Exploring the Antarctic

Space Applications Centre

Indian Space Research Organisation

Department of Space

Government of India

Ahmedabad - 380015

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FOREWORD

Global climate change has been a major issue of concern since past few decades. Therefore, it is widely deliberated in several International and national forums and several policies are being agreed upon to manage and mitigate its possible consequences. Earth's polar regions covering ice sheets, sea ice cover and deep-water formation/ventilation sites, have the potential to influence global atmospheric and oceanic circulations. Huge ice reservoir exists over the Antarctica and Greenland in the form of ice sheets and any negative change in ice volume leads to rise in the global sea level. Moreover, small change in sea ice extent can cause big change in the polar climate through the ice-albedo feedback mechanism. Present day global climate models and satellite-based evidences indicate the thinning as well as shrinking of polar ice cover.

It is difficult to acquire conventional field based data in Polar regions due to extreme weather conditions, inaccessibility in many regions and frozen ocean all around ice sheets. Therefore, polar orbiting Earth Observation satellite data are being widely used for constant monitoring and modeling of polar cryosphere. Space Applications Centre (SAC), Indian Space Research Organisation (ISRO), Ahmedabad is contributing in the Indian Antarctic Science Programme by actively participating in several Indian Scientific Expeditions to Antarctica and collecting in-situ data useful for development and validation of several parameters retrieved using satellite data.

I am happy to note that Team at SAC has compiled glimpses of various features over sea ice and continental regions over the Antarctic captured during different expedition and voyages along with related brief on satellite data analysis. I hope that this book would serve as a useful reference source for concerned scientists, academicians and researchers and will inspire them to contribute further in the endeavor to understand the complex natural processes operating in the Antarctic.

Place: Ahmedabad
Date: February 19, 2020

(डी के दास) / (D K Das)

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We would like to express our gratitude towards Dr. D. K. Das, Director, Space Applications Centre (SAC) and former Directors Dr. R. R. Navalgund and Shri Tapan Misra for their kind direction and suggestions that have given a boost to the remote sensing activities to study the Antarctic cryosphere. We are indebted to Shri Nilesh M. Desai, Associate Director, SAC for his meticulous comments and suggestions in his various capacities, which has helped the team to develop Antarctic science knowledgebase at SAC.

Our heartfelt appreciation goes to Shri Rajeev Jyoti, Deputy Director, SAC and other former Deputy Directors Dr. J. S. Parihar, Dr. P. K. Pal, Dr. B. S. Gohil, Dr. S. S. Rana who have provided kind guidance, warm encouragement and support for the Antarctic expedition activities and associated scientific research.

Inspiration and guidance received from late Dr. N. K. Vyas has helped in initiating the expedition activities and we are grateful to him. We have been greatly benefited by the suggestions, support and guidance received from present and former Scientists Dr. V. K. Agarwal, Dr. Abhijit Sarkar, Dr. Rashmi Sharma, Dr. Alok Mathur, Dr. Markand P. Oza, Shri D. B. Dave, Smt. Jolly Dhar, Shri Rakesh Bhan and Shri Deepak Putrevu. Generous support received from Smt. Swati Duggal Shukla and Shri Deepak Putrevu is sincerely acknowledged. We acknowledge the help received from Shri Naveen Tripathi, Shri Ritesh Agarwal, Shri Saurabh Tripathi and Shri Ujjwal Gupta.

National Centre for Polar and Ocean Research (NCPOR) is coordinating the entire program of Indian Scientific Expedition to Antarctica. We owe our deepest gratitude to Dr. M. Ravichandran, present Director, NCPOR and former directors Dr. Prem Chand Pandey, Dr. Rasik Ravindran and Dr. Rajan for giving us an opportunity to participate in the expedition and providing their insightful comments and suggestions for the betterment of the science at Antarctica. Our deepest appreciation goes to Shri Mirza Javed Beg and Dr. Rahul Mohan, Project Directors, NCPOR and their logistic and science team for their constructive comments and generous support, without which we could not have been able to conduct the scientific experiments in the prevailing harsh environment over the Antarctica.

Executive Summary

The coldest and the driest continent of the globe, Antarctica is also the least explored and least understood continent. Without exploring its cryospheric features and involved processes, we cannot understand the global climate in its entirety. The Antarctic processes are extremely important to comprehend, especially in this era of earth's changing climate. The polar ice regime consists of ocean, ice sheet, sea ice, ice shelf, atmosphere, polynyas etc. Because of the complex feedback mechanism amongst these components, improved knowledge of the physical processes is required for better understanding of the potential changes in ice mass balance and global energy balance. Polar sea ice has an important climate regulating impact by limiting exchanges of momentum, heat and moisture between the ocean and atmosphere. It modulates the normal exchange of heat and mass between the atmosphere and ocean by isolating sea surface from atmosphere. Subtle changes in surface fluxes can have intense long-term impacts on polar environmental conditions, which in turn influence physical processes at lower latitudes. The climate of the high latitude areas of the Arctic and the Antarctic is more variable than that of tropical or mid-latitude regions. High-latitude fluxes differ prominently from those in temperate regions.

Prior to satellite era, very limited and scattered information was available on polar ice features. This limited information was available through the whalers or other ships that visited the polar sea ice regions. All the traditional methods of data collection over ocean and Polar Regions have certain limitations. Insufficient data and time consumption are two of the major concerns. The availability of useful data in Southern Hemisphere is further poor in comparison to Northern Hemisphere. A major emphasis of contemporary Antarctic science is to understand the earth system, its components, connections and feedbacks system. As far as the Antarctic science is concerned, we know far less than we need to know about the past and present of it. Today, there are more science questions than the answers before us, as far as the Antarctic, science is concerned. To answer the Antarctic science questions, the global scientists and policy makers will require sustained and stable efforts towards:

- *Access to all of Antarctica throughout the year;*
- *Application of emerging technologies;*
- *Strengthened protection of the region;*
- *Growth in international cooperation; and*
- *Improved communication among all interested parties.*

With the increasing availability of remotely sensed data, this situation is gradually improving. It has offered an opportunity to monitor these usually inaccessible regions in near real time. Now-a-days sea ice records prepared based on satellite data include sea ice extent, area, concentration, thickness and the age of the sea ice. Similarly, a lot of information related to ice sheets, ice shelves, polar glaciers, Arctic and Antarctic coastal regions etc. became available after satellite era. The availability of vast amount of satellite data does not eliminate the need and requirement of in-situ data. The in-situ data provide training data to various models and satellite data analyses. It is also used to validate results obtained from model and satellite data analyses.

A number of countries including many developed and developing nations have taken of the task of carrying out research in the direction of understanding the Antarctic processes and regular monitoring using satellites data as well as by carrying out scientific expeditions to Antarctica for collecting field data. India is among the countries who took this responsibility early and at priority. It got in the Antarctic Treaty in 1983 and thereafter obtained consultative status. Dakshin Gangotri, India's first committed research facility was established in 1983-84. Today, we have two all-round Indian Antarctic Research Stations, Maitri and Bharati. Scientists from India visit Antarctic region every year for carrying out various experiments and field data collection through Indian Scientific Expeditions to Antarctica (ISEA). Participation of Space Applications Centre (ISRO) in the Antarctic Expedition for the exploration of remote sensing technology to understand the polar cryosphere processes started with the 28th Indian Scientific expedition to Antarctica in 2008-09. Since 28th Expedition, SAC has participated for eight times. In addition, SAC scientists are involved in satellites data applications in various aspects of the Antarctic cryosphere studies.

India's Oceansat-1 Multi frequency Scanning Microwave Radiometer (MSMR) data was used for mapping of month-wise sea ice extent and it was found that there was a marginal increasing trend in the Antarctic. The analysis of QuikSCAT scatterometer data found the increasing and decreasing trend in the Antarctic summer sea ice cover during the period from 1999 to 2009. Derivation of sea ice freeboard from Ka-band Altimeter (Satellite with ARGOS and AltiKa (SARAL))/AltiKa) over the Arctic region for 15 March–15 April 2013 (spring) and 15 September–15 October 2013 (autumn) was demonstrated. SAC has been providing near real time sea ice advisories for safer ship navigation since 2013 to the Indian Antarctic Expeditions. Sea ice *area modelled using MITgcm was compared with that derived from National Snow and Ice Data Centre (NSIDC) sea ice concentration products. Sea ice trends were studied in the Arctic as well as the Antarctic. An algorithm based on Advance Microwave Scanning Radiometer-Earth observing system (AMSR-E) data (89 GHz) was developed for estimating sea ice thickness in the Arctic polynya, which was found valid up to the sea ice thickness of 10 cm. The potential of SARAL/AltiKa Ka-band altimeter data for the generation of ice sheet Digital Elevation Model (DEM) has been demonstrated. The altimeter data from SARAL/AltiKa has been used for the assessment of change in surface elevations over Antarctic ice sheet. Intra-annual and inter-annual elevation changes over the 40 Hz geophysical data record products for the period 2013-2016 were studied. Surface ice velocity of the Pine Island and Thwaites glacier using Moderate Resolution Image Spectroradiometer (MODIS) data between 2000 and 2017 using feature tracking method based on Normalized cross correlation method were derived. Spatial and temporal pattern of surface melting observed over the Antarctic ice shelves using Ku-band QuikSCAT and OceanSat-2 scatterometer (OSCAT) scatterometer data have been studied. Potential uses of Radar Imaging Satellite (RISAT-1) Synthetic Aperture Radar (SAR) data for mapping of ice calving and other changes around Antarctic ice margin and preparation of an Antarctic region have been demonstrated. Applications of Scatsat-1 super resolution data for preparing daily sea ice images have been explored and demonstrated. Some of the data products generated by SAC using satellites data are made available to global community through the SAC web portal (http://vedas.sac.gov.in).*

The field data pertaining to ice feature identification over the satellite images, GPS locations of various Antarctic ice features, multiple Ground Penetrating Radar (GPR) data over the Antarctic sea ice and different parts of the Antarctic ice sheet, Differential GPS data for glacier surface ice velocity have been collected by SAC participants of 7 Indian Antarctic expeditions. The meteorological data related to atmospheric parameters (temperature, humidity, pressure, etc.) during ship voyages and at various locations in Antarctica along with atmospheric aerosol optical depth, ozone content, water vapour content were collected.

This book presents salient observations made during 7 Indian Expeditions on the land and sea ice features, experiences gained by SAC teams, potentials of Indian Earth Observations data and future scope of research.

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1.0 Introduction

Of all the continents on earth, Antarctica is the least explored and the least understood owing to its unique geographical location and associated climatic, crustal and cryospheric processes. It is extremely important to comprehend the Antarctic processes, if we need to understand our earth's changing climate. The climate of the high latitude areas of the Arctic and the Antarctic differs markedly from mid-latitude regions due to significant differences in the energy fluxes. The climatic significance of Polar Regions is far out of proportion to its geographic area.

The present climate and paleoclimate of Polar Regions has been responsible for the occurrence of large ice sheets, ice shelves and vast extents of sea ice. The huge extents of snow and ice in the Polar Regions are not only responsible for governing the global climate system but also controlling the global sea level.

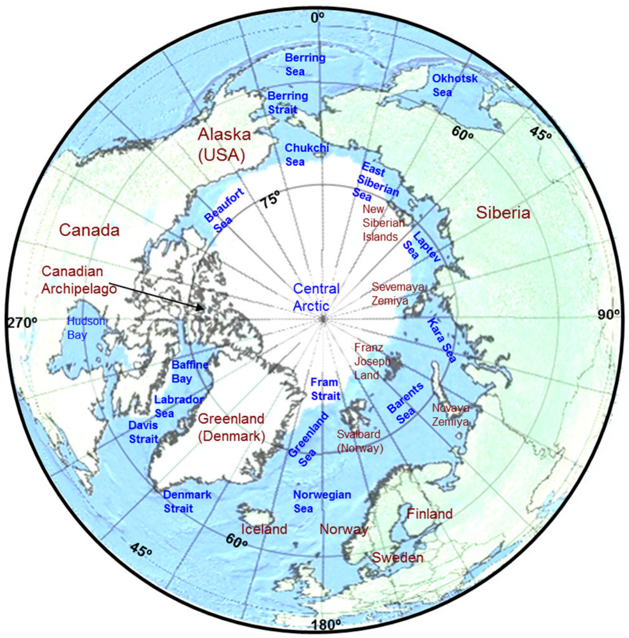
Polar sea ice has an important climate, regulating impact by limiting exchanges of momentum, heat and moisture between the ocean and the atmosphere. It modulates the normal exchange of heat and mass between the atmosphere and ocean by isolating sea surface from atmosphere. Subtle changes in surface fluxes can have intense long-term impact on polar environmental conditions, which in turn influence physical processes at lower latitudes.

Because of the complex feedback mechanism between ice, ocean and atmosphere in the Polar Regions, improved knowledge of the physical processes is required for a better understanding of the potential changes in the climate and mass balance. Prior to satellite era, availability of information on polar ice features was scarce. Limited information was available through the whalers, submarines or other ships that navigated through the polar sea ice regions.

Conventional methods of data collection over Polar Regions have certain limitations. Harsh weather conditions cause excessive time consumption which results into insufficient in-situ data collection. Moreover, in many cases, incompatible policies prevent neighbouring countries from sharing relevant data with each other. Upon comparison, we find that less amount of useful data is available for the Southern Hemisphere than the Northern Hemisphere. With the increasing availability of remotely sensed data, however, this situation is gradually improving. A lot of information related to ice sheets, ice shelves, polar glaciers; polar coastal regions etc. have become available after the satellite era. The availability of space-borne sensors over the Polar Regions has offered an opportunity to monitor and generate forecasts for these usually inaccessible regions in near real time (Bhandari et al., 2002; Cavalieri *et al*., 1984; Oza et al., 2017a). Now-a-days, sea ice products retrieved from the satellite data include sea ice extent, area, concentration, thickness and the age of the sea ice. In spite of the availability of vast amount of remotely sensed data, the need and requirement of in-situ data cannot be eliminated. The in-situ data provides training dataset to various models for forecasting. In addition to that, it is very useful for validating the results obtained from models and space-borne sensor data derived products. Hence, there is a need to prepare a digital database of in-situ data collected during the Antarctic expeditions that may be further utilized by the global scientific community.

1.1 About Antarctica & the Arctic

When we talk of Antarctica, the first thing that comes to our mind is its proximity to the South Pole. In-fact, the regions around the North Pole and the South Pole are called the Arctic and the Antarctic regions, respectively. The Figure 1.1 shows the Arctic Polar Regions and the surrounding areas prepared using Arc Globe module of ARCGIS. The ice in the Arctic Ocean can survive for a long time due to the big oceanic gyre present in the Arctic Ocean, which allows ice to grow and increase in its thickness. Ice rotates for years due to this gyre until it leaves the basin through one of the straits/outlets. In the Arctic, there are two main large-scale wind driven drift components, the first is the Beaufort gyre, a clockwise rotation near the North Pole, which results from an average high-pressure system that creates the winds in the region. The second is the transpolar drift, where ice moves from the Siberian coast across the Arctic basin to the north coast of Greenland. This allows the flow of ice into the North Atlantic through the Fram Strait between Greenland and Svalbard. Arctic sea-ice extent varies between 8 to 15 million km^2 during the annual cycle (Eicken and Lemke, 2001). Figure 1.2 shows the geographical extent of the Antarctic Polar Regions and the surroundings. The Antarctic region of the Southern Ocean is surrounded by a circumpolar ocean current. Though the atmosphere in the Antarctic is colder than in the Arctic, the heat flux from the turbulent unprotected sea is much higher. This condition leads to the highly variable sea-ice cover. It is estimated that sea ice cover of up to 20 million km^2 extent girdles the Antarctic continent during winter (Eicken and Lemke, 2001) while it almost disappears in the summer which leads to the prevalence of lower ice thickness and higher ice drift as compared to the Arctic. In summer, only patches of perennial ice, covering about 4 million km² area, remain in the Weddell Sea sector (60° W to 20°E), Amundsen Bellingshausen Sea sector (130° W to 60° W) and Ross Sea sector (160° E to 130° W). Ice sheets are the greatest potential source of global freshwater, holding approximately 99% of the global total [(https://nsidc.org/cryosphere/sotc/ice_sheet.html)](https://nsidc.org/cryosphere/sotc/ice_sheet.html). This corresponds to 70 m of world sea-level equivalent, with Antarctica accounting for 90% of this. Greenland accounts for most of the remaining 10%, with other ice bodies and glaciers accounting for less than 0.5%. Because of their size in relation to annual rates of snow accumulation and melt, the residence time of water in ice sheets can extend to 100,000 or 1 million years. Consequently, any climatic perturbations produce slow responses, occurring over glacial and interglacial periods.



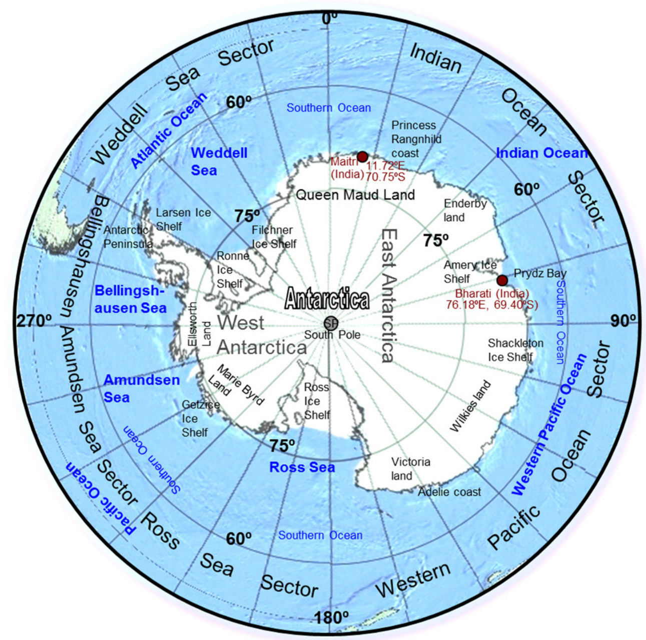


Figure 1.1: Arctic Polar Region and its surroundings

Figure 1.2: Antarctic Polar Region and its surroundings

1.2 Antarctic Science and Challenges

Recent observations indicate that the Polar Regions have been amongst the most rapidly changing areas on the planet, showing major shifts in cryospheric, oceanic and atmospheric processes. A major endeavour of contemporary Antarctic science is to understand the Earth system, its components, connections and feedbacks mechanisms. As far as the Antarctic science is concerned, we know far less than we need to predict about the past and present of it. Research in the Antarctic requires facing the challenges of conducting science in one of the most remote and extreme environments on the Earth. The major challenges for the Antarctic science is to understand the future scenario of (i) loss of ice mass from the ice sheets to ocean, leading to rise in the sea level; and (ii) variability in sea ice cover influencing the air-sea interaction and thereby influencing the global atmospheric and oceanic circulation. Following are some of the major Antarctic science questions identified by The Scientific Committee on Antarctic Research (SCAR):

- How is climate change and variability in the high Southern latitudes connected to lower latitudes including the tropical ocean and monsoon systems?
- How do Antarctic processes affect mid-latitude weather and extreme events?
- How have teleconnections, feedbacks and thresholds in decadal and longer-term climate variability affected ice sheet response since the Last Glacial Maximum, and how can this inform future climate projections?
- Does past amplified warming of Antarctica provide insight into the effects of future warming on climate and ice sheets?
- What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice?
- How has Antarctic sea ice extent and volume varied over decadal to millennial time scales?
- How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation?
- What are the processes and properties that control the form and flow of the Antarctic Ice Sheet?
- How will changes in surface melt over the ice shelves and ice sheet evolve, and what will be the impact of these changes?
- How do oceanic processes beneath ice shelves vary in space and time, how they modified by sea ice and do they

affect ice loss and ice sheet mass balance?

- How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance?

Though this is not an exhaustive list of the science questions related to Antarctic studies; there are more scientific questions than the answers with us. Lack of complete understanding of the Antarctic system on one hand and prime importance of the Antarctic in global climate poses a number of serious challenges to human kind. One way of listing some major challenges is to categorise the challenges in following five classes: forecasting, observing, confining, responding, and innovating. To improve the usefulness of forecasts of future environmental conditions and their consequences for people is of prime importance for human- and nature relationship. To develop, enhance, and integrate the observation systems needed to manage global and regional environmental change is equally a big challenge for the scientific community. Challenges of confinements refer to determine how to anticipate, recognize, avoid and manage disruptive global environmental change. Appropriate response to the changing climate need to determine what institutional, economic and behavioural changes can enable effective steps toward global sustainability. Then we need to encourage innovation in developing technology, policy and social responses to achieve global sustainability, which is again a challenging task. To answer the scientific questions pertaining to the Antarctic, we will require sustained and stable efforts towards:

- Access to Antarctica throughout the year;
- Application of emerging technologies;
- Strengthened protection of the region;
- Growth in international cooperation;
- Improved communication among all interested parties.

Plate 1: Have you ever seen beautiful icy lotus leaf like structures floating on the ocean? Freezing of ocean water has already been started with the formation of pancake ice observed near New Indian barrier (69^{0} 52’ 01’’ S, 11^{0} 33’ 19’’ E; 19 March 2016; 35 ISEA).

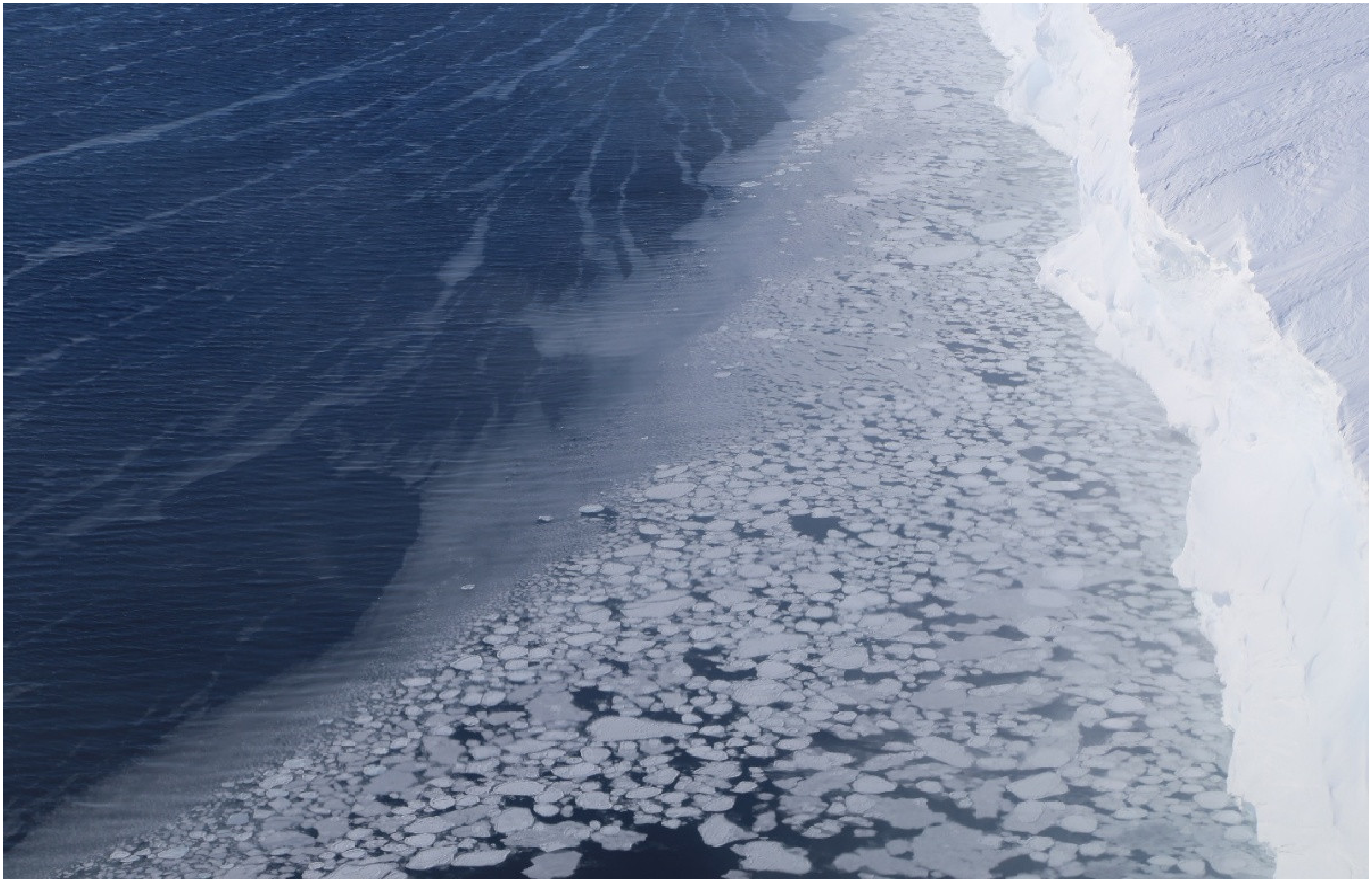


Plate 2: Pancakes – Predominantly circular fragments of ice from 0.3 – 3 m in diameter, and up to 10 cm in thickness (unrafted), with raised rims due to the fragments striking against one another. Top right shows Lazarev Ice Shelf and its ice front. Top left portion shows greece ice formation in Southern Ocean (70^0 04’ 21’’ S, 12^0 42’ 07’’ E; 18 March 2017; 36 ISEA).

Plate 3: Proceeding towards Antarctica, occurrence of sea ice starts initially in low concentration called marginal sea ice (63^0 22’ 33’ S, 68^0 29’ 29’ E; 21 December 2013; 33 ISEA).

Plate 4: Low concentration sea ice in marginal zone encountered while sailing towards Larsemann Hills (670 50’ 21’’ S, 730 22’ 26’’ E; 16 January 2009; 28 ISEA).

Plate 5: Sea ice fastened to continental ice front is visible along with appearance of melt pond on sea ice surface (69^0 37' 49'' S, 75^0 26' 24'' E; 02 February 2009; 28 ISEA).

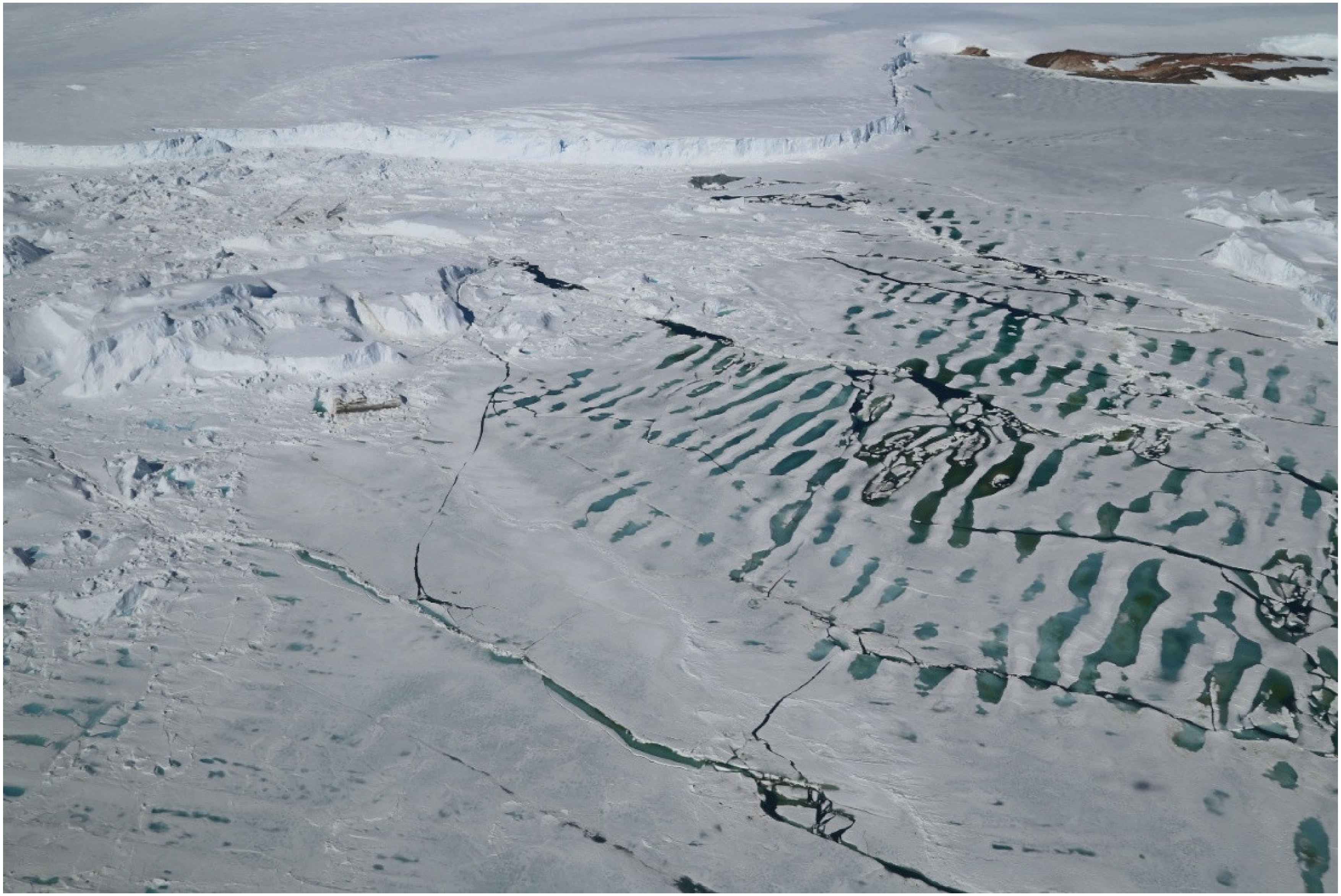


Plate 6: A section of East Antarctic coast having a number of leads, melt ponds over fast ice and coastal deformation (69^0 39' 07'' S, 74^0 49' 13'' E; 08 January 2014; 33 ISEA).

Plate 7: An iceberg and its large size crevasses formed due to disintegration are seen in the foreground. (69^0 16’ 04’’ S, 76^0 07’ 51’’ E; 29 January 2009; 28 ISEA).

Plate 8: Continental ice front, in Schirmacher Oasis behind Maitri research station (70^0 46' 40'' S, 11^0 49' 21'' E; 06 March 2016; 35 ISEA).

Plate 9: Melt ice drainage at Schirmacher Oasis (70^{0} 46' 25'' S, 11^{0} 47' 09'' E; 21 January 2014; 33 ISEA).

Plate 10: Air bubbles are squeezed out and ice crystals enlarge, making the ice appear blue. Blue ice, the hardest ice structure observed near Novo Lazarevasky Russian air field (70^0 48’ 32’’ S, 11^0 36’ 40’’ E; 04 March 2016; 35 ISEA).

Plate 11: Advance planning is much needed to take up and successfully complete a task in Antarctica. Summer, winter and crew team members are chalking out a plan to offload heavy machinery items for transporting it to Bharati station for supporting construction (69° 24’ 14’’ S, 76° 12’ 11’’ E; 27 January 2018; 37 ISEA).

Plate 12: Aurora Australis: Dancing curtains of lights. Hotness and coldness, both are relative terms… Antarctica is the land where, coldness of an icy continent beneath your feet & hotness of "Natural Plasma" in the sky…simultaneously…!!! Bharati Research Station comes under "Auroral Oval Zone" (06 March 2017; 36 ISEA).

Plate 13: Penguins on Rookery Island (69^0 16' 24'' S, 76^0 50' 10'' E; 06 January 2014; 33 ISEA).

2.0 Antarctic Cryosphere

Antarctic ice features may be broadly grouped under two categories; land ice features and sea ice features. Some of the major Antarctic ice features like ice sheet, ice shelf, ice berg, sea ice etc. are shown in figure 2.1. This chapter introduces briefly about these two categories along with their field photographs and satellites images.

2.1 Land Ice Features

A number of ice features found abundantly on Antarctica are largely unseen by the general public in their life time.

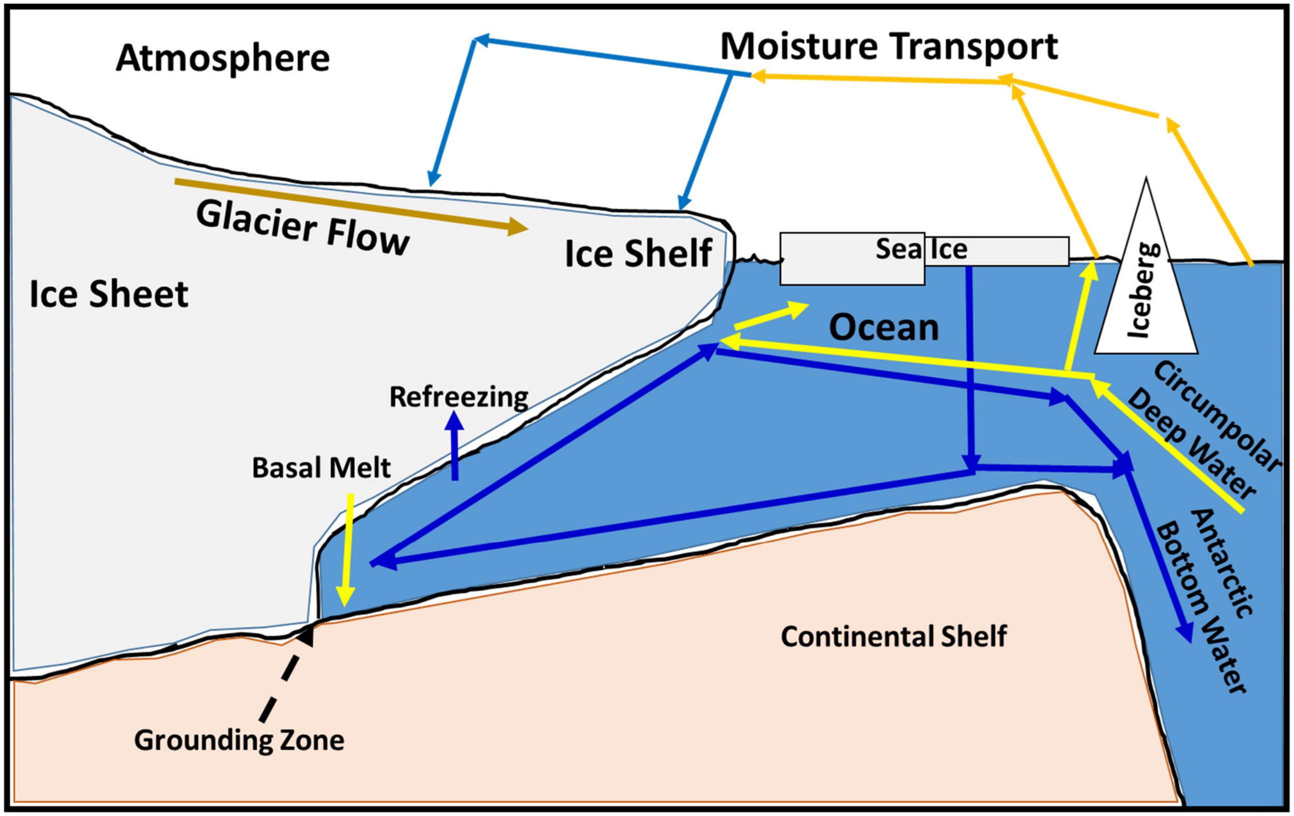


Figure 2.1: Depiction of some major Antarctic ice features (www.antarcticglaciers.org)

a) Ice Sheet

Antarctica is icy continent. It's almost 97% area is covered by ice. The ice cover has different names. A mass of glacier ice that covers surrounding terrain and is greater than 50,000 km^2, is called Ice Sheet. Ice sheets form in areas where snow that falls in winter does not melt entirely over the summer. Over thousands of years, the layers of snow pile up into thick masses of ice, growing thicker and denser as the weight of new snow and ice layers compresses the older layers. Currently, ice sheets exist in Antarctica and Greenland only. The size of ice sheets is more than ice shelves or alpine glaciers. Ice mass covering less than 50,000 km^2 area is termed as an ice cap. The Antarctic ice sheet of almost 14 million km^2 is the largest single ice mass on Earth. It contains almost 30 million km^3 of ice. Around 99% of the fresh water on the Earth's surface is held in two ice sheets. The Antarctic ice sheet is divided by the Trans-Antarctic Mountains into two unequal sections called the East Antarctic Ice Sheet and the smaller West Antarctic Ice Sheet. The Greenland ice sheet occupies about 82% of the surface of Greenland i.e. about 1.7 million km^2. The Greenland and the Antarctic ice sheets are losing mass due to melting and calving from outlet glaciers and ice shelves.

b) Ice Shelf

A thick floating platform of ice that forms where a glacier or ice sheet flows down to a coastline and onto the ocean surface is called Ice Shelf. It is an extension of an ice sheet floating over ocean surface. It is therefore made up entirely of fresh water, in contrast to sea ice, which has some salt in it from the ocean. The Antarctica, Greenland and Canada are the only places where ice shelves are found. The boundary between the floating ice shelf and the grounded (resting on bedrock) ice that feeds it is called the grounding line. The thickness of ice shelves ranges from about 100 to 1000 m. In Antarctica, a total of 44% of its coastline has ice shelves attached. Their aggregate area is about 1,541,700 km^2. Ice shelves are principally driven by gravity-driven pressure from the grounded ice. The flow continually moves ice from the grounding line to the seaward front of the shelf. The primary mechanism of mass loss from ice shelves was thought to have been iceberg calving, in which a chunk of ice breaks off from the seaward front of the shelf. Typically, a shelf front extends forward for years or decades between major calving events. Snow accumulation on the upper surface and melting from the lower surface are also important to the mass balance of an ice shelf. A study by NASA and university researchers - published on the June 14, 2013 issue of Science - found however, that ocean waters, melting the undersides of Antarctic ice shelves, are responsible for most of the continent's mass loss (https://climate.nasa.gov/news/937/warming-ocean-causing-most-antarctic-ice-shelf-mass-loss).

The world's largest ice shelves are the Ross Ice Shelf and the Filchner-Ronne Ice Shelf in Antarctica. In the last several decades, glaciologists have observed consistent decrease in ice shelf extent through melt, calving, and complete disintegration of some shelve.

C) Glaciers

Glaciers are among the most impressive creation of nature. They are found all over the world, from the equator (at the top of Mount Kilimanjaro in Africa) to the poles (flowing from the ice sheets of Greenland and Antarctica). We call glaciers advancing or growing / retreating or shrinking when the amount of new snow is more / less than the amount of melt (respectively) over a period of time. The glacier region where more mass is gained than lost over a period of time is called accumulation zone; while the region of higher loss than gain is called ablation zone. The major processes like evaporation surface water, sublimation of snow/ice, calving of icebergs, melting of snow/ice etc. are responsible for advancing or retreat of the glaciers. The Lambert Glacier in Antarctica is the largest glacier in the world. It measures more than 400 km long and up to 100 km wide. It has been observed that some of the outlet glaciers in Antarctica are undergoing rapid changes in flow velocity and ice thickness. Climate changes and glacier dynamics are found to be linked in a complex manner. The regular monitoring of the global glaciers and their linkages with climate change are the need of time.

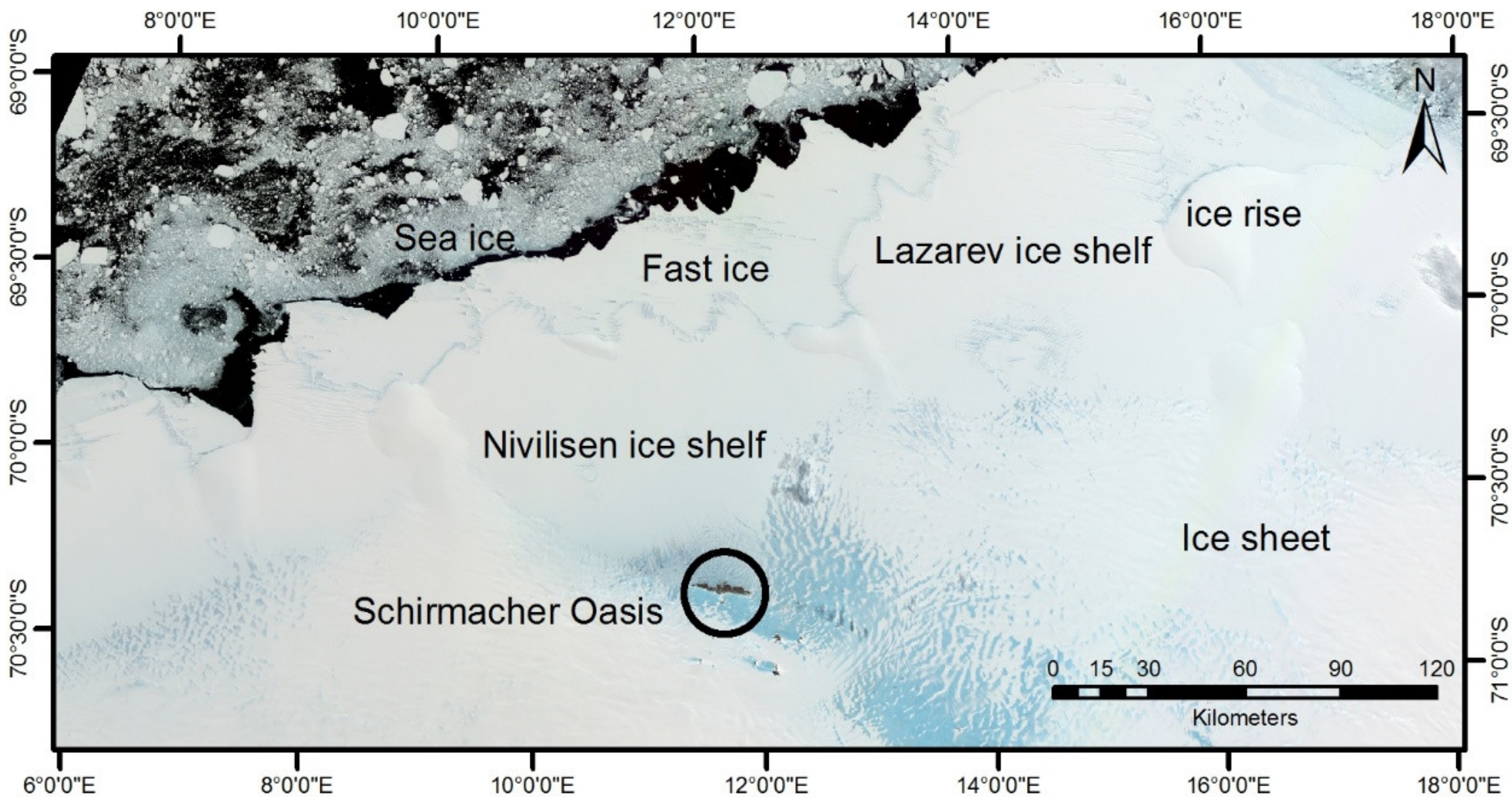


Figure 2.2: A satellite view showing a part of the Antarctic Ice Sheet covering Schirmacher Oasis, Nivilisen Ice Shelf, a number of ice rises, fast ice near New Indian Barrier, floating sea ice. (Resourcesat-2; AWiFS; False Colour Composite(FCC);432(R: Band 4, G: Band 3, B:Band 2);20 December 2015).

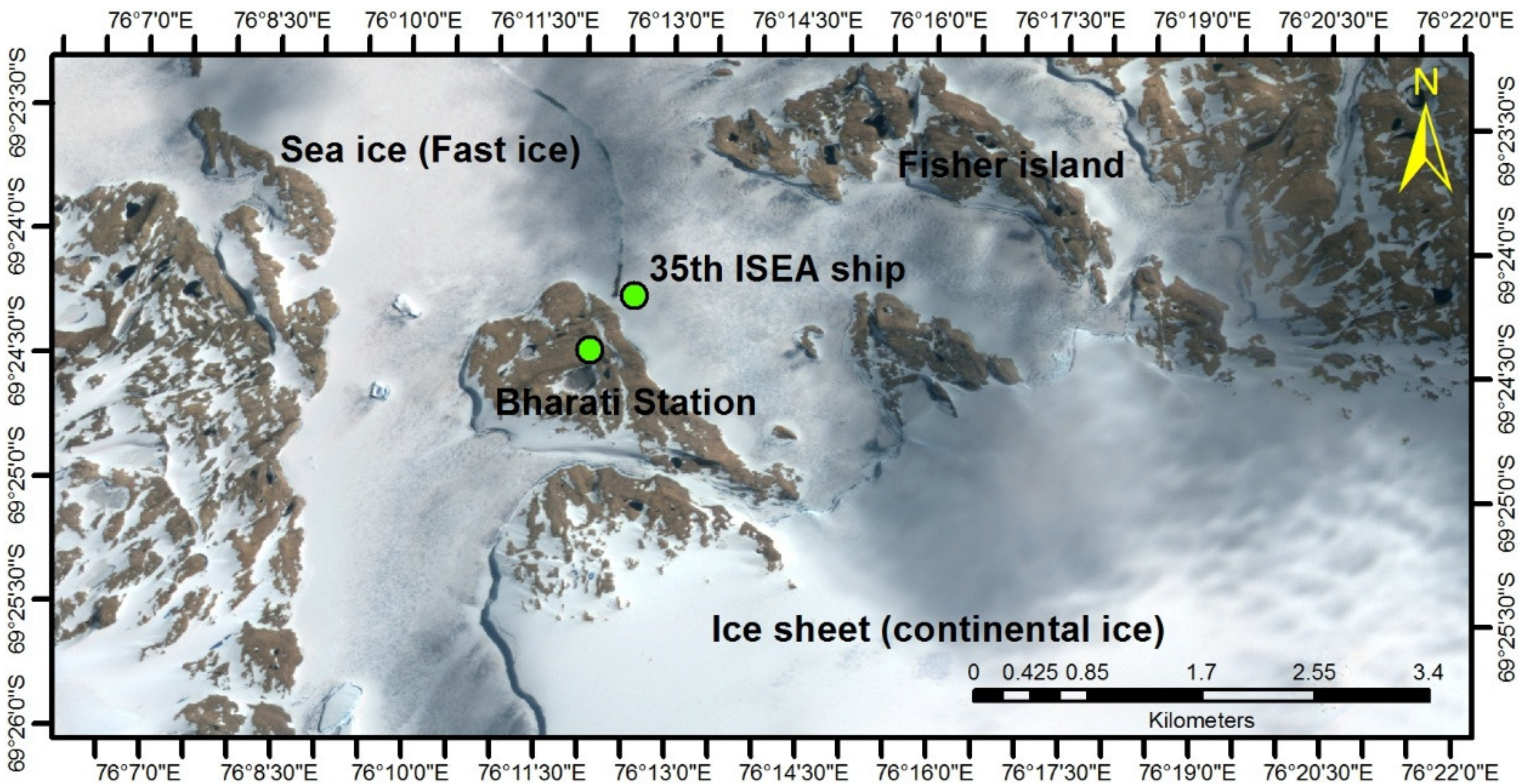


Figure 2.3: A satellite view covering a part of Larsemann Hills area including Bharati research station, Fisher Island and its surroundings (Resourcesat-2; LISS IV; FCC432; 24 January 2016).

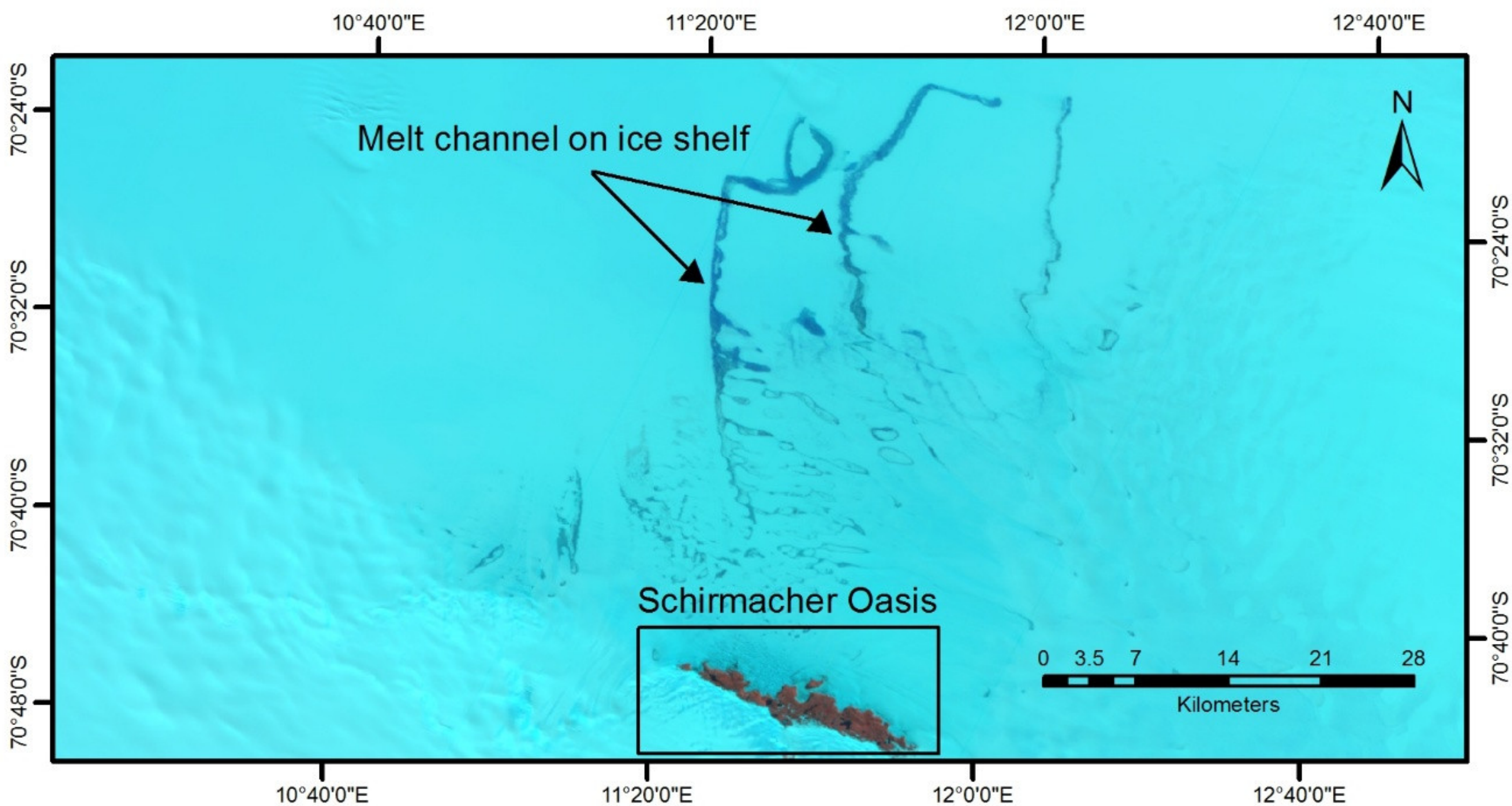


Figure 2.4: A satellite view showing melt channels on ice shelf near Schirmacher Oasis (Resourcesat-2; AWiFS, FCC532; 07 February 2018).

Figure 2.5: Field photo of a melt channel on Antarctic Ice Sheet near Maitri station (69^0 52' 50'' S, 75^0 43' 23'' E; 02 February 2009; 28 ISEA).

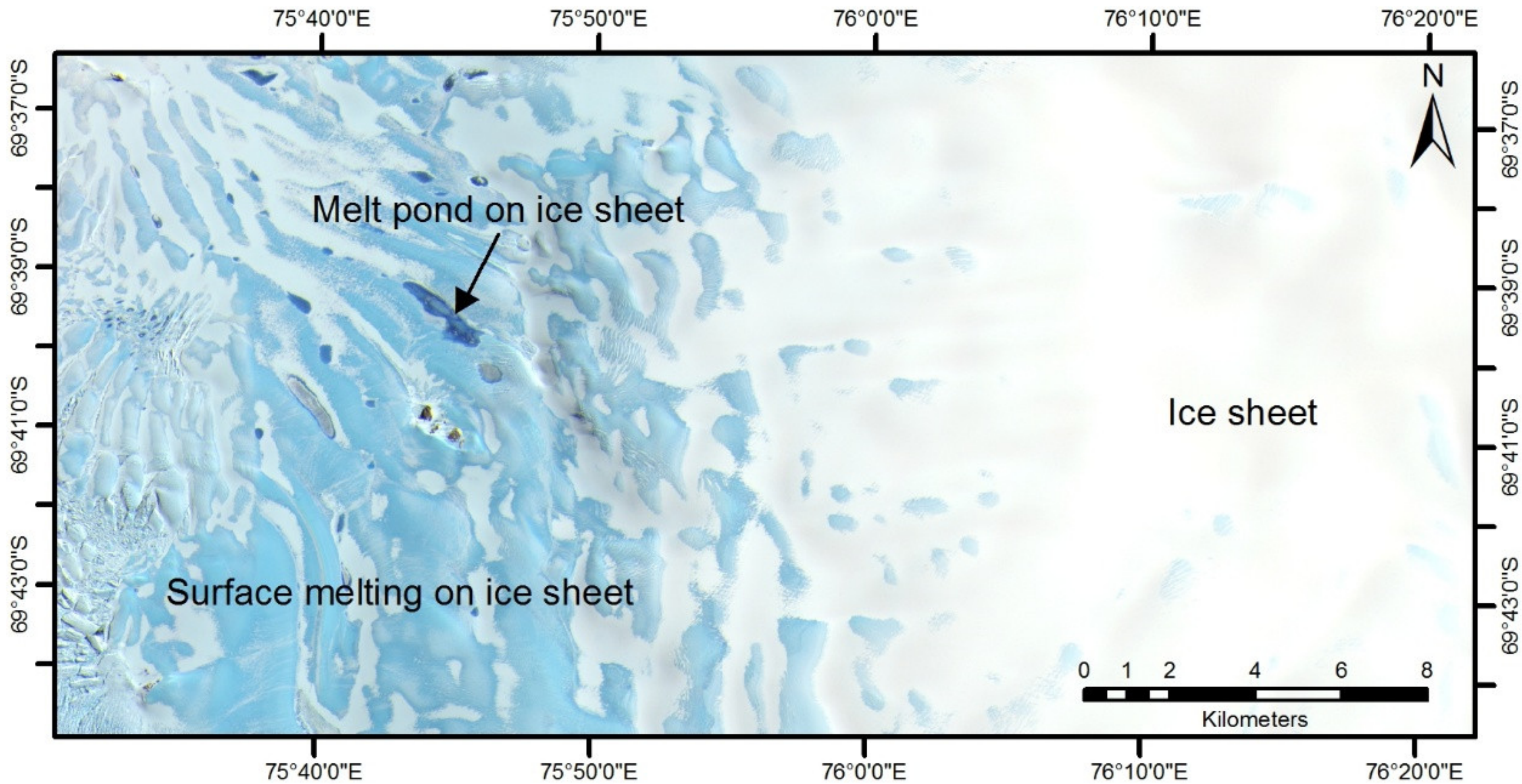


Figure 2.6: A satellite view showing surface melt on ice sheet near Polar Record Glacier (Resourcesat-2; LISS IV; FCC 432; 13 February 2018).

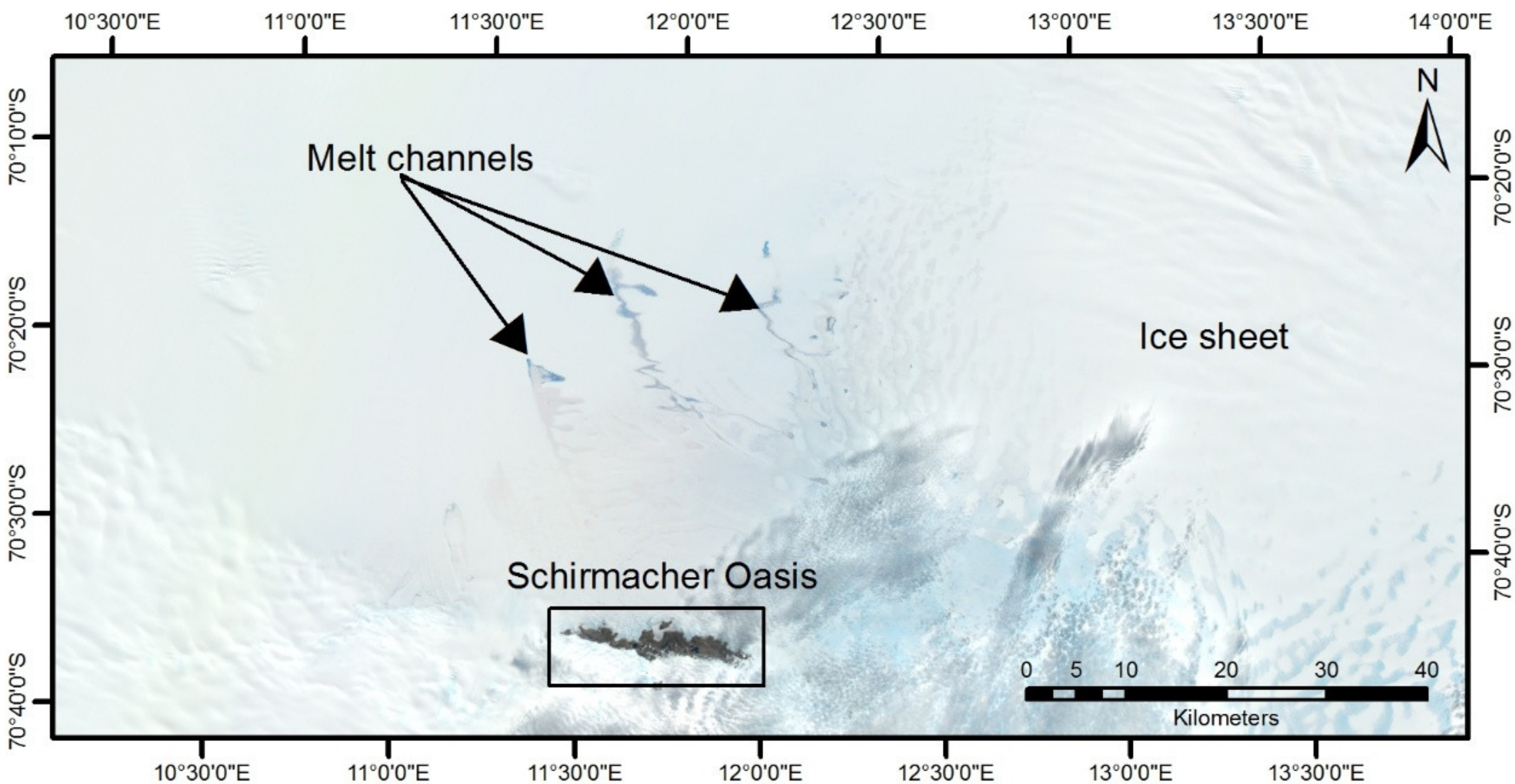


Figure 2.7: A satellite view showing melt channel on ice shelf near Schirmacher Oasis (Resourcesat-2; AWiFS; FCC 432; 05 February 2018).

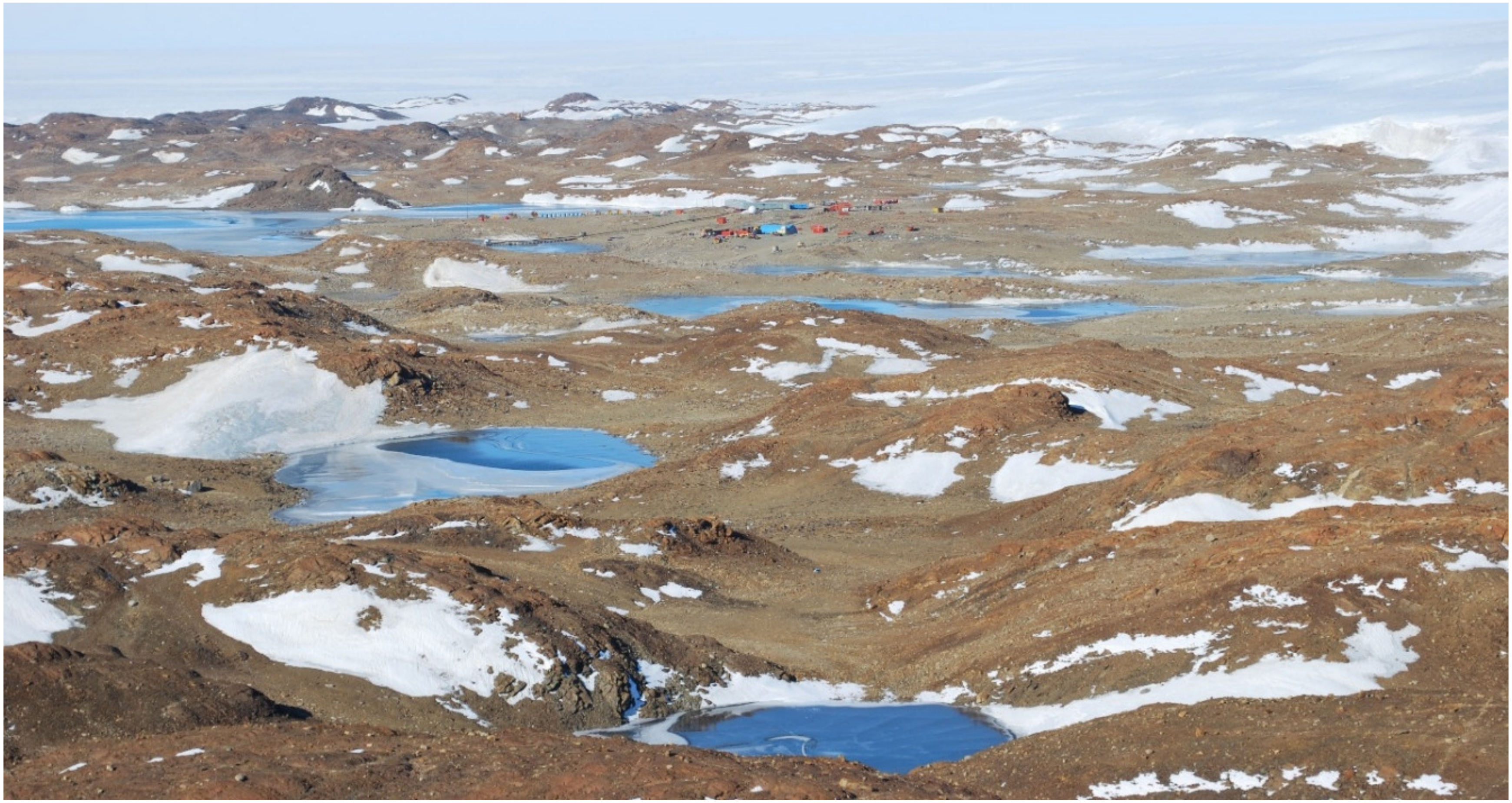


Figure 2.8: A ground based synoptic view of Maitri Station and surroundings including a section of ice sheet and number of partially frozen lakes (70^0 46' 00'' S, 11^0 43' 53'' E; 28 February 2009; 28 ISEA).

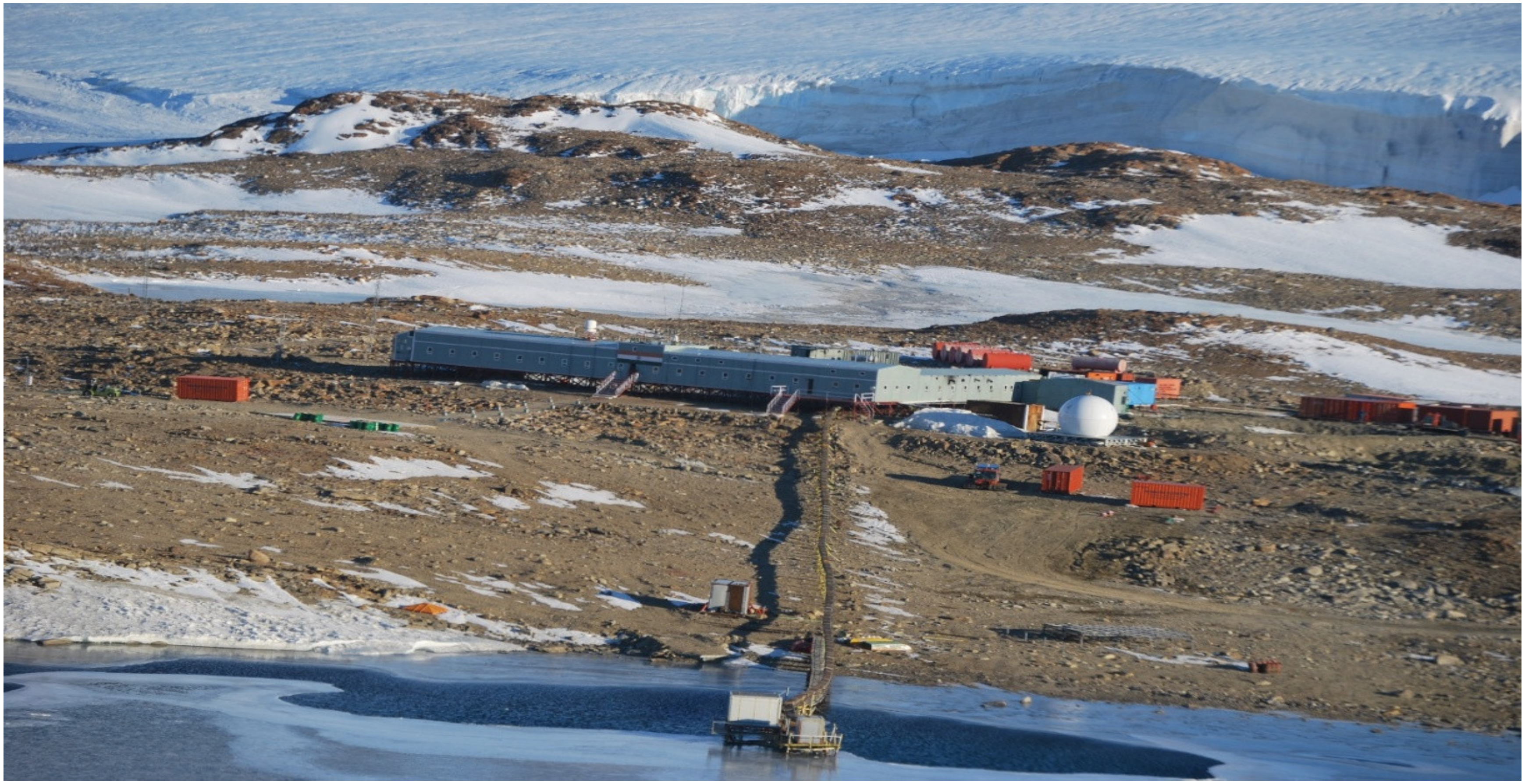


Figure 2.9: Maitri and its surrounding including Priyadarshini Lake, ice sheet, ice wall, Schirmacher Oasis, ISRO's satellite communication dome (70^0 46' 00'' S, 11^0 43' 53'' E; 20 February 2009; 28 ISEA).

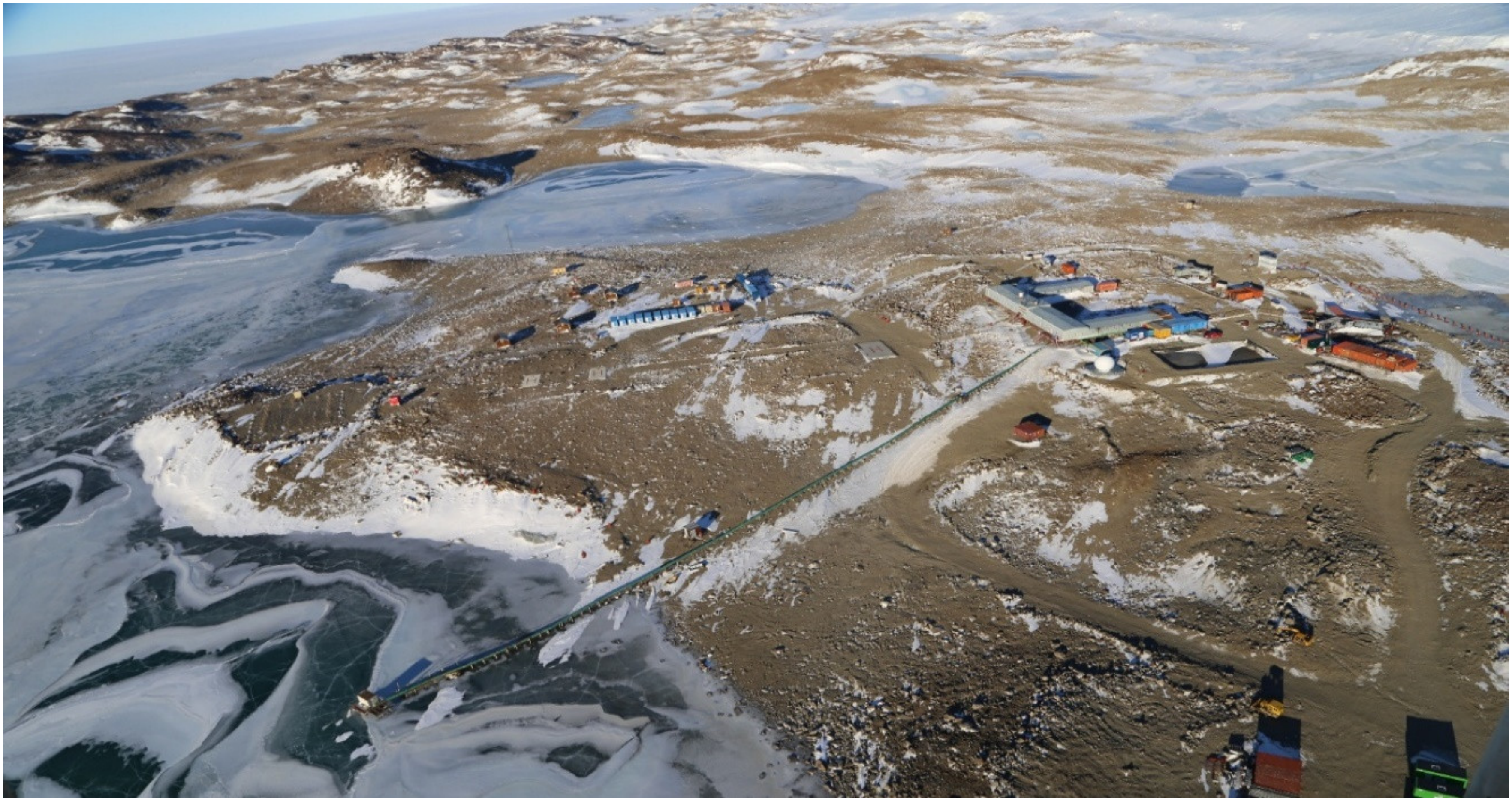


Figure 2.10: An aerial view of Maitri station (constructed on Schirmacher Oasis, 1989) and its surrounding. The continental ice sheet extending from top right to top left. Pre winter state of "Priydarshini" Lake (also known as "Zub" lake) at the bottom left is seen which is the ultimate life line for drinking water (70^0 45' 53'' S, 11^0 43' 31'' E; 24 March 2017; 36 ISEA).

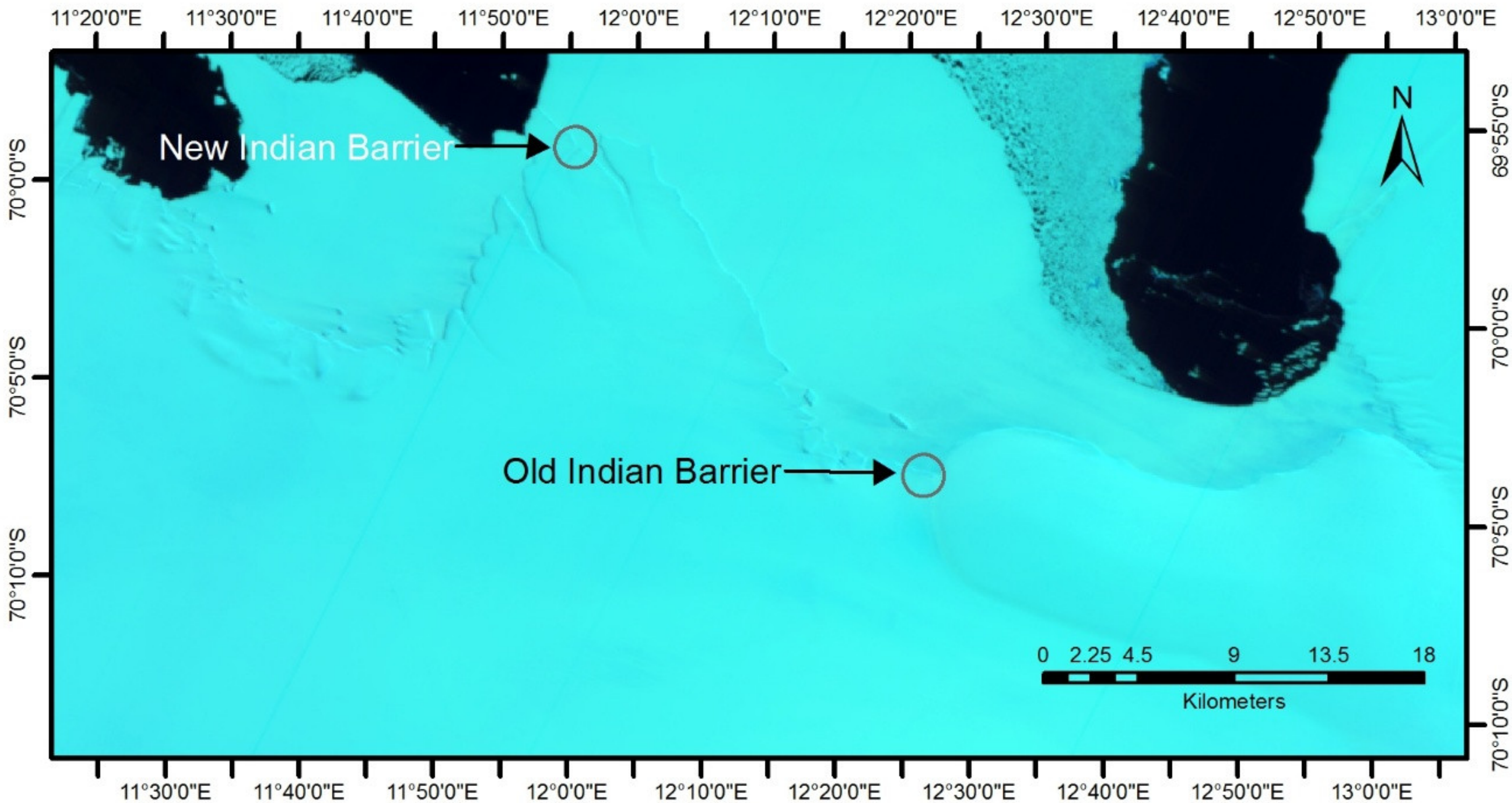


Figure 2.11: A satellite view showing New Indian Barrier and Old Indian Barrier (Resourcesat-2; AWiFS; FCC 532; 07 February 2018).

Figure 2.12: Ship Ivan Papanin, anchored in between the rift structure of Nivilisen Ice Shelf and the location is referred as New Indian Barrier (69^0 58’ 40’’ S, 12^0 04’ 21’’ E; 02 March 2016; 35 ISEA).

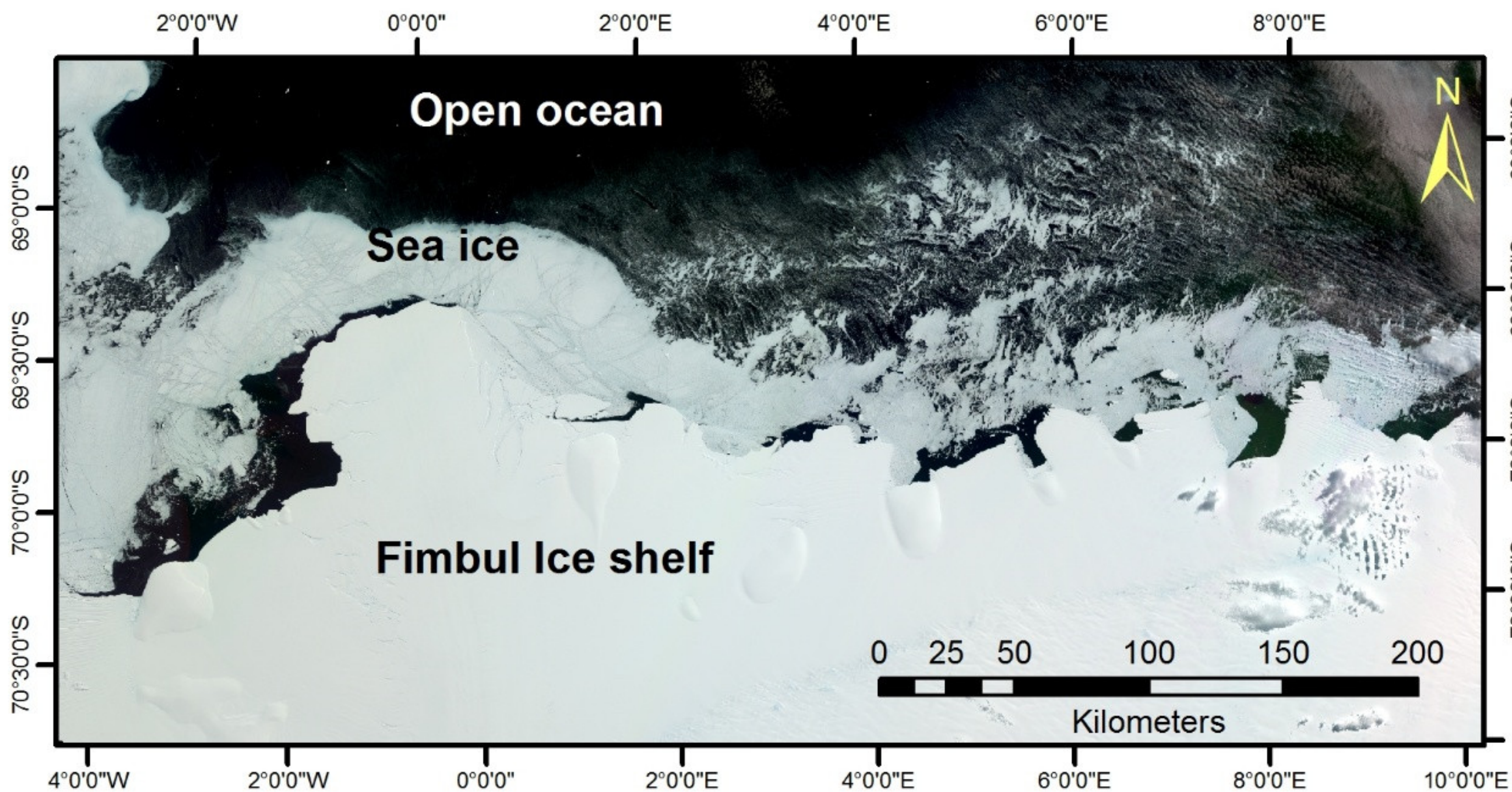


Figure 2.13: A satellite view showing Fimbul Ice Shelf and coastal region (Resourcesat-2; AWiFS; FCC 532; 13 February 2015).

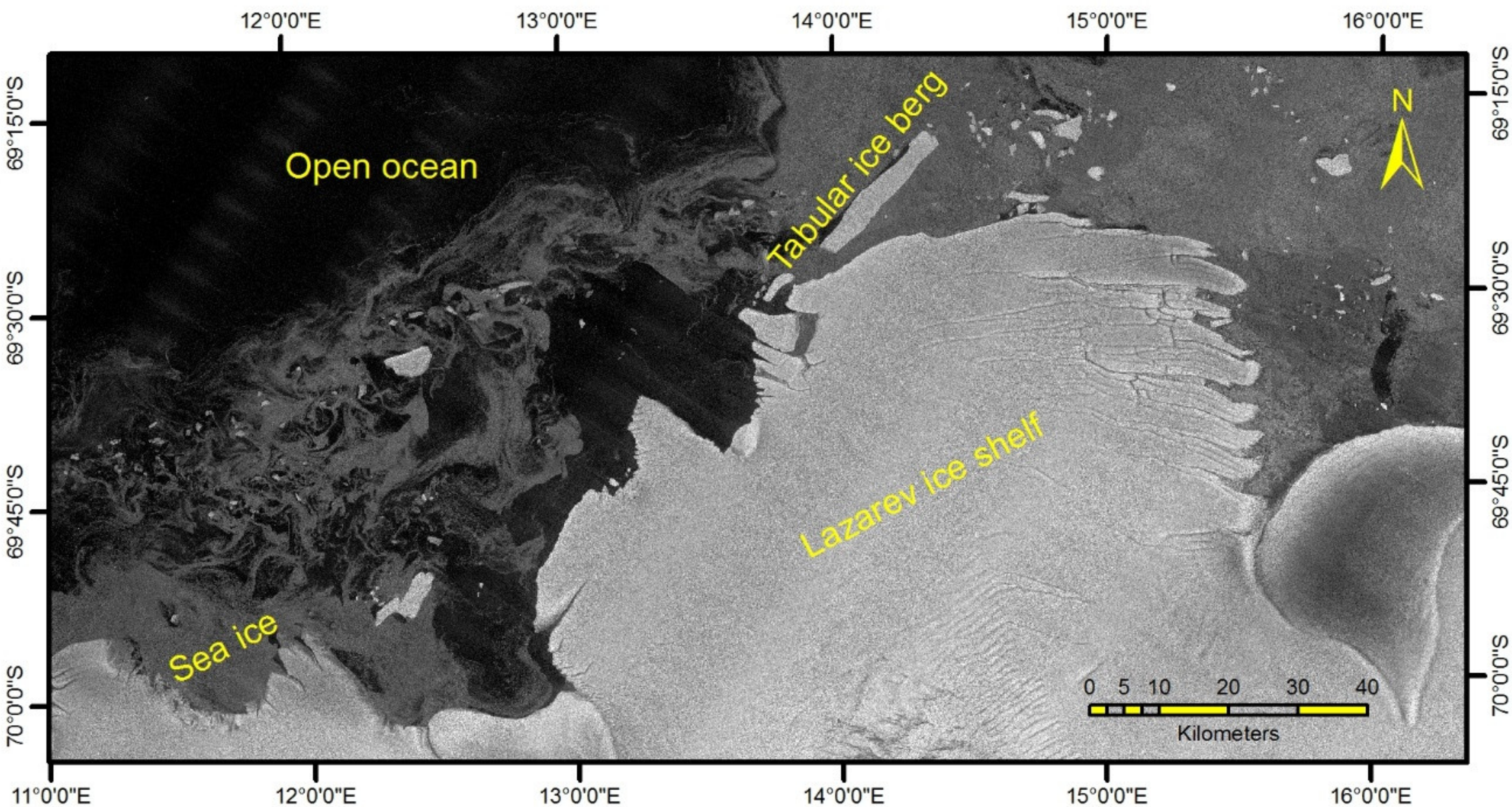


Figure 2.14: A satellite view showing Lazarev Ice Shelf and coastal region (RISAT-1; CRS; RH; 23 February 2016).

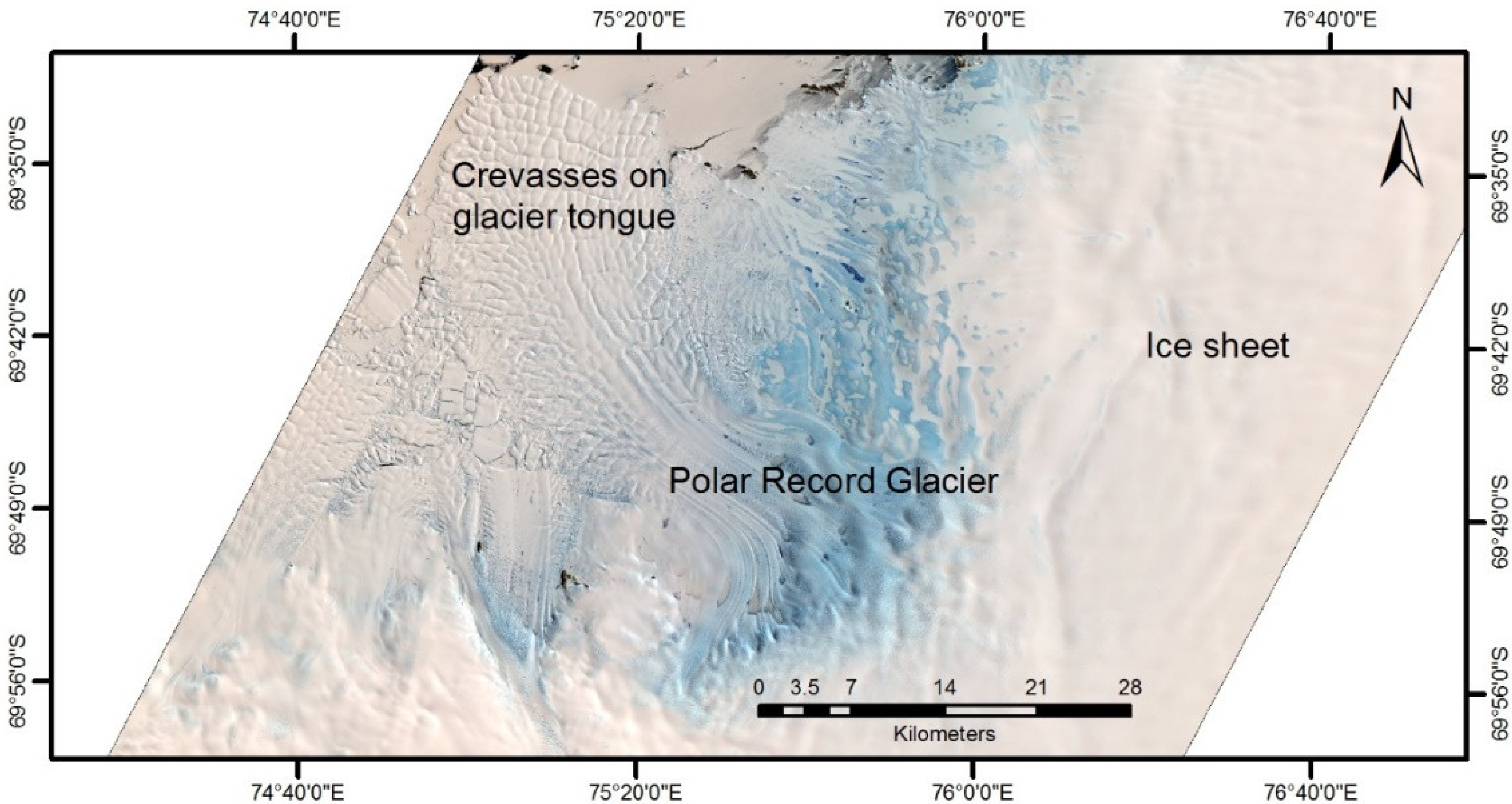


Figure 2.15: A satellite view showing Polar Record Glacier and its crevasses (Resourcesat-2; LISS-IV; FCC432; 06 February 2018).

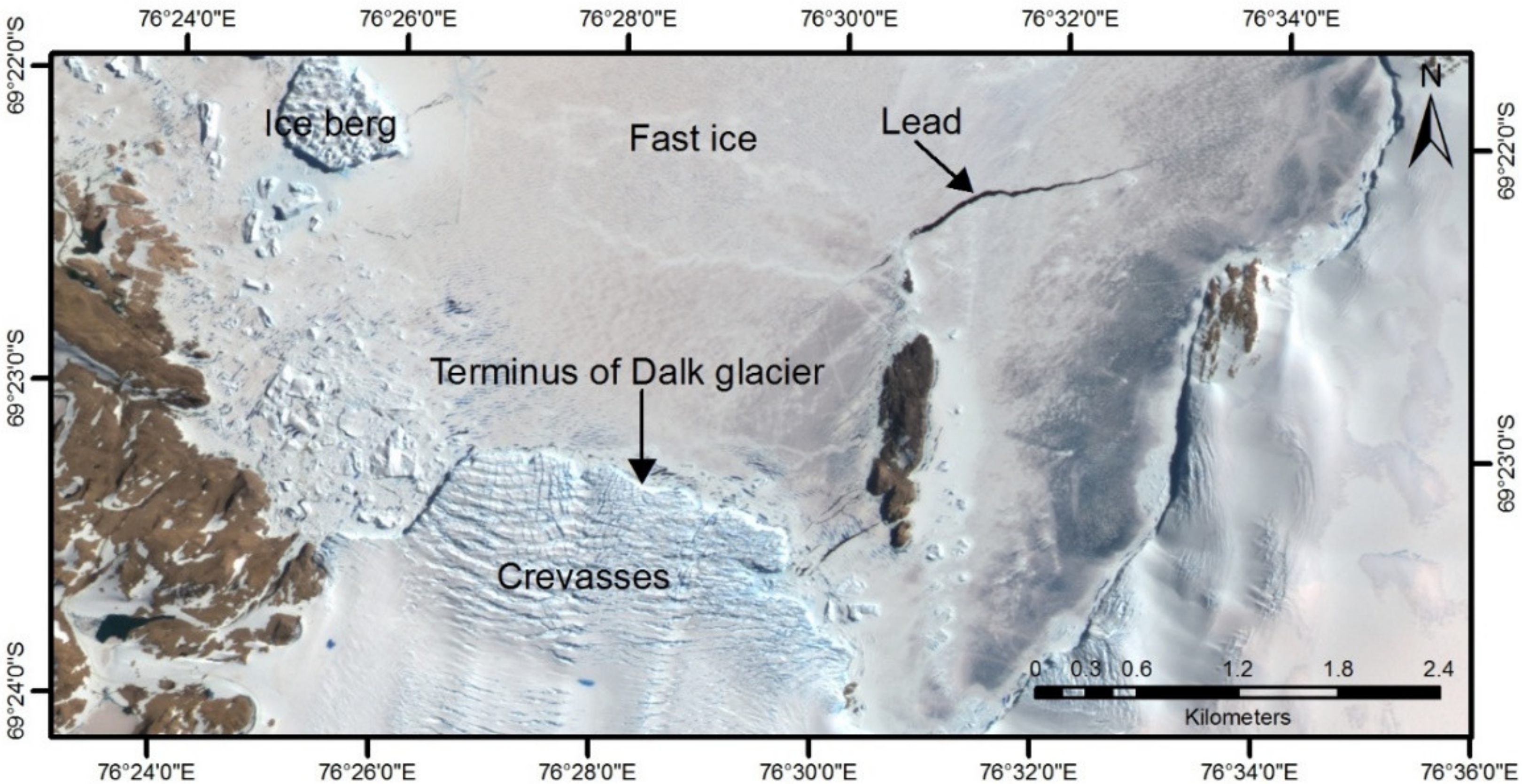


Figure 2.16: A satellite view-covering terminus of Dalk Glacier and its crevasses (Resourcesat-2; LISS-IV; FCC432; 10 January 2016).

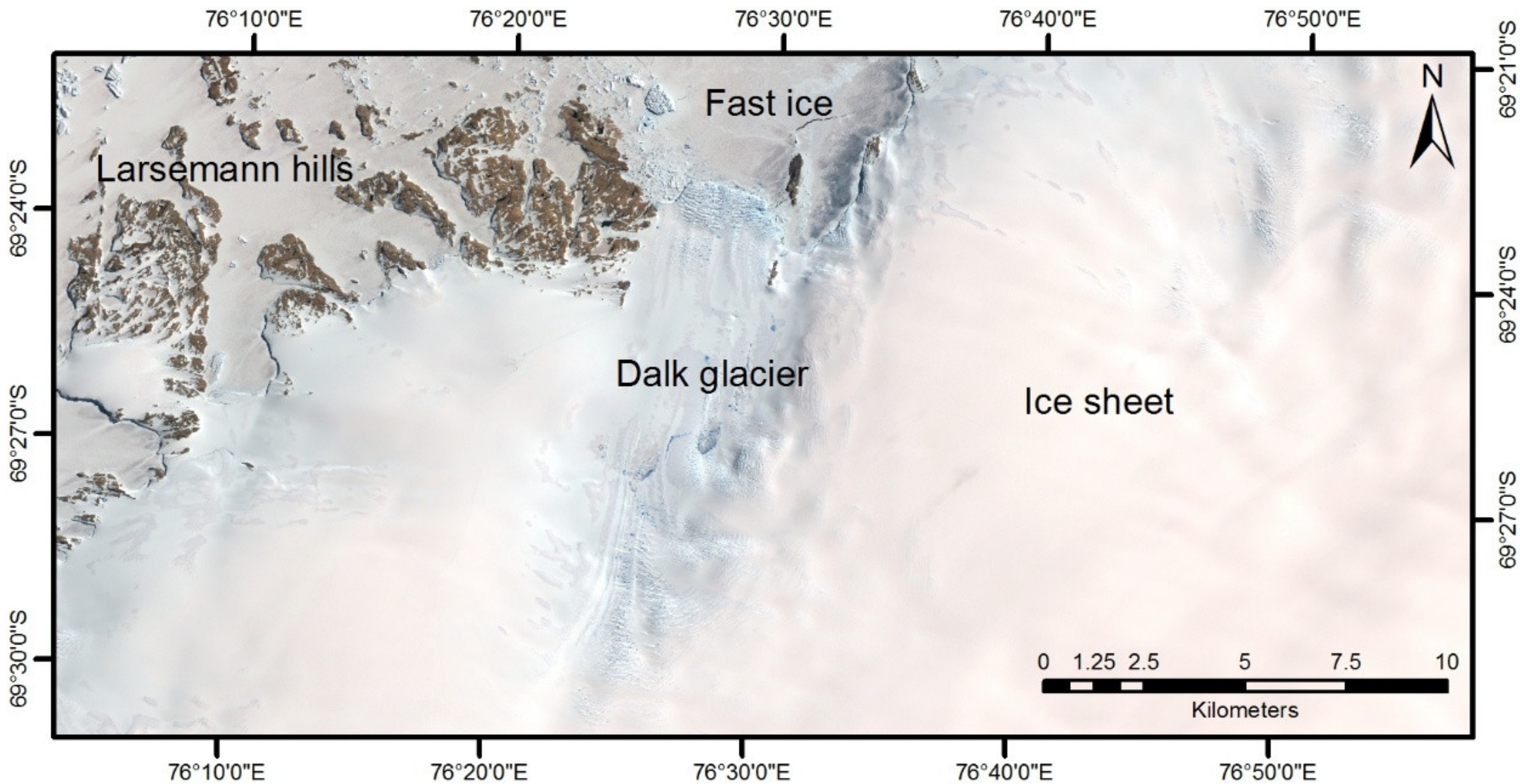


Figure 2.17: A satellite view covering Dalk Glacier and its surroundings (Resourcesat-2; LISS-IV; FCC432; 10 January 2016).

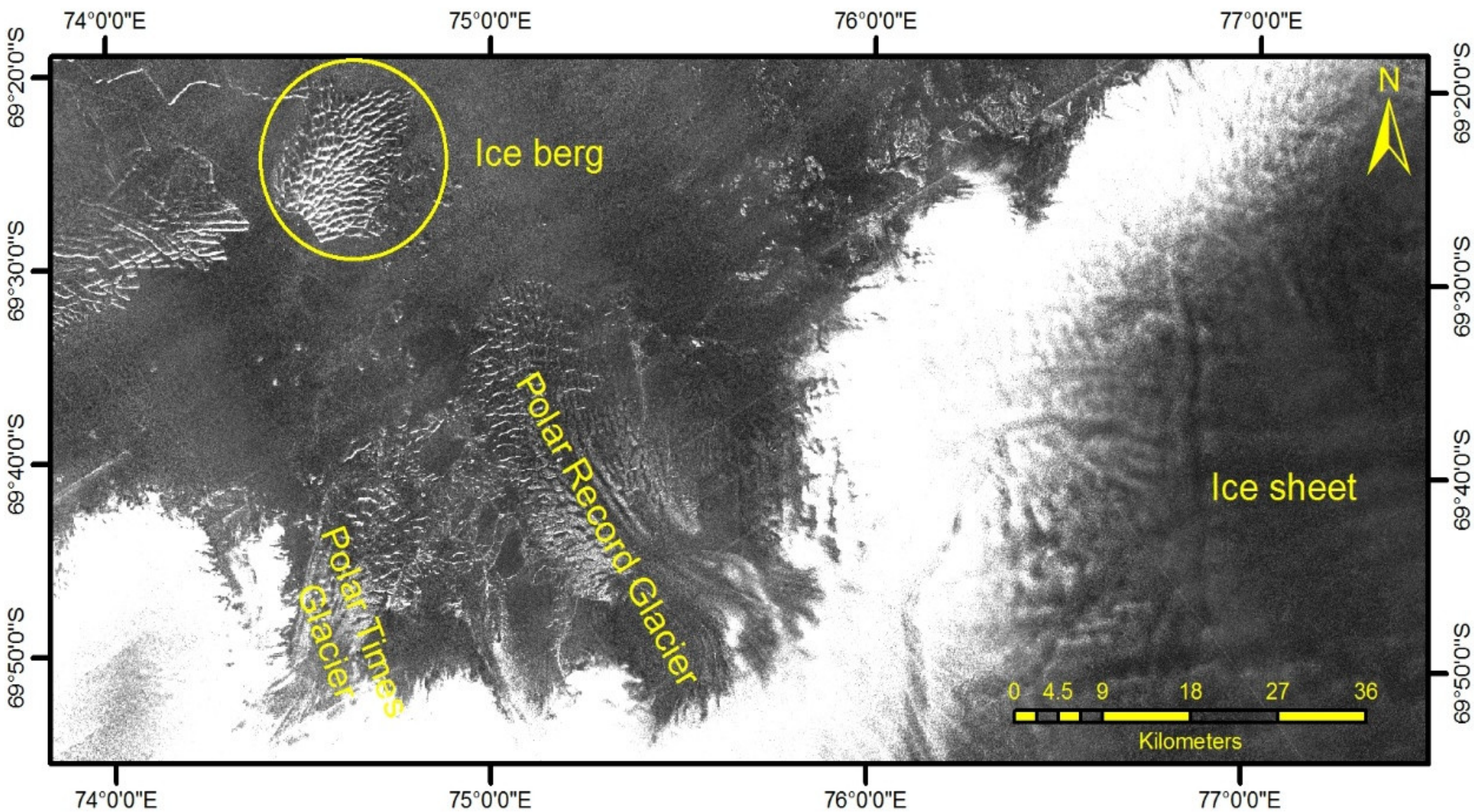


Figure 2.18: A satellite view covering Polar Record Glacier and iceberg calved from its frontal part (RISAT-1; CRS; RH; 05 January 2016).

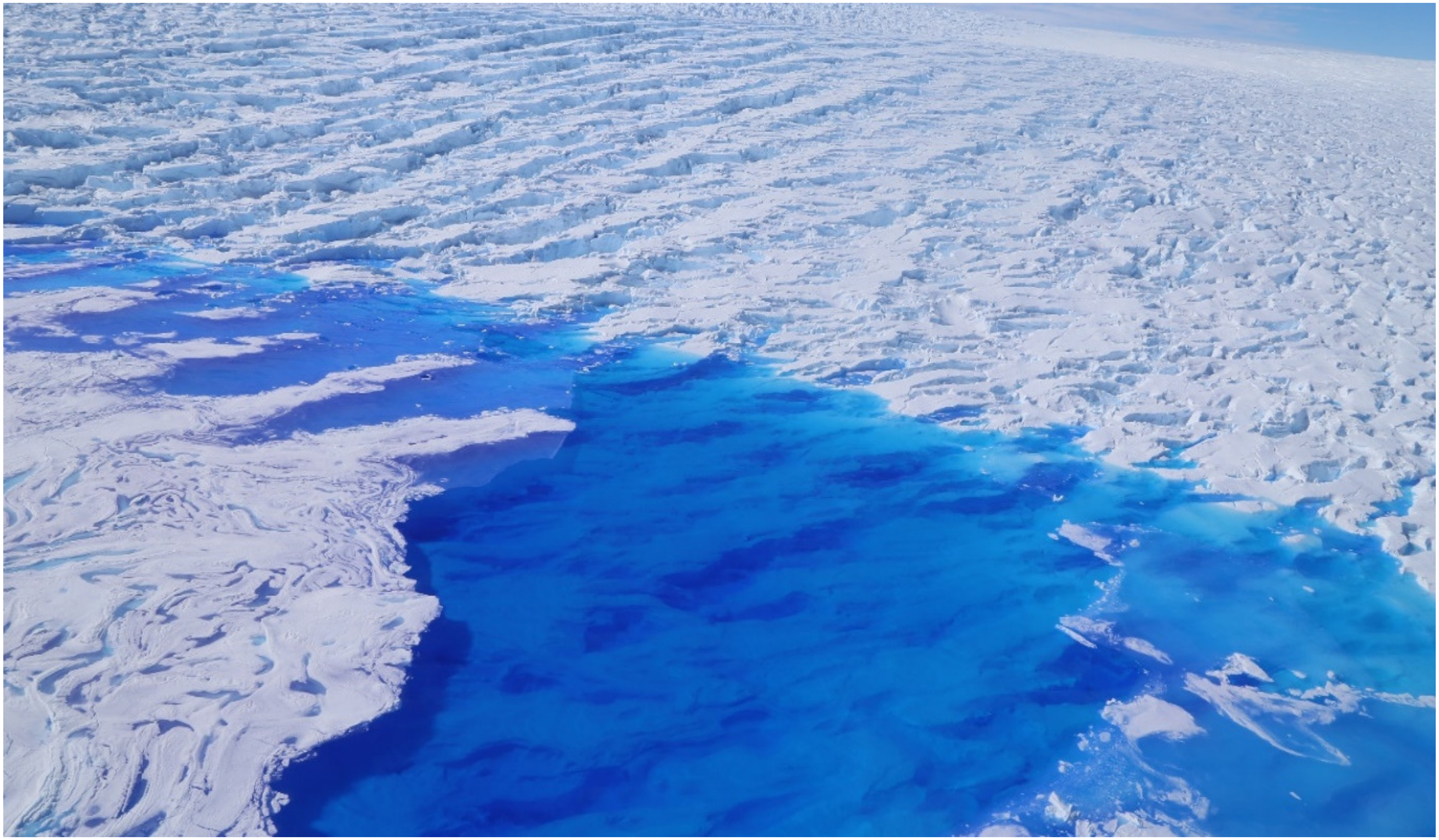


Figure2.19: Field photo of Polar Record Glacier full of multiple crevasses and melted glacier ice (seen in blue) (69^0 50’ 02’’ S, 75^0 43’ 33’’ E; 06 January 2017; 36 ISEA).

Figure 2.20: Field photo of the East Antarctic Ice Sheet (foreground) and Dalk Glacier front (centre right) full of crevasses, terminating into the open ocean. (69^0 24' 42'' S, 76^0 29' 59'' E; 21 January 2017; 36 ISEA).

d) Crevasses

Deep cracks, or fractures, found in ice sheets or glaciers are called crevasses. They are the results of the movements of ice masses at different rates. Crevasses often have vertical or near-vertical walls. These walls sometimes expose layers that represent the glacier's stratigraphy. A crevasse may be several hundred metres long. Depth may vary from a few meters to around 40 meters. It may be as wide as 20 metres. Transverse, Longitudinal, and Splashing crevasses are the three major types of crevasses. The transverse crevasses stretch across the glacier transverse to the flow direction while the longitudinal crevasses form parallel to flow direction where the glacier width is expanding. Splashing or Marginal crevasses form as a result of shear stress from the margin of the glacier, and longitudinal compressing stress from lateral extension. Crevasses are like rattlesnakes, not a problem if you know where they are, but if you don't know their presence and work in the region, they can be dangerous. Crevasses are likely the biggest danger the Antarctic Expedition teams face, and they are abundant across the Antarctica. Crevasses are the major hindrance to convoy operations. The danger of a crevasse is that it may be covered by a snow bridge that conceals a wide space below.

e) Rift

A rift in any ice-shelf is a tensional fracture through the entire thickness of the ice shelf. It propagates from sides into the shelf. Rifts can have significant effect on the dynamics of an ice shelf. Rifts contribute to marginal calving of ice-shelves. On the ice shelves fringing continental Antarctica, the largest calving events involve the release of tabular icebergs following the propagation of rifts, or crevasses that penetrate the full thickness of the shelf. Rifts are initiated in areas of high strain rates, such as where floating ice shears past grounded ice or land masses, or where longitudinal or lateral spreading rates are high. Once rifts have formed, a variety of factors can cause them to propagate across the shelf, eventually isolating tabular bergs, sometimes of immense size. Hence, rifts are a precursor to iceberg calving. They are deep enough to penetrate the entire shelf thickness, and their spacings are associated with parameters such as size and frequency of iceberg calving events.

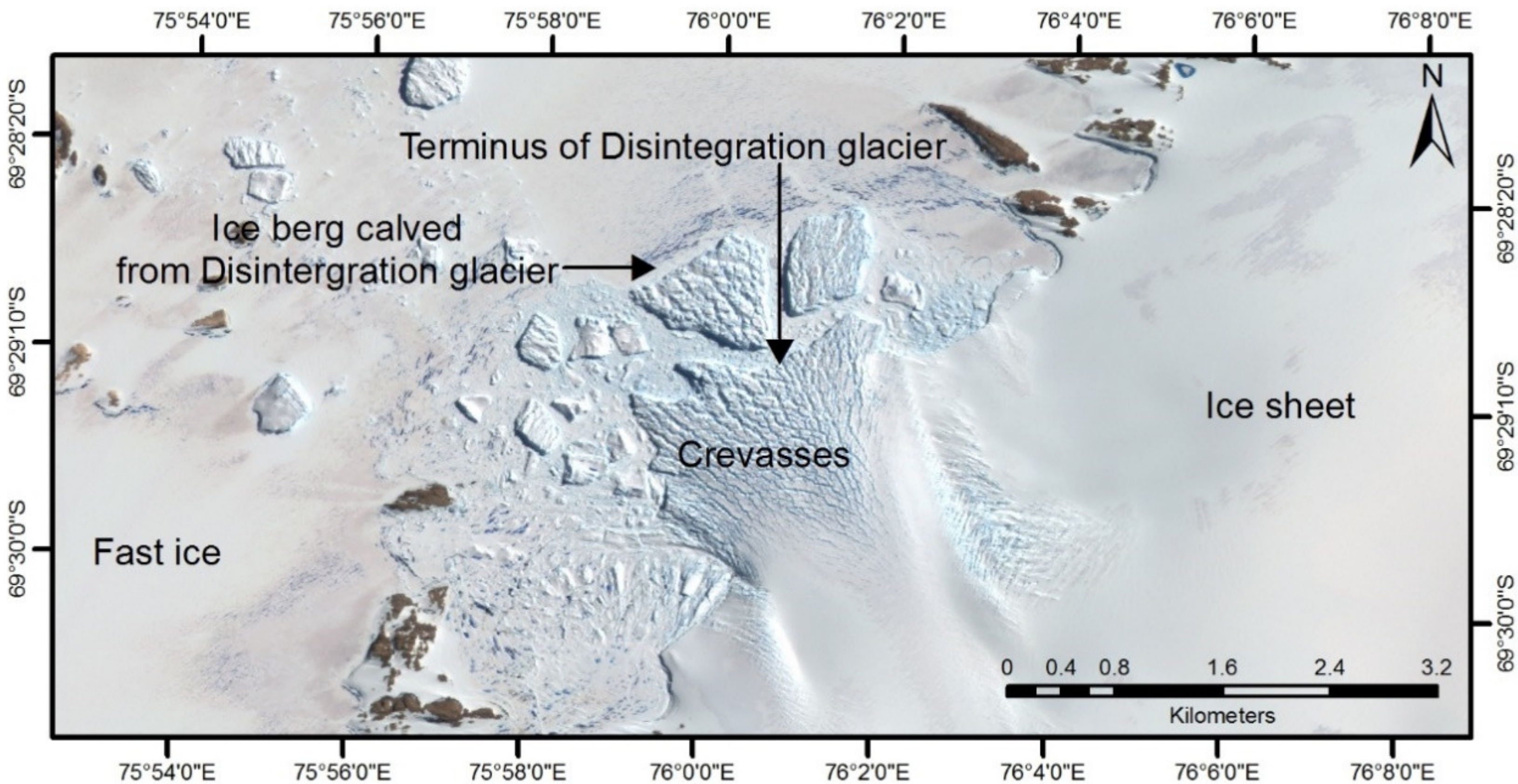


Figure 2.21: A satellite view covering terminus of Disintegration Glacier and its crevasses (Resourcesat-2; LISS-IV; FCC432; 10 January 2016).

Figure 2.22: Field photo of crevasse which has opened up to reveal the blue ice which probably runs very deep and long. No one would dare to explore this. Would you be crazy enough to?(69^{0} 32’ 58’’ S, 76^{0} 11’ 56’’ E; 22 January 2017; 36 ISEA).

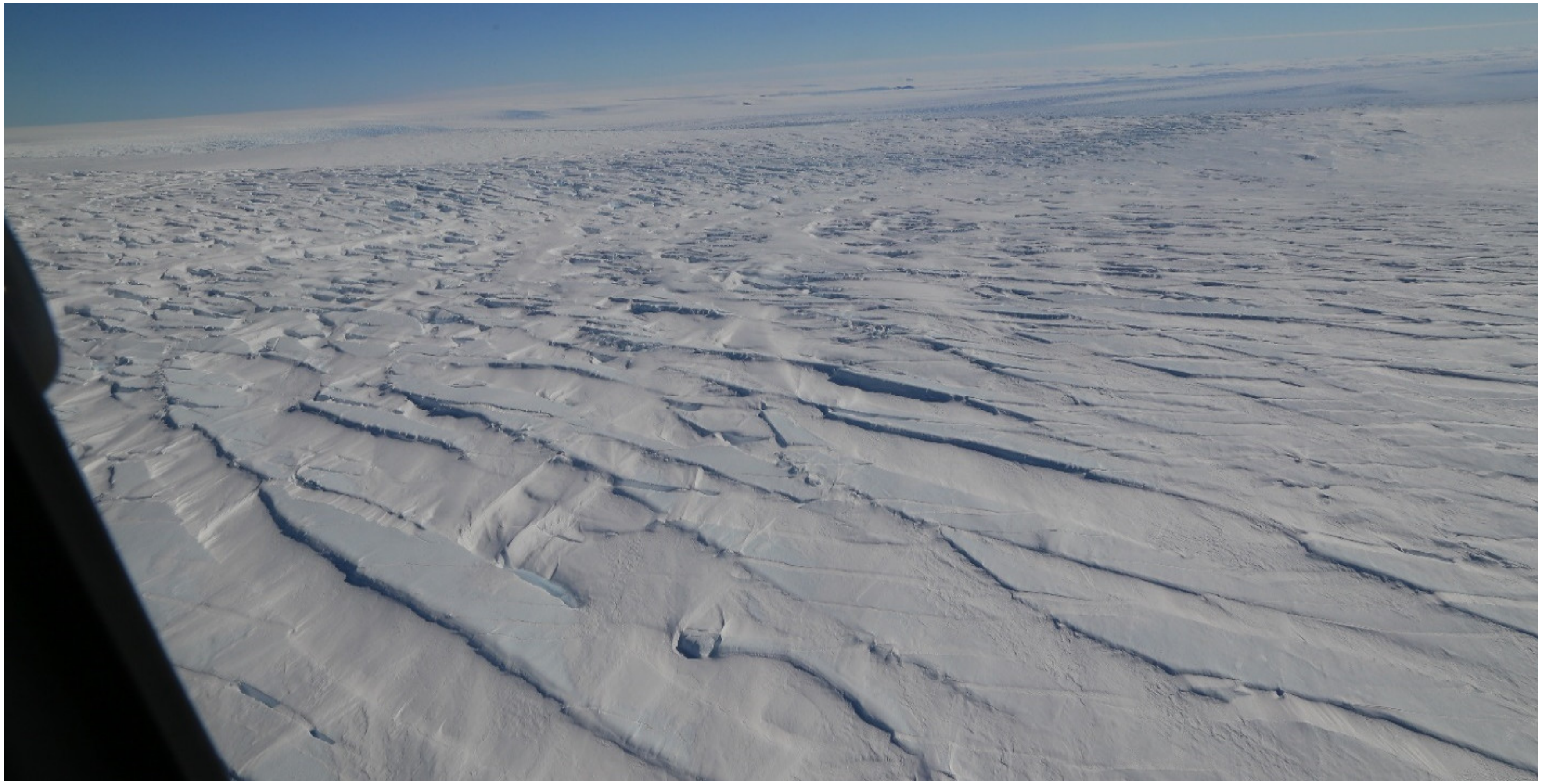


Figure 2.23: Field photo indicates that during the movement of ice sheet, crevasses/fractures/cracks are developed due to shear stress, and followed by snowfall. (69^0 48' 37'' S, 76^0 02' 32'' E; 02 February2018; 37 ISEA).

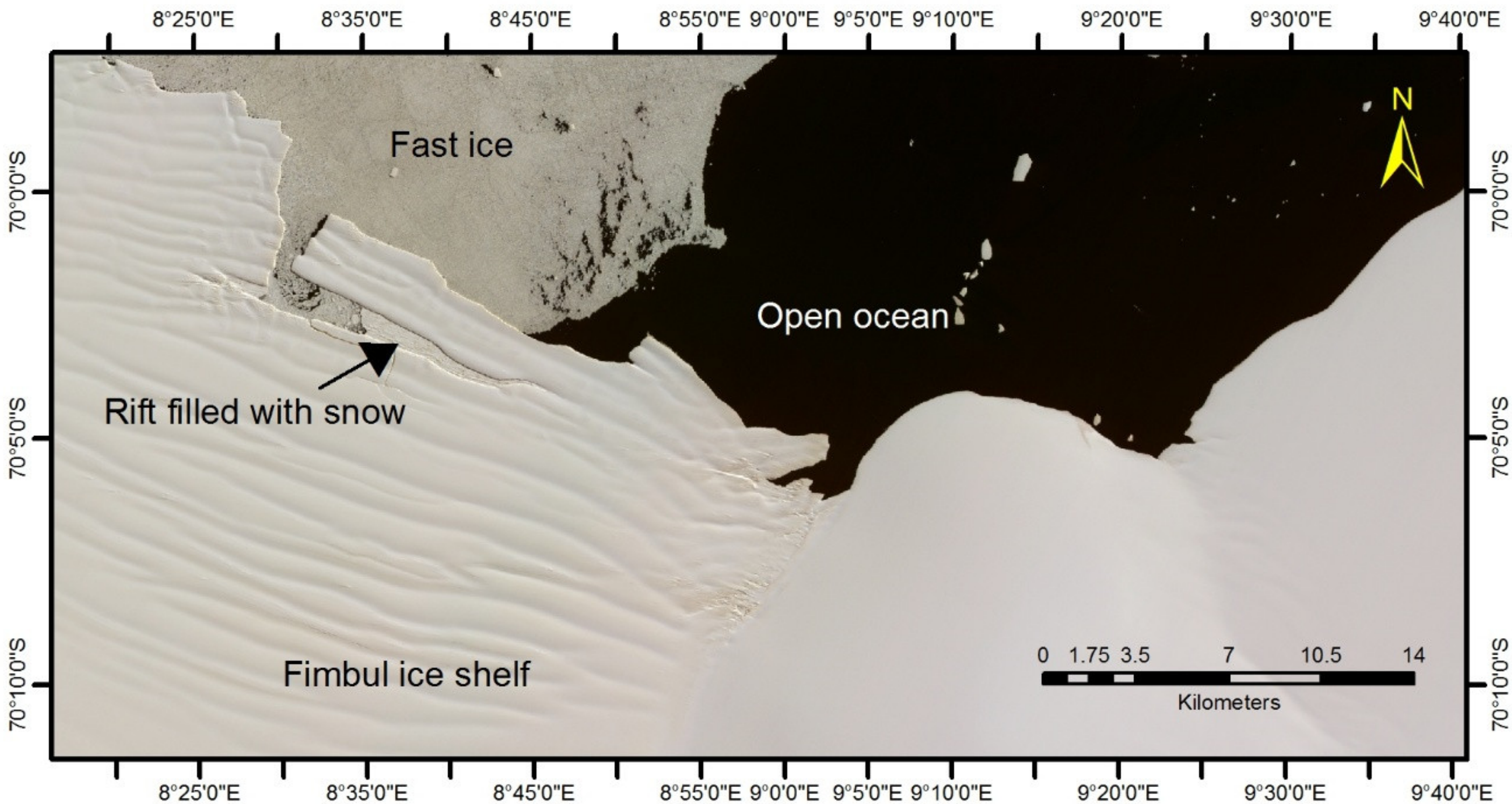


Figure 2.24: A satellite view covering rift structure on Fimbul Ice Shelf, filled with snow (Resourcesat-2, LISS-III, FCC432, 05 February 2015).

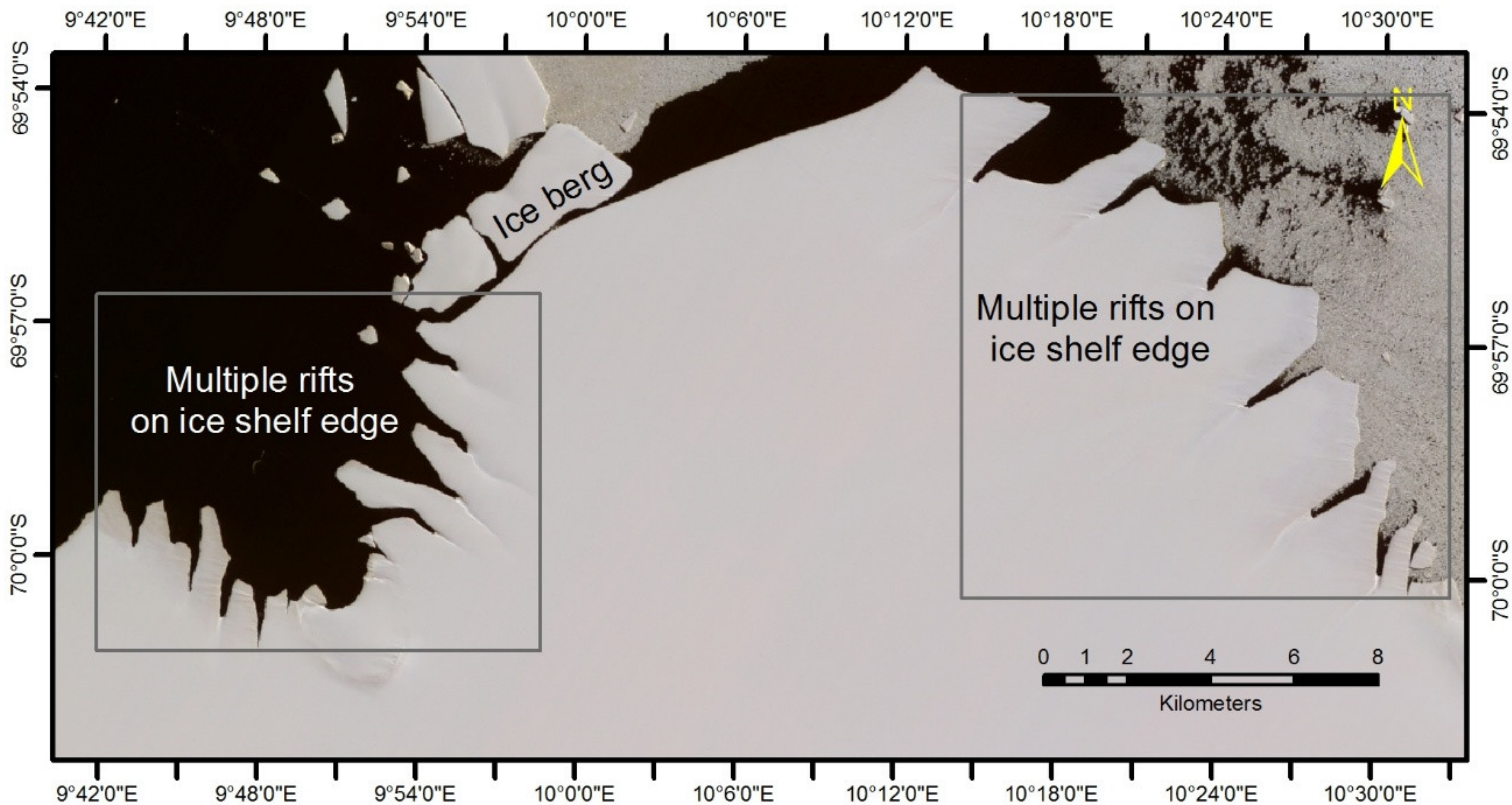


Figure 2.25: A satellite view covering multiple rift structure on Fimbul Ice Shelf, (Resourcesat-2, LISS-III, FCC432, 05 February 2015).

Figure 2.26: Ice shelf, which is an extended cantilever part of ice sheet floating over the ocean. Field photo shows multiple parallel rift structures observed at Lazarev Ice Shelf. (69^0 42' 48'' S, 13^0 14' 02'' E; 02 March 2016; 35 ISEA).

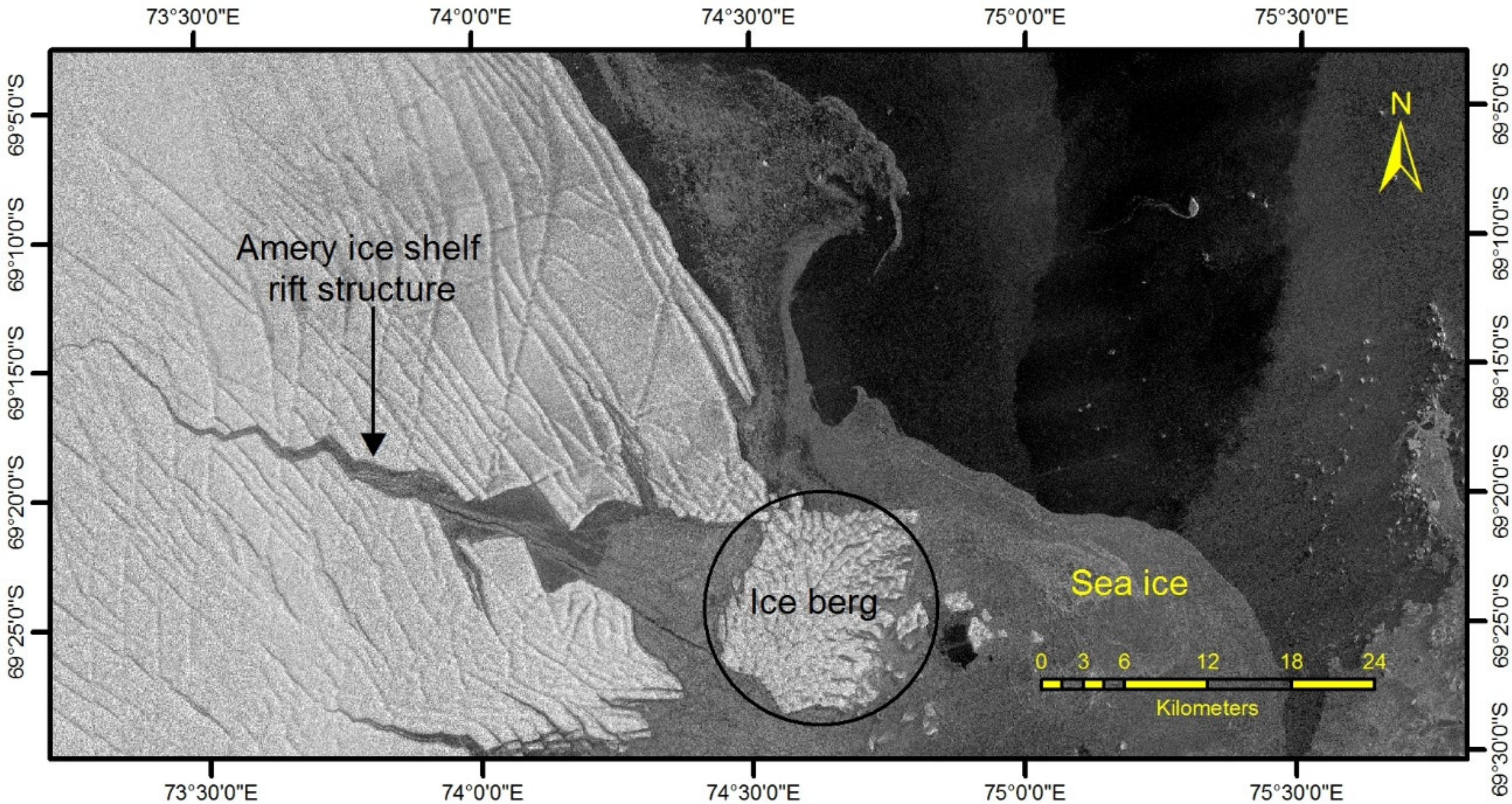


Figure 2.27: A satellite view covering rift structure on Amery Ice Shelf and an iceberg detached from Polar Times Glacier (RISAT-1; CRS; RH;28 February 2016).

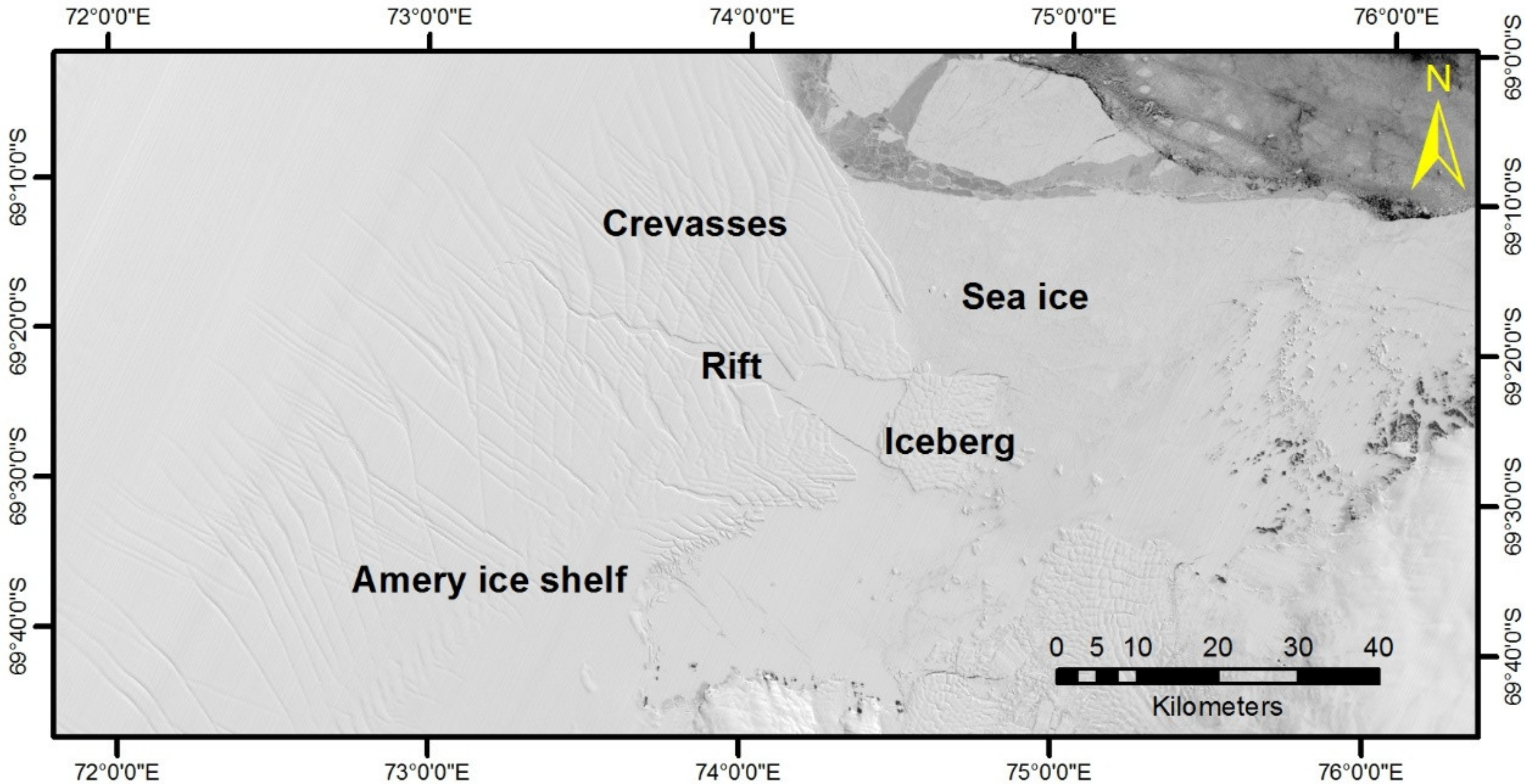


Figure 2.28: A satellite view covering rift structure on Amery Ice Shelf and an iceberg detached from Polar Times Glacier (Resourcesat-2; AWiFS- Band 2, 30 December 2015).

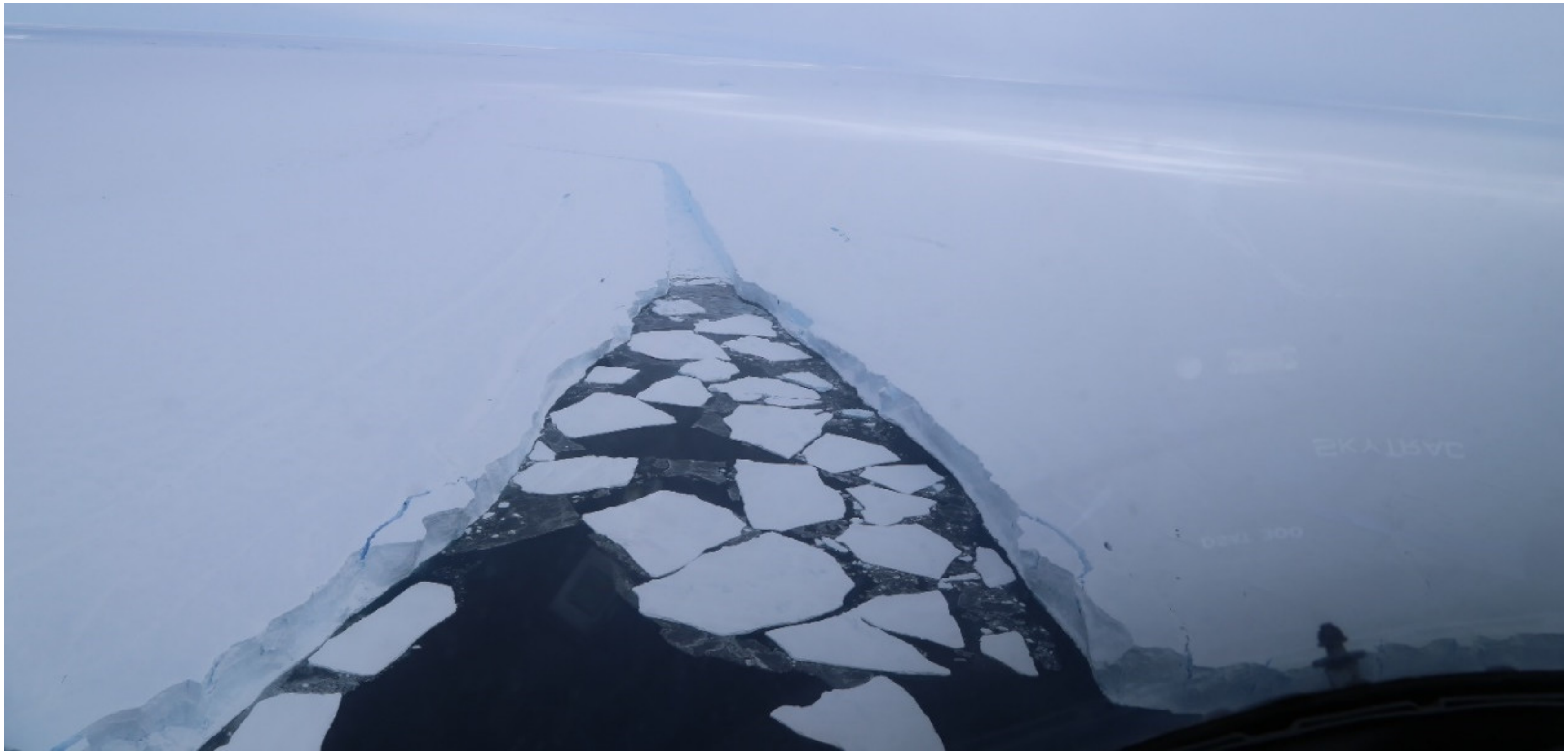


Figure 2.29: Rift structure, which is defined as the fracture along the entire thickness of ice shelf, makes open ocean visible. A field photo of aerial view showing rift structure of third largest Amery Ice Shelf, being fed by the largest and the fastest moving Lambert Glacier in the world (69^0 22' 21'' S, 74^0 32' 23'' E; 13 February 2016; 35 ISEA).

f) Iceberg

A large piece of freshwater ice that has broken off an ice sheet or an ice shelf or glacier and is floating freely in open ocean is called an iceberg. They are pieces of land ice floating in an ocean. Icebergs come in all shapes and sizes, from ice-cube-sized chunks to ice islands with the size of a small country. Typically, only one-tenth of the volume of an iceberg floats above water because the density of pure ice is about 920 kg/m^3 and that of seawater is about 1025 kg/m^3. Icebergs generally ranges from 1 to 75 m above sea level. The largest icebergs recorded have been calved, or broken off, from the Ross Ice Shelf of Antarctica. Iceberg B-15, photographed by satellite in 2000, measured 295 km ×37 km, with a surface area of ~11,000 km^2. The North Atlantic and the cold waters surrounding Antarctica are home to most of the icebergs on Earth. Icebergs are monitored worldwide by the U.S. National Ice Centre (NIC), established in 1995, which produces analyses and forecasts of Arctic, Antarctic, Great Lakes and Chesapeake Bay ice conditions.

The NIC is the only organization that names and tracks all icebergs (https://www.antarcticreport.com/articles/the-national ice-centre-naming-antarctic -icebergs).It assigns each iceberg larger than 19 km along at least one axis. A name composed of a letter indicating its point of origin and a running number. The letters used are as follows: A – 0° to 90° W (Bellingshausen Sea, Weddell Sea) B –90° W to 180° (Amundsen Sea, Eastern Ross Sea) C–90°E to 180° (Western Ross Sea, Wilkes Land) D – 0° to 90° E (Amery Ice Shelf, Eastern Weddell Sea).

g) Ice Rise

Locally grounded features in an ice shelf are called an ice rise. Ice rise is a mass of ice resting on rock and surrounded either by an ice shelf, or partly by an ice shelf and partly by sea; without exposed rock. Ice rises often have a dome-shaped surface; the largest known ice rise is about 100 km across. Ice rises play a key role buttressing discharge from the Antarctic Ice Sheet and regulating its contribution to sea level. This feature typically rises several hundreds of meters above the surrounding ice shelf. Ice rises contain rich histories of de-glaciation and climate that extend back over timescales ranging from a few millennia to beyond the last glacial maximum.

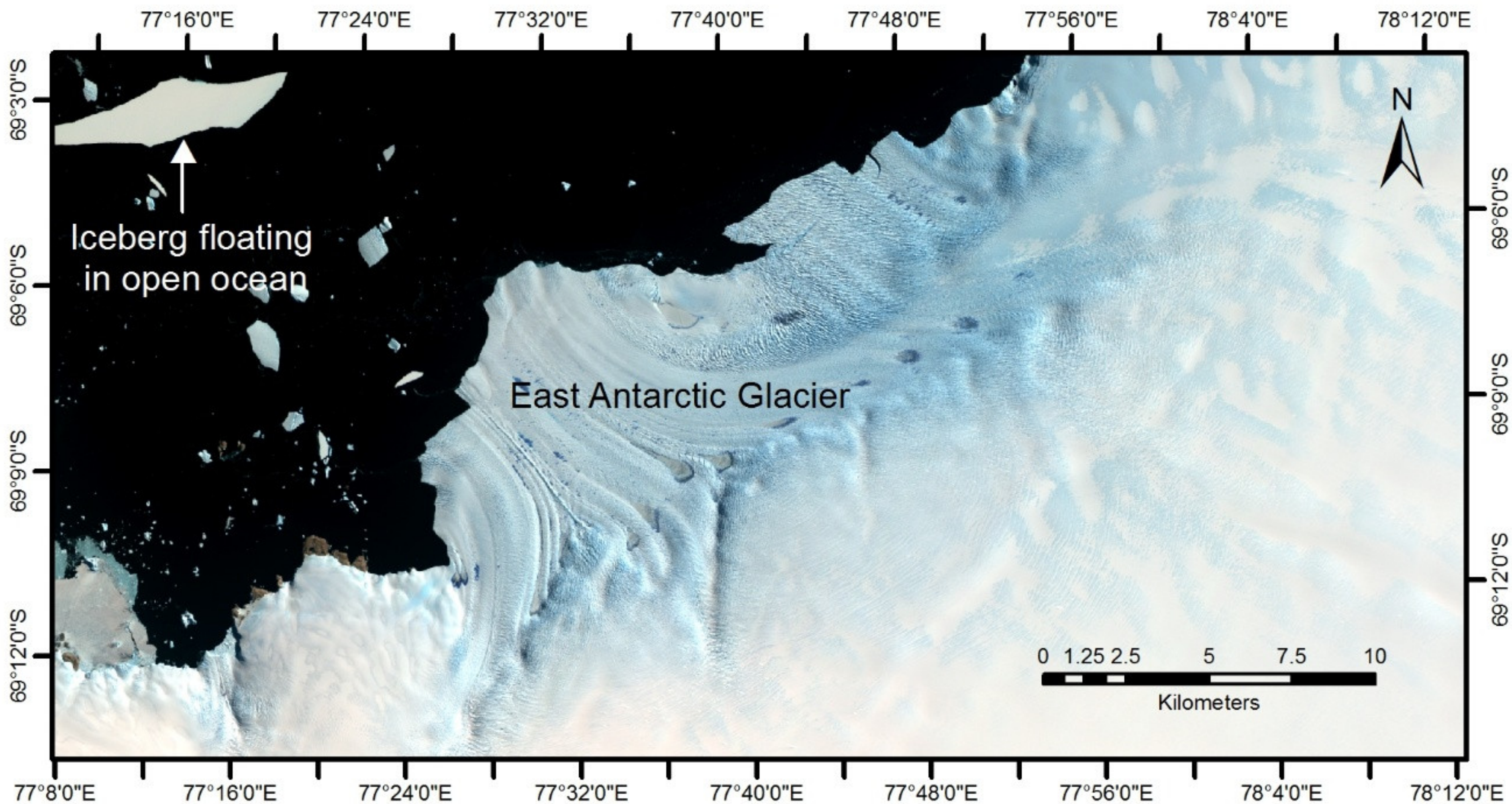


Figure 2.30: A satellite view covering huge floating iceberg in an open ocean (Resourcesat-2, LISS-IV, FCC432).

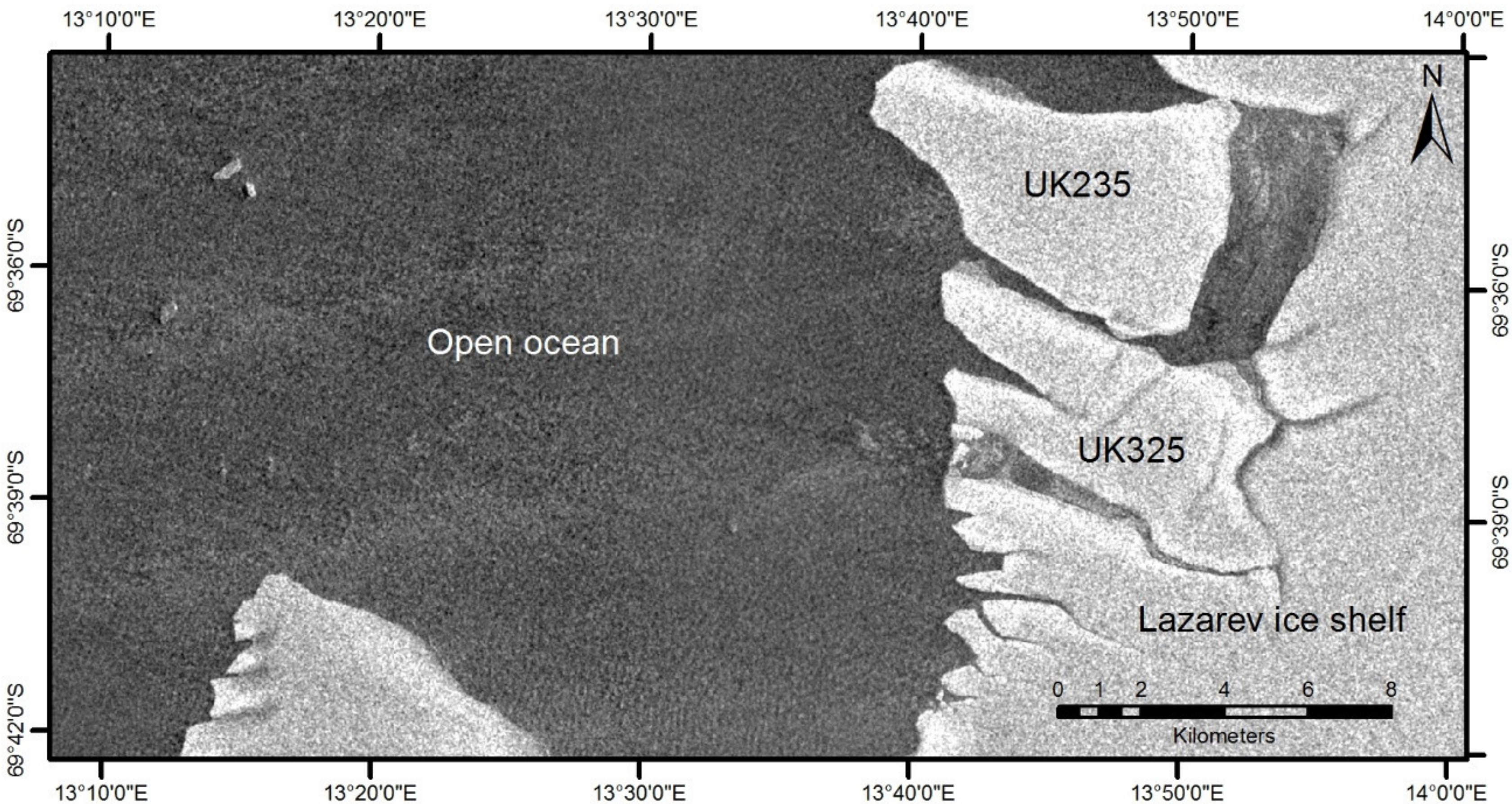


Figure 2.31: A satellite view covering iceberg UK235, UK325 calved from Lazarev Ice Shelf (RISAT-1; MRS; RH; 10 March 2016).

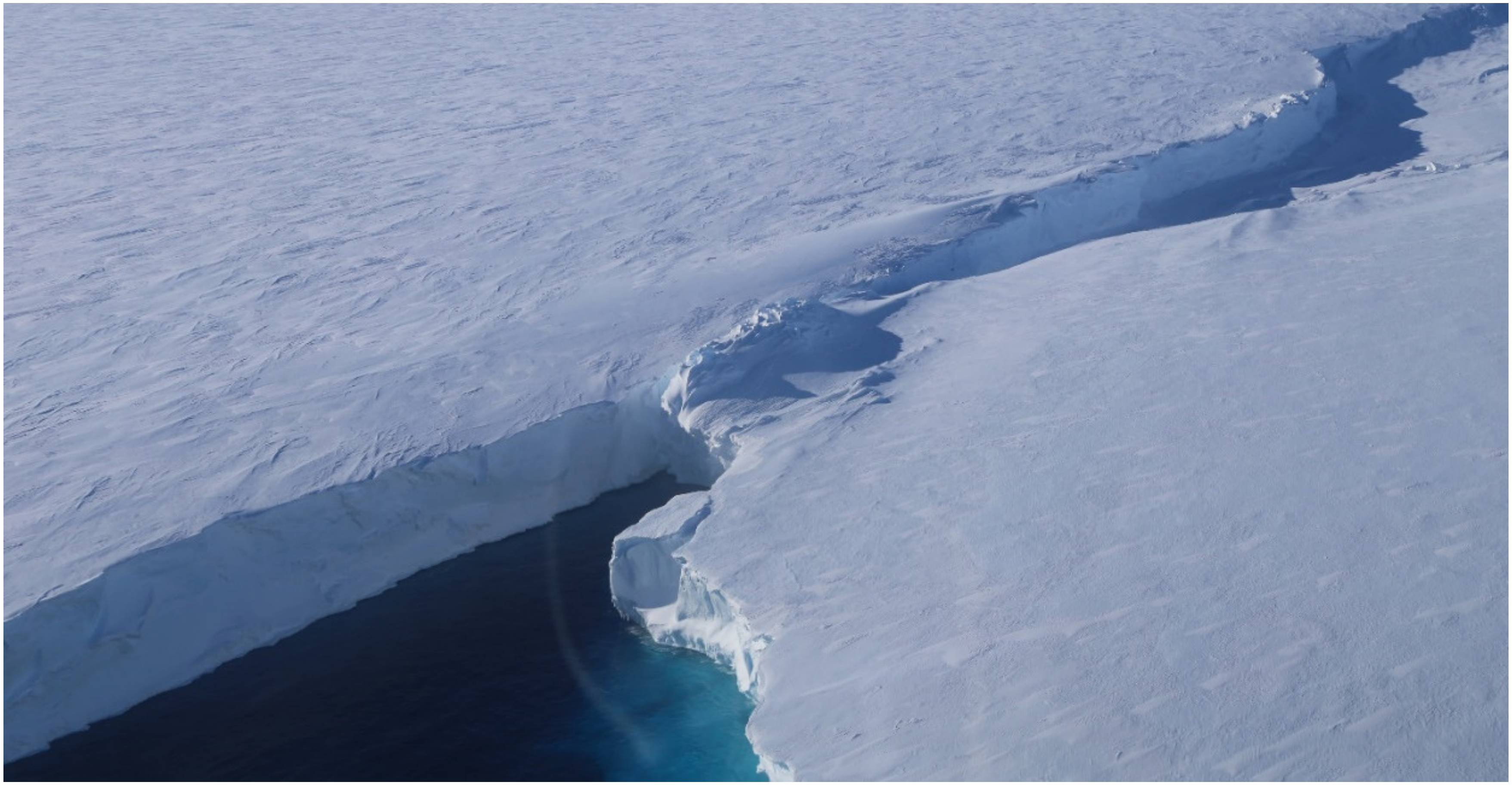


Figure 2.32: Parting ways. A gap between the break off iceberg (UK235, Bottom right) and the Lazarev Ice Shelf (Top left) can be seen very clearly in the field photo, which extends over many kms. Can you delineate between Icebergs (UK235 & UK325) and Lazarev Ice Shelf identified by RISAT-1 of ISRO for the first time? (69^0 33' 26'' S, 13^0 49' 59'' E; 18 March 2017; 36 ISEA).

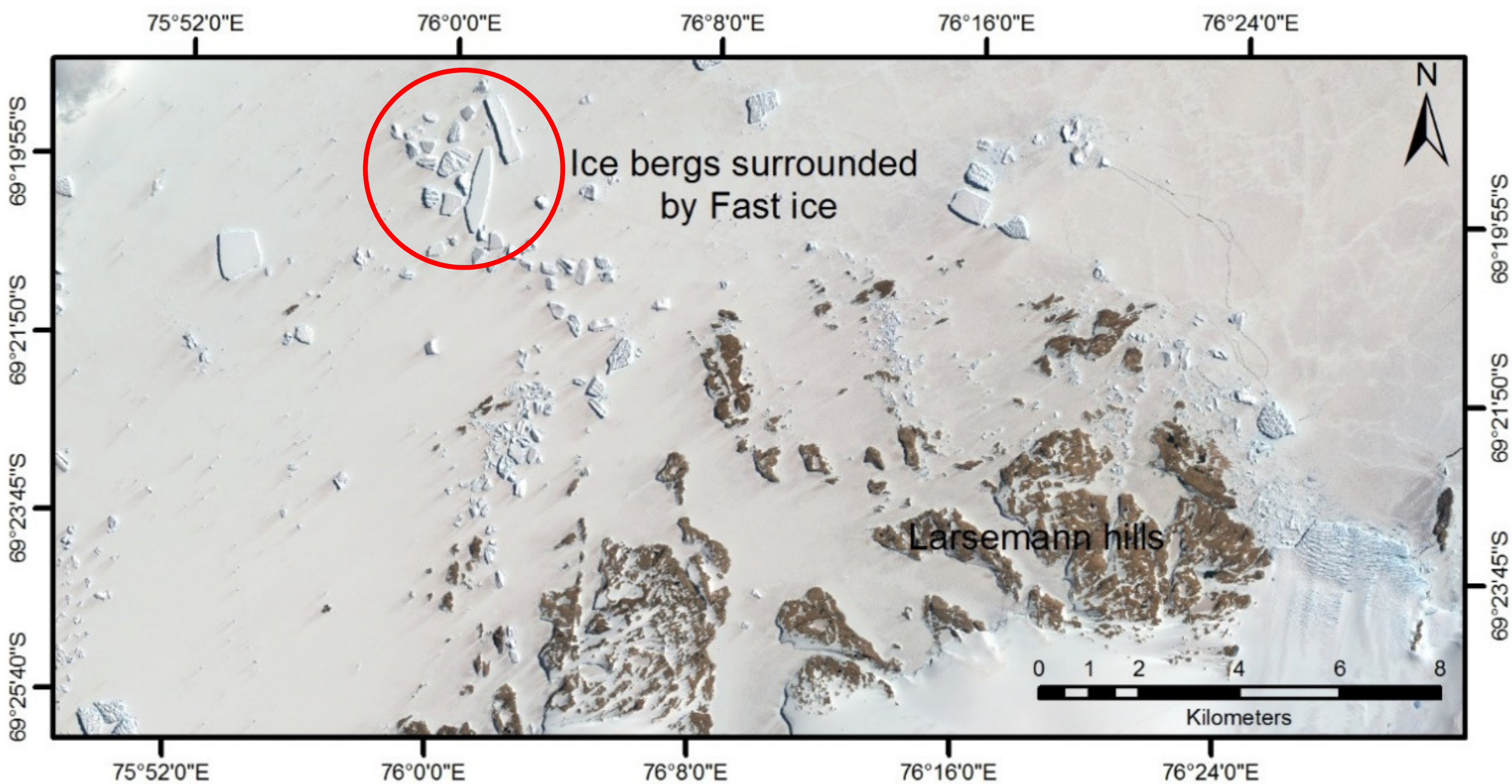


Figure 2.33: A satellite view covering large number of icebergs trapped in fast ice near Larsemann Hills (Resourcesat-2; LISS-IV; FCC432; 10 January 2016).

Figure 2.34: The 33rd ISEA, ship reached a region where iceberg was available visibly. (62^0 22' 20'' S, 64^0 27' 47'' E; 21 December 2013, 33 ISEA).

Figure 2.35: An iceberg, which is in an elephant shape…!!! The nature creates innumerous crafts in its cradle but one needs the heart and mind to interpret which one can only do by being with the nature…!!!(68^0 38' 30'' S, 73^0 15' 20'' E; 17 February 2017; 36 ISEA).

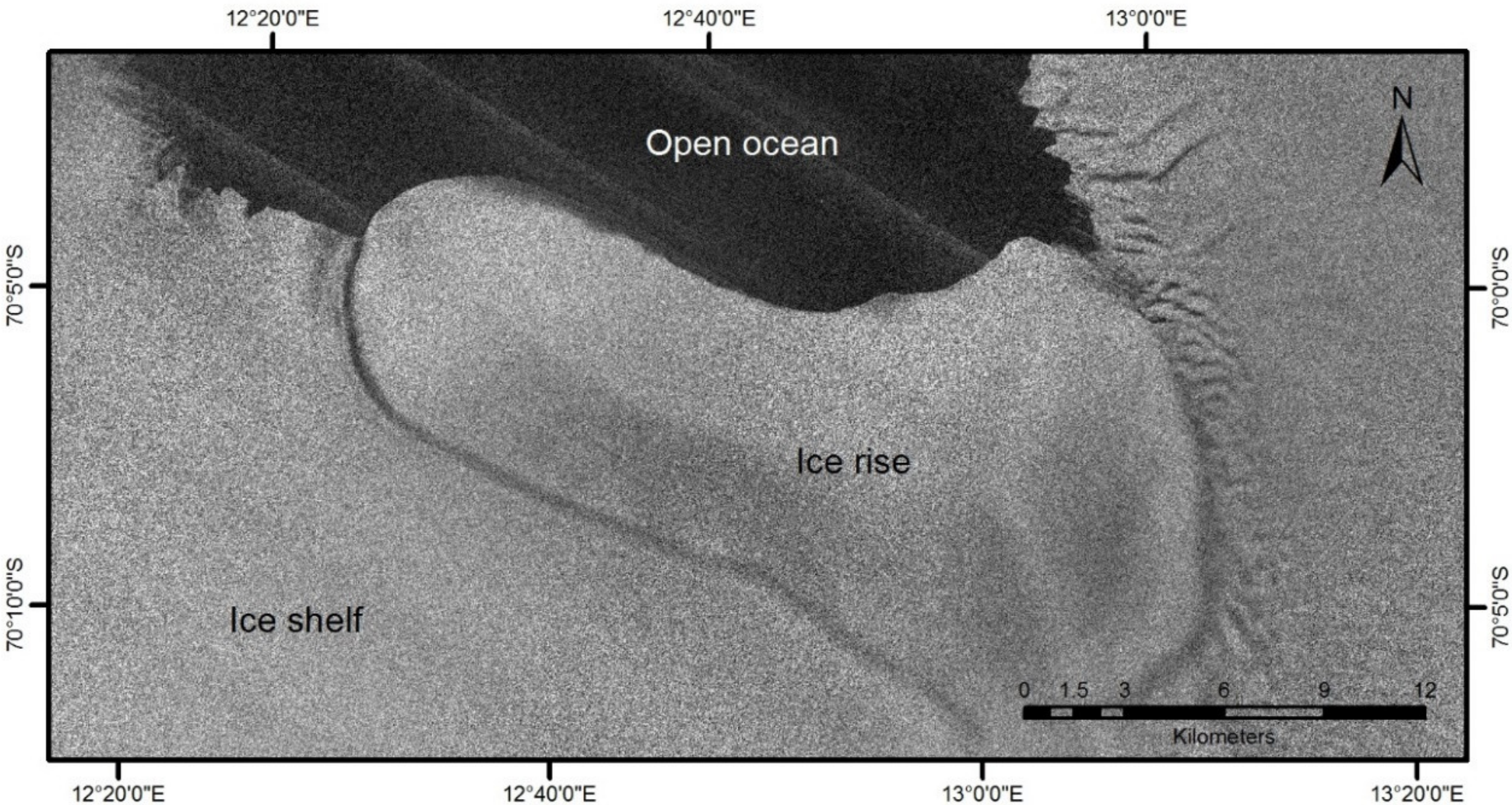


Figure 2.36: A satellite view covering ice rise near Lazarev Ice Shelf (RISAT-1; MRS; RH; 20 February 2016).

Figure 2.37: Ice rise, locally grounded ice due to bathymetry beneath it. An aerial view of ice rise near Nivilisen Ice Shelf is visible. (70^0 05' 16'' S, 12^0 22' 46'' E; 22 February 2016; 35 ISEA).

2.2 Sea Ice Features

Some of the major sea ice features found in the Antarctic are: sea ice floe, fast ice, lead, deformed sea ice, polynya etc. Sea ice is nothing but the frozen ocean water. On an average, it covers about 25 million km^2 area of the Earth, i.e. about 8 fold of geographic area of India. Sea ice, which is about 7% of the Earth's surface, covers about 12% of the world's oceans. The density of sea ice is less than that of water and hence it floats on the ocean's surface. Sea ice forms, grows, and melts in some of the oceans. In contrast, icebergs, glaciers, ice sheets, and ice shelves all originate on land from precipitation. Sea ice regions in Northern Hemisphere covers Arctic Ocean, some areas just below it and some other cold oceans, seas and gulfs. In the North, it also exists at much higher latitude in Bohai Bay, China (which is actually about 700 km closer to the Equator than it is to the North Pole). In the Southern Hemisphere, sea ice only develops around Antarctica almost up to 55^0 south latitude. Much of the world's sea ice is enclosed within the polar ice packs in the Earth's Polar Regions. Due to the action of winds, currents and temperature fluctuations, sea ice is very dynamic, leading to a wide variety of ice types and features. One of the classifications of sea ice is based on its age based on the development stages. These stages are: new ice, nilas, young ice, first-year, and multi-year sea ice. New ice is usually very salty because it contains concentrated droplets called brine that are trapped in pockets between the ice crystals, and so it would not make good drinking water. As ice ages, the brine eventually drains through the ice, and by the time it becomes first-year ice, majority of the brine content is gone. Multiyear ice is the sea ice survived during more than one summer. Sea ice can also be classified according to whether or not it is attached to the shoreline or grounded to icebergs. If attached, it is called fast ice (word fast from fastened). If not attached and is free to move with currents and winds, it is usually known as drift ice, which occurs further offshore in very wide areas. The physical boundary between fast ice and drift ice is the fast ice boundary. A small fraction of human population actually is able to see the sea ice during their lives because we don't live near poles and other sea ice regions. However, it is an extremely important part of our environment and climate. A brief description of major sea ice features is presented below.

a) Pan Cake

Pancake ice is a term used to describe generally circular ice formations that range from 30 cm to 3 m across and up to 10 cm thick. Size increases due to grouping of multiple pancakes. Smaller pancakes generally formed from grease ice, which is a thin layer of ice that gathers on the surface of agitated water (such as swelling seas) and often includes frazil ice and slush. If the ocean is rough, the frazil crystals accumulate into slushy circular disks, called pancakes or pancake ice, because of their shape. Far from an isolated phenomenon, pancake ice occurs among a wide variety of ice formations and behaviours. A signature feature of pancake ice is raised edges or ridges on the perimeter, caused by the pancakes bumping into each other from the ocean waves and winds. If the motion is strong enough, rafting occurs. If the ice is thick enough, ridging occurs, where the sea ice bends or fractures and piles on top of itself, forming lines of ridges on the surface. The accumulation of slush and frazil ice, which is a collection of ice crystals that take shape on moving water, also contributes to the raised edges of pancake ice.

b) Floe

Size of sea ice increases due to consolidation of multiple large-sized pancakes. A large pack of floating sea ice, often defined as a flat piece having size of about 20 m across at its widest point, and up to more than 10 km across, is called a sea ice floe. There are names for various floe sizes: small – 20 m to 100 m; medium – 100 m to 500 m; big – 500 m to 2,000 m; vast – 2 km to 10 km; and giant – more than 10 km.

c) Drift Ice

Any sea ice that is not fastened to any solid object like shoreline, shoal, grounded iceberg, ice-shelf etc., is called drift ice. It has got its name because it is carried along by winds and sea currents and keep on drifting. Drift ice consists of several floes, individual pieces of sea ice 20 metres or more across.

d) Fast Ice

Sea ice "fastened" to either coastline or any grounded iceberg is known as fast ice or land-fast ice (also land fast ice) or shore-fast ice. It forms in two ways: by freezing of surface sea water near the coast or by freezing pieces of drifting ice to the shore or other anchor sites. Unlike drift ice, it does not move with currents and winds and remain stationary due to its attachment with the land or iceberg / ice-shelf. The presence of this ice zone is usually seasonal and depends on ice thickness, topography of the sea floor, sea surface state etc. Seaward expansion is a function of a number of factors e.g. water depth, shoreline protection, time of year and pressure from the pack ice etc. Its extent may range from a few meters to several hundred kilometres. This zone lies usually between a coastline and drift ice zone; however sometimes there may not exit any drift ice zone.

e) Ice Foot

The ice foot refers to ice that has formed at the shoreline, through multiple freezing of water between ebb tides, and is separated by the remainder of the fast ice surface by tidal cracks.

f) Bottom Fast Ice

Further, away from the coastline, the sea ice may become anchored to the sea bottom-it is then referred to as bottom fast ice.

g) Pack Ice

The term pack ice is used either as a synonym to drift ice or to designate drift ice zone in which the floes are densely packed. As per one definition, when drift ice is driven together into a large single mass (>70% coverage), it is called pack ice. It can be very flat (because the ocean is flat), but it is usually covered with very rough areas caused by the movement of floes of ice against one other. This collision can increase the thickness of the ice from just a few inches or centimetres to tens of meters thick. Although pack ice moves with ocean currents and wind, it is not free-floating like ice-floes, and it is not always continuous. At times it can be very broken, with leads (cracks of open water) opening up without warning.

h) Leads and Polynyas

Leads and polynyas are regions of open water within sea ice cover, and they share several characteristics. They are the areas or pockets of persistent open water where we normally expect to find sea ice. They are different in fundamental ways. A sea-ice lead is defined by the World Meteorological Organisation (WMO) as a rectilinear or wedge-shaped crack in the sea-ice cover. According to this definition, a lead is wider than 50 m and ranges from several kilometres to hundreds of kilometres in length. Leads are narrow, linear features, while polynyas are generally more uniform in shape and larger in size. Polynyas tend to be roughly oval or circular in shape, but they can be of any regular or irregular shape of open water surrounded by sea ice cover. The polynyas are of two types, differentiated by the mechanism of ice removal: Sensible heat polynya, and Latent heat polynya. One process often dominates in a given polynya, but both can occur. A sensible-heat polynya forms when water that is above freezing up wells, or moves from the lower depths of the ocean to the surface. A latent-heat polynya forms as a result of winds blowing in a persistent direction that push the ice away from a barrier, such as the coast, fast ice, a grounded iceberg, or an ice shelf. Leads form because of the motion of the ice, when ice floes diverge or shear as they move parallel to each other; while polynyas form from either upwelling warm water or persistent winds. During winter, open water remains in leads for only a short time before it begins to refreeze, while polynyas usually remain unfrozen for long periods of time. Leads play very important role in ocean-atmosphere interaction. They are important for marine life. Seals, whales, penguins, and other animals rely on leads for access to oxygen. Polar bears in the Arctic often hunt near leads, because they know that their prey is likely to come to the surface in such areas. Leads are also important for navigation. Even when they freeze, leads tend to contain thinner and weaker ice that allows submarines to move easily to surface through the ice and icebreakers to more easily traverse the ice. Similarly, Polynyas are important for various reasons. Like leads, they are a source of heat and moisture to the atmosphere, so they modify the weather in surrounding areas. Polynyas are also important resources for marine life. They provide access between the ocean and atmosphere for a variety of animals, including seals and penguins. Because polynyas persist for longer time periods than leads, and because overturning ocean water brings nutrients to the surface, phytoplankton thrives in polynyas. During the summer, Antarctic polynyas are one of the most biologically productive regions in the world's oceans.

i) Stamukha

Stamukhi (plural of stamukha) are made of broken sea ice resulting from the interaction between fast ice and drifting pack ice. A stamukha is a grounded accumulation of sea ice rubble that typically develops along the boundary between fast ice and the drifting pack ice, or Stamukhi tend to occur in belts that are parallel to the shoreline, along coastal shoals, usually at water depths of about 20 to 50 m. Their height may reach 10 m or more above the waterline. Although they remain pinned to the seabed, these features can be subject to small displacements, either due to thermal expansion or to the pressure exerted by the drifting pack ice onto the fast ice. Since Stamukhi extend downward into the seabed, they present a risk to submarine pipelines and telecommunications cables that cross the shoreline.

2.3 Sea Ice Deformation

Sea ice is not a continuous, uniformly smooth sheet of ice, but rather a complex surface that varies dramatically across even short distances. The continuous interaction between ice floes as they are driven against each other due to currents and winds produces deformed sea ice deformations. The sea ice deformations may result in three types of features: (i) Rafted ice, when one piece is overriding another; (ii) Pressure ridges, a line of broken ice forced downward and upward; and (iii) Hummock, a hillock of broken ice that forms an uneven surface. While the in-situ field observations were made during the expeditions, good amount of earth observation data was collected through Indian and foreign satellites over the Antarctic. Various ice features in Antarctica and the Antarctic sea ice region were captured in these satellites data. While the scatterometer data at coarse resolution could observe the sea ice at synoptic scale, RISAT-1 and Advanced Wide Field Sensor (AWiFS) sensors could capture the finer details in comparison to scatterometer. Some glimpses of various ice features as seen by earth observation data are presented here in the form of figures (Figure 2.38 to Figure 2.50).

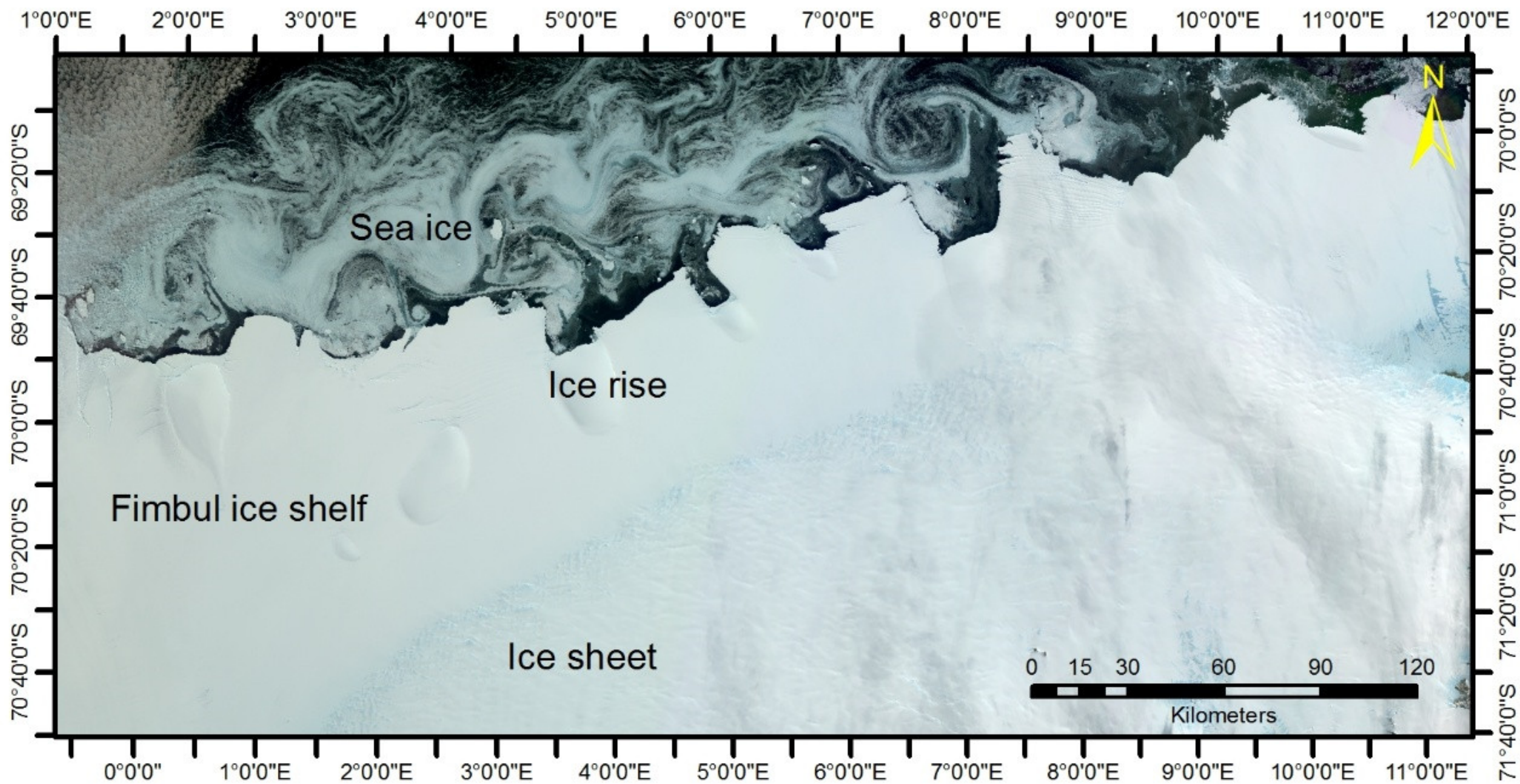


Figure 2.38: A satellite view showing formation of sea ice near Fimbul Ice Shelf. (Resourcesat-2; LISS-IV; FCC432; 13 February 2015).

Figure 2.39: Rafting of pan cakes (70^0 03’ 42’’ S, 12^0 26’ 00’’ E; 20 February 2009; 28 ISEA).

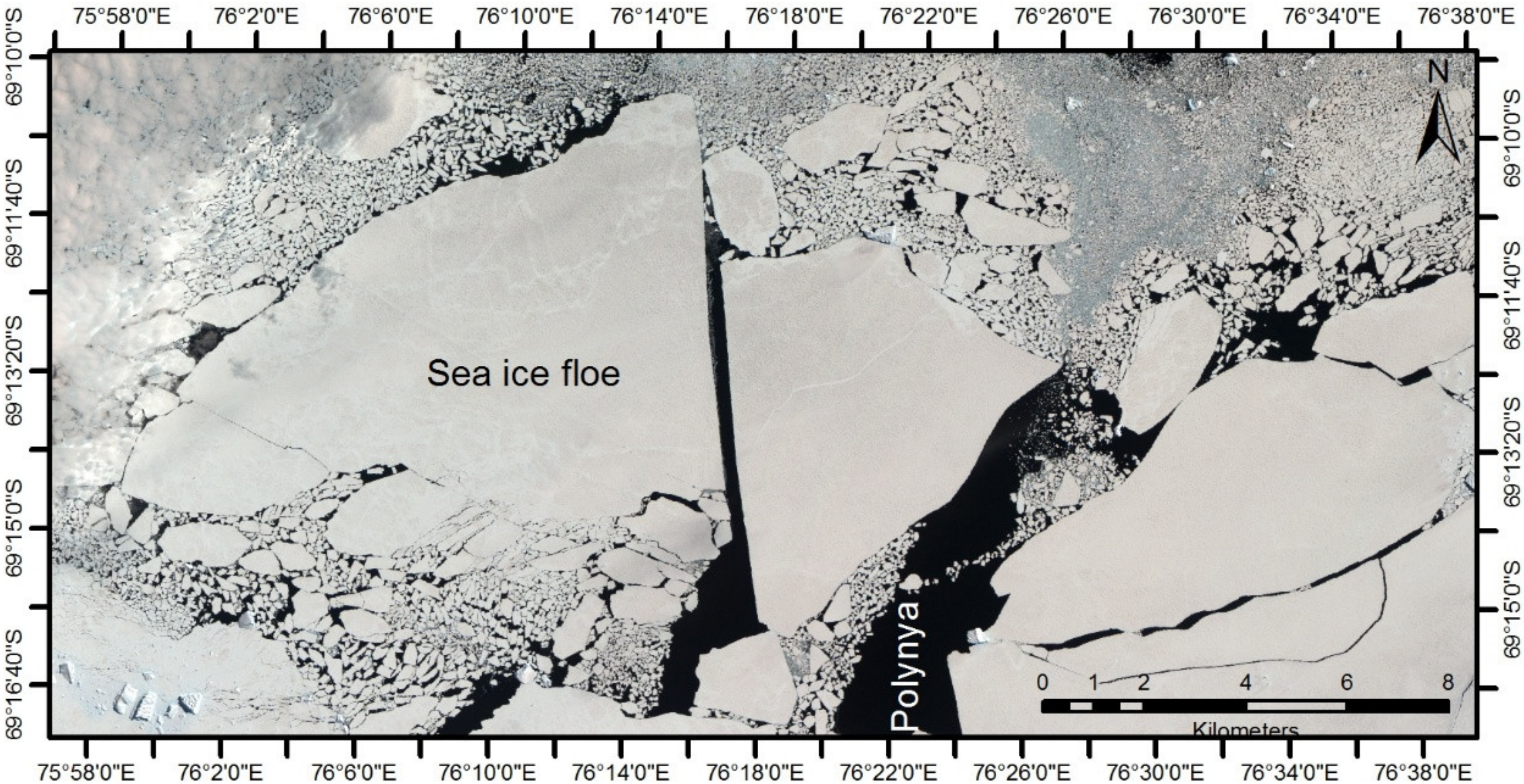


Figure 2.40: A satellite view covering large floes and polynyas. (Resourcesat-2; LISS IV; FCC432; 10 January 2016).

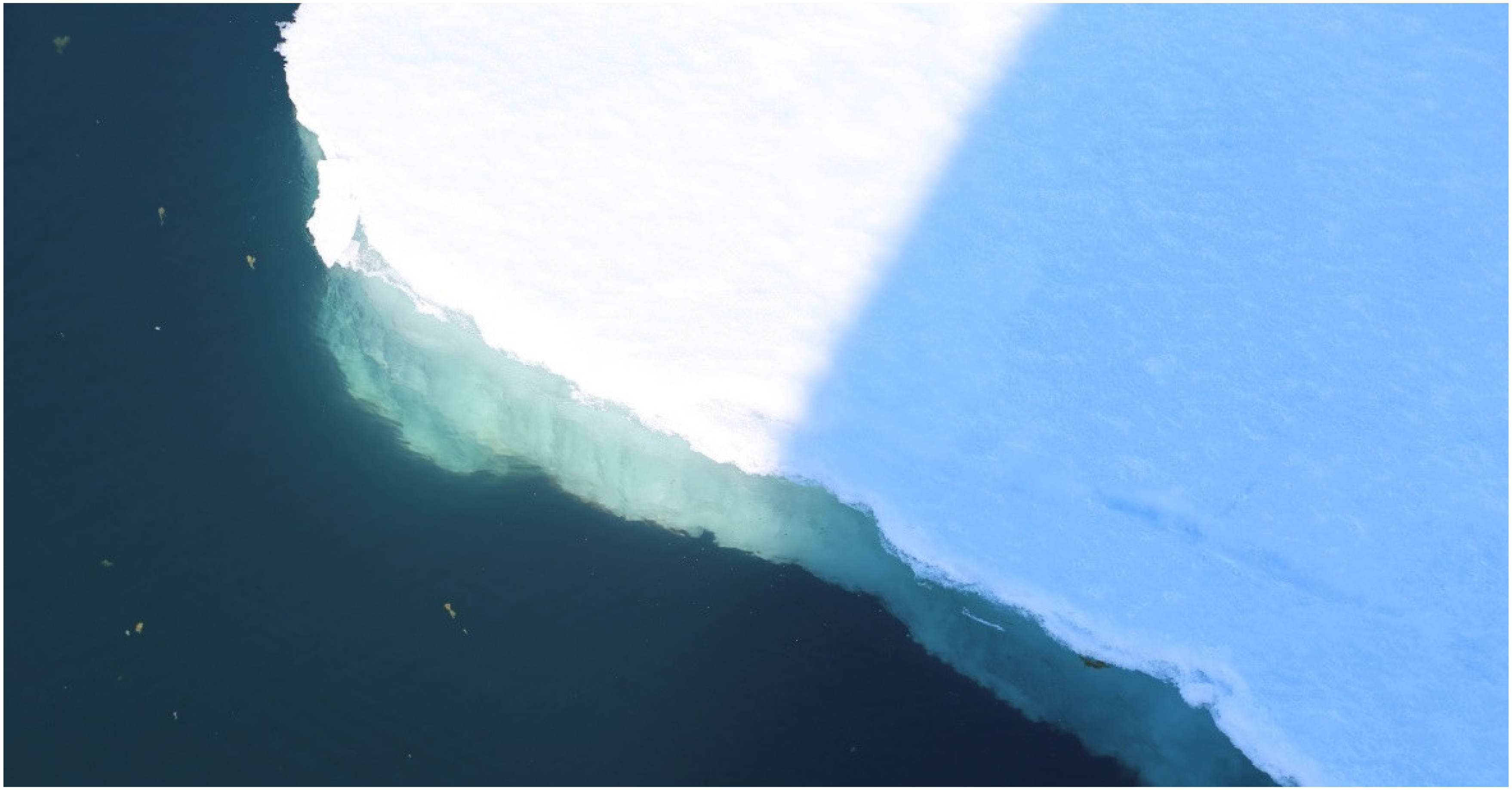


Figure 2.41: A large sea ice floe (extending from centre and right top to bottom right) and its edge showing sea ice thickness, which is an important parameter for safer ship navigation. Open ocean centre left bottom to top left. (05 January 2017; 36 ISEA).

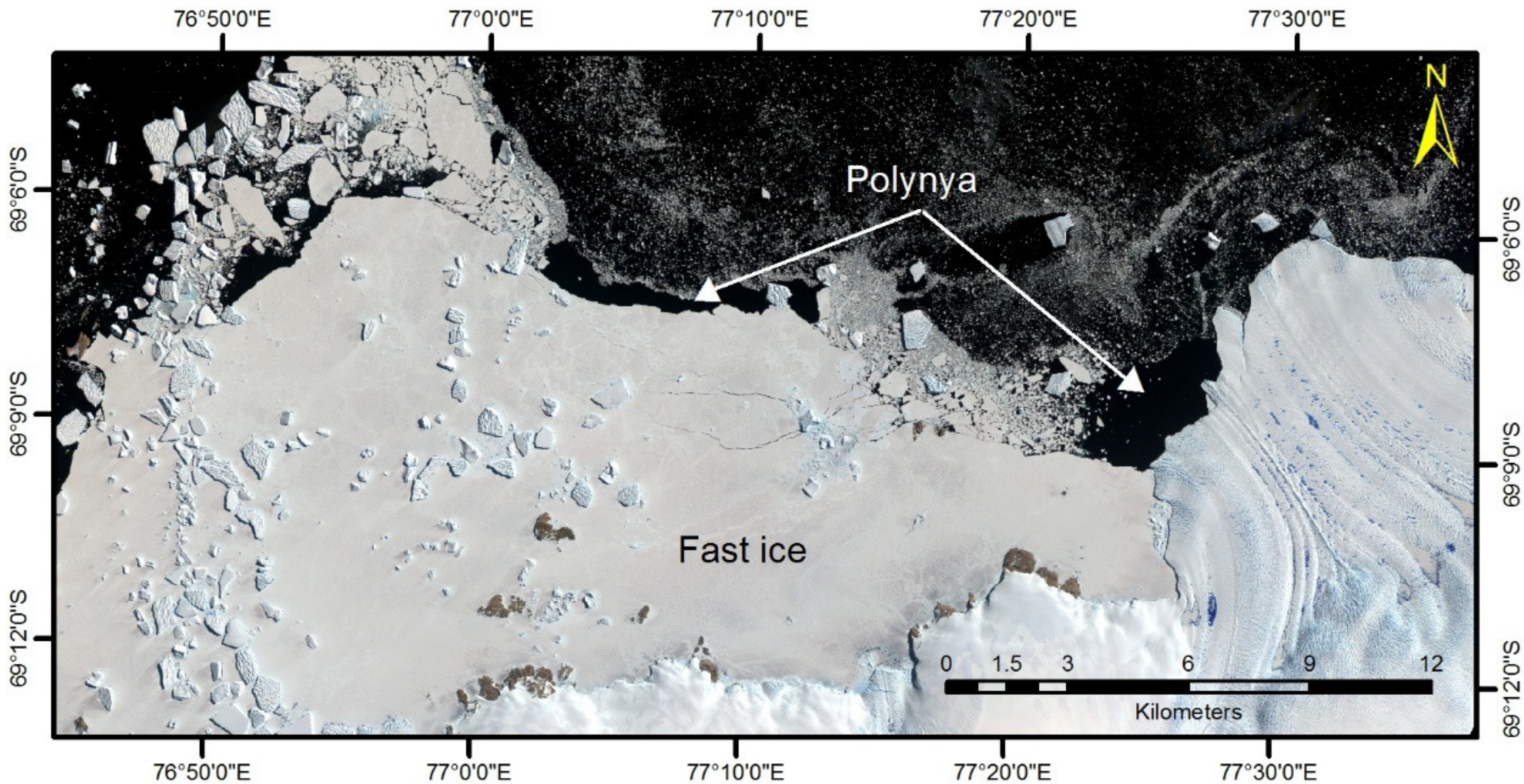


Figure 2.42: A satellite view covering large number of icebergs trapped into fast ice and polynya. (Resourcesat-2; LISS-IV; FCC432; 10 January 2016).

Figure 2.43: Lead propagation through the sea ice (05 January 2017; 36 ISEA).

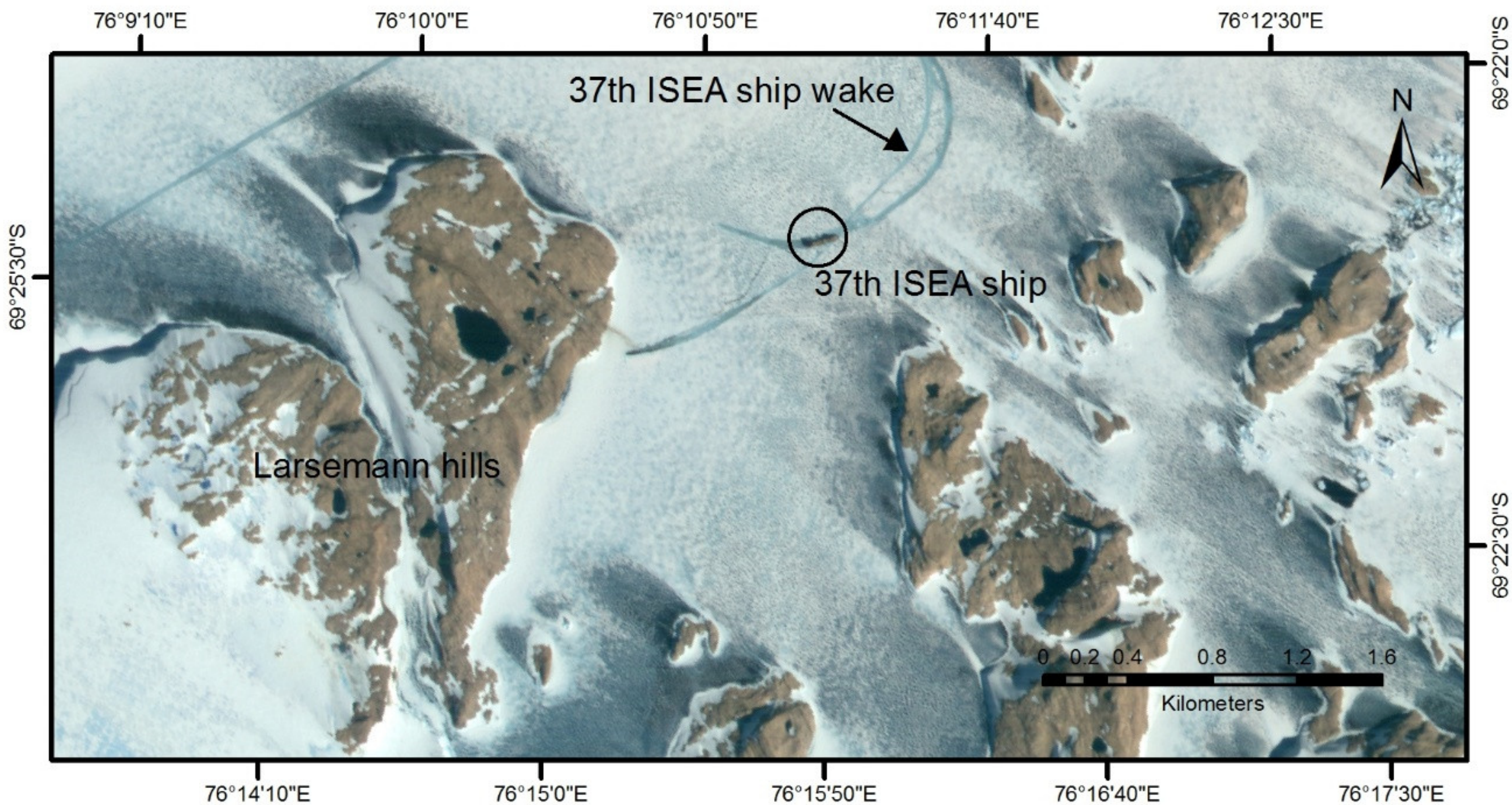


Figure 2.44: A satellite view covering 37th ISEA ship wakes approaching to Bharati Station. (Resourcesat-2; LISS-IV; FCC432; 06 February 2018).

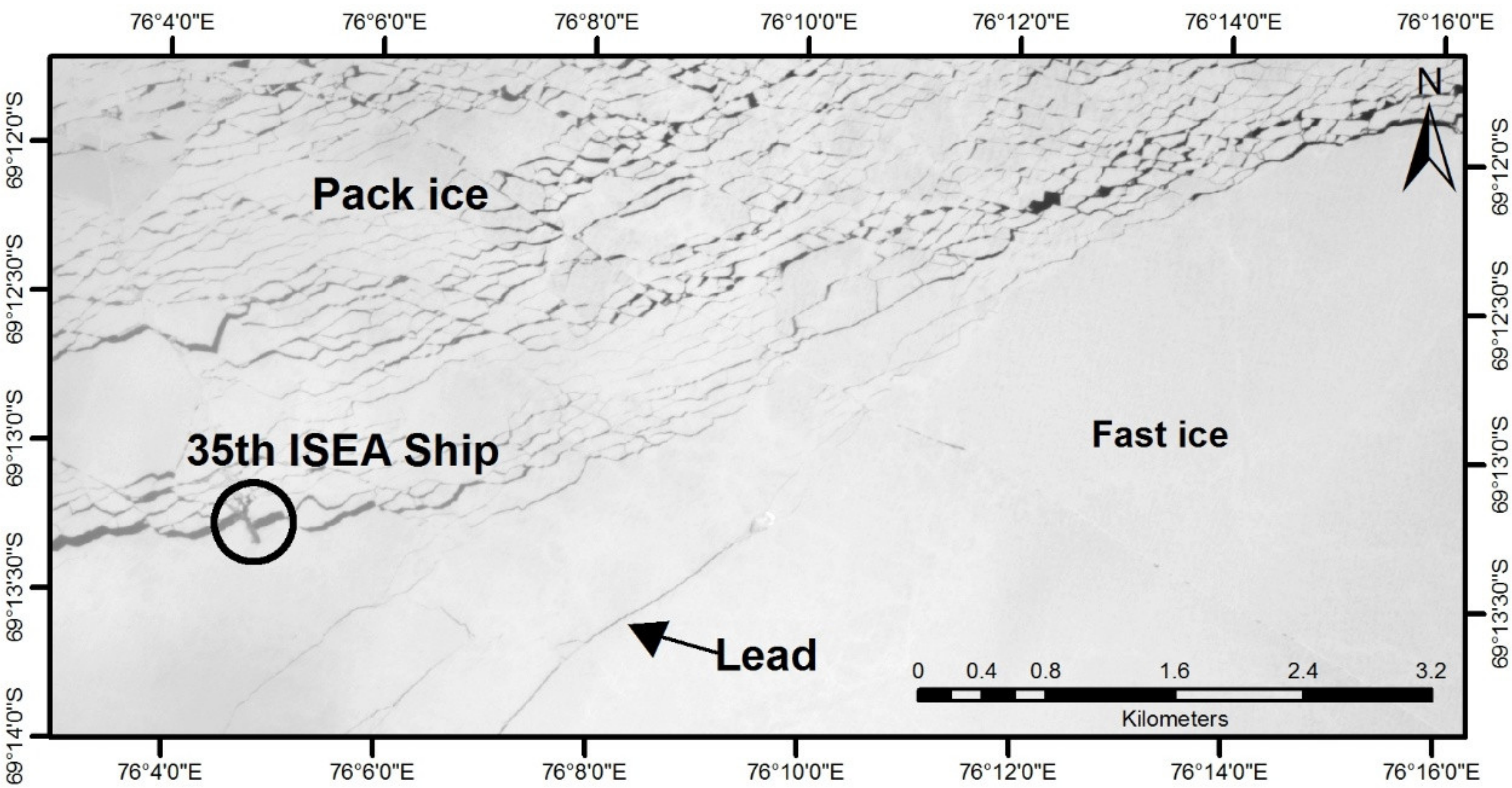


Figure 2.45: A satellite view covering location of ship, navigating in pack ice and lead during 35th ISEA. (Resourcesat-2; LISS IV; Band 2; 15 January 2016).

Figure 2.46: A large canvas of sea ice showing multiple linear fractures with varying widths making open ocean visible known as leads extended over several kilometres. Large number of sea ice melt ponds can be seen as we progress towards summer. (69^{0} 19’ 06’’ S, 76^{0} 04’ 20’’ E, 06 January 2017, 36 ISEA).

Figure 2.47: Ivan Papanin, ice class vessel surrounded by drifting large chunks of ice referred as pack ice zone. Presence of linear or straight opening in sea ice making open ocean visible referred as lead. (69^0 16' 44'' S, 76^0 07' 02'' E; 09 Jan 2016; 35 ISEA).

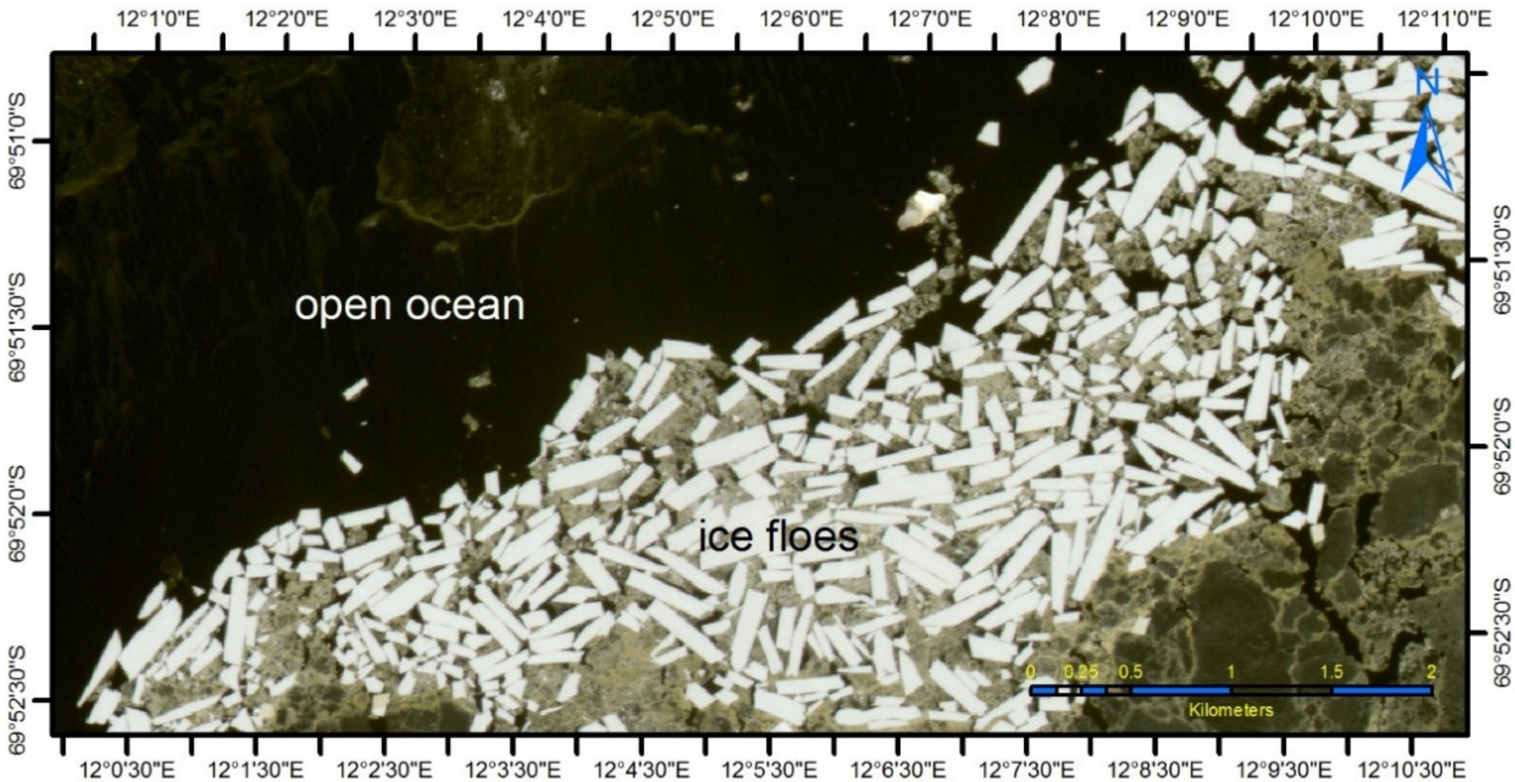


Figure 2.48: A satellite view covering large number of floes. (Resourcesat-2; LISS-IV; FCC432; 28 February 2015).

Figure 2.49: Medium concentration sea ice will be encountered as one moves further towards Antarctica. Floes of various size are visible in the field photograph. (66^0 16’ 03’’ S, 75^0 40’ 09’’ E; 22 December 2013; 33 ISEA).

Figure 2.50: Process of snow melting during day and refreezing during night over floe is visible in the field photograph. (69^0 08' 02'' S, 76^0 01' 15'' E; 24 December 2013; 33 ISEA).

3.0 Earth Observation Data Analysis

3.1 Remote Sensing of Polar Cryosphere: State of Art

As discussed earlier, major components of the polar cryosphere are sea ice floating over ocean, ice sheet grounded over continent and extended portion of the ice sheet or glaciers floating over ocean in the form of ice shelves or ice tongue. Sea ice type, area, concentration, thickness and transport are the important parameters that define the sea ice distribution, its dynamics and thermodynamics. Important ice sheet parameters include surface elevation, ice velocity, calving front, crevasses and rift structures. The ultimate goal of the polar cryosphere studies is to understand the role of polar ice cover in regulating the global ocean and atmosphere circulation and the rise in sea level. Considering the vast remote area and harsh environment, establishing large network of sites for in-situ data collection is rather impossible. Thus, remote sensing becomes the only viable tool for continuous monitoring in the Polar Regions. Since, the Arctic and the Antarctic are located in Northernmost and Southernmost regions of Earth, they face prolonged periods of darkness. Hence, microwave remote sensing is the most popular technology for scientists working in the field of polar ice applications and modelling.

3.2 Remote Sensing of Sea Ice

Sea ice is one of the most seasonally varying geophysical features on Earth. It covers 7% of the Earth's surface at the minimum and 13% at the maximum level. In simple words, sea ice can be considered as any form of ice found at sea and has originated from the freezing of seawater (below -1.8^{0} C temperature). One of the most important properties of sea ice is that it is less dense than the seawater and therefore it floats over the ocean surface. According to its stage of development, there are various types of sea ice. First-year ice is not more than one winter's growth, developing from young ice, with a thickness of 30 cm or greater while 'The old (multi-year) ice is defined as sea ice that has survived at least one summer's melt. Its topographic features are generally smoother than those observed over first-year ice. However, due to the harsh climate and the remoteness of the polar oceans, sea ice features are among the least understood regions of the planet. The thin sea ice layer over the ocean surface just accounts for the 0.1% of the Earth's permanent ice volume but covers the 70% of the ice areal extent.

3.2.1 Sea Ice Area and Concentration

A number of studies have been carried out for the assessment of sea ice concentration using passive microwave remote sensing techniques due to its all-weather and day-night sensing capability. Vyas et al. (2004) utilized the Oceansat-1 Multi-frequency Scanning Microwave Radiometer (MSMR) data for the mapping of month-wise sea ice extent in the Arctic. They found a marginal increasing trend in the Antarctic wide sea ice extent. Using the QuikSCAT scatterometer data, Oza et al. (2010c) found that some of the regions showed increasing trend, whereas some showed decreasing trend in the Antarctic summer sea ice cover during the period from 1999 to 2009. Based on Moderate Resolution Imaging Spectroradiometer (MODIS) time series data, Fraser *et al.* (2012) concluded that fast ice extent across the East Antarctic coast showed a statistically-significant (1.43±0.30% yr ^{1}) increase. Regionally, there is a strong increase in the Indian Ocean sector (20° E to 90° E, 4.07 ± 0.42% yr ^{1}), and a non-significant decrease in the Western Pacific Ocean sector (90° E to 160° E, 0.40 ±0.37% yr ^{1}). Among the most useful sea ice parameters derived from passive microwave data is sea ice concentration (Comiso *et al.*, 1997), useful to retrieve ice extent, ice area and the area of open water within the ice pack. Various ice types and the emissivity of water differ at different microwave frequencies and forms the physical basis for the retrieval of sea ice properties from microwave radiometer. Zwally et al. (1983) derived the Antarctic sea ice concentrations using radiative transfer equation using a simple mixing algorithm considering two end members, ice and water. They considered only one category of sea ice and assumed that brightness temperature varies linearly with ice temperature. Considering the presence of significant multi-year sea ice in the Arctic, Parkinson et al. (1987) proposed the formulation with three end members, ocean, multi-year ice (MYI) and first year ice (FYI) respectively. There are two known algorithms for the derivation of sea ice concentration using multi-channel, multi-polarised passive microwave radiometer data, namely, (i) National Aeronautics and Space Administration (NASA) Team algorithm and (ii) Bootstrap algorithm. Originally, NASA team algorithm was developed for Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) data (Calvalieri et al., 1984), subsequently modified for Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSMI) (Cavalieri *et al.*, 1991). The bootstrap technique was first proposed by Comiso (1995). Active microwave scatterometers have also shown potential to study the sea ice. Yueh *et al.* (1997) attempted sea-ice identification using dual polarized Ku-band scatterometer data. They found that the higher salinity and the reduced air bubble density cause the scattering by the first year ice to be dominated by surface scattering whereas the scattering from the multi-year ice is dominated by the volume scattering.

Remund and Long (1999) developed an automatic ice-ocean discrimination algorithm using NASA Scatterometer (NSCAT) data for the Arctic region. De Abreu *et al.* (2002) found that the retrieved ice edge successfully maps pack ice areas having ice cover higher than 70% but it fails in case of the areas having thin ice or ice with low concentration. Automatic identification of sea-ice edge and its validation using enhanced resolution QuikSCAT data has been carried out by Haarpaintner *et al.* (2004). As mentioned earlier, Scatterometer data has shown its potential in delineating the sea ice extent (Oza et al., 2010d; Rivas and Stoffelen, 2011; Rivas *et al.*, 2018; Haarpaintner *et al.*, 2004). Li *et al.* (2016) have demonstrated the potential of Chinese HY-2A Scatterometer for sea ice monitoring. Lindell and Long (2016) suggested that combining data from both active and passive sensors can improve the performance of MY and FY ice classification.

3.2.2 Sea Ice Thickness

Sea ice thickness estimation using remote sensing data is a tricky task. Optical remote sensors cannot provide any direct estimation of sea ice thickness. Active microwave sensors like Synthetic Aperture Radar also have limited scope in determining sea ice thickness. It is difficult to attain thickness information from passive microwave radiometry since the microwave emission from sea ice is mostly restricted to a layer of the top few centimetres, which depends on the wavelength of the radiation. Notwithstanding, previous work suggests that microwave radiometric signals carry information on ice thickness for thin ice. Generally, ice with a thickness <0.3 m is referred to as thin ice. It includes nilas (thickness <0.1 m) and young ice (0.1–0.3 m of thickness) according to the World Meteorological Organization (WMO) nomenclature. Troy *et al.* (1981) reported that the emissivity increases from nilas to young and to first- year ice (>0.3 m). Tucker et al. (1991) also presented similar results, while Eppler *et al.* (1992) summarized results from various field and laboratory experiments. It was observed that a polarization ratio and a related brightness temperature ratio between vertical and horizontal polarization correlate well with sea ice thickness. Algorithms are developed for classification of thin ice (Steffen, 1991; Cavalieri, 1994) and for estimation of thin ice thickness (Drucker *et al.*, 2003; Martin *et al.*, 2004; 2005). Naoki *et al.* (2008) examined the extent to which the relationships of thickness with brightness temperature and with emissivity hold for thin sea ice, (approximately <0.2–0.3 m), and how those relationships may arise from changes in brine characteristics through modification of dielectric properties near the ice surface. Altimeter data are in use for the retrieval of sea ice thickness for the thicker ice, generally with thickness higher than 0.7 m. The difference in the elevation of sea ice floe from surrounding ocean forms the basis for the retrieval of height of the floating part of sea ice, known as freeboard. Utilisation of SARAL/AltiKa altimeter data for the estimation of sea ice freeboard and thickness was demonstrated by various researchers (Joshi and Oza, 2018; Maheshwari et al., 2015a).

3.2.3 Sea Ice drift and advisory.

The measurements of sea ice motion started with ship's observations (the Nansen's expedition in 1893-96) and some manned drifting stations. Since the 1990's, the sea ice drift can be estimated from satellite data, with daily and global coverage of the polar oceans. In order to determine an ice cover displacement, surface patterns compatible in size with the sensor's spatial resolution and satellite repeat cycle must persist for several days. A major difference between satellite and buoys measurements is that buoys are representative of single point displacement while satellite sensor provides information over the entire footprint area. For limited time duration, demonstration, and/or local or regional studies, high spatial resolution satellite sensors have been used to estimate sea ice drift, for example use of Advanced Very High Resolution Radiometer (AVHRR) data (Emery et al., 1991), Seawinds/QuikSCAT enhanced resolution data (Haarpaintner, 2006) and Synthetic Aperture Radar (SAR) data (Kwok et al., 1990; Geiger and Drinkwater, 2005). The pattern and variability of Antarctic sea-ice drift in the Indian Ocean and Western Pacific sectors have been investigated by Heil and Allison (1999). They analysed the data from 39 satellite-tracked buoys, deployed during various seasons from the year 1985 to 1996 in the sea ice of the Southern Ocean, off East Antarctica between 20° and 160°E longitude. They found that the dominant features of the ice motion in the region are a westward drift parallel to the bathymetry near the Antarctic continent, a cyclonic circulation cell in Prydz Bay. As discussed by them, the oceanic circulation along the coast is generally barotropic and the ice drift is well correlated with bottom topography. They observed that the daily average ice-drift speed was 0.23 ms ^{1} (19.8 km d ^{1}) in the westward flow, with considerable spatial and temporal variability. The eastward flow averaged around 0.17ms ^{1} (15.1 km d ^{1}). Safer sailing through ice covered ocean requires integrated sea ice information. Safe shipping depends on a number of factors related to sea state, weather conditions and ship's own characteristics. The ship routing for a scientific expedition may differ a lot than that from a cargo ship and is a little more complicated due to an additional factor of achieving scientific objectives. Research Vessels or ships on a scientific mission may not necessarily follow the shortest route or the most economic route with least fuel consumption because of the scientific objectives / targets that are to be met. Navigation in Polar Regions through sea ice is perhaps the most tedious task and requires a lot of extra information on sea ice condition for routing through path of least resistance. Continuous processes of sea ice melting, freezing and drifting warrants near real time information on sea ice condition. Traditional ship routing does not provide adequate real time information on sea ice status. The availability of remote sensing data over ocean offers an opportunity to derive and use near real time information needed for ship routing (Rajak et al., 2011b, Rajak et al.,2015). Attempts have been made to develop an algorithm and to numerically model the problem of ship routing (Tsou and Cheng, 2013; Mannarini *et al.*, 2013; Al-Hamad *et al.*, 2012; Shiotani *et al.*, 2010; Kotovirta *et al.*, 2009). A prototype Decision Support System for an operational ship routing using time-dependent meteoro-oceanographic fields was presented by Mannarini *et al.* (2013). Another prototype system for optimizing routes through the ice field was presented by Kotovirta *et al.* (2009). Vlachos (2004) presented a method for manipulating the POSEIDON system, forecasts for the Greek seas and for producing optimal routes for small and medium size ships. Shigeaki *et al.* (2010) created a numerical navigation system for a small ship sailing in coastal waters with Simulating WAves Nearshore (SWAN), Resource Investment Optimization System (RIOS) and Manoeuvring Modelling Group (MMG) models which concluded that it is possible to achieve an optimum route by numerical simulation of winds, waves, and tidal currents. The basic isochrone method was attempted to obtain an optimal route on the basis of the dynamically changing weather, which could be forecasted by the coupled atmosphere wave-ocean model (Zhang and Huang, 2007).

3.3 Remote Sensing of Ice Sheet, Ice Shelf and Glacier

Figure 3.1 shows a schematic diagram showing polar cryospheric features and their interaction with ocean and atmosphere. Ice sheet is the continent-wide cover of very thick layer of ice. Ice flowing from centre to outward direction towards the ocean adds fresh water into the ocean leading to the sea level rise. Ice shelf is the extended portion of ice sheet floating over an ocean. At many places around Antarctica, ice shelves extend almost 250 km or more over the ocean. An ice shelf acts as a sensitive indicator of climate change. The degree to which ice sheets and glaciers are changing is reported as “mass balance” and is measured by assessing the net inputs and net losses. The total of precipitation, accumulation, ablation, melting, run-off, sublimation/ evaporation and iceberg calving needs to be investigated over the course of each year to compute the net balance either as a gain in mass (positive) or negative loss in mass (negative). There are indications of the rapid changes taking place particularly around the margins of the Greenland and the Antarctic Ice Sheets (Oza et al., 2011d; Rignot et al., 2006).

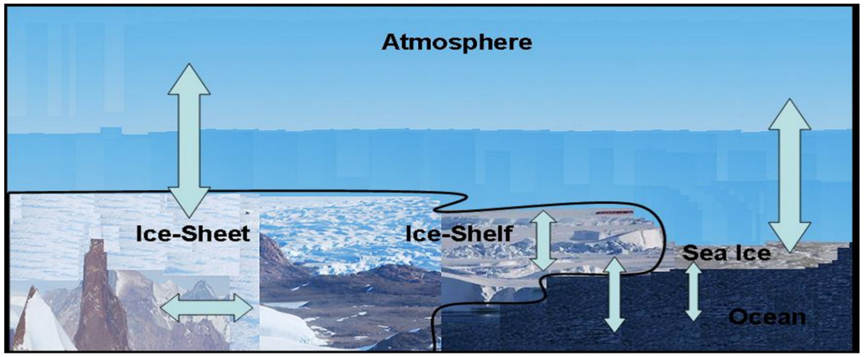


Figure3.1: Schematic diagram showing polar cryosphere elements and their interactions.

3.3.1 Estimation of Surface Elevation and Change Detection

Digital Elevation Models (DEMs) of Antarctica are important datasets required for the planning of fieldwork, numerical ice sheet modelling and the tracking of ice motion. Measurements of ice sheet topography are needed as a boundary condition for numerical projections of ice dynamics and potential sea level contributions. A new Digital Elevation Model of Antarctica was derived from CryoSat-2 altimetry (Slater *et al.*, 2017) by carrying out spatio-temporal analysis of data acquired between July 2010 and July 2016. The two main approaches (Xiaoli *et al.*, 2016) to derive elevation changes over the ice sheet are (i) crossover method (Wingham *et al.*, 1998; Davis *et al.*, 2004) and ii) repeat track method (Legresy *et al.*, 2006). Davis *et al.* (2004) used a crossover method and observed a strong negative trend in elevation change of West Antarctic glacier outlets consistent with increased basal melting at glacier grounding lines caused by ocean thermal forcing. Helm *et al.* (2014) derived new DEMs, elevation change maps (using the repeat track method) and volume change estimates for both Antarctic and Greenland ice sheets using CryoSat-2 (Ku band) data from January 2011 to 2014. These elevation changes, when compared to ICESat (2003-2009) data, revealed that in West Antarctica volume loss has increased by a factor of 3, which is partly compensated by anomalous thickening in Dronning Maud Land, East Antarctica. ICESat data acquired between 2003 and 2008 over the Antarctic Ice Sheet indicated that snow accumulation exceeded loss from ice discharge by 82±25 Gt a^{-1}. Their study found positive mass balance in East Antarctica and negative mass balance in the Antarctic Peninsula and West Antarctic near-coastal region (Zwally et al. 2015). Utilisation of SARAL/AltiKa altimeter data for the assessment of elevation change was demonstrated by Suryawanshi et al. (2019).

3.3.2 Estimation of Ice Sheet and Glacier Velocity

During the last decade, ice velocity mapping at continental scale (Joughin *et al.*, 2010; Rignot *et al.*, 2011; 2012) has allowed major advances in the study of Polar Regions by providing complete and accurate observations of the complex flow pattern of the ice sheets from coastal regions to the deep interior. This has considerably enhanced our understanding of the physics of ice flow, the estimation of the mass balance of ice sheets, and their influence to sea level. Satellite borne observations in particular have made it possible not only to map ice motion but also to detect significant changes in ice dynamics over the last 40 years.

3.3.3 Assessment of Surface Melting

Antarctic ice sheet surface melting can regionally influence ice shelf stability, mass balance, and glacier dynamics, in addition to modulating near-surface physical and chemical properties over wide areas (Trusel *et al.*, 2012). Ice shelves over the Western Antarctica have shown consistent surface melting and East Antarctic ice shelves are prone to warming (Trusel *et al.,* 2012; Oza *et al.*, 2015; Bothale *et al.*, 2015; Wang *et al.*, 2016; 2018). Hence, continuous monitoring of Antarctic ice is the key component to understand the climate change and the only viable tool for the continuous monitoring is utilisation of microwave remote sensing data due to its cloud penetration and all season observation capabilities. Passive microwave radiometer data (Ridley, 1993; Kunz and Long, 2006; Liu *et al.*, 2006; Picard and Filly, 2006; Trusel *et al.*, 2012; Wang *et al.,* 2018; Tedesco, 2009) and scatterometer data (Oza *et al.,* 2011d; 2015; Bothale *et al.*, 2014; 2015) have been used widely for the monitoring of surface snowmelt over Antarctic ice shelves.

3.3.4 Changes Around Ice Margins

The changing position of the margin of the Antarctic ice sheet, both floating and grounded, is currently being mapped as part of the United States Geological Survey (USGS) Coastal-change and Glaciological Maps of Antarctica programme (Williams and Ferrigno, 1998). As part of this programme, a comprehensive time-series of ice front changes around the Antarctic Peninsula was compiled from sources dating from 1940 to 2002 (Cook *et al.*, 2005). The time-series further reveals changes in glacier, ice shelf and other ice fronts and is published as hardcopy maps with detailed accompanying reports (Ferrigno *et al.*, 2006; 2008) and digital data (Scientific Committee on Antarctic Research, 2005).

3.4 Studies at SAC

Remote sensing of polar ice was conceptualized at SAC during the planning phase of ISRO's Oceansat-1 utilization programme in 1998. The studies of polar ice characteristics were initiated using the brightness temperature data from space-borne SMMR and SSM/I passive microwave radiometers. The activities received a boost after the launch of Oceansat-1 carrying MSMR on board, in May 1999. Oceansat-1 was placed in a near circular, polar, sun-synchronous orbit at an altitude of 720 km. The MSMR operated at (6.6 GHz, 10.65 GHz, 18 GHz and 21 GHz), having both, vertical and horizontal polarizations.

3.4.1 Sea Ice Studies

Oza et al. (2008; 2010b) presented a review on the polar sea ice observations and analysis using space-borne passive microwave radiometer region from MSMR. Vyas and Dash (2000) \ concluded that the MSMR has high potential for the study of polar ice features. SAC jointly with National Centre for Polar and Ocean Research (NCPOR) centre carried out an extensive study and published an atlas of Antarctic sea ice using Oceansat-1 MSMR passive microwave data (Vyas et al., 2004). The atlas of sea ice maps has served as a useful reference source for researchers in India and abroad. The large scale Antarctic features captured by MSMR were investigated and reported in Vyas et al. (2001). Dash et al. (2001) and Vyas et al. (2001) demonstrated the capability of MSMR in capturing the sea-ice distribution over the Antarctic Circumpolar Sea, as well as land-ice signatures matching with some known geomorphological features on the continent of Antarctica. Bhandari et al. (2002) further discussed the results obtained from microwave remote sensing data for sea ice studies in the Antarctic. Oza et al. (2008) carried out five-year moving trend analysis of sea ice concentration and demonstrated that ice concentration is consistently declining in the Arctic. They have also demonstrated the use of long-term database of melt- onset dates to identify the regions, which are prone to ice-free condition in subsequent summers. Indian studies on advances in Antarctic sea ice were discussed in details by Oza et al. (2011a; 2012a; 2013; 2017) and Rajak et al. (2014; 2015a; 2015b; 2015c). Investigation of linkage between changes observed in the Polar Regions with that observed over the tropical area is still a grey area for research. Kumar et al. (2017; 2018) have attempted to address this teleconnection topic using MITgcm sea ice modelling. Most of the studies presented in this chapter were carried out under PENGWIN (Polar Environment processes, Global Warming effects and their Indian teleconnection) theme of Meteorology and Oceanography – phase III (MOP-III) program of ISRO. Rajak et al. (2014a; 2015b) discussed the result of comparison of MITgcm based modelled sea ice concentration with the sea ice concentration product obtained from National Snow and Ice Centre (NSIDC) (Figure 3.2). The simulated sea ice area trends were quite similar to satellite derived area trends; however, model overestimated the rate of decrease of sea ice area. Sea ice monitoring capability of Scatterometer launched by India were utilised by Oza et al. (2011d; 2012a; 2012b; 2013) and Singh et al. (2014a; 2014b; 2014c; 2018). Inter-comparison of OSCAT and QuikSCAT Ku-band backscatter signatures for polar sea ice was attempted by Oza et al. (2010a). An attempt was also made to estimate the sea ice concentration using OSCAT (Ku-band) and ASCAT (C-band) Scatterometer data (Singh et al. 2014c). In the study carried out by Oza et al. (2010d), various values of Active Polarisation Ratio (APR) ranging from (-0.01) to (-0.04) at 0.005 interval were used to arrive at the optimum APR threshold for sea ice detection in the Arctic and the Antarctic regions. The recent work carried out by SAC using SCATSAT-1 Scatterometer is shown in Figure 3.4. Oza et al. (2009a; 2009c, 2010c; 2012a) have discussed the trends in sea ice during summer and winter of the Arctic and Antarctic (Figure 2.6). Statistically significant declining trend in majority of the Arctic Ocean was observed during the Northern summer. However, in the Antarctic, anomaly of positive and negative trends was observed. Data for the monthly sea ice trends is available on the VEDAS web-site (http://vedas.sac.gov.in). Trends observed are also supported by the findings from long term analysis of sea surface temperature data (Singh et al., 2012; 2013, Maheshwari et al., 2012a; 2012b; 2013). Some preliminary studies have also been taken-up for the retrieval of sea ice melt-onset dates (Singh et al., 2014a); long-term analysis of melt-onset dates (Oza et al., 2011b) and sea ice–albedo feedback analysis (Srivastava et al. 2010; Das et al., 2011a). Singh et al. (2011) have also developed an algorithm for the estimation of thin sea ice thickness (Figure 2.7) in the Arctic polynya from 89 GHz channel data of AMSR-E and found that the algorithm is valid up to the sea ice thickness of 10 cm. Demonstration of altimetry peaks at sea ice (Oza et al., 2011c) was published online on the AVISO website (http://www.aviso.altimetry.fr/es/idm/2011/jul-2011-altimetry-peaks-at-sea-ice.html). They have studied the sea ice extent using altimeter data of 2009 and 2010 for the investigation of year-to-year variations (Figure 3.7). Scatterometer derived sea ice extent of 2009 was also compared with altimetry-deduced sea ice cover for the same year and it was found that both are closely following each other. Maheshwari et al. (2014;2015b) demonstrated the first use of SARAL/AltiKa Ka-band altimeter data for the estimation of sea ice freeboard (Figure 3.8).

Table3.1: List of Indian sensors utilized and their specifications.

Sr. No.	Satellite	Sensor	Characteristic			Potential Applications
1	ResourceSAT-2/2A	AWiFS	Band 2/Green	0.5-0.59 µm		1.Polar ice albedo 2.Sea ice advisory
			Band 3/Red	0.62-0.68 µm		
			Band 4/NIR	0.77-0.86 µm		
			Band 5/SWIR	1.55-1.70 µm		
			Spatial resolution	56 m		
2	ResourceSAT-2/2A	LISS-III	Band 2/Green	0.5-0.59 µm		1.Polar ice albedo 2.Sea ice advisory
			Band 3/Red	0.62-0.68 µm		
			Band 4/NIR	0.77-0.86 µm		
			Band 5/SWIR	1.55-1.70 µm		
			Spatial resolution	23.5 m		
3	ResourceSAT-2/2A	LISS-IV	Band 2/Green	0.5-0.59 µm		1.Polar ice albedo 2.Sea ice advisory 3. Change around ice margins
			Band 3/Red	0.62-0.68 µm		
			Band 4/NIR	0.77-0.86 µm		
			Spatial resolution	5.8 m		
4	RISAT-1	RISAT-1	Operating Mode	Azimuth	Range	1.Mosaic of Polar Regions 2. calving front delineation 3. Estimation of ice sheet and Glacier velocity
			HRS	1 m	0.67 m	
			FRS-1	3 m	2 m	
			FRS-2	3 m	4 m	
			MRS	21-23 m	8 m	
			CRS	41-55 m	8 m	
5	SARAL	AltiKa	Ka band : 35.75 GHz			1.Estimastion of sea ice thickness 2. Estimation of ice sheet elevation and change detection
6	SCATSat-1	OSCAT-2	Ku band : 13.515 GHz			1.Assessment of surface Melting 2. sea ice extent

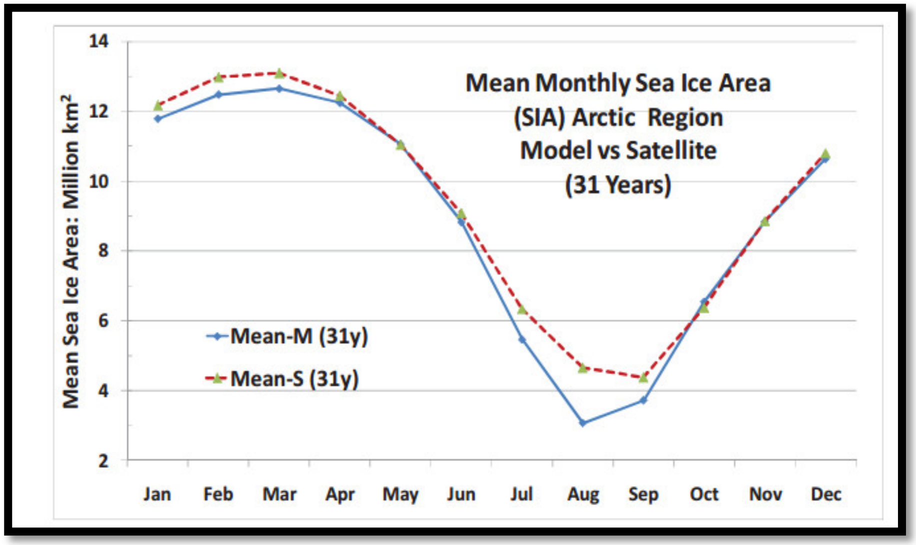


Figure 3.2: Comparison of MITGCM derived sea ice concentration with PMR based concentration products.

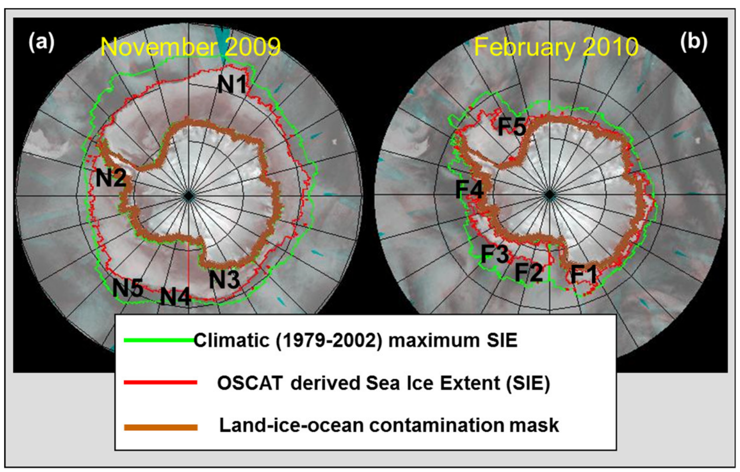


Figure 3.3: SIE derived using 10-day 12.5km gridded OSCAT data (a) November 2009 and (b) February, 2010.

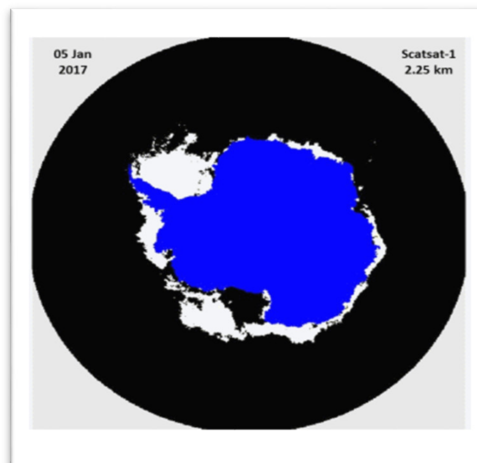


Figure 3.4: SCATSAT-1 derived sea ice extent (Source: http://vedas.sac.gov.in).

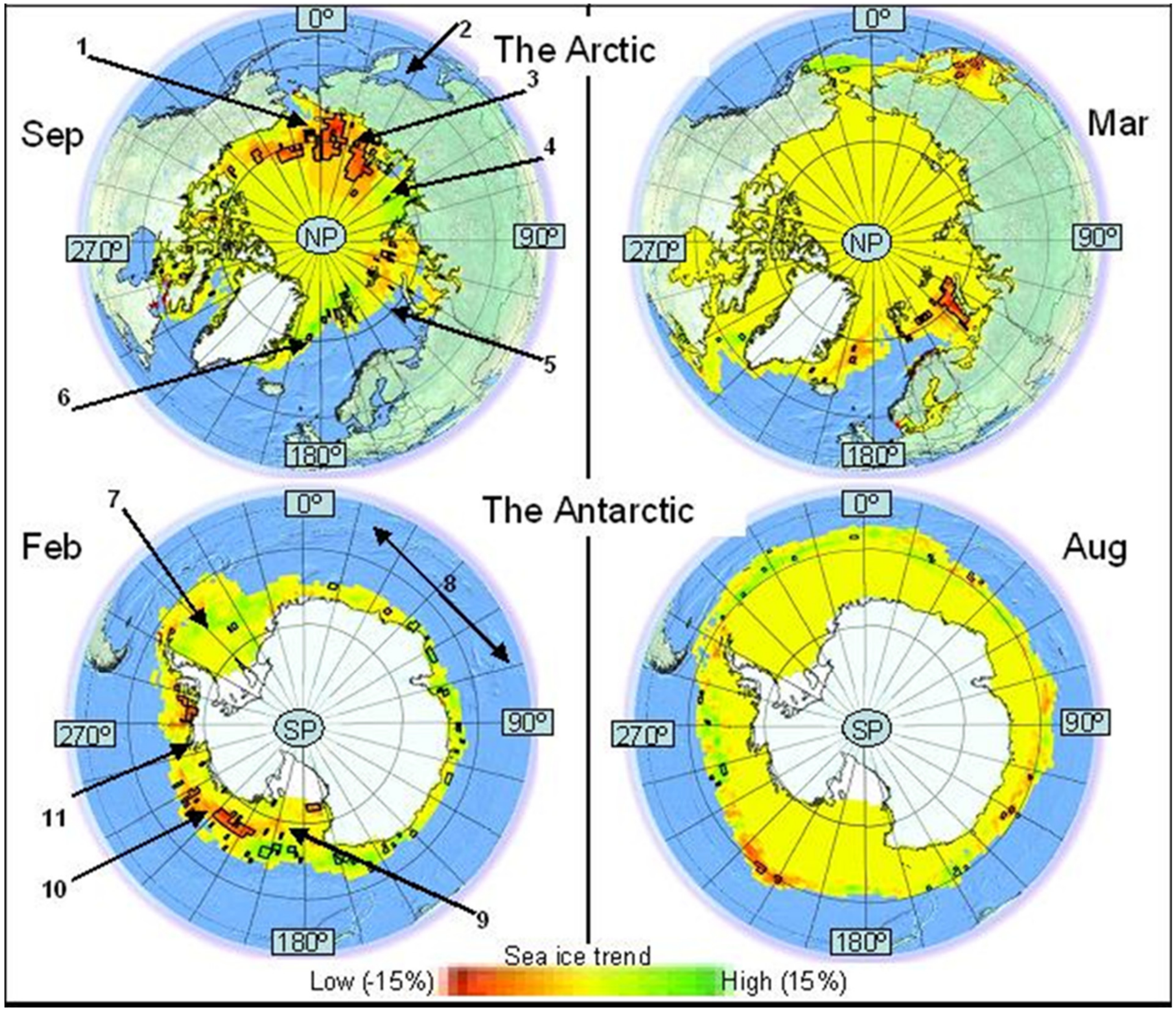


Figure 3.5: Decadal (2000-2009) polar sea ice trends derived using scatterometer data over various polar seas (1) Chukchi (2) Okhotsk (3)East Siberian (4)Laptev (5)Barents (6)East Greenland (7)Weddell (8)Indian (9)Ross (10)Amundsen (11)Bellingshausen.

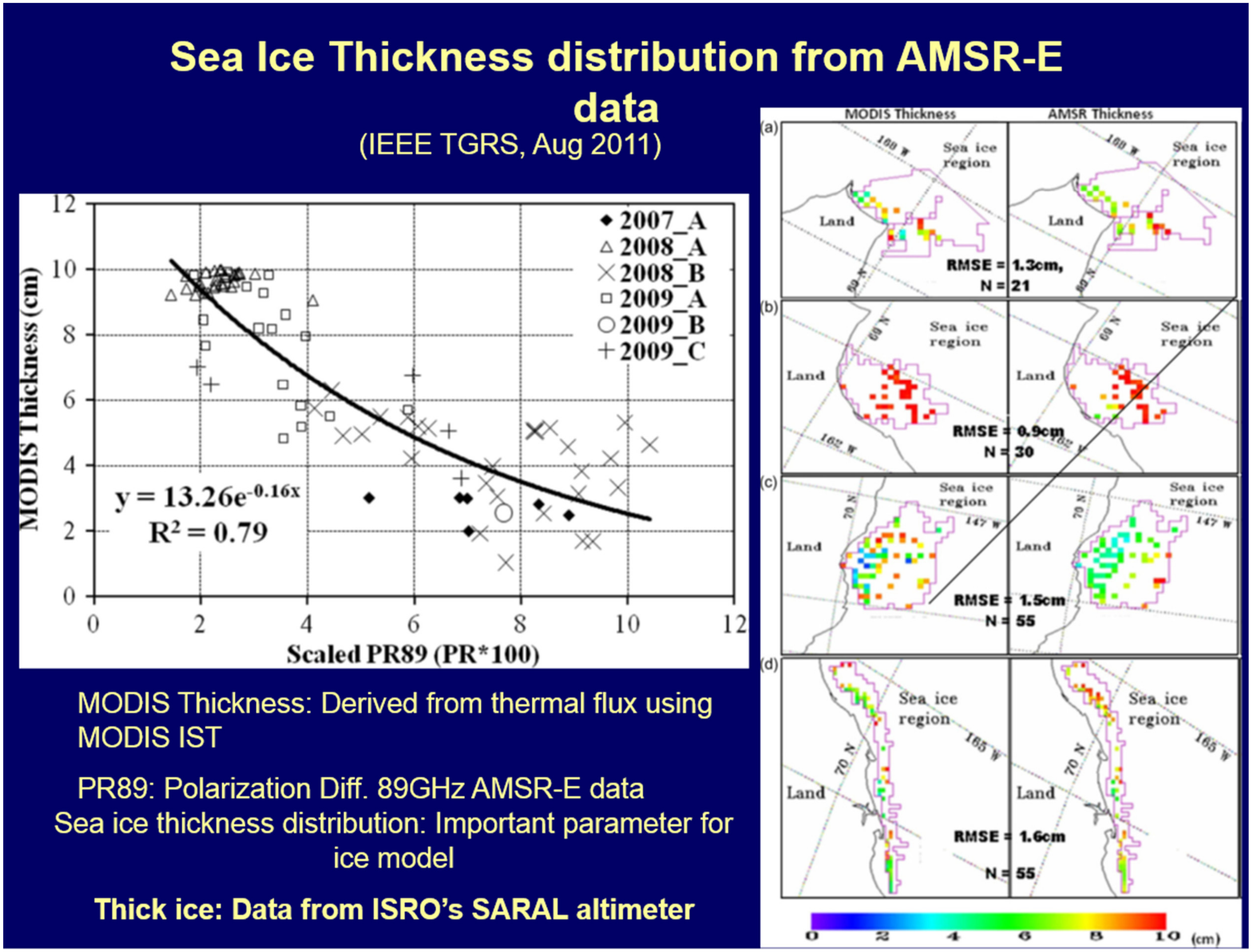


Figure 3.6: Thin sea ice thickness in Arctic polynya derived using AMSR-E data.

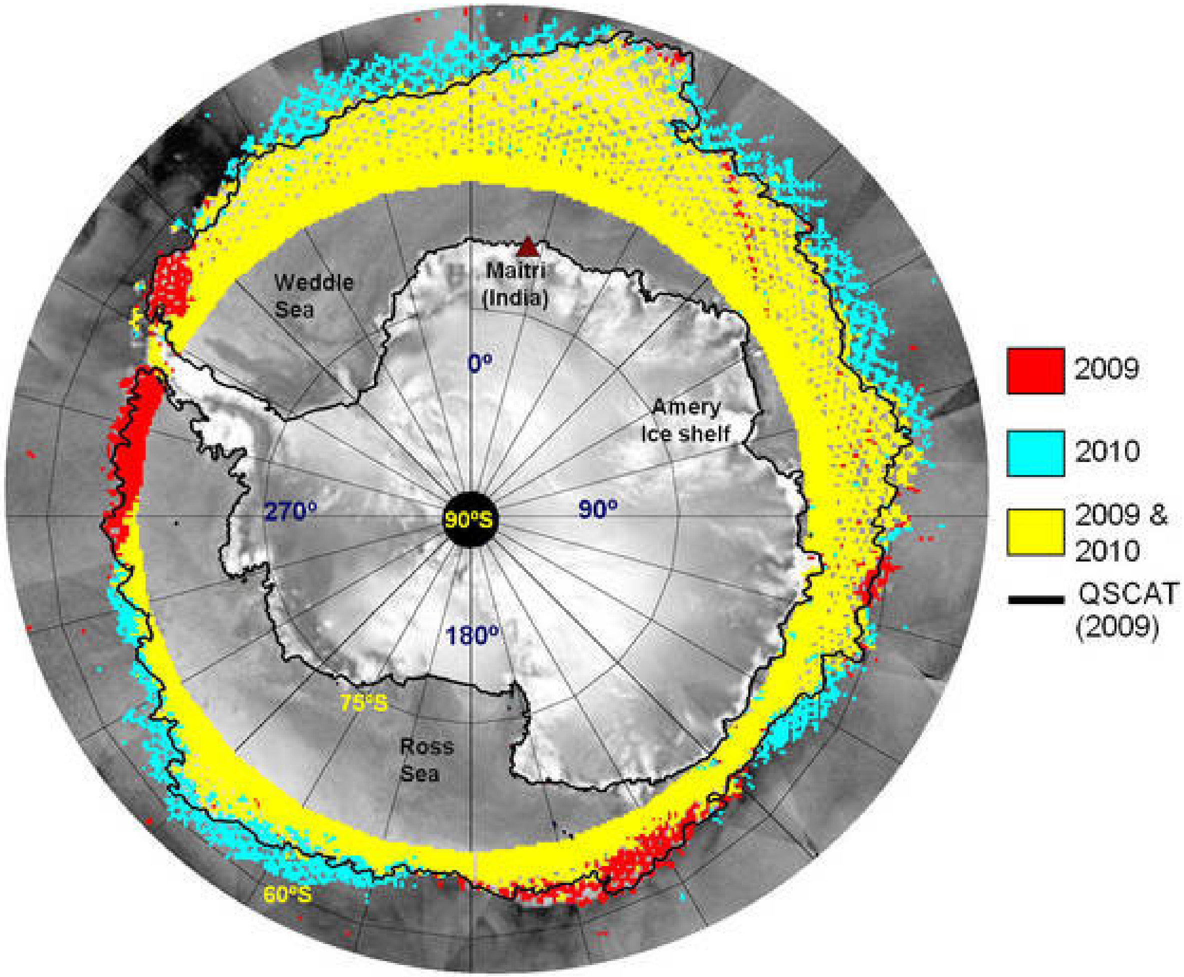


Figure 3.7: Sea ice cover deduced from altimetry echo shapes for the austral winter of 2009 and 2010 (yellow sea ice cover for both winters, red only 2009, blue only for 2010). Source: https://www.aviso.altimetry.fr/es/news/idm/2011/jul-2011-altimetry-peaks-at-sea-ice.html.

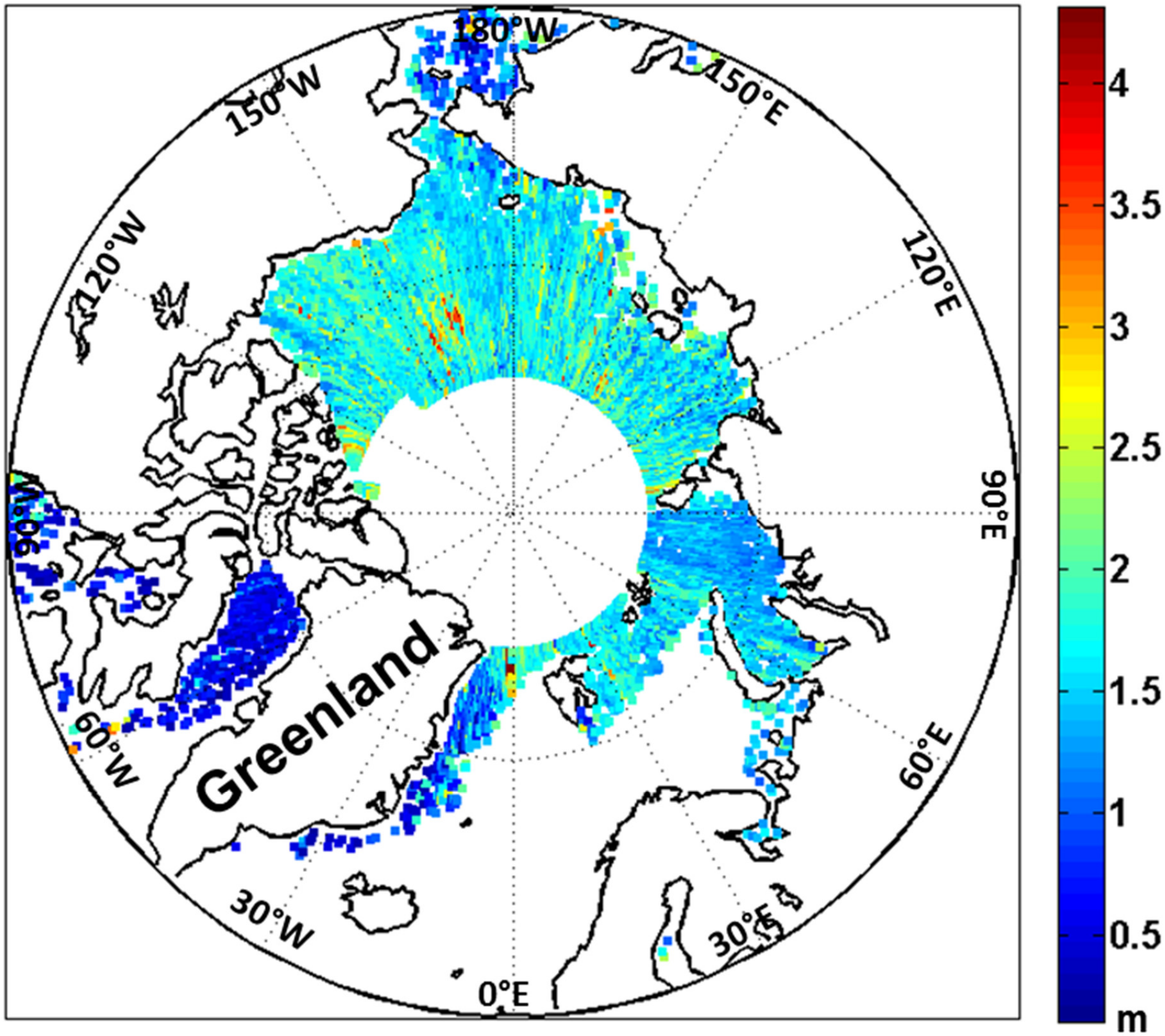


Figure 3.8: Freeboard derived using SARAL/AltiKa in the Arctic region for the spring season 15 March -15 April, 2013.

An attempt was made (Gupta *et al.,* 2016; Maheshwari *et al.,* 2015b) to derive sea ice freeboard from Ka-band Altimeter (SARAL/AltiKa) data. Maheshwari *et al.* (2015b) studied sea ice freeboard in the Arctic region using AltiKa data for the spring season from 15 March to 15 April 2013 (Figure 3.8) and autumn (15 September –15 October 2013) period. A waveform template matching technique was employed for classification of leads and floe pixels. The estimated sea ice freeboards were found in close agreement with "Operation Ice Bridge quick look" freeboards (RMSD 0.30 m). The differences between the two freeboards were largely due to snow layer over sea ice (RMSD 0.8). The estimated freeboards were of the order of 0.08–0.15 m during the two seasons. Maheshwari *et al.* (2015a) have also tried to demonstrate how to derive sea ice thickness using AltiKa derived freeboard. Joshi and Oza (2018) have suggested an improved procedure for estimation of sea ice thickness from AltiKa altimeter waveform data as shown in figure 3.9. Estimation of thickness in the polynya region, where the effective thickness is very low, can also be used for safer ship navigation. We can also observe (figure 3.10) one obvious phenomenon that fast ice is much thicker than marginal sea ice, as fast ice is supported by coastal ice shelf/glacier for deposition and growth both. Moreover, fastened ice does not come into the contact of warmer ocean. Attempts were made for characterisation of sea ice and ice sheet features by using the AltiKa altimeter data (Das *et al*., 2011b; Oza *et al*., 2011c; 2014a; Raj Kumar *et al*., 2017). Singh *et al*. (2015a; 2015b) have demonstrated the improved characterisation by concurrent use of AltiKa with OSCAT scatterometer and SSMIS passive microwave radiometer data.

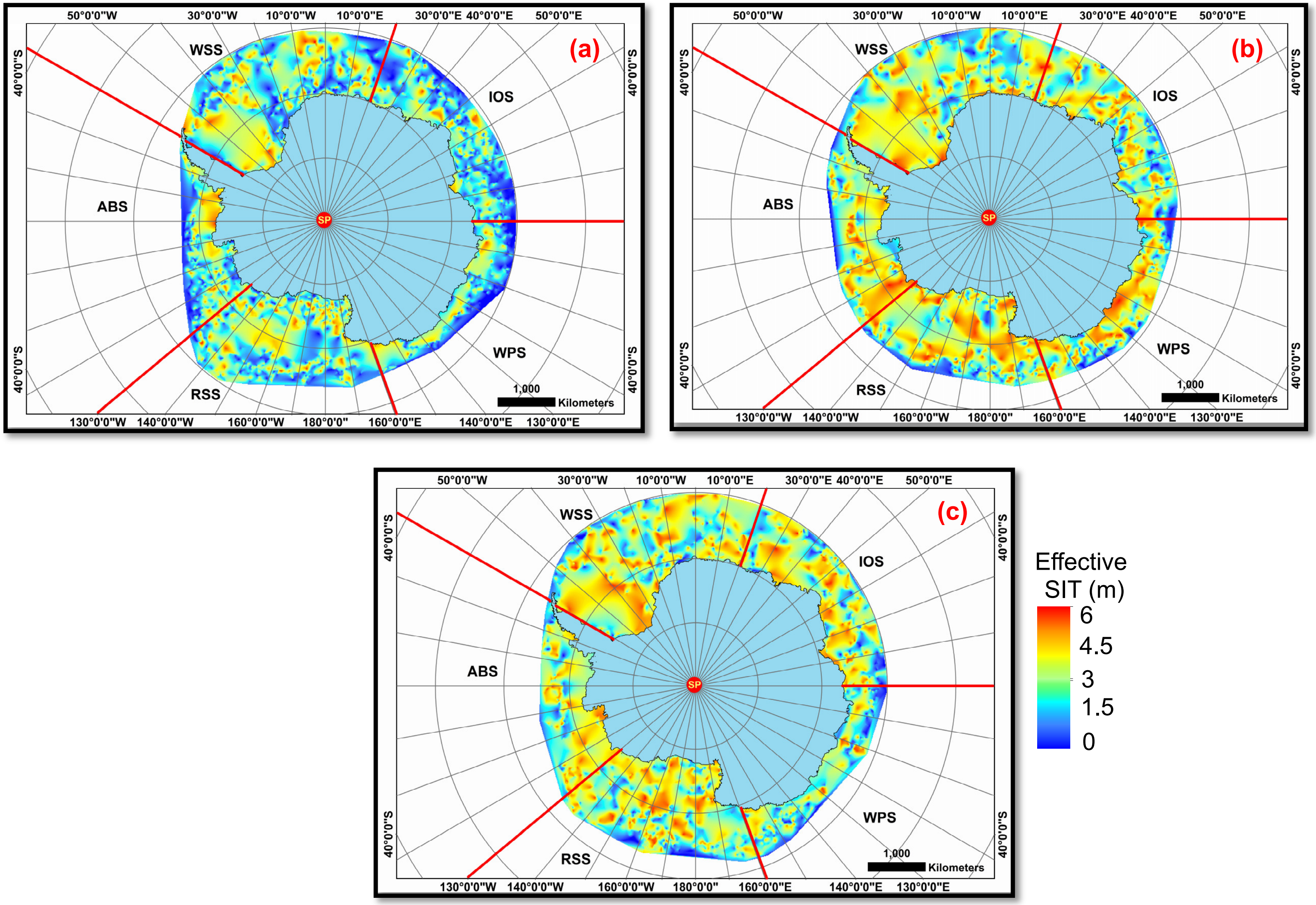


Figure 3.9: Map (a), (b) & (c) show sea ice thickness images for quarter-4 (Oct-Nov-Dec) for 2016, 2017 and 2018 respectively at spatial resolution of 10 km.

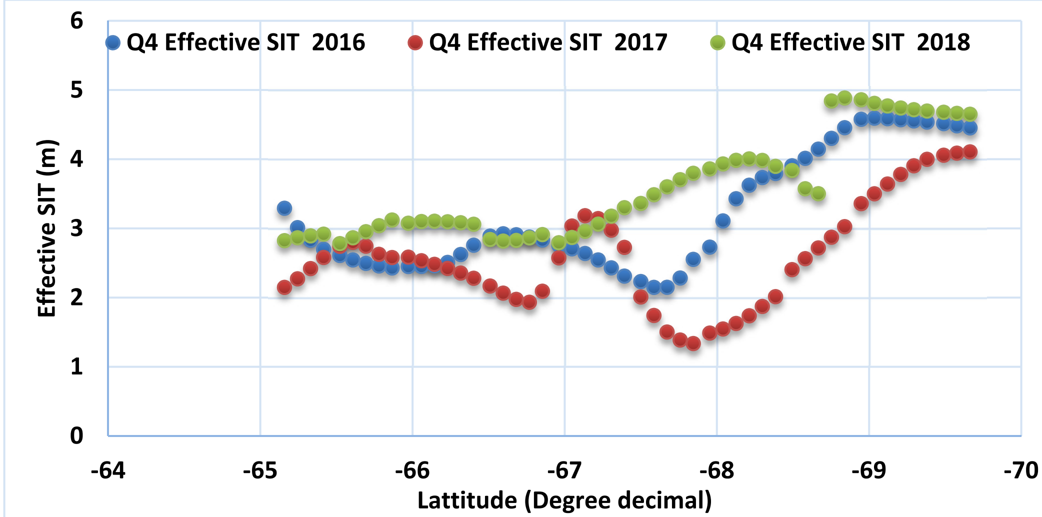


Figure 3.10: Transect profile of sea ice thickness.

3.4.2. Continental Ice & Ice Shelves Studies

Oza *et al.*, 2017b have demonstrated the use of SARAL/AltiKa Ka-band altimeter data for the generation of ice sheet DEM (Figure. 3.11). Elevations data are regularly being generated and available on the web portal of SAC (http://vedas.sac.gov.in). Derived 10km gridded elevation image is 3x3 median filtered image of 4000 Hz. The footprint size is ~2 km for the flat surface with along-track spacing of 175 m for a 40 Hz dataset (Remy *et al.*, 2014). Details of the SARAL/AltiKa Level-2 product formats are provided in the handbook (SARAL/AltiKa product handbook, 2013). Changes in surface elevations of Polar Ice Sheets are the result of changes in ice dynamics and surface mass balance. Suryawanshi *et al.* (2017a; 2017b; 2019) utilised the SARAL/AltiKa altimeter data for the assessment of change in surface elevations over Antarctic ice sheet (Figure. 3.12). They presented intra-annual and inter-annual elevation changes over the Antarctic ice sheet using the AltiKa radar altimeter's 40 Hz geophysical data record products for the2013-2016. Slope correction was applied on the elevations using a Digital Elevation Model (DEM) available from NASA's Ice, Cloud and land Elevation Satellite (ICESat). Comparison of elevations from AltiKa and ICESat DEM yielded correlation, bias and root-mean-square-deviation values of the order of 0.99, -2.88 m and 23.04 m, respectively, indicating the first-level accuracy of a former dataset. Further comparison of Airborne Topographic Mapper dataset with AltiKa derived elevation yielded 0.4 m root-mean-square-deviation over a part of Vostok Subglacial Lake. Suryawanshi *et al.* (2018) discussed the utilisation of AltiKa data for the assessment of ice shelf grounding zone. Grounding zone is the buffer lie beyond which the ice sheet extends over ocean from the continent.

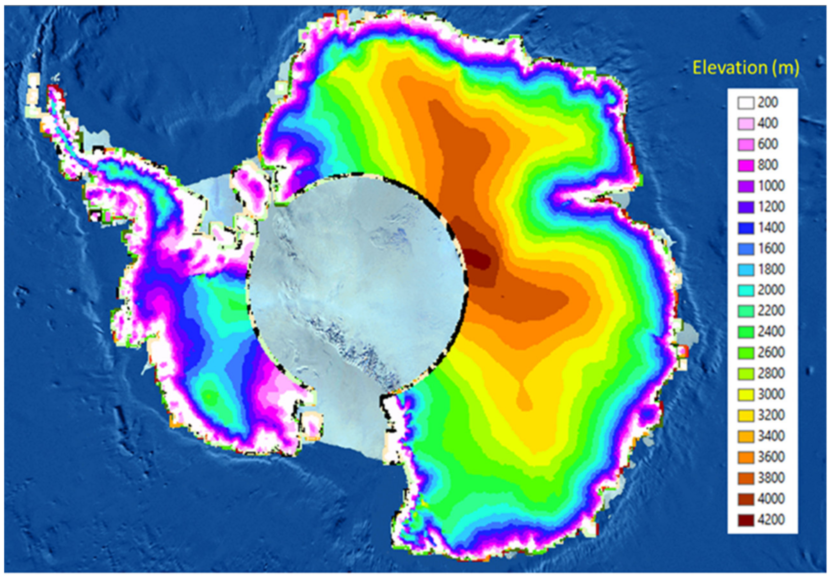


Figure 3.11: Surface height classified at 200m interval derived using AltiKa data for winter season 2013-14 (Cycle-13, 14, 15).

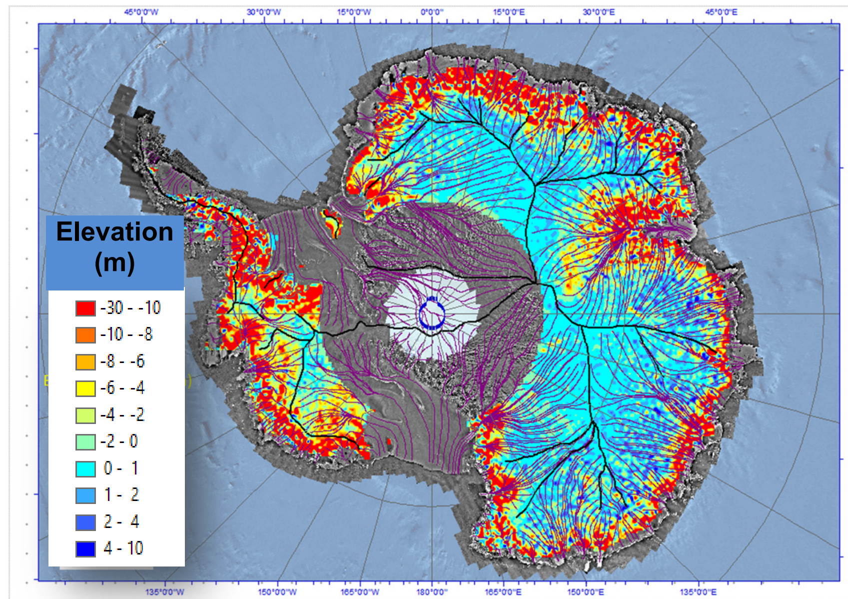


Figure 3.12: Elevation change indicating loss of ice mass observed during one decade between 2003-05 and 2013-16. Thin and thick black lines are Ice flow and ice divide lines obtained from Radarsat Antarctic Mapping Project dataset.

Ice velocity is one of the important parameter in the glaciological studies. The Western part of Antarctica is constantly changing and the two important glaciers of Western Antarctica region are Pine Island Glacier and Thwaites Glacier. Darji *et al*. (2017) presented the surface ice velocity of the Pine Island and Thwaites Glacier using Moderate Resolution Image Spectroradiometer (MODIS) data between 2001 and 2017 (Figure. 3.13). They derived the ice velocity using Normalised cross correlation method based feature tracking method. The derived surface velocity of Pine Island Glacier ranges between 2000 and 3000 my^{-1}, and that of Thwaites Glacier ranges between 2500 and 3500 my^{-1}. The speed of glaciers keeps on accelerating since last 3 decades, which enhances the importance of these glaciers and demand constant monitoring. In addition to surface melting, there are many factors, which are responsible for the high surface velocity of Pine Island and Thwaites Glaciers. There is a need to investigate further to understand the real cause for mass loss.

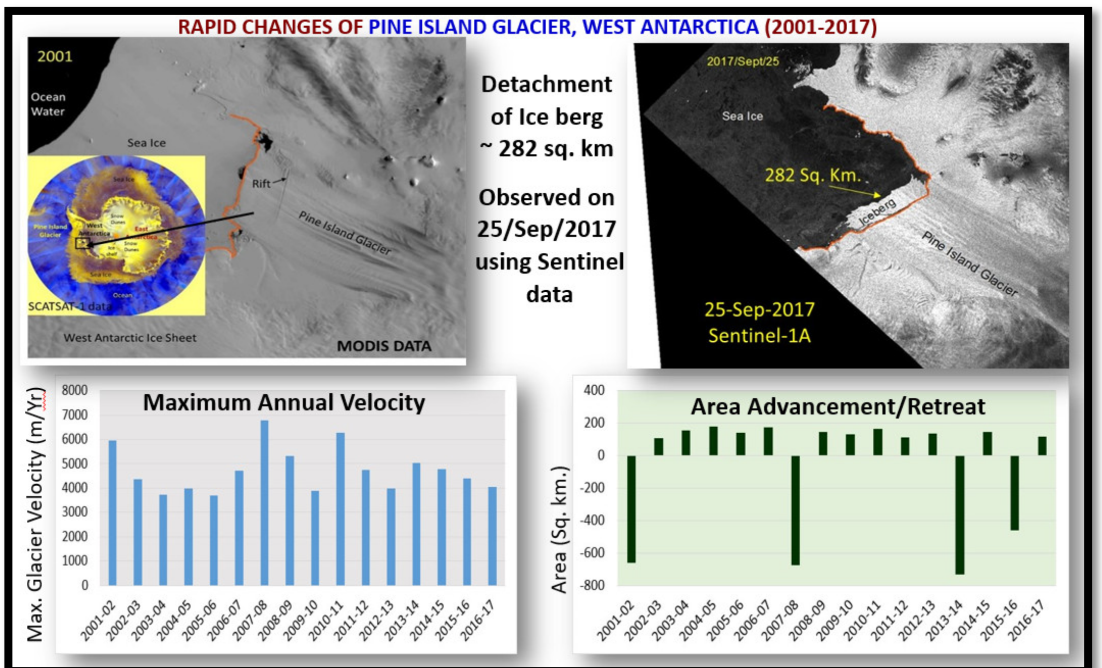


Figure 3.13: Time series of ice velocity and calving events of Pine Island Glacier, West Antarctica.

Figure 3.14 shows the Average Melt Intensity (AMI) observed over the study region using SCATSAT-1 BT data. As observed, large sized Ronne and Ross Ice S helves (Figure 3.14a) are showing lower AMI compared to relatively small-sized ice shelves like Larsen-C, West and Shackleton. This supports the findings of other researchers who studied melt using backscatter data or passive microwave data (Bothale *et al.*, 2014; Oza, 2014b; Oza *et al.*, 2009b;2016).

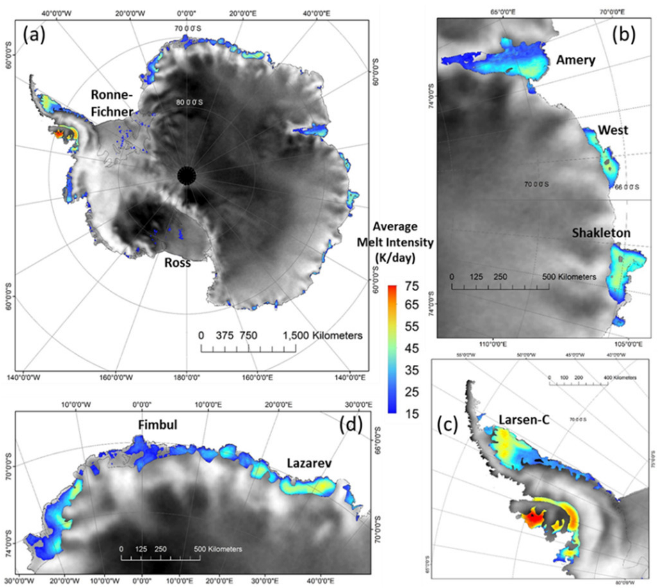


Figure 3.14: Average melt observed using SCATSAT-1 BT data over (a) Antarctic ice shelves for the study period (b) region covering Amery Ice Shelf, (c) region covering Antarctic Peninsula and (d) region covering Fimbul Ice Shelf.

Darji *et al*. (2017) documented the year-to-year changes in the position of ice front of the Pine Island Glacier, West Antarctica (Figure 3.15). Darji *et al*. (2018) studied the propagation-widening of five active rifts and future potential calving zones on Amery Ice Shelf (AIS), East Antarctica, between 2000 and 2017 using moderate resolution image spectroradiometer (MODIS) data. Darji *et al*. (2019) discussed, whether the Pine Island glacier, Antarctica calving triggered by earthquakes and tsunamis?

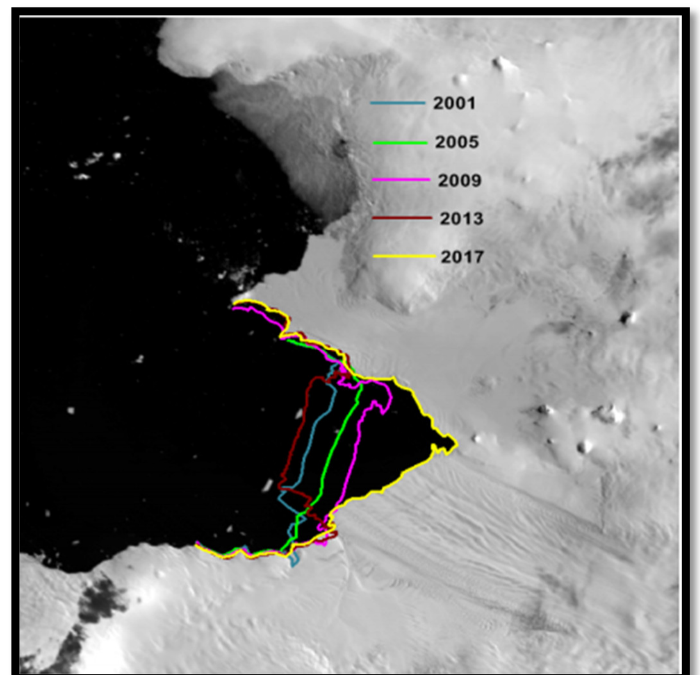


Figure 3.15: The advance and retreat of frontal portion of Pine Island Glacier (2001- 2017).

At SAC, various studies have been carried out (Figure 3.16) demonstrating the utilization of RISAT-1 SAR for the mapping of ice calving and other changes around Antarctic ice margin (Jayaprasad *et al.*, 2014; 2016; 2017a, Patel *et al.*, 2016a; 2016b, Shah *et al.* 2016a; 2016b; 2017). Jayaprasad *et al.* (2017b, 2018) and Suryawanshi *et al.* (2016) have also reported the breaking of Larsen-C Ice Shelf monitored using high resolution space-borne data. They also discussed the MOSAIC prepared using RISAT-1 SAR data. However, much more work needs to be carried out at SAC using high resolution optical and SAR data for the assessment of changes around ice margins.

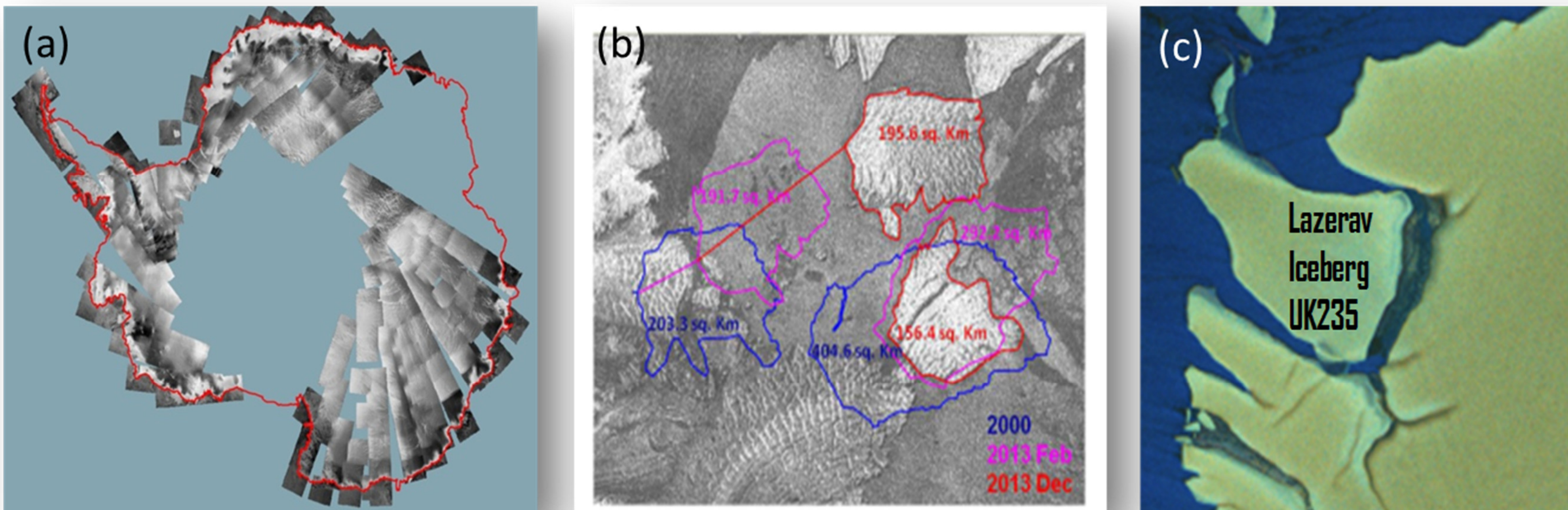


Figure 3.16: Typical results of SAR data utilization for the identification of changes around margin including (a) RISAT mosaic of Antarctica; (b) Calving of icebergs from Polar Record Glacier and (c) UK235 Iceberg calved from Lazarev Ice Shelf.

Energy balance is one of the approach to study the mass balance of the ice sheet. An attempt has been made to study the long-term variations observed in energy fluxes over the Indian Antarctic stations Maitri and Bharati using parameters from European Centre for medium range weather forecasts (ECMWRF) Reanalysis-Interim (ERAI) dataset. Monthly time series of the net energy fluxes obtained shows remarkable separation in net fluxes over Maitri and Bharati. From October, the separation starts increasing and reaches to a maximum during December. From January, it starts decreasing and vanishes in March (Figure 3.17).

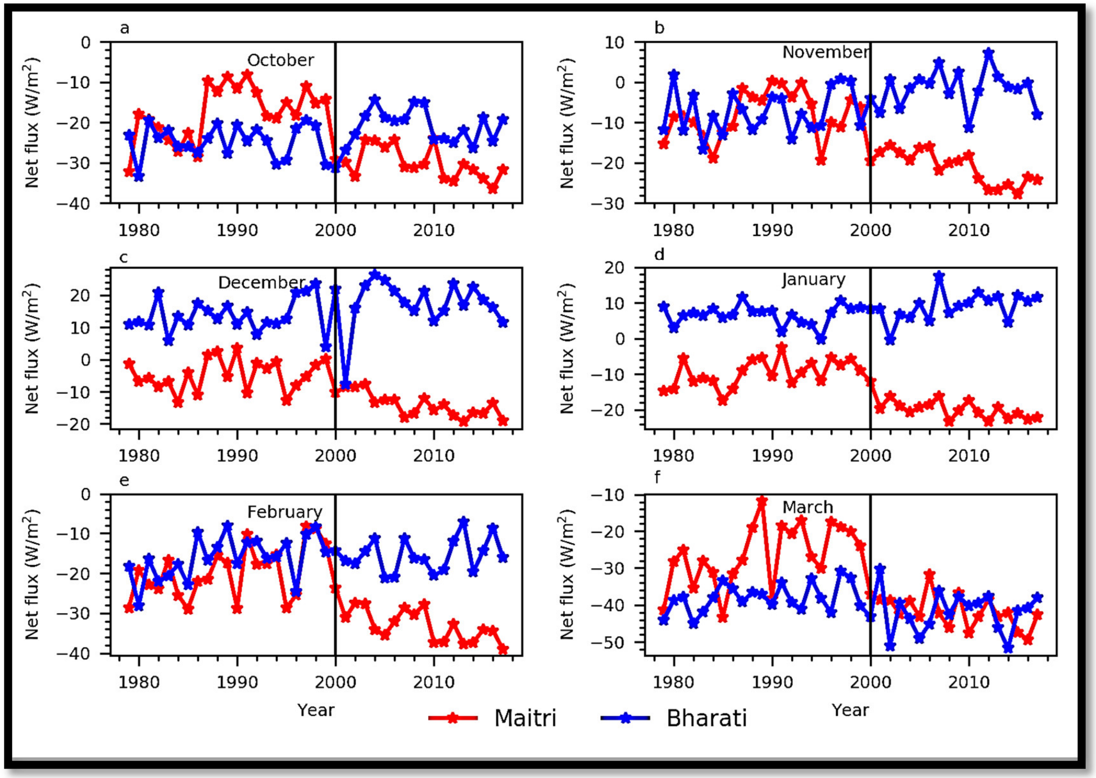


Figure 3.17: The month wise (October - March) net energy fluxes over Maitri and Bharati during 1979-2017. Vertical black line is drawn to visualize the changes after the year 2000.

4.0 Participation in Indian Scientific Expeditions to Antarctica

National Centre for Polar and Ocean Research (NCPOR), Goa, has been identified by Government of India as the nodal agency for execution and coordination of expeditions to Antarctica by Indian teams. India got involved in the Antarctic science expeditions during 1980s. On 19 August 1983, India was admitted to the Antarctic Treaty and thereafter obtained Consultative Status.

India's first committed research facility, Dakshin Gangotri (70° 05′37″S, 12°00′00″E) was established during the third Indian Expedition to Antarctica in 1983-84. The station was built in eight weeks by team of eighty-one expeditioners and the construction was completed late in January 1984. The Indian team spent first winter in Antarctica to carry out scientific experiments and data collection. The station was abandoned in 1988-1989 after it got buried under the ice. In the year 1989 the Second Indian Antarctic Research Station, Maitri (70°45' S, 11°43' E) was commissioned which has been built on an ice free, rocky area on the Schirmacher Oasis (Queen Maud Land). It serves as a gateway to one of the largest mountain chains in central Dronning Maud land, located southward of Schirmacher. It is situated about 100 km from the Antarctic shore at an elevation of about 50 m. Indian Antarctic research station, Bharati, is India's third Antarctic research facility and one of the two active Indian research stations. It is situated on a rocky promontory fringing the Prydz Bay between Stornes and Broknes peninsula in the Larsemann Hills area. It is located approximately midway between the eastern extremity of the Amery Ice Shelf and the Southern boundary of the Vest fold Hills. Since its completion, India has become one of the nine nations to have multiple stations within the Antarctic Circle.

Maitri and Bharati research stations have been platform for conducting experiments in glaciology, geology, geography, medicine, climate change and many other fields. The communication with Maitri and Bharati stations is through dedicated satellite channels provided by Indian Space Research Organization (ISRO).

Participation of SAC, ISRO in the Antarctic Expedition started with the 28th Indian Scientific Expedition to Antarctica (ISEA) in 2008-09 to understand the polar cryospheric processes using remote sensing technology. The major goal of SAC in 28th expedition was to explore the possibility of remote sensing technology for polar science studies. From 32nd expedition onwards, SAC started providing advisories for safer ship navigation. In 33rd expedition, feasibility study of getting sea ice thickness observation were experimented. Thirty-fifth expedition onwards retrieval of sea ice thickness information became possible using Ground Penetrating Radar (GPR) data. Another important work component of glacier velocity measurement was taken-up from 36th expedition onwards by installing stakes over the ice sheet and glaciers and first measurement of displacement was recorded in subsequent 37th expedition. Detailed snow surface characterization using snow fork attempted in 37th expedition along with detailed hyperspectral studies.

Figure 4.1: Bharati research station and Ivan Papanin ship (surrounded by fast ice in the Quilty Bay) - An aerial view captured during 36 ISEA.

Figure 4.2: Maitri research station along with a part of the Antarctic ice sheet seen in the background – As seen from Summer Modules during 36 ISEA.

Table 4.1: Brief details on participation of SAC in Indian Scientific Expedition to Antarctica.

ISEA No.	Year	Participants	Major Task
28ISEA	2008-09	Dr. Sandip R. Oza & Mr. Dipak A. Maroo	• Meteorological observation • Hyperspectral observation
29ISEA	2009-10	Dr. R. K. Kamaljit Singh	• Meteorological observation
32ISEA	2012-13	Ms. Megha Maheshwari	• Laser profilometer measurement
33ISEA	2013-14	Dr. D. Ram Rajak & Mr. P. Jayaprasad	• GPR survey • Aerial survey
34ISEA	2014-15	Mr. Manish Kumar & Dr. R. K. Kamaljit Singh	• GPR survey
35ISEA	2015-16	Mr. Rajendra Singh & Ms. Maya Suryawanshi	• GPR survey • Aerial survey
36ISEA	2016-17	Ms. Kiral Ghodadra & Ms. Purvee Joshi	• GPR survey • Differential Global Positioning System (DGPS) measurement • Aerial survey
37ISEA	2017-18	Dr. Sushil K Singh & Ms. Lakshmipriya Prushty	• GPR survey • DGPS measurement • Snow fork and Spectroradiometer observations
38ISEA	2018-19	Mrs. Shweta Sharma Mr. Ananya Ray Mr. Nilesh Makawana	• CR & ARC installation • DGPS measurement • Reflectometry

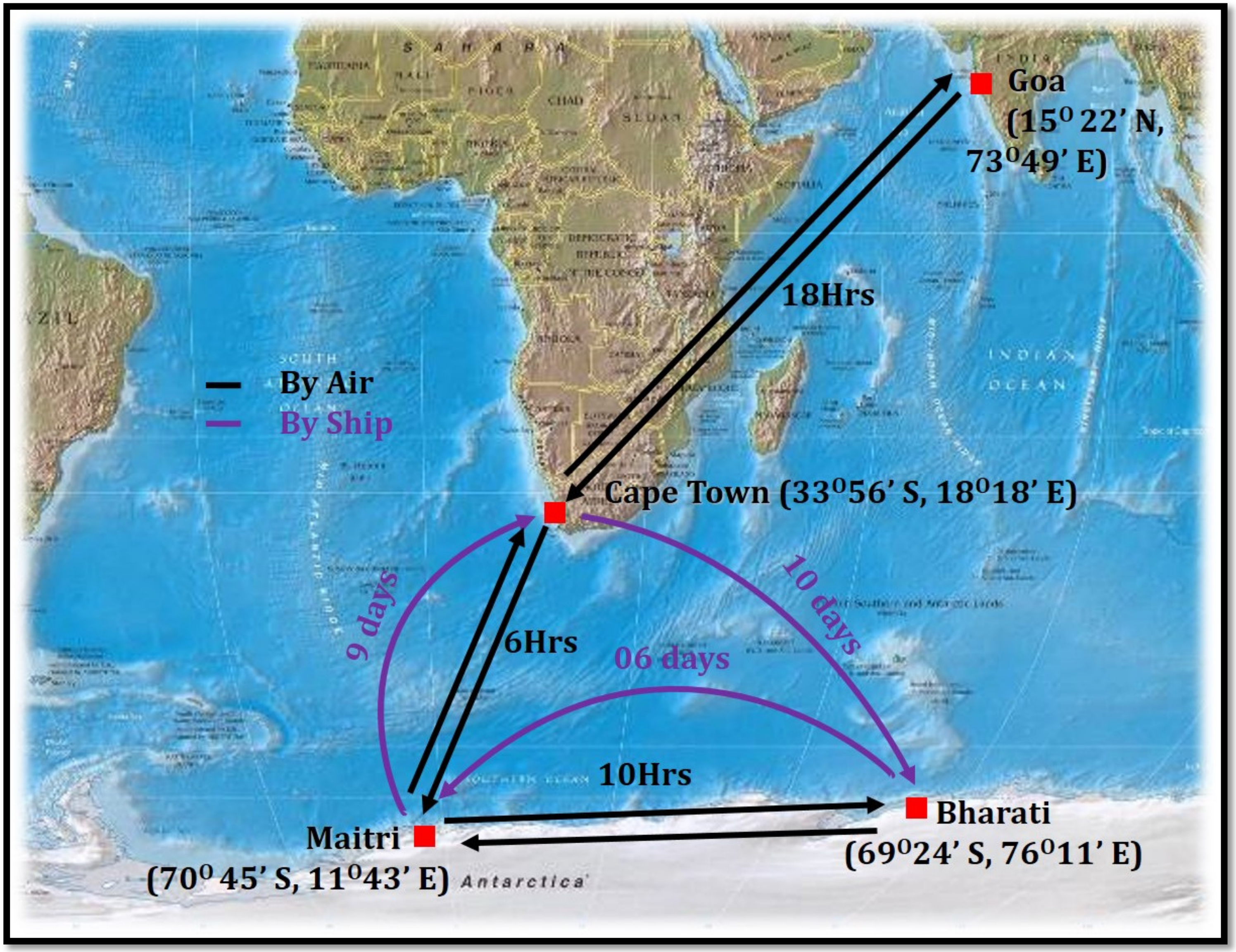


Figure 4.3: A typical expedition route, followed by the Indian Expeditioners to reach Antarctica.

28th ISEA

The participation of scientists from SAC in Indian Scientific Expedition to Antarctica (ISEA) during 2008-09 was first attempt towards understanding the Antarctic ice features and exploring the feasibility of Indian remote sensing data to study land ice and sea ice variations. The field data were collected using Met Observation Kit and hyper spectral radiometer.

Figure 4.4: Hyperspectral radiometer Observation during 28th ISEA.

The highlights of this expedition include insight into the scientific areas where remote sensing can play a significant role; sites were selected from polar ice region which have different backscattering properties in Ku band Scatterometer.

Figure 4.5: Snow pit observation during 28th ISEA.

29th ISEA

The 29th ISEA was an important expedition because it was during the time when construction work of the third Indian Antarctic research base, Bharati station, just started. One can say the focus of that expedition was clearly the establishment of this new base. Surface meteorological parameters namely, air pressure, air temperature, wind speed and direction, were noted on a 3-hourly interval during the 29th ISEA. These surface meteorological observations were done at ~30 m above sea level (ASL). Besides these parameters, dry bulb/wet bulb temperatures for relative humidity calculations, sea surface temperature (SST) and information on cloud coverage (in scales of okta) including weather conditions were also collected. SST measurements were done twice daily, one in morning (0900 GMT or 1200 GMT) and the other at afternoon (either at 1500 GMT or 1800 GMT) during the onward journey from Cape Town to the Larsemann Hills, East Antarctica and during the stay at the Larsemann Hills, during the 29th ISEA. Moreover, several snow-pack samplings were done in the polar ice sheets for ground-truth investigations. Certain regions showing distinctive roughness features have been identified and the satellite backscattering signatures from such features are used to study in detail. Early stages of the formation of sea ice have been recorded which is very useful in any polar ice studies.

Figure 4.6: Snow pit in Antarctic ice cap during 29th ISEA.

Figure 4.7: Air temperature measurement during 29th ISEA.

32nd ISEA The contribution summarized by participants in the following manner. From the first day on ship, collection of meteorology and ocean parameters such as wind speed, wind direction, pressure, humidity etc., were carried out with the help of instruments fitted in the ship. The sensors in the ship were installed at a height of 40 m from sea level. It took 11 days to reach to the newly constructed Indian base station Bharati and members of 32nd ISEA reached there on February 02, 2013. To determine the surface roughness laser profilometer had been and hand held weather tracker to get weather condition of the site such as wind speed, direction, pressure, humidity etc. The snow pit was also dug to know snow depth, snow layer and grain information. Post processing of collected measurements suggested that around the Bharati, roughness was in the range 0.7-1.2 cm. Snowfall and wind introduced fluctuations in surface roughness measurements.

Figure 4.8: GPS observation during 32nd ISEA.

Snow depth of the area varied from 3.5 to 18 inch. at 69°29' S 76°19' E and altitude 427 m, snow pit was dug and an ice slab was found of 11 inch which contained three different layers of snow. The temperature was -8.2 0C with wind speed 2.5 m/s. Around the Maitri station roughness measurements were collected with varying latitude.

Measurements around Maitri showed that different ice surfaces have different values of roughness (0.6-1.4 cm), with the minimum roughness in the interior ice sheet surrounded by hummocks.

Figure 4.9: A photograph of instrumental set up (laser profilometer mounted on a tripod) at a location (71.47° S, 12.29° E) on 4th March 2013 around Maitri station.

33rd ISEA

A large in-situ dataset of vital importance was prepared from the observations made at different locations of Antarctica covering ice sheet, ice shelf and sea ice regions. The observations pertain to various parameters needed for calibration and validation studies to be carried out under MOP-III project were collected. The experience gained was very useful for providing sea ice condition advisory for ship routing during second leg of 33rd ISEA.

Figure 4.10: GPR observation on sea ice during 33th ISEA.

The analysis of data obtained from two frequency GPRs was carried out. Observed sea ice thickness was found of the order of 1.0 to 1.4 m thickness along with a snow pack thickness varying 10 to 50 cm. The depth of snow over sea ice could be estimated using the GPR data at multiple locations. Handheld GPS was used to collect location coordinates of study sites and to track the ship route during voyage. In this edition of the Expedition, the main thrust was given to the observation of sub-surface ice features in Antarctica (ice sheet and fast ice) using a non-invasive technique- the GPR.

Figure 4.11: GPR observation on continent during 33th ISEA.

34th ISEA

Figure 4.12: GPR observation on ice sheet during 34th ISEA.

The SAC team carried two GPRs: Pulse Ekko Pro working at central frequency of 1000 MHz and a step- frequency (between 250-750 MHz) GPR assembled at SAC.

Figure 4.13: Ground observation using the ground penetrating radar (GPR) on 7 February 2015 at 69°26'S, 76°16'E.

35th ISEA

Geotagged camera, Handheld GPS, meter scale and mainly two GPR at two different frequencies: 1. In-house designed and developed GPR with central frequency of 500 MHz and 2. Commercial GPR with frequency 1000 MHz, for estimating snow depth and understanding stratigraphy of Antarctic snow and ice have been utilized.

Figure 4.14: GPR observation on sea ice during 35th ISEA.

Seventeen locations were pre-selected based on Radar Imaging Satellite (RISAT)-1 Synthetic Aperture Radar (SAR) data interpretation, for in-situ measurement using GPR over the area surrounding the Indian Antarctic stations. GPR measurements have been successfully done on various ice features like ice sheet, ice shelf, iceberg and sea ice etc. The profiles available from the two GPRs (500 MHz and 1000 MHz) differ from each other due to different spatial resolution and penetration capabilities. However, the overall patterns of the two GPRs are almost same for the similar features. Wet snow was observed over fast ice in Quilty Bay while very dry snow was observed over Amery ice shelf. Bare blue ice observed near

Russian Air Field in Schirmacher Oasis. Participants have also witnessed blizzard on 30th January 2016 and Advanced Scatterometer (ASCAT) observed wind speed of same day near Bharati station coast was greater than 13 m/s. In addition, stratification of iceberg UK235 was also observed which was separated from Lazarev ice shelf up to few meters.

Figure 4.15: GPR observation on iceberg UK235 during 35th ISEA.

36th ISEA

The objectives of SAC in 36th ISEA are (1) To measure glacier ice movement near Bharti stations using DGPS measurement (2) To measure snow depth over sea ice, ice shelf and change in ice (3) layer thickness for mass balance study, using GPR survey (1000 MHz, 500 MHz, 400 MHz) (4) Exploratory study to measure surface root mean square roughness using profilometer (designed and fabricated in house in association with Mechanical Engineering Systems Area, MESA SAC, ISRO). (5) To capture the geotagged field photos using DSLR camera.

Figure 4.16: GPR observation on sea ice during 36th ISEA.

Antarctic ice margins between Larsemann Hills and Amery Ice Shelf is a potential region for ice loss as there are a number of glaciers in this area. The surface ice motion rate serves as a control parameter to determine the mass balance of ice sheets and furthermore helps to understand the climate changes. Ice velocity measurements of the Antarctic ice sheet indicate how ice is transported from the interior of the continent to the oceans through glacier calving process. The ice velocity of Polar

Record Glacier increases rapidly seaward, from ~ 200 ma^{1} in inland areas to >700 ma^{1} at the front of the glacier tongue. Hence being fast moving glacier, ice sheet locations were attempted which is feeding Polar Record Glacier for surface ice velocity measurement.

Figure 4.17: DGPS observation on glacier ice during 36th ISEA.

Sea ice conditions in the Prydz Bay are controlled by the presence of Dalk Glacier. This glacier produces large icebergs in this context, Dalk Glacier has been chosen for measuring glacier ice movement. SAC team has installed five bamboo logs on ice sheet independently and three bamboo logs on Dalk Glacier along with Geological Survey of India (GSI) team and took DGPS measurement for 30 minutes on each location during 36th ISEA. DGPS data were also utilized for validating elevation change data derived from SARAL/AltiKa on Antarctic Ice Sheet. SAC team has utilized GPRs having different frequencies (1000 MHz, 500 MHz and 400 MHz) to understand Antarctic ice features near Bharati research station and Maitri research station. Stratification of ice over various locations were observed. Hyperbolic signature from frozen water channel and unknown objects beneath the blue ice were also scanned using multi frequencies GPRs. All GPRs were unable to penetrate through blue ice. Average snow depth measured near Bharati and surrounding is more as compared to Maitri. GPR measured snow depth is found to be overestimated as compared with actual field measurement done with meter scale.

SARAL/AltiKa (35.75 GHz) derived elevations were compared with in-situ DGPS (Differential Global Positioning System) measurement on feeder ice sheet of polar record glacier in east Antarctica near Bharati station during 36th ISEA. SARAL/AltiKa derived elevations were obtained using 40 Hz Geophysical Data Record (GDR) data set and were w.r.t. WGS84. Elevations were corrected for various atmospheric and tidal correction. Further elevations were gridded and corrected for slope-induced correction using direct method. Ice, Cloud and Land Elevation

Satellite (ICESat) derived Digital Elevation Model (DEM) was used to obtain slope at required location. However, after applying slope correction, elevation differences were reduced but still there is considerable difference between SARAL/AltiKa derived and In-situ measurement. This is because, in-situ data was compared at nearest time domain and nearest spatial domain of SARAL/AltiKa pass and footprint as mentioned in Table 4.2. Another factor in order to improve results is, direct method for slope correction have been used instead of relocation method that works better.

Table 4. 2: Comparison of SARAL/AltiKa derived elevation with in-situ measurement on feeder ice sheet of Polar Record Glacier during 36 ISEA.

Distance between and In-situ and SARAL/ AltiKa measurement (m)	In-Situ Measurement (14th January, 2017)			SARAL/AltiKa Measurement Cycle105 (Pass No. 26 (27th December, 2017) and 45 (28th December, 2017))			Slope (degree)	SARAL/ AltiKa Slope Corrected Elevation (m)
	Longitude (degree decimal)	Latitude (degree decimal)	Elevation (m)	Longitude (degree decimal)	Latitude (degree decimal)	Elevation (m)		
6551.71	75.35	-70.42	1396.68	75.50	-70.39	1396.24	0.45	1357.07
2433.60	75.51	-70.44	1421.90	75.56	-70.43	1441.35	0.66	1400.76
650.52	75.57	-70.43	1415.21	75.56	-70.43	1437.85	0.57	1397.07
3273.02	75.64	-70.41	1396.14	75.56	-70.43	1440.97	0.57	1412.94
9594.01	75.67	-70.31	1297.27	75.44	-70.35	1358.61	0.34	1285.61

37th ISEA

Team could reach Bharati station on 27th January 2018 and GPR survey using 500 & 1000 MHz antenna was carried out to collect data to assess sea ice conditions in view of voyage movement. First task of our team was to help in offloading heavy machines weighing 12 & 32 metric ton, which was required to help in constructions for proposed Data Receiving Station (DRS) at Bharati by NRSC and ECIL team.

Figure 4.19: GPR observation on sea ice during 37th ISEA.

Lot of team efforts, manual work has been carried out to place heavy logs for designing track to take load and GPR survey for evaluating sea ice conditions. Field observations were executed to safely offload machines from ship to Bharati station. To meet our scientific objectives, DGPS measurements were taken of the bamboo stacks, installed during 36th ISEA, at feeder ice sheet of Polar Record Glacier and Dalk Glacier as shown in Table 4.3.

Figure 4.20: DGPS observation on glacier ice during 37th ISEA.

One bamboo stack of approximately 1.25 m height was lost due to solid precipitation in polar record glacier and only four stacks out of five could be found. Elevation change has also been observed as shown in figure 4.19. GPR survey using two different frequencies i.e. 500 MHz antenna (in-house developed) and 1000 MHz (commercially available) was carried out over different targets such as sea ice thickness, blue ice & ice sheet near disintegration glacier, airfield of progress runway etc. Snow fork instrument was used to estimate wetness and density of snow at different sites.

Radiometric measurements were also carried out on top layer of snow over sea ice, melt-freeze layer over sea ice, rocky terrain in Larsemann Hills along with meteorological observations using sun photometer & ozonometer.

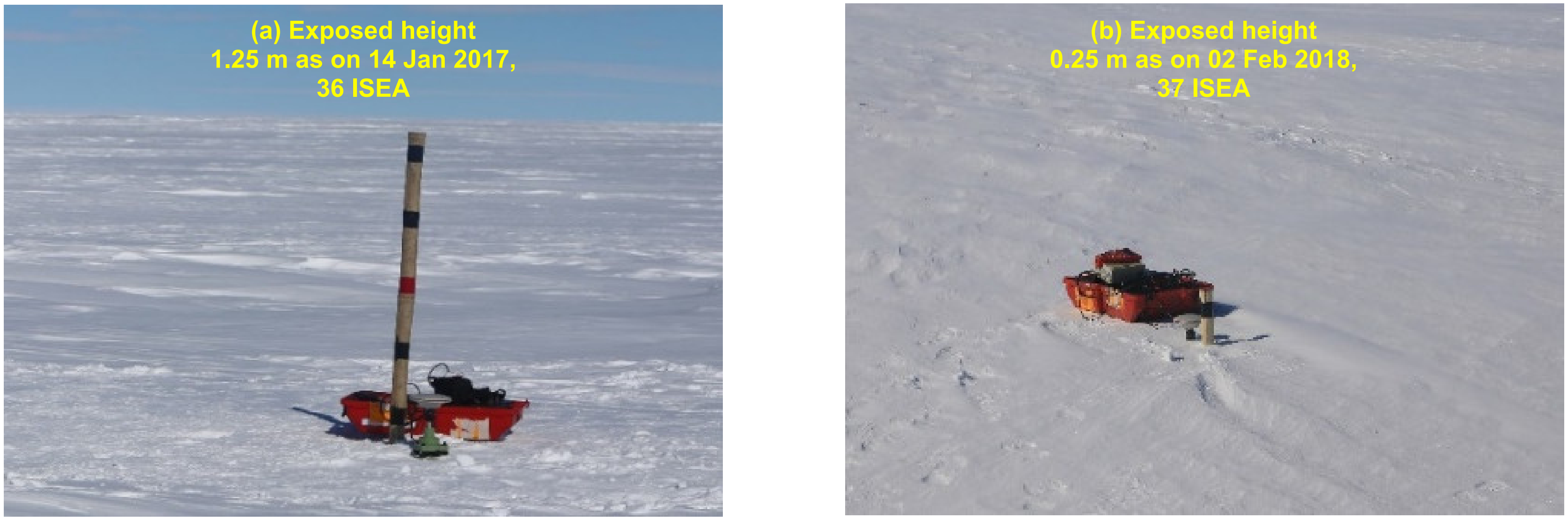


Figure 4.21: Field photo of DGPS measurement on feeder ice sheet of Polar Record Glacier installed bamboo log (a) exposed (a) exposed height 1.24 m as on 14 Jan 2017(36 ISEA) (b) exposed height 0.25 m as on 02 Feb 2018 (37 ISEA).

Table 4.3: Measured displacement/year in polar stereographic south pole projection using DGPS on feeder ice sheet of Polar Record Glacier and Dalk Glacier.

	Locations	**P1**	**P2**	**P3**	**P4**	**P5**
Displacement (m/year)	**Feeder ice sheet of Polar Record Glacier**	Buried	18.25	20.61	23.67	41.98
	Dalk Glacier	5.744	141.4	3.851	-	-

38th ISEA

The highlight of the work carried out during 38th ISEA is the installation of Corner Reflectors (CR) around Bharati and Maitri stations (Figure 4.22). Calibration of the space-borne SAR sensors is one of the key activity to ensure the highest quality of backscatter data. CR is widely used equipment for the calibration of SAR data. Initially team has identified the sites (at different land targets) that are suitable for CR installation around the stations. The response from the CRs on the SAR images, at different land targets, were investigated at SAC and feedback was provided to the team for finalizing the installation. Based on this feedback, participants from SAC have finalized the site and fine-tuned the geometrical configuration of CR for best response in the Sentinal-1 SAR data, which can be utilized to calibrate the sensor. Attempt has also been made to check the feasibility of installation of CR and Active Radar Calibrator (ARC) over the Antarctic Ice Sheet. This activity is towards the establishment of CAL/Val network over Antarctica, which can be utilized to calibrate the forthcoming Indian SAR missions.

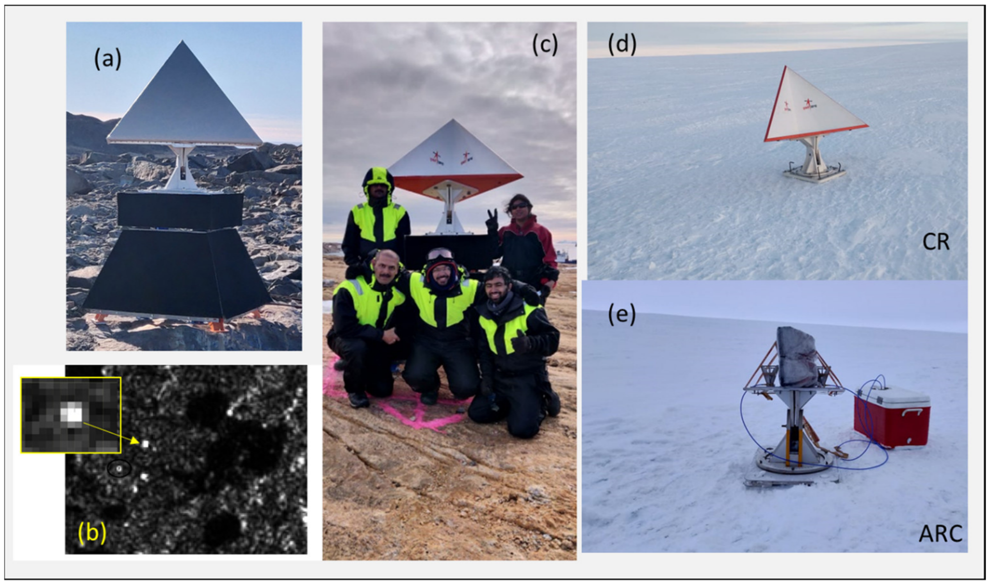


Figure 4.22: Installation of Corner Reflector (CR) (a) at Indian Antarctic Stations Maitri and (b) Response CR observed on Sentinel-1 SAR data. (c) CR installed at Bharati. Feasibility of installation of (d) CR and (e) ARC over Antarctic ice sheet.

Sea Ice Advisory for Safer Ship Navigation

The actual route to be followed by ship can be determined only based on near real time sea ice condition. Voyage Leader of 32nd ISEA requested the first satellite based sea ice advisory in December 2012. This has initiated task of providing sea ice advisory to NCAOR (now named as NCPOR) for safer ice navigation. Passive microwave based sea ice concentration (SIC) products were investigated and trend analysis was carried out to generate an image showing increasing/decreasing SIC trends (Figure 4.23). Region with decreasing trend could be an indicative of reduced impact from sea ice and could be preferred for the safer ice navigation. Subsequent to 32nd ISEA continuous improvement undergone for the betterment of the advisory. During first leg of 33rd ISEA (December 2013) information was enriched by (i) AltiKa derived sea ice freeboard data and (iii) MODIS based optical data (Figure 4.24). In addition to the data, SAC has suggested three routes for the Ship to enter into the sea ice region for heading towards Indian Antarctic station “Bharati”. At the same time near-real time SAR data from RISAT-1 indicated the presence of large-size ice berg, which was located on the potential route, hence this information was also passed on to the voyage leader. Rajak *et al.* (2014a; 2014b; 2015a) describe the attempts made by SAC for the generation of sea ice advisory for safer ship navigation during Indian Expedition to Antarctica. They have also suggested that the use of sea ice occurrence probability (Rajak et al. 2015a) can be utilized as climatic information for the pre-planning of the possible voyage route. An attempt was made to provide the information of sea ice drift by visual interpretation of time series of MODIS data (Figure 4.25) during 34th ISEA. Figure 4.26 and Figure 4.27 are showing some of the example of RISAT based information provided (34th ISEA) on various sea ice features and SIC based likely routes for safer ship navigation.

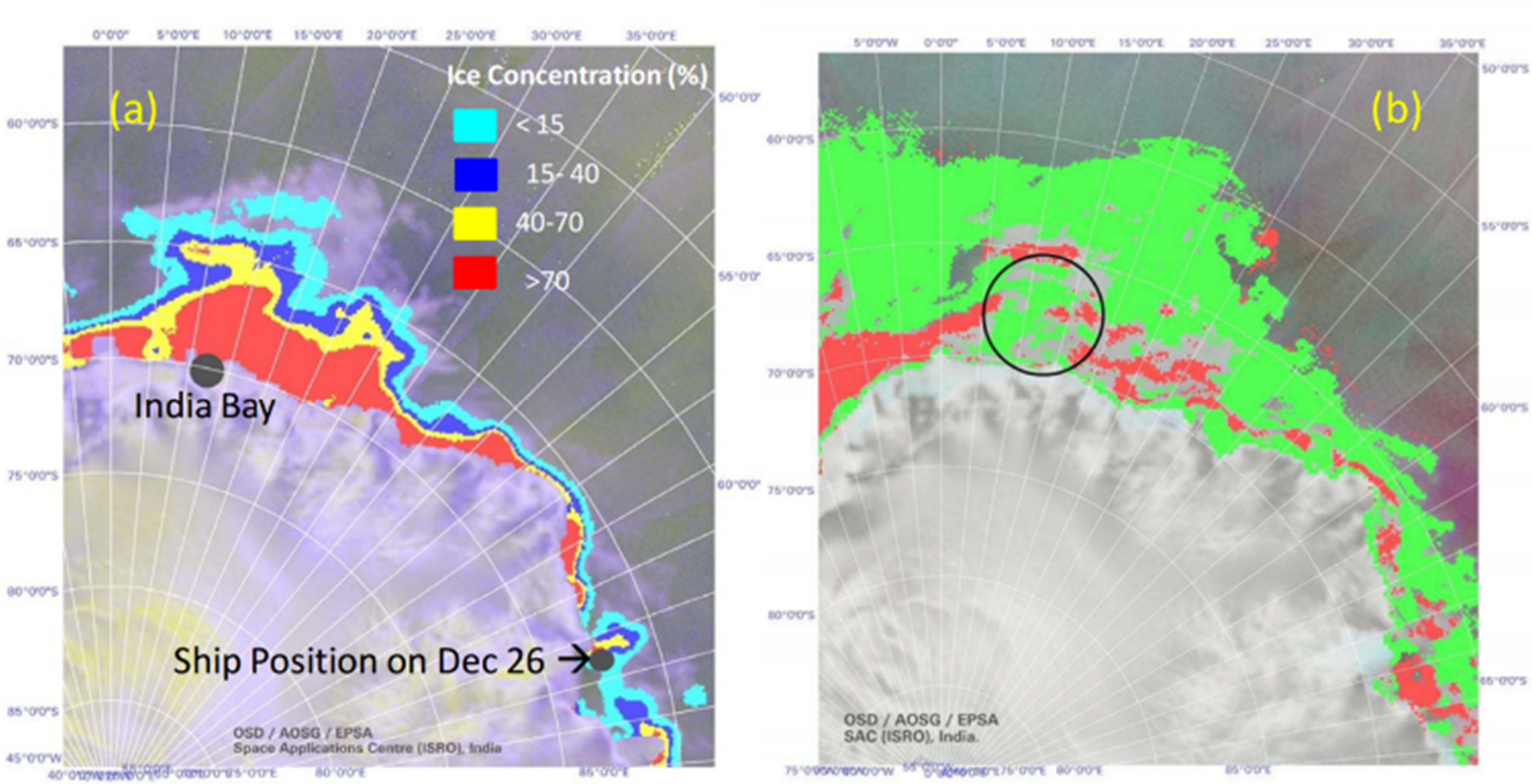


Figure 4.23: Advisory on sea ice condition to NCAOR, MoES during 32nd ISEA in December 2012 showing (a) Sea ice concentration and (b) result of trend analysis (increasing trend in red and decreasing trend in green).

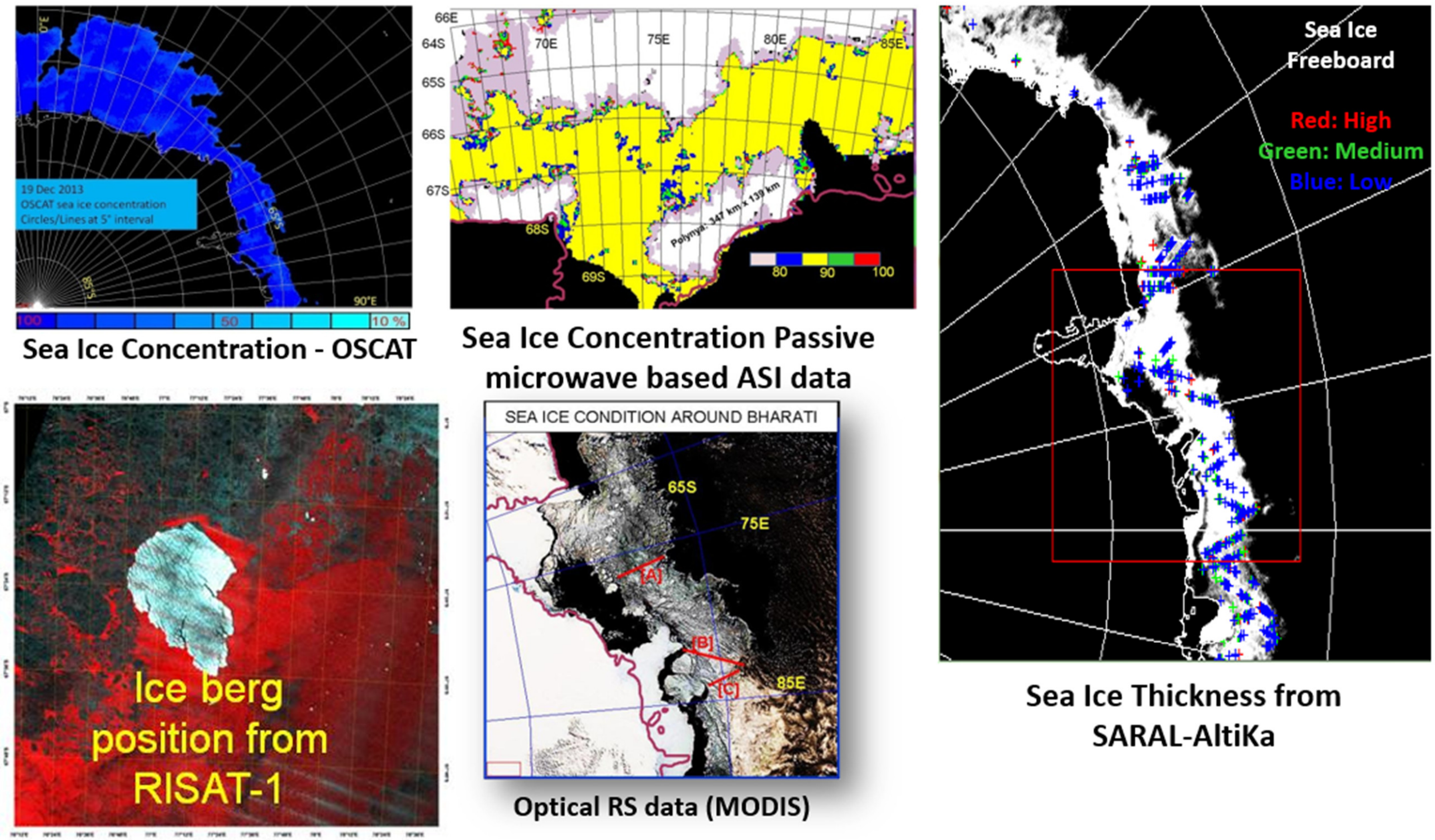
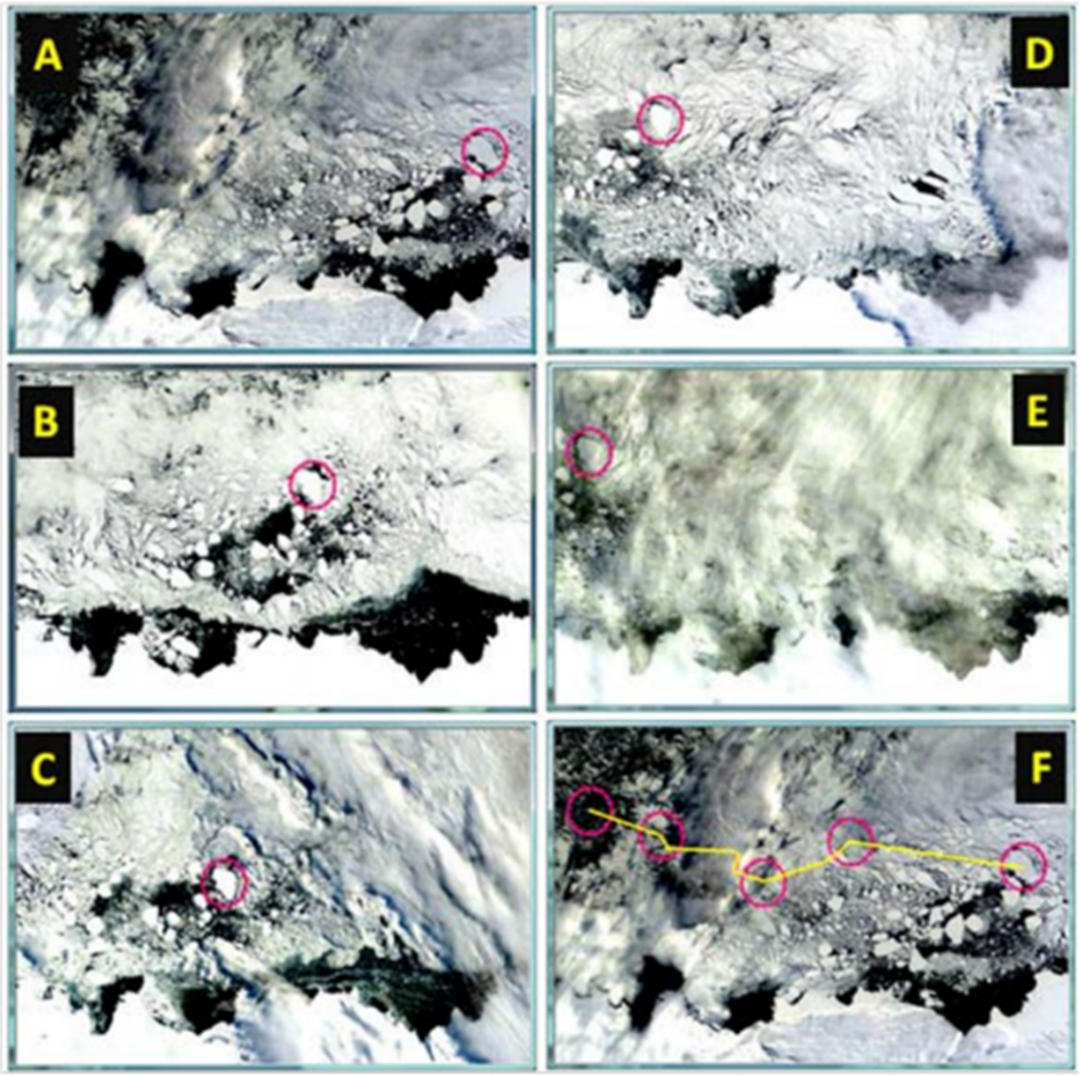


Figure 4.24: Integrated sea ice advisory provided during 33rd ISEA in December 2013. (a) OSCAT based SIC; (b) AMSR-2 SIC product; (c) AltiKa based sea ice freeboard; (c) RISAT-1 image showing ice berg and (e) Potential routes for safer ice navigation based on MODIS data.



A: Feb 23, 2014
B: Mar,2014
C: Mar 05,2014
D: Mar 10, 2014
E: Mar 15, 2014
F: Drift Path

Drift path is based on 12 dates data Feb 23, Feb 28, Mar 01, Mar 02, Mar 03, Mar 05, Mar 06, Mar 07, Mar 08, Mar 10, Mar 12, Mar 15.

284.4 km drift in 20 days i.e. 14.2 km/day.

Figure 4.25: Sea ice drift monitored using MODIS data (Feb 23 to March 15, 2014).

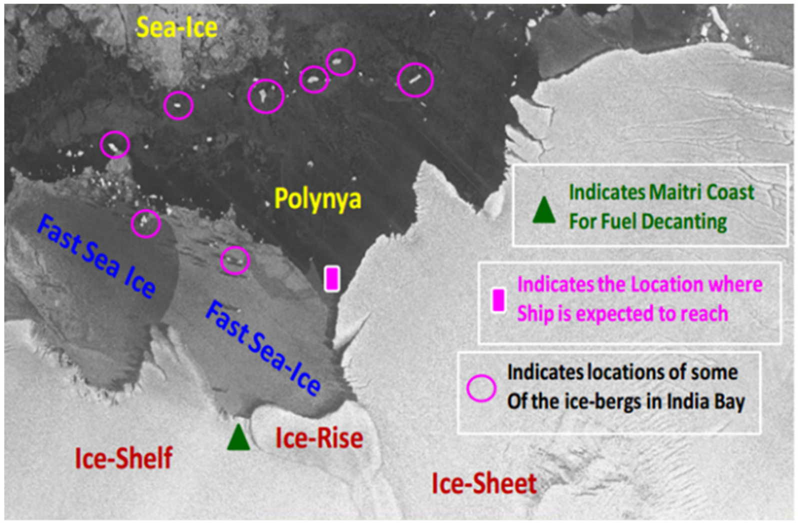


Figure 4.26: A RISAT-1 SAR scene (March 8, 2014) show in different polar ice features (35th ISEA).

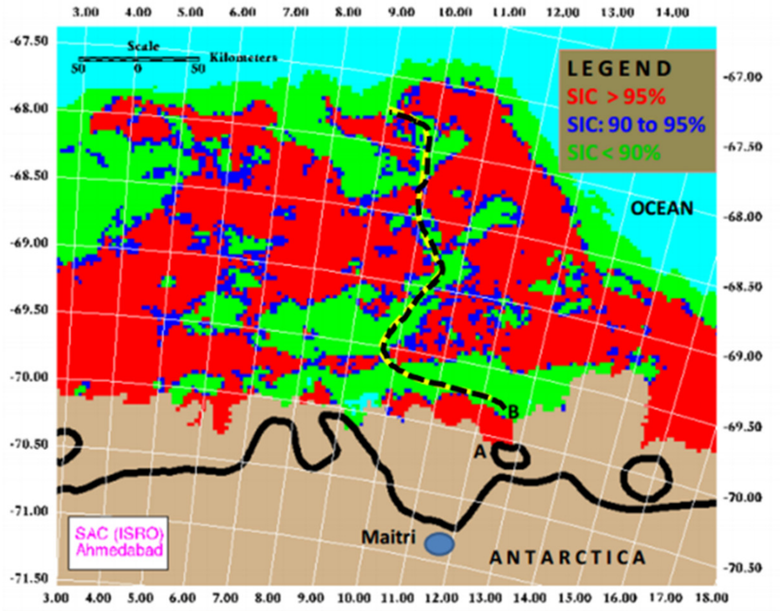


Figure 4.27: Likely safe ship entry points to reach New Indian Barrier (sea ice advisory sent to NCAOR on March 7, 2014).

Subsequent to 34th expedition every year, sea ice advisories are provided using sea ice concentration products, AltiKa based ice freeboard and inferences drawn by visualizing the RISAT, AWiFS, LISS3, LISS4 and MODIS data. Based on the experience gained and feed-back received from these expeditions, an attempt was made during 2018-19 (38th ISEA) for the development of Graphical User Interface (GUI) based Web-GIS application to automatize the procedure using SCATSAT-1 derived sea ice extent (SIE), AltiKa derived sea ice thickness (SIT) and SIC product. SIT and SIC data was processed to their weighted version with an indigenously developed individual weighting schemes. Weights are given such a way that higher the weights, high suitability for ship navigation (Figure 4.28). The procedure will improve by implementing the feedback received from the expedition team.

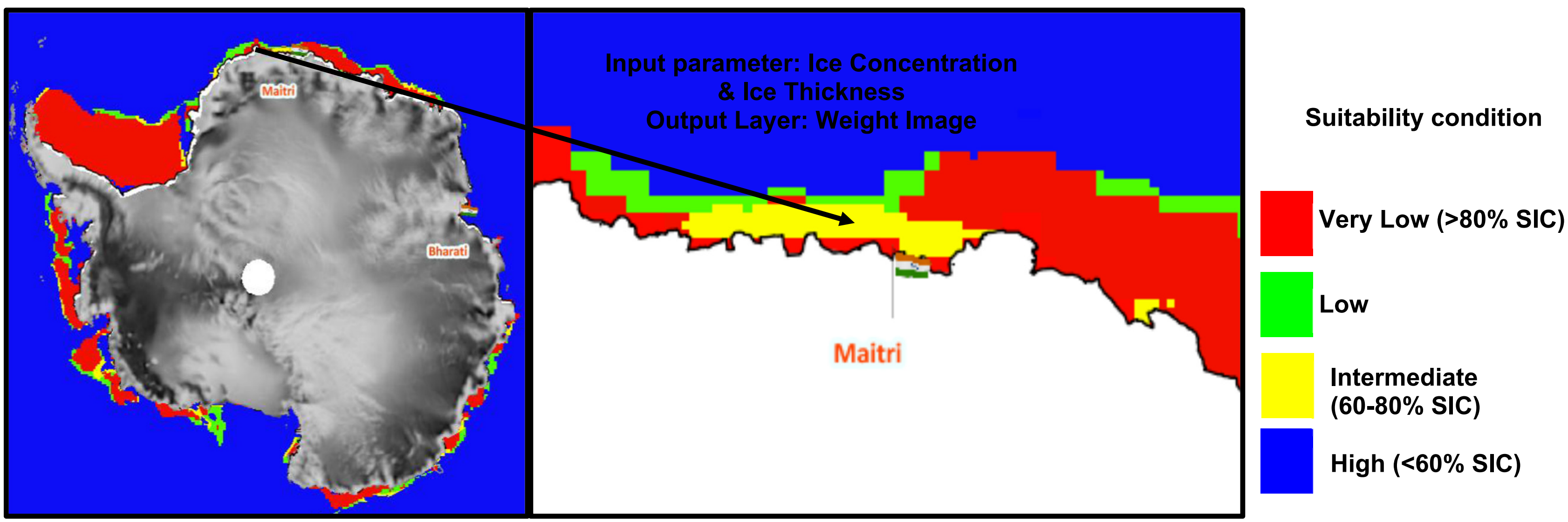


Figure 4.28: Suitability map for safer ship navigation.

5.0 Way forward

As far as the Antarctic science is concerned we know far less than we need to know about the past and present of it. Today, there are more science questions than the answers before us. We have been in the development phase of utilising earth observation data from orbital platforms for monitoring the elements of Polar cryosphere. Based on the experience gained so far, the importance of multiple sensors on board multiple missions has been realised to address all dimensions of Antarctic cryosphere. Two operational sensors of ISRO i.e. Scatterometer and Altimeter have immensely utilized in knowing the status of Polar Ice Sheets and sea ice. Now, the continuity of such missions is required to comprehend the processes of mass changes of ice sheets and sea ice.

Future work is required for forecasting of sea ice conditions during expeditions for safer ship navigation. Another thrust area is energy balance studies over ice sheets and sea ice which will enable scientists to accurately estimate the energy fluxes governing the climate. Coupled modelling comprising interactions between ice and atmosphere is a vital area of research. Towards achieving these goals ISRO has planned various missions such as NASA-ISRO L & S band SAR, TRISHNA, OSCAT on board OCEANSAT-3. Ice dynamics studies such as Ice velocity, calving processes, sea ice deformation will get boost by using L & S band SAR data. TRISHNA thermal bands will enable us to recognise melt-freeze cycle over polar ice regions. One of the important instruments required on board satellites is multi-channel Microwave Radiometer which will help in retrieval of snow depth, sea ice concentration and atmospheric corrections. Another potential area of research lies in the use of hyperspectral data in order to identify various classes of sea ice and ice features on ice sheets.

To validate various science products retrieved from Space borne Sensors, enormous instrumentations are needed in the field. We have already initiated process of infrastructure development for calibration sites in Antarctica. Airborne flights are envisaged using multi-frequency GPRs, Thermal camera and altimeters to infer topography above or below the ice surfaces. These kinds of tasks can be accomplished only by cooperation of multiple organisations in the country. As far as field data collection is concerned, any single country may not be able to collect data from various locations well spread over the continent, without getting support from other countries. Hence, international collaboration is the need of an hour. Large areas of the Southern Ocean and ice sheet remain data void due to difficult and expensive logistics and inclement weather.

For selecting a safer and optimum navigation ship route, near real time information of sea ice, atmosphere and ocean conditions are needed. Timely information on the spatial distribution of icebergs is also needed for safe ship navigation. Satellite based active and passive sensors with finer resolution, higher temporal frequency and more spectral bands offer a solution to overcome these problems. SAC is planning to develop a tool to support a Decision Support System (DSS) for providing near real time sea ice advisories to ISEA. It will use meteorological parameters (surface winds speed, wind direction, atmospheric pressure, surface temperature, air temperature etc.) and ocean surface parameters (e.g. surface currents, wave height) along with the sea ice conditions derived from near real time remote sensing data.

In the long run the key science question that needs to be answered are:

(i) how much of ice volume from ice sheet getting added to the ocean to rise the sea level?

(ii) how much change we expect in sea ice volume and distribution, which cover/expose the ocean surface with the atmosphere and thereby contributing into the global cooling/warming.

To address these questions, we need to model the thermodynamics and dynamics of ice sheet and sea ice components of the polar cryosphere. The ice sheet and sea ice model coupled with atmosphere and ocean models will be able to provide the present and future scenario of loss of continental ice volume and sea level rise.

References

Al-Hamad, K., Al-Ibrahim, M. and Al-Enezy, E., 2012. A genetic algorithm for ship routing and scheduling problem with time window. *American Journal of Operations Research* 2(3): 417-429.

Bhandari, S. M., Dash, M. K., Vyas, N. K., Khare, N. And Pandey, P. C., 2002. Microwave remote sensing of sea ice in the Antarctic region from Oceansat-1 MSMR. *Advances in marine and Antarctic science 423.*

Bothale, R. V., Rao, P. V. N., Dutta, C. B. S. and Dadhwal, V. K., 2014. Dynamics of surface melting over Amery and Ross ice shelf in Antarctic using OSCAT data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL (8): 505-509.

Bothale, R. V., Rao, P. V. N., Dutt, C. B. S., Dadhwal, V. K. and Maurya, D., 2015. Spatio-temporal dynamics of surface melting over Antarctica using OSCAT and QuikSCAT scatterometer data (2001–2014). *Current Science* 109: 733-744.

Cavalieri, D. J., Gloersen, P. and Campbell, W. J., 1984. Determination of sea ice parameters with the Nimbus 7 SMMR. *Journal of Geophysical Research* 89: 5355-5369.

Cavalieri, D. J., Crawford, J., Drinkwater, M. R., Eppler, D. T., Farmer, L. D., Jentz, R. R. and Wackerman, C., 1991. Aircraft active and passive microwave validations of sea ice concentrations from the DMSP SSM/I. *Journal of Geophysical Research* 96(21): 21,989-22,008.

Cavalieri, D. J., 1994. Microwave technique for mapping thin sea ice. *Journal of Geophysical Research* 99(12): 561–572.

Comiso, J. C., 1995. SSM/I ice concentrations using Bootstrap algorithm. *NASA Reference Publication 1380.*

Comiso, J. C., Cavalieri, D. J., Parkinson, C. L. and Gloersen, P., 1997. Passive microwave algorithms for sea ice concentration: A comparison of two techniques. *Remote Sensing of Environment* 60: 357-384.

Cook, A. J., Fox, A. J., Vaughan, D. G. and Ferrigno, J. G., 2005. Retreating glacier fronts on the Antarctic Peninsula over the past half century. *Science* 308: 541–544.

Darji, S., Oza, S. R., Shah, R. D. and Bahuguna, I. M., 2017. Spatial-temporal investigation of ice velocity over Pine Island and Thwaites glacier, West Antarctica. *38th Asian Conference on Remote Sensing (ACRS 2017), October 23 – 27, 2017, New Delhi, India.*

Darji, S., Oza, S. R., Shah, R. D., Rathore, B. P. and Bahuguna, I. M., 2018. Rift Assessment and Potential Calving Zone of Amery Ice Shelf, East Antarctica. *Current Science* 115: 1804.

Darji, S., Shah, R. D., Oza, S. R. and Bahuguna, I. M., 2019. Is Pine Island glacier, Antarctica calving triggered by the earthquake and tsunamis? *Current Science* 116: 1057-1059.

Das, I. M. L., Mitra, A., Srivastava, A., Dash, M. K, Oza, S. R. and Vyas, N. K., 2011a. Quantitative studies of sea ice melting rates in the Antarctic using SSMI data. *Science and Geopolitics of Arctic and Antarctic* 118.

Das, I. M. L., Srivastava, A., Dash, M. K., Singh, R. K. K., Oza, S. R. and Vyas, N. K., 2011b. Polar sea ice patterns as observed from altimeter coastal products. *AltiKa Science Workshop, March 2011, Space Application Centre, Ahmedabad, India.*

Dash, M. K., Bhandari, S. M., Vyas, N. K., Khare, N., Mitra, A. and Pandey, P. C., 2001. Oceansat MSMR imaging of the Antarctic and the Southern Polar Ocean. *International Journal of Remote Sensing* 22: 3253-3259.

Davis, C. H. and Ferguson, A. C., 2004. Elevation change of the Antarctic ice sheet, 1995–2000, from ERS-2 satellite radar altimetry; *IEEE Transactions on Geoscience and Remote Sensing.* 42(11): 2437–2445.

De Abreu, R., Wilson K. J., Arkett, M. and Langlois, D., 2002. Evaluating the use of QuikSCAT data for operational sea-ice monitoring. *IEEE International Geoscience and Remote Sensing Symposium* 5:3032-3033.

Drucker, R., Martin, S. and Moritz, R., 2003. Observation of ice thickness and frazil ice in the St. Lawrence Island polynya from satellite imagery, upward looking sonar, and salinity/temperature moorings. *Journal of Geophysical Research* 108(C5): 3149.

Eicken, H. and Lemke, P., 2001. The response of polar sea ice to climate variability and change. *Climate of the 21st century: Changes and risks* 206-211.

Emery, W. J., Fowler, C. W., Hawkins, J. and Preller, R. H., 1991. Fram strait satellite image derived ice motions. *Journal of Geophysical Research* 96 (C3): 4751-4768.

Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M. J., van Angelen, J.H. van den, Broeke, M. R., 2014. An improved mass budget for the Greenland ice sheet. *Geophysical Research Letters* 41: 866–872.

Eppler, D. T., Anderson, M. R., Cavalieri, D. J., Comiso, J. C., Farmer, L. D., Garrity, C., Gloersen, P., Grenfell, T., Hallikainen, M., Lohanick, A. W., Maetzler, C., Melloh, R. A., Rubinstein, I., Swift, C. T. and Garrity, C., 1992. Passive microwave signatures of sea ice. *American Geophysical Union* 68:47-71.

Ferrigno, J. G., Cook, A. J., Foley, K. M., Williams, R. S. J., Swithinbank, C., Fox, A. J., Thomson, J. W. and Sievers, J., 2006. Coastal change and glaciological map of the Trinity Peninsula area and South Shetland Islands, Antarctica: 1843–2001: USGS Geologic Investigations Series. *US Geological Survey: Reston, VA, USA.*

Ferrigno, J. G., Cook, A. J., Mathie, A. M., Williams, R. S. J., Swithinbank, C., Foley, K. M., Fox, A. J., Thomson, J. W. and Sievers, J., 2008. Coastal-change and glaciological map of the Larsen Ice Shelf area, Antarctica: 1940–2005. US Department of the Interior, *US Geological Survey*.

Fraser, A. D., Massom, R. A., Michael, K. J., Galton-Fenzi, B., K. and Lieser, J. L., 2012. East Antarctic land fast sea ice distribution and variability, 2000–08. *Journal of climate* 25: 1137-1156.

Geiger, C. A., and Drinkwater, M.R., 2005. Coincident buoys and SAR derived surface fluxes in the western Weddell sea during ice station Weddell 1992. *Journal of Geophysical Research* 110 (C4).

Gupta, M., Rajak, D. R., Oza, S. R., and Sharma, R., 2016. Derivation of polar sea ice freeboard and thickness using SARAL/AltiKa data. *Scientific Report, SAC/EPSA/GHCAG/CSD/SR/PC/01/2016*. Space Applications Centre, Ahmedabad 380015 India.

Haarpaintner, J., Tonboe, R. T. and Long, D. G., 2004. Automatic Detection and Validity of the Sea-Ice Edge: An application of Enhanced-Resolution QuikSCAT/ Sea Winds Data. *IEEE Transactions on Geoscience and Remote Sensing* 42: 1433-1443.

Haarpaintner, J., 2006. Arctic wide operational sea ice drift from enhanced resolution QuikSCAT/Sea Winds scatterometry and its validation. *IEEE Transactions on Geoscience and Remote Sensing*. 44 (1):102-107.

Heil, P., and Allison, I., 1999. The pattern and variability of Antarctic sea-ice drift in the Indian Ocean and western Pacific sectors. *Journal of Geophysical Research* 104 (C7): 15789-15802.

Helm, V., Humbert, A. and Miller, H., 2014. Elevation and elevation change of Greenland and Antarctica derived from Cryosat-2. *Cryosphere*. 8: 1539–1559.

Jayaprasad, P., Rajak, D. R., Singh, R. K. K., Oza, S. R., Sharma, R. and Raj Kumar, 2014. Ice Calving and Deformation from Antarctic Ice Margins Using Risat-1 Circular Polarization SAR Data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 40(8):525.

Jayaprasad, P., Mehra, R., Chawla, S., Rajak, D. R. and Oza, S. R., 2016. Role of Indian Remote Sensing Imaging Satellites for the Antarctic Monitoring and Mapping: A case Study Around Indian Antarctic Research Stations. *Land Surface and Cryosphere Remote Sensing III* 9877:17. International Society for Optics and Photonics.

Jayaprasad, P. and Misra, A., 2017. A glimpse of India by RISAT-1, Part-1, *ISBN 978-93-82760-26-9*, Space Applications Centre, Ahmedabad, India.

Jayaprasad, P., Ahmad, T., Maity, S. and Misra, A., 2017. Rift Propagation and Ice Calving at Larsen C, Antarctica. *Scientific Report, SAC/EPSA/AMHTDG/MTDD/SR-01/June 2017*. Space Applications Centre, Ahmedabad 380015 India.

Jayaprasad, P., Ahmad, T., Maity, S. and Misra, A., 2018. Breaking News of LARSEN-C from Antarctica, *Current Science* 114 (5): 961-962.

Joshi, P. and Oza, S. R., 2018. Sea ice thickness distribution from AltiKa: A case study of the Indian Ocean Sector in the Antarctic. *Scientific Report, SAC/EPSA/GHCAG/CSD/ SR/128/2018*. Space Applications Centre, Ahmedabad 380015 India.

Joughin, I., Smith, B., Howat, I., Scambos, T. and Moon, T., 2010. Greenland flow variability from ice sheet-wide velocity mapping. *Journal of Glaciology* 56: 416–430.

Kotovirta, V., Jalonen, R., Axell, L., Riska, K. and Berglund, R., 2009. A system for route optimization in ice-covered waters. *Cold Regions Science and Technology* 55: 52-62.

Kumar, A., Dwivedi, S. and Rajak, D. R., 2017. Ocean Sea-Ice Modeling in the Southern Ocean around Indian Antarctic Stations. *Journal of Earth System Sciences* 126(5):70.

Kumar, A., Dwivedi, S., Rajak, D. R. and Pandey, A. C., 2018. Impact of Air-Sea Forcings on the Southern Ocean Sea Ice Variability around the Indian Antarctic Stations. *Polar Science* 18: 197-212.

Kunz, L. B. and Long, D. G., 2006. Melt Detection in Antarctic Ice Shelves Using Scatterometers and Microwave Radiometers. *IEEE Transactions on Geoscience and Remote Sensing* 44: 2461-2469.

Kwok, R., Curlander, J. C., Mc Connell, R. and Pang, S. S., 1990. An ice motion tracking system at the Alaska SAR Facility. *IEEE Journal of Oceanic Engineering* 15: 4454, 1990.

Legresy, B., Blarel, F. and Remy, F., 2006. Along track repeat altimetry for ice sheets and continental surface studies. *Proceedings of the Symposium on 15 Years Progress in Radar Altimetry, Venice, Italy, March 13-18, 2006* 181: ESA-SP614.

Li, M., Zhao, C., Zhao, Y., Wang, Z. and Shi, L., 2016. Polar Sea Ice Monitoring Using HY-2A Scatterometer Measurements, *Remote Sensing* 8(688).

Lindell, D. B. and Long, D. G., 2016. Multiyear Arctic Ice Classification Using ASCAT and SSMIS. *Remote Sensing* 8(294).

Liu, H., Wang, L. and Jezek, K. C., 2006. Spatiotemporal variations of snowmelt in Antarctica derived from satellite scanning multichannel microwave radiometer and Special Sensor Microwave Imager data (1978–2004). *Journal of Geophysical Research: Earth Surface* 111(F1).

Maheshwari, M., Singh, R. Kl. K., Oza, S. R. and Raj Kumar, 2012a. A 30-year analysis of Sea surface temperatures in the polar Oceans. *Scientific Report, SAC/EPSA/AOSG/OSD/SR/01/2012*. Space Applications Centre, Ahmedabad 380015 India.

Maheshwari, M., Singh, R. K. K., Srivastava, A., Dash, M. K., Oza, S. R., Raj Kumar and Vyas, N. K., 2012b. Long-term variability of sea surface temperature and ice concentration over the Antarctic. *National Space Science Symposium (NSSS) 2012*, Tirupati (A.P.), India, Feb. 14-17, 2012.

Maheshwari, M., Singh, R. K. K., Oza, S. R. and Raj Kumar. 2013. An Investigation of the Southern Ocean Surface Temperature Variability

Using Long-Term Optimum Interpolation SST Data. *ISRN Oceanography*, 2013.

Maheshwari, M., Mahesh, C., Singh, R. K. K., Jayaprasad, P., Rajak, D. R., Oza, S. R., Raj Kumar and Sharma, R., 2014. Estimation of sea ice freeboard from SARAL-AltiKa. *International SARAL-AltiKa Science & Applications Meet, 22-24 April 2014*, Space Applications Centre, Ahmedabad, India.

Maheshwari, M., Jayaprasad, P., Rajak, D. R., Oza, S. R. and Sharma, R., 2015a. Arctic sea ice thickness from AltiKa. *Bulletin of the National Natural Resources Management System, NNRMS(B)* 39:102-107.

Maheshwari, M., Mahesh, C., Singh, R. K. K., Jayaprasad, P., Rajak, D. R., Oza, S. R. and Raj Kumar, 2015b. Estimation of Sea Ice freeboard from SARAL-AltiKa data. *Marine Geodesy* 38: 487-496.

Mannarini, G., Coppini, G., Oddo, P. and Pinardi, N., 2013. A Prototype of Ship Routing Decision Support System for an Operational Oceanographic Service. *TransNav, International Journal on Marine Navigation and Safety od Sea Transportation* 7(1).

Martin, S., Drucker, R., Kwok, R. and Holt, B., 2004. Estimation of the thin ice thickness and heat flux for the Chukchi Sea Alaskan coast polynya from Special Sensor Microwave/Imager data, 1990–2001. *Journal of Geophysical Research* 109(C10).

Martin, S., Drucker, R., Kwok, R. and Holt, B., 2005. Improvements in the estimates of ice thickness and production in the Chukchi Sea polynyas derived from AMSR-E. *Geophysical Research Letters* 32(5).

Naoki, K., Ukita, J., Nishio, F., Nakayama, M., Comiso, J. C. and Gasiewski, A., 2008. Thin sea ice thickness as inferred from passive microwave and in situ observations. *Journal of Geophysical Research: Oceans* 113(C2).

Oza, S. R., Vyas, N. K., Singh, R. K. K., Sarkar, A. and Agarwal, V. K., 2008. Polar sea ice observations and analysis using space-borne passive microwave radiometers: A review. *Scientific Report, SAC/RESA/MOG/OSD/SR/01/2008*, Space Applications Centre, Ahmedabad, India.

Oza, S. R., Vyas, N. K., Singh, R.K.K. and Sarkar, A., 2009a. Investigation of the Arctic and Antarctic Sea ice trends from QuikSCAT. *SAC/RESA/MOG/SR/23/2009*, Space Applications Centre, Ahmedabad.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2009b. Study of inter-annual Ku-band backscatter variations of Amery ice shelf, East Antarctica. *ISPRS WG III/6, GEO AG 0703 & ISRS joint international workshop on "Impact of climate change on Agriculture"*, Space Applications Centre, Ahmedabad, Dec. 17-18, 2009.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2009c. Investigations of inter-annual trends in polar sea-ice cover using Ku-band scatterometer data. *Indo-Russian Workshop on Regional Climate Change*, NERC, Oct. 8-9, 2009, Ernakulum, India.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2010a. Inter-comparison of OSCAT and QuikSCAT Ku-band backscatter signatures for polar sea ice. *Scientific Report, SAC/EPSA/AOSG/OSD/SR/51/2010.* Space Applications Centre, Ahmedabad 380015 India.

Oza, S. R., Vyas, N. K. and Sarkar, A., 2010b. Climate change studies of the Arctic and the Antarctic polar ice using active and passive microwave remote sensing. *Bulletin of the National Natural Resources Management System, NNRMS,* December 2010.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2010c. Recent trends of arctic and antarctic summer sea-ice cover observed from space-borne scatterometer. *Journal of Indian Society of Remote Sensing*. 38:611-616.

Oza, S. R., Singh, R. K. K., Vyas, N. K., Gohil, B. S. and Sarkar, A., 2010d. Spatio-temporal coherence based technique for near-real time sea-ice identification from scatterometer data. *Journal of Indian Society of Remote Sensing*. 39: 147-152.

Oza, S. R., Das, I. M. L., Singh, R. K. K., Srivastava, A., Dash, M. and Vyas, N. K., 2011a. Inter-annual variations observed in winter and summer Antarctic sea ice extent in recent decade. *MAUSAM* 62:633-640.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2011b. Spatio-temporal analysis of melting onset dates of sea-ice in the Arctic. *Indian Journal of Marine Sciences*, 40:497-501.

Oza, S. R., Dash, M. K., Singh, R. K. K., Srivastava, A., Das, I. M. L. and Vyas, N. K., 2011c. Investigations of the inter-annual variations of polar ice surface characteristics using altimetric observations, *AltiKa Science Workshop*, March 2011, Space Applications Centre, Ahmedabad 380015 India.

Oza, S. R., Singh, R. K. K, Vyas, N. K. and Sarkar, A., 2011d. Study of inter-annual variations in surface melting over Amery Ice Shelf, East Antarctica using space-borne scatterometer data. *Journal of Earth System Science*, 120:329-336.

Oza, S. R., Singh, R. K. K., Vyas, N. K. and Sarkar, A., 2012a. An atlas of the Arctic and the Antarctic sea ice trends (1999-2009) - derived from QUIKSCAT scatterometer data. *Scientific Report, SAC/EPSA/AOSG/OSD/SR/04/2012*. Space Applications Centre, Ahmedabad 380015 India.

Oza, S. R., Singh, R. K. K., Maheshwari, M., Srivastava, A., Dash, M. K., Raj Kumar and Vyas, N. K., 2012b. Synergistic use of multi-sensor satellite and in-situ data for monitoring and modelling of polar ice sheet and sea ice parameters. *National Space Science Symposium (NSSS) 2012*, Tirupati (A.P.), India, Feb. 14-17, 2012.

Oza, S. R., Singh, R. K. K. and Maheshwari, M., 2013. Investigations of the recent polar ice variations observed from the space borne optical and microwave sensors. In Ramesh, R., Sudhakar, M., Chattopadhyay, S. (Eds.), Scientific and geopolitical interests in Arctic and Antarctic, *Proceedings of International conference on science and Geopolitics of Arctic and Antarctic (iSaGAA)*, March 2013, LIGHTS Research Foundation, New Delhi, India.

Oza, S. R., Maheshwari, M., Singh, R. K. K., Jayaprasad, P., Rajak, D. R. and Raj Kumar, 2014a. Characterizing polar ice surface features using SARAL-AltiKa waveforms. *International SARAL-AltiKa Science & Applications Meet*, April 22-24, 2014, Space Applications Centre, Ahmedabad, India.

Oza, S. R., Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Rajak, D. R., Sharma, R. and Raj Kumar, 2014b. Assessment and Understanding of Energy and Mass Balance Dynamics of Antarctic Ice-sheet. *Scientific Report, SAC/EPSA/AOSG/SR/24/2014*, Space Applications Centre (ISRO), Ahmedabad – 380015, India.

Oza, S. R., 2015. Spatial-temporal patterns of surface melting observed over Antarctic ice shelves using scatterometer data. *Antarctic Science*, 27:403-410.

Oza, S. R., Singh, R. K. K., Jayaprasad, P. and Rajak, D. R., 2016. Spatial and inter-annual variations in surface melting observed over Antarctic ice shelves using scatterometer data. *In Compendium of Research* at SAC, Jan. 2013 - Dec. 2014, 2:464-466.

Oza, S. R., Rajak, D. R., Dash, M. K., Bahuguna, I. M. and Raj Kumar, 2017a. Advances in Antarctic Sea Ice Studies in India. Proceedings of National Academy of Sciences 83:427-435.

Oza, S. R., Suryawanshi, M., Chander, S. and Bahuguna, I. M., 2017b. Spatial-Temporal Variations in Surface Elevation Changes of Antarctic Ice Sheet Observed Using SARAL/AltiKa Data, Proceedings of the *38th Asian Conference on Remote Sensing (ACRS 2017)*, New Delhi, India, October 23 – 27, 2017, 3:1515-1520.

Parkinson, C. L., Comiso, J. C., Zwally, H. J., Cavalieri, D. J., Gloersen, P., and Campbell, W. J. (1987). Arctic sea ice 1973-1976 from satellite passive microwave observations. *NASA Special Publication (489)*.

Patel, S., Shah, E., Jayaprasad, P. and James, M.E., 2016a. Temporal Changes in the Antarctic Ice Margins. *Tropmet symposium*, Bhuvaneshwar, Dec. 18 -21, 2016.

Patel, S., Shah, E., Jayaprasad, P., James, M.E. and Misra, A., 2016b. Analyzing the Temporal Changes in the Antarctic Ice Margins. *SAC/EPSA/GHCAG/MHTD/SR/11/2016.* Space Applications Centre, Ahmedabad 380015 India.

Picard, C. and Fily, M., 2006. Surface melting observations in Antarctica by microwave radiometers: Correcting 26-year time series from changes in acquisition hours. *Remote Sensing of Environment* 104:325-336.

Rajak, D. R., Agarwal, N., Jayaprasad, P., Singh, R. K. K., Oza, S. R. and Sharma, R., 2014a. Comparing Modelled Polar Sea Ice Trend with Remotely Sensed Estimates. *ISPRS TC VIII International Symposium On "Operational Remote Sensing Applications: Opportunities, Progress and Challenges",* Hyderabad, India, Dec 9 – 12, 2014.

Rajak, D. R., Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Oza, S. R., Beg, J. M., Sharma, R. and Raj Kumar, 2014c. Sea Ice Advisory using Earth Observation Data for Ship Routing during Antarctic Expedition. *Scientific Report, SAC/EPSA/AOSG/SR/22/2014*, Space Applications Centre, Ahmedabad, India.

Rajak, D. R., Singh, R. K. K., Jayaprasad P., Oza, S. R. and Beg, M. J., 2015a. Sea Ice Advisories for Indian Research & Supply Vessels Operating in East Antarctica. *COMNAP 2015: Sea Ice Challenges* (Hobart, Tasmania, Australia on May 12-13, 2015).

Rajak, D. R, Agarwal, N., Jayaprasad, P., Singh, R. K. K., Oza, S. R. and Sharma, R., 2015b. Comparing modelled Arctic sea ice trend with remotely sensed estimates. *Journal of Geomatics*, 9: 93-98.

Kumar, 2015c. Sea ice occurrence probability data and its applications over the Antarctic. *Journal of Geomatics*, 9: 193-197.

Rajak, D. R, Singh, R.K.K, Jayaprasad, P., Oza, S. R, Sharma, R., and Raj Kumar, Sharma, R., Singh, R. P., Gupta, P. and Oza, S. R., 2017. SARAL/AltiKa mission: Applications using Ka-band altimetry. Proceedings of National Academy of Sciences*, India. Section A* 87(11):581-592.

Remund, Q. P. and Long, D. G., 1999. Sea Ice Extent Mapping Using Ku-band Scatterometer Data. *Journal of Geophysical Research* 104 (C5): 11 515-11 527.

Remy, F., Flament, T., Michel, A. and Verron, J., 2014. Ice sheet survey over Antarctica using satellite altimetry: ERS-2, Envisat, SARAL/AltiKa, the key importance of continuous observations along the same repeat orbit. *International Journal of Remote Sensing* 35:5497–5512.

Ridley, J., 1993. Surface melting on Antarctic Peninsula ice shelves detected by passive microwave sensors. *Geophysical Research Letters* 23:2639-2642.

Rignot, E. and Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland ice sheet. *Science* 311:986–990.

Rignot, E., Bamber, J. L., Broeke, M. R. V. D., Davis, C., Li, Y., Berg, W. J. V. D. and Meijgaaed, E. V., 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience* 1:106-110.

Rignot, E., Velicogna, I., Van den Broeke, M. R., Monaghan, A. and Lenaerts, J., 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* 38(5).

Rignot, E. and Mouginot, J., 2012. Ice flow in Greenland for the International Polar Year 2008-2009. *Geophysical Research Letters* 39(11).

Rivas, M.B., and Stoffelen, A., 2011. New Bayesian algorithm for sea ice detection with QuikSCAT. *IEEE Transactions on Geoscience and Remote Sensing* 49:1894 -1901.

Rivas, M. B., Otosaka, I., Stoffelen, A. and Verhoef, A., 2018. A scatterometer record of sea ice extents and backscatter: 1992-2016, *The Cryosphere Discuss.*

SARAL/AltiKa products handbook, 2013 SARAL/AltiKa products handbook, *SALP-MU-M-OP-15984-CN,* Available on MOSDAC website (https://www.mosdac.gov.in).

Scientific Committee on Antarctic Research, 2005. *The Antarctic digital database*, Version-4.1, http://www.add.scar.org.

Shah, E., Jayaprasad, P. and James, M. E., 2016a. Monitoring of Mt. Erebus Volcano using Landsat Thermal Infrared Band and Short Wave Infrared Band. *Tropmet symposium*, *Bhuvaneshwar,* Dec 18 -21, 2016.

Shah, E., Jayaprasad P, Mehra, R. and James, M. E., 2016b. Merging of SAR and Optical Data for Characterising Antarctic Ice Features. *Indian Society of Remote Sensing* (*ISRS) Symposium, Dehradun, Dec 7-9, 2016*.

Shah, E., Lyngdoh, R., Jayaprasad P, James, M. E. and Putrevu, D., 2017. Multi-temporal Average Sigma naught variations over Antarctic ice features around Maitri using SAR Data. *Intromet-2017 Poster Presentation*, SAC Ahmedabad, Nov 7-10, 2017.

Shiotani, S., SaSa, K., Tarada, D., Makino, H. and Shimada, Y., 2010. Numerical Navigation for a Ship in Simulation of Waves. Proceedings of the *20th International Offshore and Polar Engineering Conference, Beijing, China*, June 20-25, 2010.

Singh, R. K. K., Oza, S. R., Vyas, N. K. and Sarkar, A., 2011. Estimation of Thin Ice Thickness from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) for a Coastal Polynya in the Chukchi and Beaufort Seas. *IEEE Transactions on Geoscience and Remote Sensing* 49: 2993-2998.

Singh, R. K., K., Maheshwari, M., Srivastava, A., Dash, M. K., Oza, S. R., Raj Kumar and Vyas, N. K., 2012. A 30-year extended analysis of sea surface temperature in the Arctic. *National Space Science Symposium (NSSS) 2012*, Tirupati (A.P.), India, Feb. 14-17, 2012.

Singh, R. K. K., Maheshwari, M., Oza, S. R., and Raj Kumar, 2013. Long-term variability in Arctic Sea Surface Temperatures. *Polar Science*, 7:233-240.

Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Rajak, D. R., Oza, S. R. and Raj Kumar, 2014a. Scatterometric Determination of Antarctic Sea Ice Melt Onset. *Scientific Report, SAC/EPSA/AOSG/SR/19/2014*. Space Applications Centre, Ahmedabad, India.

Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Rajak, D. R., Oza, S. R. and Raj Kumar, 2014b. Determination of Southern Hemisphere Sea Ice Extent from Oceansat-2 Scatterometer data. *Scientific Report, SAC/EPSA/AOSG/SR/20/2014*. Space Applications Centre, Ahmedabad, India.

Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Rajak, D. R., Oza, S. R. and Raj Kumar, 2014c. Determination of Arctic Sea Ice Concentration from Scatterometer Data. *Scientific Report, SAC/EPSA/AOSG/SR/21/2014*. Space Applications Centre, Ahmedabad, India.

Singh, R. K. K., Jayaprasad, P., Rajak, D. R. and Oza, S. R., 2015a. Synergistic use of AltiKa and Special Sensor Microwave Imager/Sounder data for characterizing Arctic cryosphere. *Bulletin of the National Natural Resources Management System, NNRMS(B)*-39:97-101. April 2015.

Singh, R. K. K., Maheshwari, M., Jayaprasad, P., Rajak, D. R., Raj Kumar and Oza, S. R., 2015b. Concurrent use of OSCAT and AltiKa to characterize Antarctic Ice Surface Features. *Marine Geodesy, Marine Geodesy* 38:497-509.

Singh, R. K. K., Singh, K. N., Mainsnam, M., Jayaprasad, P. and Maity, S., 2018. Antarctic sea ice extent from ISRO's SCATSAT-1 using PCA and an unsupervised classification. *Proceedings* 2:340.

Srivastava, A., Das, I. M. L., Oza, S. R., Mitra, A., Dash, M. and Vyas, N. K., 2010. Assessment of sea ice melting rates in the Antarctic from SSM/I observations. *MAUSAM* 62:601-608.

Steffen, K., 1991. Energy flux density estimation over sea ice based on satellite passive microwave measurements, *Annals of Glaciology* 15:178–183.

Suryawanshi, M. R., Jayaprasad, P., Oza, S. R. and Rajak, D. R., 2016. Ice Margin Calving Around Lassiter Coast of Antarctic Peninsula Using SAR Data. Indian Society of Remote Sensing (*ISRS) Symposium, Dehradun,* Dec. 7-9, 2016.

Suryawanshi, M. R., Chander S., Oza, S. R. and Bahuguna, I. M., 2017a. Elevation changes over Antarctic Ice sheet using SARAL/AltiKa Radar Altimeter. *National Conference on Polar Sciences, NCPOR, Goa*, May 16, 2017.

Suryawanshi, M., Chander, S., Oza, S. R. and Bahuguna, I. M., 2017b. Variability in Elevations over Antarctica Ice Sheet during 2013-2016 using SARAL/AltiKa Radar Altimeter. *Scientific Report, SAC/EPSA/GHCAG/CSD/SR/116/2017*. Space Applications Centre, Ahmedabad, India.

Suryawanshi, M., Oza, S. R., Bahuguna, I. M. and Rajawat, A. S., 2018. Grounding zone and ice rise in Antarctica: A case study using SARAL/AltiKa radar repeat pass altimetry. *SAC/EPSA/GHCAG/CSD/SR/120/18.* Space Applications Centre, Ahmedabad, India.

Suryawanshi, M. R., Chander, S., Oza, S. R. and Bahuguna, I. M., 2019. Variability in the ice sheet elevations over Antarctica derived from repetitive SARAL/AltiKa radar altimeter data (2013-2016). *Journal of Earth System Sciences* 128:64-74.

Tedesco, M., 2009. Assessment and development of snowmelt retrieval algorithms over Antarctica from K-band space borne brightness temperature (1979-2008). *Remote Sensing of Environment* 113:979-997.

Troy, B. E., Hollinger, J. P., Lerner, R. M. and Wisler, M. M., 1981. Measurement of the microwave properties of sea ice at 90GHz and lower frequencies. *Journal of Geophysical Research* 86:4283–4289.

Trusel, L. D., Frey, K. E. and Das, S. B., 2012. Antarctic surface melting dynamics: Enhanced perspectives from radar scatterometer data. *Journal of Geophysical Research*: *Earth Surface* 117(F2).

Tsou, M. C. and Cheng, H. C., 2013. An Ant Colony Algorithm for efficient ship routing. *Polish Maritime Research* 20:28–38.

Tucker III, W. B., Grenfell, T. C., Onstott, R. G., Perovich, D. K., Gow, A. J., Shuchman, R. A. and Sutherland, L. L., 1991. Sea ice properties in the winter marginal ice zone. *Journal of Geophysical Research* 96:4573–4587.

Vlachos, D. S., 2004. Optimal Ship Routing Based on Wind and Wave Forecasts. *Applied Numerical Analysis and Computational Mathematics* 1(2): 547 – 551.

Vyas, N. K. and Dash, M. K., 2000. Oceansat-MSMR observes interesting features on the frozen continent and surrounding sea. *Journal of Indian Society of Remote Sensing* 28: 67.

Vyas, N. K., Dash, M. K., Bhandari, S. M., Khare, N., Mitra, A. and Pandey, P. C., 2001. Large scale Antarctic features captured by Multi-Frequency Scanning Microwave Radiometer onboard Oceansat-1. *Current Science* 80: 1319-1322.

Vyas, N. K., Bhandari, S. M., Dash, M. K., Pandey, P. C., Khare, N., Khanolkar, A. and Sharma, N., 2004. An Atlas of Antarctic Sea Ice from OCEANSAT-1. *MSMRSAC-NCAOR-01-2004*. National Centre for Polar and Ocean Research, Goa, India.

Wang, X, Wang, C. and Xi, X., 2016. Spatio-temporal analysis of Greenland snowmelt using microwave radiometer data (1988-2014). *The 6th PEEX Meeting*, 529, 2016.

Wang, X, Wang, C. and Li, B., 2018. Spatiotemporal analysis of Antarctic snowmelt changes using microwave radiometer data (1978-2015). *Fresesius Environmental Bulletin*, 3028-3034.

Williams, R. S. J. and Ferrigno, J. G., 1998. Coastal-Change and Glaciological Maps of Antarctica *USGS Fact Sheet FS* 50–98. https://pubs.usgs.gov/fs/1998/0050/report.pdf.

Wingham, D. J., Ridout, A. J., Scharroo, R., Arthern, R. J. and Shum, C. K., 1998. Antarctic elevation change from 1992 to 1996. *Science* 282:456–458.

Xiaoli, S., Shum, C. K., Kuo, C. and Yi, Y., 2016. Improved Envisat altimetry ice sheet elevation change data processing algorithms using repeat-track analysis. *IEEE Transactions on Geoscience and Remote Sensing* 13(8).

Yueh, S. H., Kwok, R., Lou, S. H. and Tsai, W. Y., 1997. Sea Ice Identification Using Dual-polarized Ku-band Scatterometer Data. *IEEE Transactions on Geoscience and Remote Sensing* 35:560-569.

Zhang, J. and Huang, L., 2007. Optimal Ship Weather Routing Using Isochrone Method on the Basis of Weather Changes. *International Conference on Transportation Engineering* 2650-2655.

Zwally, H. J., Bindschadler, R. A., Brenner, A. C., Martin, T. V. and Thomas, R. H., 1983. Surface Elevation Contours of Greenland and Antarctic Ice Sheets. *Journal of Geophysical Research* 88(C3): 1589-1596.

Zwally, H. J., Li, J., Robbins, J., Saba, J., Yi, D. and Brenner, A., 2015. Mass gains of the Antarctic ice sheet exceed losses. *Journal of Glaciology* 61: 1019-1036.

Annexure: Glossary

[A] Land Ice

1. Ablation: The removal of material from a glacier, melting, evaporation, or calving (bits dropping off the end into the sea to form icebergs). Opposite of accumulation. That portion of a glacier where more material is lost (by melting or evaporation) than gained by snowfall is called ablation zone.

2. Accumulation: The addition of material to glaciers, snow, rain, material blown by wind, and avalanches. Opposite of ablation. The region of the glacier where mass is only added (as snow or rain), no mass is lost. Usually this area is near the origin of the glacier at higher altitudes is called accumulation zone.

3. Blizzard: A cold storm with winds of at least 56 kilometres per hour (35 miles per hour) and temperatures below - 6.7°C (20°F). Usually also characterized by poor visibility due to snow blowing around. Little snow may actually fall during a blizzard, the high winds pick up snow from the ground and carry it around, and visibility is often greatly reduced.

4. Blue ice: A bare ice section of any ice shelf or ice sheet where air bubbles are squeezed out, ice crystals are enlarged and it appears blue in colour.

5. Calve: The formation of an iceberg from a glacier. Once the ice flowing from a glacier reaches a body of water it begins to float and may crack at the "hinge zone", once free of the glacier a piece of ice becomes an iceberg and the glacier has calved.

6. Crevasses: A deep, usually vertical, crack or split in a glacier occurs as a result of the brittle ice flowing over a uneven surface beneath the ice. Crevasses can easily become covered by blown snow, even very wide ones. Great care must be taken when crossing ice and snow fields to avoid them as falling down one is really going to hurt.

7. Firn: A transitional stage between snow and glacial ice, a type of snow that has survived a summer melting season and has become more compact than freshly falling snow.

8. Fjord (fiord): A long, narrow, steep-walled, u-shaped coastal inlet. Fjords typically have been excavated by glaciers.

9. Glacier: A mass of ice predominantly of atmospheric origin, usually moving from higher to lower ground. A seaward margin of a glacier that is aground, the rock basement being at or below sea-level, is termed an ice wall. The projecting seaward extension of a glacier, which is usually afloat, is termed a glacier tongue. In the Antarctic, glacier tongues may extend over many tens of kilometres.

10. Grounding line: The point a glacier that is flowing into a sea or lake loses contact with seafloor and begins to float as an ice shelf.

11. Iceberg: A massive piece of ice of varying shape, protruding more than 5 m above sea-level, which has broken away from a glacier or an ice shelf, and which may be afloat or aground. Icebergs by their external look may be subdivided into tabular, dome-shaped, sloping and rounded bergs.

12. Ice cap: A large dome-shaped mass of ice that is thick enough to cover all the landscape beneath it so appearing as a smooth coating of ice. Ice caps are smaller than ice sheets, usually under 50,000 square kilometres (19,000 square miles). Ice caps can deform and flow with gravity and spread outward in all directions.

13. Ice cliff: Walls of ice where glaciers meet the sea. Ice cliffs occur because icebergs calve from the front of them giving a continually breaking edge the full height of the glacier.

14. Ice crystals: Tiny particles of ice that grow on all surfaces when the air is supersaturated with water (cold air doesn't hold much moisture so ice crystals are readily formed in Antarctica). Ice crystals account for the majority of the accumulation of glacial ice on the Polar Plateau. They may also be referred to as ice needles, even though they are not needle shaped.

15. Ice rise: An ice shelf touching the ground or having a ground support.

16. Ice sheet: A large mass of ice that is thick enough to cover the landscape beneath it so appearing as a smooth coating of ice. Ice sheets can deform and move with gravity, they are larger than ice caps. Ice sheets cover much of Greenland and Antarctica.

17. Ice shelf: A large flat-topped sheet of ice that is attached to land along one side and floats in the sea or a lake. A floating ice sheet of considerable thickness showing 2-50 m or more above sea level, attached to the coast or a glacier. Usually of great horizontal extent and with a level or gently undulating surface. Nourished by annual snow accumulation at the surface and often also by the seaward extension of land glaciers. Limited areas may be aground. The seaward edge is termed an ice front.

18. Nunataks: An isolated peak of bedrock that sticks above the surface of an ice sheet. They are the peaks of hills and mountains standing above the ice sheet which flows around them. They offer important information about ice covered regions as they provide a sample of the rocks that lie under the ice.

19. Sastrugi: Irregular ridges of snow on a small scale (rarely more than 1 foot, 30cm) that lie parallel to the direction of the wind. Sastrugi can make travel very awkward or difficult; they can be quite soft or as hard as ice.

20.White-out: A weather condition in which the horizon cannot be identified and there are no shadows. The clouds in the sky and the white snow on the ground blend - described as like walking along inside a ping-pong ball. White out conditions are potentially dangerous because it is difficult to find a point of reference and it is very easy to walk over a cliff or fall down a crevasse in such conditions.

[B] Sea Ice

1. Bare ice: Ice without snow cover.

2. Compact pack ice: Floating ice in which the concentration is 10/10 and no water is visible.

3. Consolidated ice: Floating ice in which the concentration is 10/10 and the floes are frozen together.

4. Dark nilas: Nilas, which is under 5 cm in thickness and is very dark in colour.

5. Fast ice: Consolidated solid ice attached to the shore, to an ice wall or to an ice front. It forms by freezing to the shore of the ice cover forming in the coastal zone or as a result of freezing of drifting ice of any age category to the shore or fast ice. Vertical movement may be observed during tidal oscillations. It can be preserved without fracturing for two or more years transforming from first-year ice to multiyear ice and even shelf ice. The fast ice width can vary from several hundreds of meters to several hundreds of kilometres. That part of fast ice presenting a narrow fringe of ice directly attached to the coast with a shallow bottom and unresponsive to tidal oscillations that remains after the fast ice has moved away is called the Ice foot. Fast ice at the initial stage of formation consisting of nilas and young ice with a width up to 100-200 m is called young coastal ice. When coding and depicting fast ice on ice charts, total concentration is not indicated as this is always equal to 10/10 in accordance with the definition.

6. First-year ice: Sea ice of not more than one winter's growth, developing from young ice; thickness 30 cm to 2 m, and sometimes slightly more. May be subdivided into thin first-year ice/white ice, medium first-year ice and thick first-year ice.

7.Flaw lead: A passage-way between pack ice and fast ice which is navigable by surface vessel. [Note: shore lead is used in the Antarctic]

8. Floe: Any relatively flat piece of sea ice 20 m or more across. Floes are subdivided according to horizontal extent as follows: **Giant** - Over 10 km across; **Vast -** 2 to 10 km across; **Big** -500 to 2000 m across; **Medium** -100 to 500 m across; and **Small -** 20 to 100 m across.

9. Frazil ice: Fine spicules or plates of ice, suspended in water.

10. Grease ice: A later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the sea a matt appearance.

11. Grey ice: Young ice 10-15 cm thick. Less elastic than nilas and breaks in swell. Usually rafts under pressure.

12. Grey-white ice: Young ice 15-30 cm thick. Under pressure it is more likely to ridge than to raft.

13.Ice drift: Displacement of ice floes and other ice features resulting from the impact of wind and currents including tidal currents and of forces transferred through the ice cover from other regions. The drift direction and velocity of a specific ice feature or ice cover area depends at any specific moment on the magnitude of the external forces, on the feature is characteristics (size, concentration and upper and lower surface roughness), on its position relative to the coastline and on the seabed relief.

14. Light nilas: Nilas which is more than 5 cm in thickness and rather lighter in colour than dark nilas. Young ice is in the transition stage between nilas and first-year ice, 10-30 cm in thickness. May be subdivided into grey ice and grey-white ice.

15. Lead: A more than 50 m wide rectilinear or wedge-shaped crack from several kilometres to several hundreds of kilometres in length. At below freezing temperatures, new, nilas and young ice forms at the surface of leads.

16. Multi-year ice: Old ice up to 3 m or more thick that has survived at least two summers' melt. Hummocks are even smoother than in second-year ice and attain a look of mounds and hills. The surface of multiyear ice fields in places not subject to deformations is also hillocky due to non-uniform multiple melting. The ice is almost salt-free. Its colour, where bare, is usually blue. As a result of melting, round puddles appear at its surface in summer and a well-developed drainage system is formed.

17. New ice: A general term for recently formed ice, which includes frazil ice, grease ice, slush and shuga. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definite form only while they are afloat.

18. Nilas: A thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking 'fingers' (finger rafting). Has a matt surface and is up to 10 cm in thickness? May be subdivided into dark nilas and light nilas.

19. Old ice: Sea ice which has survived at least one summer's melt; typical thickness up to 3m or more. It is subdivided into residual first-year ice, second-year ice and multi-year ice.

20. Open water: A large area of freely navigable water in which sea ice is present in concentrations less than 1/10 and ice of land origin is absent.

21. Pack ice: Any ice at the sea surface except for fast ice and stamukha regardless of its age, form, origin and other characteristics that has a possibility of movement (drift) under the action of winds, currents and tides. As a result of the dynamic processes (drift, divergence, convergence), the total and partial concentrations of drifting ice constantly change.

22. Pancake ice: Predominantly circular plates of ice from 30 cm to 3 m in diameter, and up to about 10 cm in thickness, with raised rims due to the pieces striking against one another. It

may be formed on a slight swell from grease ice, shuga or slush or as a result of the breaking of ice rind, nilas or, under heavy swell, of grey ice.

23.Polynya: A stable ice-free water space in or at the boundary of fast ice. Polynyas may contain very open broken and brash ice or be covered with new ice, nilas or young ice. A polynya is sometimes restricted by the shore from one side and is termed a shore polynya. If it is restricted by fast ice, then it is termed a flaw polynya. If it recurs in the same position every year, it is termed a recurring polynya [Note: polynyas can form in the pack, e.g. in the Weddell Sea].

24. Residual first-year ice: First-year ice that has survived the summer melt and is now in the new cycle of growth. It is 30 to 180 cm thick depending on the region where it was in summer. After 1 January (in the Southern Hemisphere after 1 July), this ice is called second-year ice.

25. Sea ice: Ice, which has originated from the freezing of sea water. It presents the main kind of floating ice encountered at sea.

26. Sea ice concentration: The ratio of the area of ice features to the total area of a sea part (zone) delineated on the chart, expressed in tenths. The total concentration includes all stages of development and the partial concentration includes areas of ice of specific age or arrangement which comprise only part of the total concentration. Concentrations within 0-1/10 to 10/10 from instrumental observations can be expressed in hundredths.

27. Second-year ice: Old ice which has survived only one summer's melt; typical thickness up to 2.5 m and sometimes more. Because it is thicker than first-year ice, it stands higher out of the water. Ridged features as a result of melting during the preceding summer attain a smoothed rounded shape. In summer, numerous puddles of extended irregular shape form on its surface. Bare ice patches and puddles are usually greenish-blue.

28. Shore lead: A lead between pack ice and the shore or between drift ice and an ice front.

29. Shuga: An accumulation of spongy white ice lumps, a few centimetres across; they are formed from grease ice or slush and sometimes from anchor ice rising to the surface.

30. Slush: Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

31.Stamukha (Grounded hummock): A thick hummocked grounded ice formation. Stamukhas form from floe bergs and hummocked grounded ice fragments. They are distinguished by a large height (up to 10 m and more above sea level) and steep slopes. There are single grounded hummocks and lines (or chains) of grounded hummocks. Stamukhas forming at the same place from season to season are termed recurring Stamukhas.

References of Glossary

1. WMO SEA ICE NOMENCLATURE, Version 1.0, prepared by Dr A.V. Bushuyev, Russian Federation. http://www.aari.ru/gdsidb/docs/wmo/nomenclature/WMO_Nomenclature_draft_version1-0.pdf (WMO_Nomenclature_draft_version1-0.pdf).
2. WMO Sea-Ice Nomenclature, volumes I, II and III. WMO-No.259. https://www.jcomm.info/index.php?option=com_oe&task=viewDocumentRecord&docID=14598. (Sea_Ice_Nomenclature_March_2014.pdf).
3. Cryosphere Glossary. National Snow & Ice Data Centre (NSIDC). https://nsidc.org/cryosphere/glossary.

Front Cover:

Part of Resourcesat-2 LISS-III FCC of 06-02-2018 covering region around Bharati Research Station in East Antarctica (location indicated by red dot).

Back Cover:

Man's tryst with the wilderness (Upper Left): The nature creates innumerous crafts in its cradle but one needs the heart and mind to interpret which one can only do by being with the nature…!!!(Field photograph captured on 17-02-2017 during 36 ISEA; Geo location: 68^0 38’ 28.23’’ S, 73^0 15’ 13.40’’ E).

Descending into the sublime (Upper Right): The first sighting as one descends is an amazing formation of ice crystals hanging delicately from the cave roof. (Field photograph captured on 18-03-2017 during 36 ISEA; Geo location: 70^0 45’ 51.76’’ S, 11^0 37’ 47.83’’ E).

Future in quandary (Lower): Tabular iceberg calved from the continental ice sheet, says a lot…!!! (Field photograph captured on 17-01 -2017 during 36 ISEA; Geo location: 69^0 11’ 59.12’’ S, 76^0 29’ 26.90’’ E).