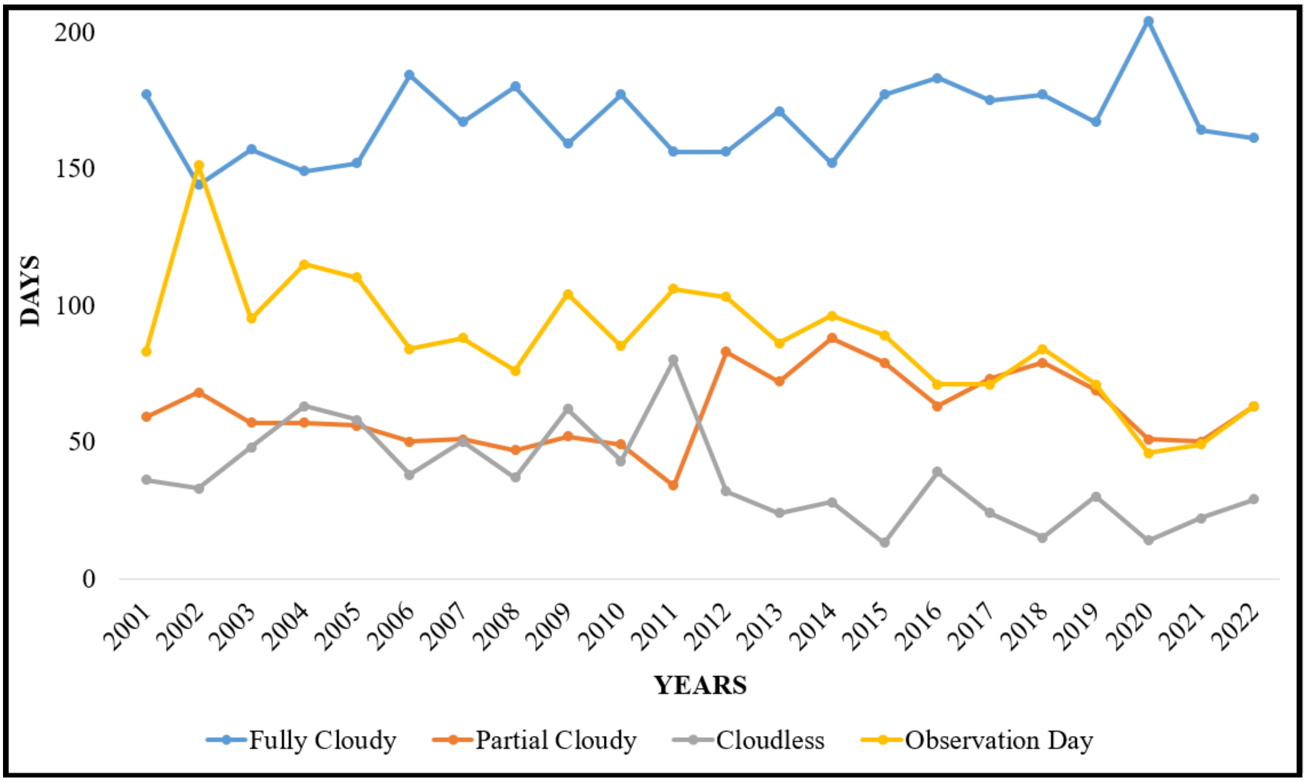


Figure 8. Cloud conditions over Horseshoe Island in 2000-2022

Satellite data show that cloudiness over Horseshoe Island is high. Cloudless means that there was less than 2/10 cloud coverage in research areas. Cloud coverage ranging from 8/10 to 10/10 means fully cloudy, partially cloudy indicates cloud coverage between blue skies (cloudless) and fully cloudy situations. The average conditions were: 168 fully cloudy days, 61 partially cloudy days, 38 blue skies days, and 89 observation days. This gives a clear understanding of sea ice coverage, and no data average is 97. The number of fully cloudy days is increasing, while the number of observation days and blue skies days is decreasing. Furthermore, partially cloudy days are more frequent than cloudless days. This outcome offers another perspective for navigation safety planning, such as celestial body observation in emergencies, etc.

Considering the findings, it appears that any Polar Code ship category would be able to navigate around Horseshoe Island in the summer season without difficulty in ice-free waters. However, in other months marked by the formation of first sea ice, Polar Code Category B ships would encounter sea ice around Horseshoe Island. Multiyear sea ice has not been observed in the last twenty years, especially in Lystad Bay and Sally Cove. Therefore, Category A ships are not required for expeditions to Horseshoe Island in the summer months. The recommended Ice Class ship types that would be capable of navigating sea ice in all waterways around Horseshoe Island, by months, are listed in Table 3.

Months / Ship Class	Polar Code Category C (Others)	Polar Code Category B (PC 6, PC7)	Polar Code Category A (PC 1 - PC 5)
January	Green	Green	Green
February	Green	Green	Green
March	Green	Green	Green
April	Green	Green	Green
May	Orange	Green	Green
June	Red	Green	Green
July	Red	Green	Green
August	Red	Green	Green
September	Orange	Green	Green
October	Orange	Green	Green
November	Green	Green	Green
December	Green	Green	Green

Green: Recommended, Orange: Variable, Red: Not Appropriate.

Table 3. Recommended ice class ship types for all waterways around Horseshoe Island

5. CONCLUSION

Given that Antarctic waters are the most challenging and least explored waters in the world, scientific study of sea ice is an important contribution to maritime navigation. Therefore, this study aims to help plan safer navigation for scientific and tourist expeditions to Horseshoe Island surroundings, characterized by engaging sites, structures, etc. frequently encountered on the southern Antarctic Peninsula. According to data obtained over the last twenty years from various satellites, cloudiness is high in the Horseshoe Island region, which makes monitoring sea ice using Terra/MODIS images a good practice. Since 2000, Horseshoe Island has only been surrounded by first-year sea ice, which melts during the summer season. Due to the presence of ice-free days, that conclusion is also supported by other research. It is evident that the western coast of Horseshoe Island has never experienced multiyear or old ice conditions. Sea ice concentration observation results indicate that Lystad Bay is more easily accessible for maritime operations than Gaul Cove. It appears that icebergs and sea ice inside Gaul Cove create additional obstacles for vessel operations. Furthermore, Sally Cove is covered by sea ice longer than Lystad Bay. Therefore, Lystad Bay, which hosts the Turkish Antarctic Scientific Camp, is the most suitable location for maritime operations such as logistics, anchoring and safekeeping. We recommend that ships visiting the area under the Polar Code use Lystad Bay or Sally Cove in case of sea ice navigation.

Apart from maritime routes, other conclusions were drawn with respect to the effect of climate change on sea ice. Recent extreme temperatures observed worldwide accelerate the rate of sea ice melting. International organizations, states, and other major entities should increase their support for ocean research by drawing attention to the importance of sea ice. One of these is the United Nations' Decade of Ocean Science for Sustainable Development which was created by the United Nations to cover the ten-year period between 2021 and 2030. It attaches great importance to studies in the Southern Ocean, especially those dealing with climate, environment and ecosystem (Ocean Decade, 2022). In this vein, we recommend that more sea ice research be conducted on the Antarctic Peninsula in the future, to improve the safety and productiveness of maritime operations using strategic SOOS and SCAR points.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

REFERENCES

Anisimov, O. et al., 2001. Polar Regions (Arctic and Antarctic). Climate change, pp. 801-841.

Antarctic Treaty, AT-Measure 19., 2015. Revised List of Historic Sites and Monuments, Measure 19 Annex.

ASPeCt, Antarctic Sea Ice Process & Climate, 2022. Available at: http://aspect.antarctica.gov.au/home/publications

Brigham, L., 2018. IMO Polar Code: New Governance for the Southern Ocean. Antarctic Science, 30(6), pp. 331-331. Available at: https://doi.org/10.1017/S095410201800041X

Chaure, M. R. and Gudmestad, O. T., 2020. Effectiveness of the Polar Code training of cruise liner crew for evacuation in the Arctic and Antarctic. TRANSNAV, 14, (4). Available at: https://doi.org/10.12716/1001.14.04.17

Comiso, J.C. et al., 2017. Positive Trend in the Antarctic Sea Ice Cover and Associated Changes in Surface Temperature, American Meteorological Society, 2017, pp. 2251–2267. Available at: https://doi.org/10.1175/JCLI-D-16-0408.1

COMNAP (Council of Managers of National Antarctic Program) Antarctic Station Catalogue, COMNAP Secretariat, 2017. Available at: https://www.comnap.aq/antarctic-facilities-information

Copernicus Sentinel data, processed by ESA 2002. Access: https://scihub.copernicus.eu/, accessed on 01 January 2023.

Drüe, C. and Heinemann, G., 2005. Accuracy assessment of sea-ice concentrations from MODIS using in-situ measurements. Remote sensing of environment, 95(2), pp. 139-149. Available at: https://doi.org/10.1016/j.rse.2004.12.004

EIES, Antarctic Treaty Electronic Information Exchange System, 2022. Available at: https://eies.ats.aq/, accessed on: 03 May 2022.

Fan, P. et al., 2020. Sea ice surface temperature retrieval from Landsat 8/TIRS: Evaluation of five methods against in situ temperature records and MODIS IST in Arctic region. Remote Sensing of Environment, 248, p. 111975. Available at: https://doi.org/10.1016/j.rse.2020.111975

Feng, J. et al., 2022. Pan-Arctic melt pond fraction trend, variability, and contribution to sea ice changes. Global and Planetary Change, 217, p. 103932. Available at: https://doi.org/10.1016/j.gloplacha.2022.103932

Fetterer, F. et al., 2016. Sea ice index, version 2. Boulder, Colorado USA. NSIDC: national snow and ice data center. Available at: https://doi.org/10.7265/N5K072F8

Florindo, F., Meloni, A. and Siegert, M., 2022. Sixty years of coordination and support for Antarctic science–the role of SCAR. In Antarctic Climate Evolution, pp. 9-40. Available at: https://doi.org/10.1016/B978-0-12-819109-5.00011-6

Fraser, A. D., Massom, R. A. and Michael, K. J., 2009. A method for compositing polar MODIS satellite images to remove cloud cover for landfast sea-ice detection. IEEE transactions on geoscience and remote sensing, 47(9), pp. 3272-3282. Available at: https://doi.org/10.1109/TGRS.2009.2019726

Fraser, A. D., Massom, R. A. and Michael, K. J., 2010. Generation of high-resolution East Antarctic landfast sea-ice maps from cloud-free MODIS satellite composite imagery. Remote Sensing of Environment, 114(12), pp. 2888-2896. Available at: https://doi.org/10.1016/j.rse.2010.07.006

Heap, J. A., 1963. Sea ice distribution in the Antarctic: between longitudes 7° W and 92° W. London, Hydrographic Department.

González-Herrero, S. et al., 2022. Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula. Communications Earth & Environment, 3(1), pp. 1-9. Available at: https://doi.org/10.1038/s43247-022-00450-5

Holland, P. R. and Kimura, N., 2016. Observed concentration budgets of Arctic and Antarctic sea ice. Journal of Climate, 29(14), pp. 5241-5249. Available at: https://doi.org/10.1175/JCLI-D-16-0121.1

Hughes, K. A. and Convey, P., 2020. Implications of the COVID-19 pandemic for Antarctica. Antarctic Science, 32(6), pp. 426-439. Available at: https://doi.org/10.1017/S095410202000053X

Hui, F. et al., 2017. Satellite-based sea ice navigation for Prydz Bay, East Antarctica. Remote Sensing, 9(6), p. 518. Available at: https://doi.org/10.3390/rs9060518

Karahalil, M., Ozsoy, B. and Oktar, O., 2020. Polar Code application areas in the Arctic. WMU Journal of Maritime Affairs, pp. 1–16. Available at: https://doi.org/10.1007/s13437-020-00200-4

Lopez-Acosta, R., Schodlok, M. P. and Wilhelmus, M. M., 2019. Ice Floe Tracker: An algorithm to automatically retrieve Lagrangian trajectories via feature matching from moderate-resolution visual imagery. Remote Sensing of Environment, 234, p. 111406. Available at: https://doi.org/10.1016/j.rse.2019.111406

Marine Traffic, Density Map, 2022. Available at: https://www.marinetraffic.com/en/ais/home/centerx:-67.7/centery:-67.8/zoom:8

Matsuoka, K. et al., 2021. Quantarctica, an integrated mapping environment for Antarctica, the Southern Ocean, and sub-Antarctic islands. Environmental Modelling & Software, 140, 105015. Available at: https://doi.org/10.1016/j.envsoft.2021.105015

McCarthy, A. H., Peck, L. S. and Aldridge, D. C., 2022. Ship traffic connects Antarctica's fragile coasts to worldwide ecosystems. Proceedings of the National Academy of Sciences, 119(3), e2110303118. Available at: https://doi.org/10.1073/pnas.2110303118

NASA Worldview, 2022, Corrected reflectance True Color (bands 1-4-3). Available at: https://worldview.earthdata.nasa.gov/

Newman, L. et al., 2019. Delivering Sustained, Coordinated, and Integrated Observations of the Southern Ocean for Global Impact. Front. Mar. Sci. 6(433). Available at: https://doi.org/10.3389/fmars.2019.00433

Nicol, S., 2015. Antarctica: Surround Sound. ANU Press.

NOAA National Centers for Environmental Information, State of the Climate: Global Climate Report for March 2022. Available at: https://www.ncdc.noaa.gov/sotc/global/202203

NSIDC, 2022 Sea Ice Extent Data, Available at: https://nsidc.org/data/search/#keywords=sea+ice

Ocean Decade, Southern Ocean Actions. Available at: https://www.oceandecade.org/decade-actions/

Perovich, D. K. et al., 2004. Winter sea-ice properties in Marguerite Bay, Antarctica. Deep Sea Research Part II: Topical Studies in Oceanography, 51(17-19), pp. 2023-2039. Available at: https://doi.org/10.1016/j.dsr2.2004.07.024

Polar Code, International Code For Ships Operating In Polar Waters (Polar Code), IMO, 2017.

Riggs, G. A., Hall, D. K. and Salomonson, V. V., 2006. MODIS sea ice products user guide to collection 5. NASA Goddard Space Flight Center, Greenbelt, MD, 49.

Rozema, P. D. et al., 2017. Interannual variability in phytoplankton biomass and species composition in northern Marguerite Bay (West Antarctic Peninsula) is governed by both winter sea ice cover and summer stratification. Limnology and Oceanography, 62(1), pp. 235-252. Available at: https://doi.org/10.1002/lno.10391

Rösel, A. and Kaleschke, L., 2011. Comparison of different retrieval techniques for melt ponds on Arctic sea ice from Landsat and MODIS satellite data. Annals of Glaciology, 52(57), pp. 185-191. Available at: https://doi.org/10.3189/172756411795931606

Sandven, S. and Johannessen, O. M., 2006. Sea ice monitoring by remote sensing. The American Society for Photogrammetry & Remote Sensing.

SCAR Bulletin No 150, July 2003: Twenty-fifth Antarctic Treaty Consultative Meeting Warsaw, Poland, 10–20 September 2002: Management Plan for Antarctic Specially Protected Area No. 107 Emperor Island, Dion Islands, Marguerite Bay, Antarctic Peninsula: Management Plan For Antarctic Specially Protected Area No. 108 Green Island, Berthelot Islands, Antarctic Peninsula. (2003). Polar Record, 39(3), pp. 273-287. Available at: https://doi.org/10.1017/S0032247403003127

Shi, Q. et al., 2020. Step-by-step validation of Antarctic ASI AMSR-E sea-ice concentrations by MODIS and an aerial image. IEEE Transactions on Geoscience and Remote Sensing, 59(1), 392-403. Available at: https://doi.org/10.1109/TGRS.2020.2989037

TARS CEE Report Draft Comprehensive Environmental Evalutaion Report, 2021. Construction and Operation of the Turkish Antarctic Research Station (TARS) at Horseshoe Island, Antarctica.

Terra/MODIS, 2022. Available at: https://terra.nasa.gov/about/terra-instruments/modis, accessed on: 01 January 2023.

Xiong, X., Che, N. and Barnes, W., 2005. Terra MODIS on-orbit spatial characterization and performance. IEEE Transactions on Geoscience and Remote Sensing, 43(2), pp. 355-365. Available at: https://doi.org/10.1109/TGRS.2004.840643

Yavasoglu, H.H. et al., 2019. Site selection of the Turkish Antarctic Research station using Analytic Hierarchy Process. Polar Science, 22. Available at: https://doi.org/10.1016/j.polar.2019.07.003

Yirmibesoglu, S., 2018. Sea Ice Observations & Maritime Meteorology Records during Turkish Antarctic Expedition–I (TAE-I), M.Sc. Thesis, Istanbul Technical University, 2018.

Yirmibesoglu, S., Oktar, O. and Ozsoy, B., 2022. Review of Scientific Research Conducted in Horseshoe Island Where Potential Place for Turkish Antarctic Base. International Journal of Environment and Geoinformatics, 9(4), pp. 11-23. Available at: https://doi.org/10.30897/ijegeo.1018913

Yu, A. et al., 2023. Sea Ice Extraction via Remote Sensed Imagery: Algorithms, Datasets, Applications and Challenges. arXiv preprint arXiv:2306.00303. Available at: https://doi.org/10.48550/arXiv.2306.00303

Wagner, P. M. et al., 2020. Sea-ice information and forecast needs for industry maritime stakeholders. Polar Geography, 43(2-3), pp. 160-187. Available at: https://doi.org/10.1080/1088937X.2020.1766592

Worby, A. P. and Comiso, J. C., 2004. Studies of the Antarctic sea ice edge and ice extent from satellite and ship observations. Remote sensing of environment, 92(1), pp. 98-111. Available at: https://doi.org/10.1016/j.rse.2004.05.007

Zeng, T. et al., 2016. Sea ice thickness analyses for the Bohai Sea using MODIS thermal infrared imagery. Acta Oceanologica Sinica, 35(7), pp. 96-104. Available at: https://doi.org/10.1007/s13131-016-0908-8