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Research Paper

Polar Ice Sheet and Glacier Studies – Indian Efforts in last Five Years

PRAVEEN K THAKUR, ARPIT CHOUKSEY, S P AGGARWAL and A SENTHIL KUMAR*
Indian Institute of Remote Sensing, Indian Space Research Organisation, Dehradun 248 001, India

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Indian scientists have been involved in studies of cryosphere in Polar Regions from past 35 years. For continuous monitoring and expanding research in the fields of atmospheric science, geosciences, glaciology, environmental sciences, etc. specific to these regions, the ESSO - National Centre for Antarctic and Ocean Research (ESSO-NCAOR) has established three permanent research stations in Antarctica. This paper addresses efforts by Indian scientists in last five years in cryospheric studies on the Antarctica using remote sensing data. Inventories of Antarctic glaciers and ice sheet features prepared by Indian researchers have facilitated for detailed long-term studies on glacier dynamics, sea ice, fluctuations of the continental ice margin and snouts of glaciers. For safe and optimal navigation of ships, a sea ice advisory has been also set up. This paper also addresses recent efforts of using high-resolution earth observation satellite data which were acquired for geospatial mapping of cryospheric features and glacial landforms and for delineation of wind induced snow deposition zones in part of the Antarctica. Spatiotemporal dynamics of surface melting over Antarctic was further studied by using moderate resolution satellite data.

Keywords: Glaciers; Ice Sheet Features; Remote Sensing; Cryospheric Features

Introduction

After the oceans, the cryosphere is the second largest component of the climate system that holds around 69% of the global freshwater resource (Shiklomanov, 1993). Various components of the cryosphere (snow, lake ice, sea ice, glaciers, ice caps, ice shelves and ice sheets) contribute to short-term climate changes, whereas the ice shelves and ice sheets also contribute to long-term changes including the ice age cycles. Thus, monitoring the changes in the cryosphere regions is very essential. Antarctic region plays an important role in the global climate change. Indian researchers have been carrying out observations on major components of the global cryosphere in the Himalayas, Antarctic and Arctic regions. Ice sheets are the greatest potential source of global freshwater ice, holding approximately 99% of the global total. This corresponds to 64 m of world sea-level equivalent, with Antarctica accounting for 90% of this rise. This paper highlights the studies carried out by Indian scientists using high – resolution optical well as microwave data in Antarctic region only during last 5 years.

This paper is organised as follows: In Section 2, application of satellite based remote sensing techniques by ISRO and ESSO-NCAOR on Antarctic studies is described. Our conclusions are given in Section 3.

Satellite-based Remote Sensing for Antarctic Studies

With high-resolution sensors on-board and high revisiting capability over the Polar Regions, the Polar orbiting satellites are best suited for Antarctic studies. Currently, three major Indian institutions involved in utilizing the satellite data for Antarctic surface and subsurface data analysis are (i) ESSO-National Centre for Antarctic and Ocean Research (ESSO-NCAOR), (ii) Geological Survey of India (GSI), and (iii) Indian Space Research Organisation (ISRO). Some of the salient outcomes of the studies carried out by ISRO are as follows:

Ship Navigation Advisory Efforts

Sea Ice advisory and utilization of RISAT-1 and

*Author for Correspondence: E-mail: senthil@iirs.gov.in

SARAL AltiKa derived free-board Climatic Sea Ice Occurrence Probability (SIOP) and sea ice type data has been operationalized for safer ship navigation by ISRO, Ahmedabad (Maheshwari *et al*., 2015; Rajak *et al*., 2014; Rajak *et al*., 2015). Results of these studies can be visualised on the website (SAC, 2015). The major highlights in this web portal are sea ice advisory and RISAT-1 CRS based 36m mosaic for Antarctic region.

Indian satellite RISAT-1 C-band imagery was used for geospatial mapping of cryospheric surface features in the Antarctic environment (Jawak *et al*., 2015a). Geospatial mapping of vegetation in the Antarctic environment using very high resolution WorldView-2 data was also done by Indian researchers (Jawak and Luis, 2014). Mapping of shoreline of more than 100 lakes on Larsemann hills and 10 lakes on Schirmacher Oasis with an accuracy of 1 meter, as a reference data for validation of algorithms for semi-automatic extraction of lake features using satellite data was completed (Jawak and Luis, 2014; Jawak *et al*., 2015b; Jawak *et al*., 2015c). Ice calving and deformation from ice margins and spatio-temporal change detection were detected using RISAT-1 SAR data. Large scale disintegration was reported at two prominent glacier tongues namely Polar Record Glacier and Polar Times Glacier. The results were verified by observations made during 33rd Indian Scientific Expedition to Antarctica (ISEA).

High-Resolution Satellite Data Applications

ESSO-NCAOR has produced the first operational digital elevation models (DEMs) for Larsemann Hills and Schirmacher Oasis, East Antarctica, using interferometric and photogrammetric techniques. To improve the DEM quality further, a precise DEM was generated by interactive synthesis of multi-temporal elevation datasets. Due to improved vertical accuracy compared to existing Antarctic DEMs, these indigenous DEMs have gained a significant attention (Jawak and Luis, 2014). An enhanced digital elevation model (DEM) of the Larsemann Hills region, east Antarctica, is constructed synergistically by using highly accurate ground-based GPS measurements, satellite-derived laser altimetry (GLAS/ICESat) and Radarsat Antarctic Mapping Project (RAMPv2) DEM-based point elevation dataset. This DEM has a vertical accuracy of about 1.5 times better than RAMPv2 DEM and seven times better than GLAS/ ICESAT-based DEM. The accuracy was improved by validating the RAMPv2 DEM elevation by supplementing with GLAS/ICESat and DGPS survey data, when compared to that of DEM constructed by using GLAS/ICESat or RAMPv2 alone. With the use of accurate GPS data as ground control points based reference elevations, the DEM extracted is much more accurate with least mean Root Mean Square Error (RMSE) of 34.5 m than that constructed by using a combination of GLAS/ICESat and RAMPv2 as true reference. The newly constructed DEM achieves highest accuracy with the least average elevation difference of 0.27 m calculated using 46 ground reference points. Available DEMs of Antarctic region generated by using radar altimetry and the Antarctic digital database indicate elevation variations in the range of 50-100 m, which necessitates the generation of local DEM and its validation by using ground truth. This was first attempt of fusing multi-temporal, multi-sensor and multi-source elevation data to generate a DEM of any part of Antarctica, in order to address the ice elevation change to infer the ice mass balance. This hybrid approach focuses on the strengths of each elevation data source to produce an accurate DEM (Jawak and Luis, 2014).

Recently, a study has been done by ISRO, Dehradun to identify and map the various ice sheet features and glacier landform in part of Antarctic using high resolution optical Cartosat-2 (resolution~1m) and RISAT-1 FRS1 (resolution~3m) datasets (Kumar *et al*., 2015). This work was done for Princess Astrid area of the coast of Queen Maud Land lying between 5° and 20° E. The study has used CARTOSAT-2 and Landsat optical datasets for its analysis and mapping. A total of 264 CARTOSAT-2 scenes from time period of December 2014 and February 2015 were acquired from ISRO in geotiff format in transverse Mercator projection on user request from 2014-15 Indian Antarctic expedition by scientists of the ESSO-NCAOR, Goa under the Ministry of Earth Sciences (MoES). All datasets were ortho-rectified with Aster GDEM (30m) in polar stereo graphic projections systems taken from Landsat 8 datasets. In first part of this work an image album has been made highlighting some of the major ice sheet features and glacier landforms present at Antarctica using ISRO's high resolution satellite CARTOSAT-2. In second part, RISAT-1 FRS1 and some MRS data has been used

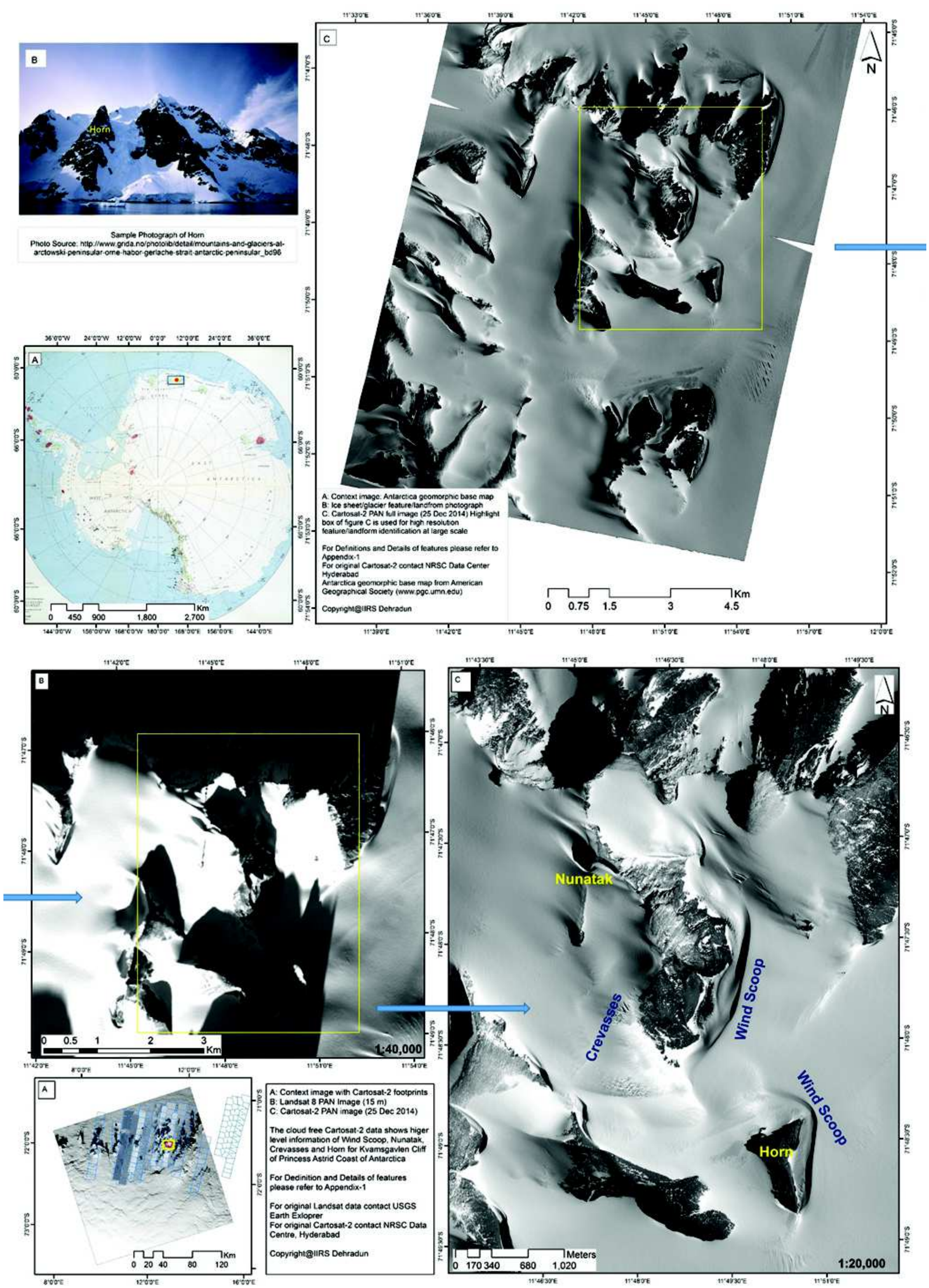

Fig. 1: Identified ice sheet features and glacier landforms in study area example from Antarctica image album showing one full map set (full cartosat-2 image and highlighted part)

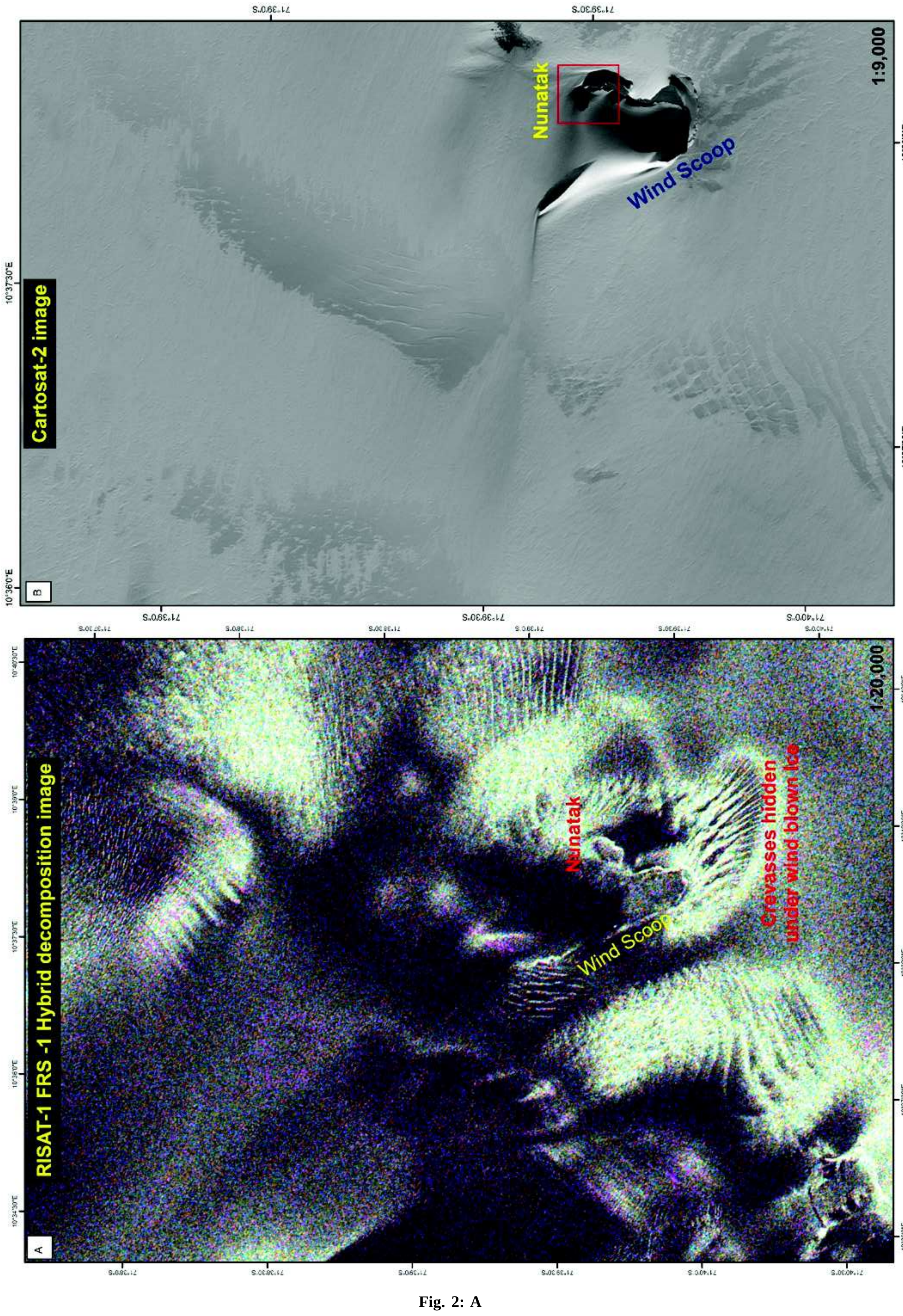
Cartosat-2 image
Nunatak
Wind Scoop
1:9,000
B
RISAT-1 FRS -1 Hybrid decomposition image
Nunatak
Wind Scoop
Crevasses hidden under wind blown ice
1:20,000
A

Fig. 2: A

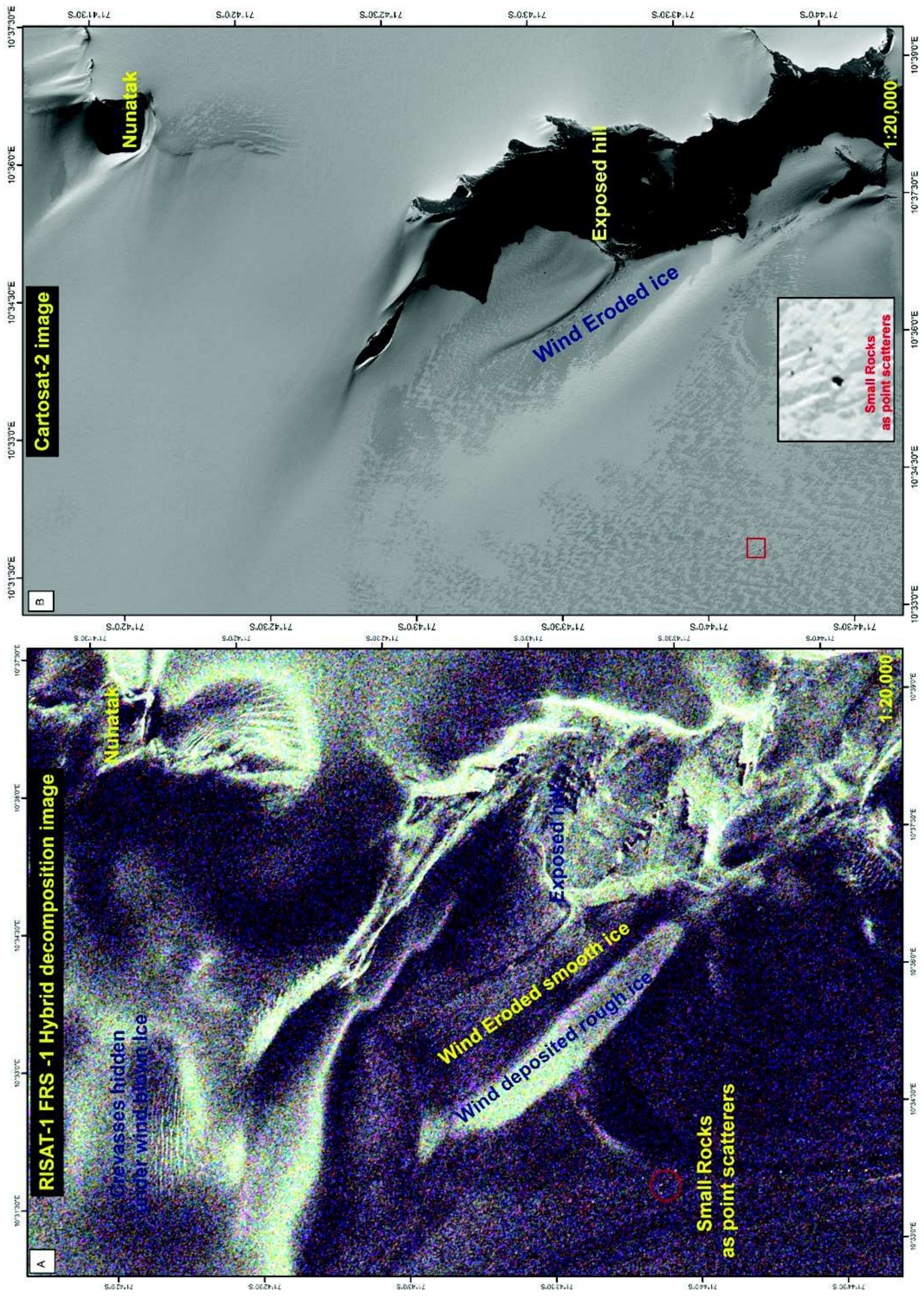
Cartosat-2 image
Nunatak
Exposed hill
Wind Eroded ice
Small Rocks as point scatterers
1:20,000
B
RISAT-1 FRS -1 Hybrid decomposition image
Nunatak
Exposed hill
Wind Eroded smooth ice
Wind deposited rough ice
Crevasses hidden under wind blown ice
Small Rocks as point scatterers
1:20,000
A

Fig. 2: B

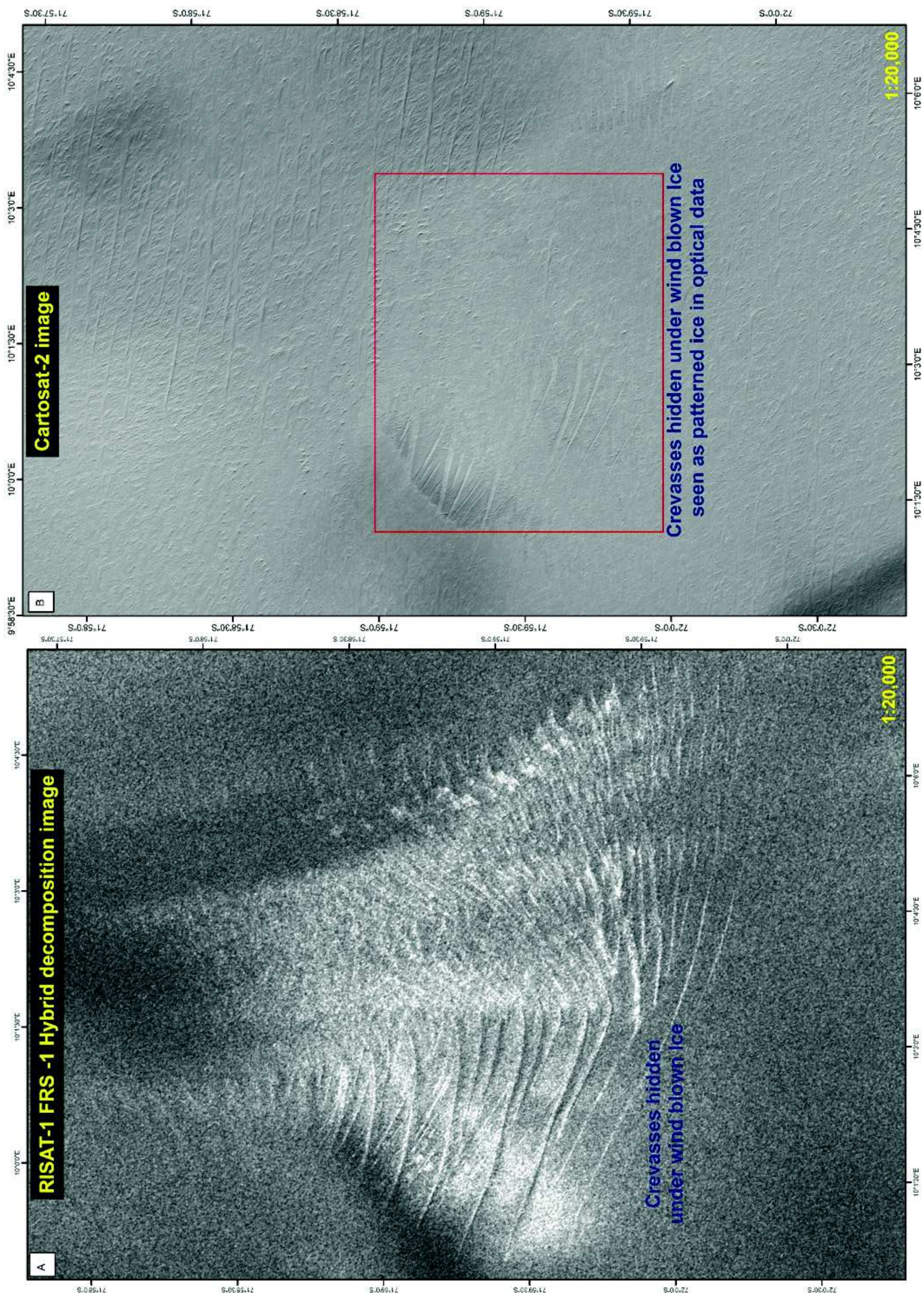
Cartosat-2 image
B
Crevasses hidden under wind blown ice
seen as patterned ice in optical data
1:20,000
RISAT-1 FRS -1 Hybrid decomposition image
A
Crevasses hidden
under wind blown ice
1:20,000

Fig. 2: C

Fig. 2: D

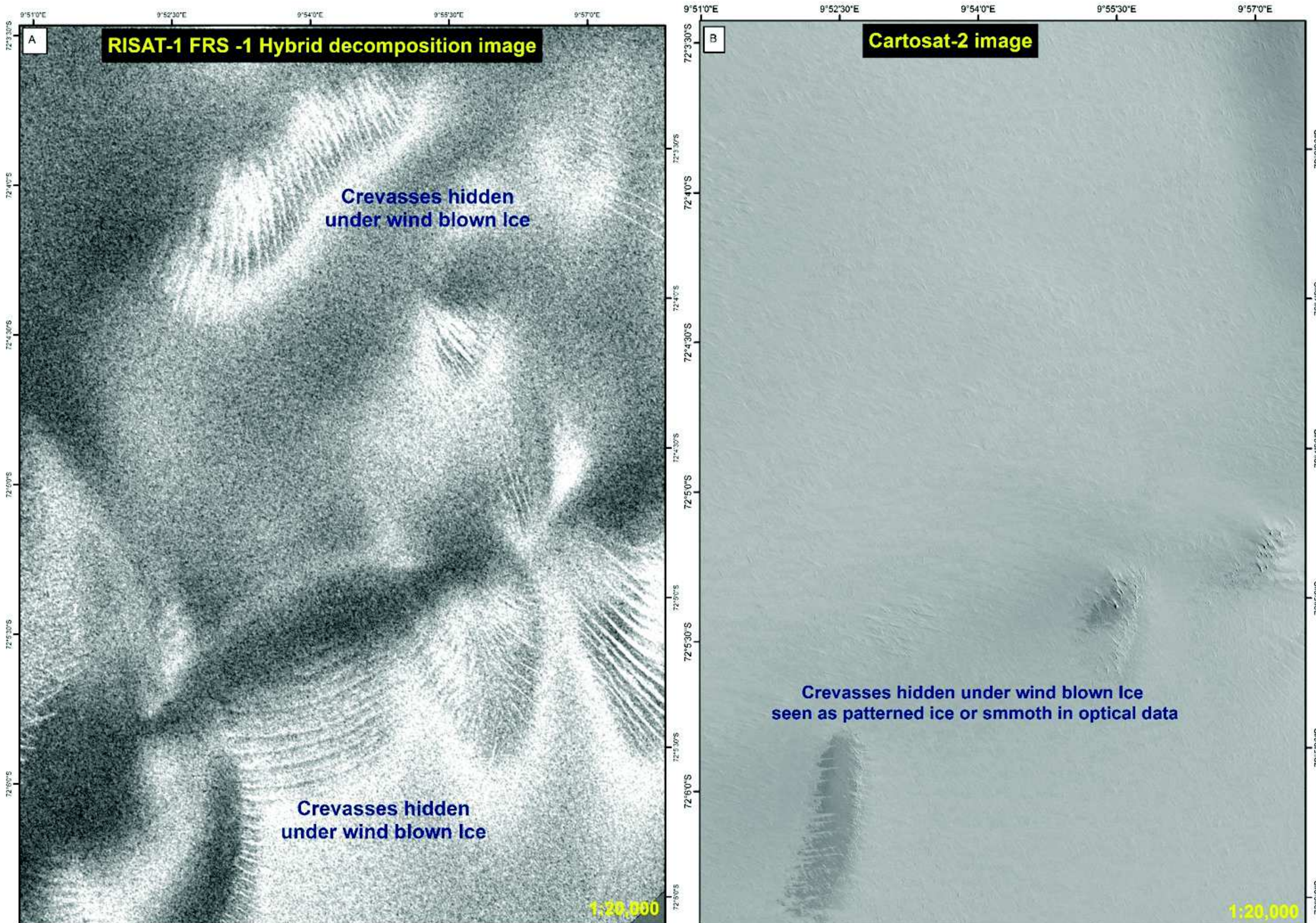

Fig. 2: (A-D): Comparison of ice sheet feature identified using RISAT-1 FRS-1 (3m) and CARTOSAT-2 (< 1m) high resolution satellite for common areas near Princess Astrid coast, Antarctica

to identify additional ice sheet and glacier features which were not detected by optical data (Thakur *et al*., 2016). The CARTOSAT-2 high resolution images were used to identify and map some of the unique ice sheet and glacier features such as crevasses, sastrugi, nunatak, ice ridges, wind scoops, rim lines, moraines, blue ice area (BIA) and deposited snow (Fig. 1). Quantification of geomorphic parameters such as size, shape, length, area were carried out using orthorectified CARTOSAT-2 and RISAT-1 FRS1 images.

In addition, some of the ice sheet features such as crevasses and sastrugi, which are not clearly visible in optical sensor data due to wind induced snow deposition, are clearly visible in RISAT-1, FRS1 data. Mapping of such features deposited under snow is feasible only in SAR datasets due to penetration capability of C-band SAR in dry snow packs (Fig. 2A-D). Spatio-temporal changes in these features due to wind and glacier movement is quantified by utilizing time series of cloud free orthorectified Landsat 8 Images. Support Vector Machine (SVM) based supervised classification techniques have been used with Landsat-8 datasets of year 2013 and 2014 for mapping some of these features and overall classification has given satisfactory results of the mapped features with overall accuracy of 91 to 94%. Further, to quantify and understand wind dynamics, wind speed and direction vector mapping was done using 10 km resolution Antarctic Mesoscale Prediction System (AMPS) datasets for the selected areas during the period of May 2013 to June 2015 on daily to monthly mean basis. These winds maps are generated to analyse the movement of winds with reference to erosional and depositional processes in the selected areas. The above study and analysis has explained the process of erosion and deposition by the wind with reference to its movement and velocity. Wind speed in this area is very high, ranging from 9.14 to 16.72 m/s. Mountainous barriers and Nunatak creates the katabatic winds that generate the huge wind scoops approximately 15m wide around Nunataks. Also the longitudinal glacier flow-strips are mapped from CARTOSAT-2 image and RISAT-1 data between the area of Wohlthat Mountains and Orvin Mountains of East Antarctica. Mapping of the flow lines of the Glaciers between the above mountains was generated to study the pattern of glacier flow lines for Somovken glacier and its flow directions with respect to its depositional and erosional processes.

Additionally, Jawak and Luis (2014) evaluated the potential of 8-band high resolutionWorldView-2 (WV-2) panchromatic (PAN) and multispectral image (MSI) data for the extraction of polar geospatial information. In this study, they introduced a novel method based on a customized set of normalized difference Spectral Index Ratios (SIRs), incorporating multiple bands, to improve the accuracy of land-cover mapping. Most recently available WV-2 data are classified into land-cover surfaces such as snow/ice, water bodies, and landmass using the customized normalized difference SIRs. Jawak *et al.* (2015d) also reviewed various methods for deriving bathymetry information using remote sensing technologies.

Indian scientists have extensively used remote sensing techniques to complement the ground surveys and Geographical Information Systems (GIS) to study the physiography, mass balance of glaciers and other polar studies. ISRO used over forty scenes of NOAA AVHRR data in two formats, local area coverage (LAC) and SCRIPPS to construct a 1km three-band Antarctic mosaic in year 2009 (NRSC, 2015). This paper demonstrates the strengths of Indian researchers to extract and study various information about Antarctic region.

The Ice Sheet Dynamics around Dakshin Gangotri Glacier, Schirmacher Oasis, East Antarctica was studied by Shrivastava *et al.* (2011). Recession of the snout of Dakshin Gangotri glacier in the western part of Schirmacher Oasis, East Antarctica has been recorded over two decades. The notable difference in the rate of recession in different parts of the Dakshin Gangotri glacier overriding Schirmacher Oasis can be attributed to combined effect of natural factors, including meteorological parameters, ice sheet dynamics and geomorphology of that area. Global positioning system (GPS) campaigns were conducted during summer seasons to obtain insight into the velocity and strain-rate distribution on Schirmacher Glacier, central Dronning Maud Land, East Antarctica. GPS data were collected at 21 sites and analysed to estimate the site coordinates, baselines and velocities (Sunil *et al*., 2007). The velocity and strain-rate distributions across the GPS network in Schirmacher Glacier were spatially correlated with topography, subsurface undulations, fracture zones/crevasses and the partial blockage of the flow by Nunataks and the Schirmacher Oasis (Fig. 3).

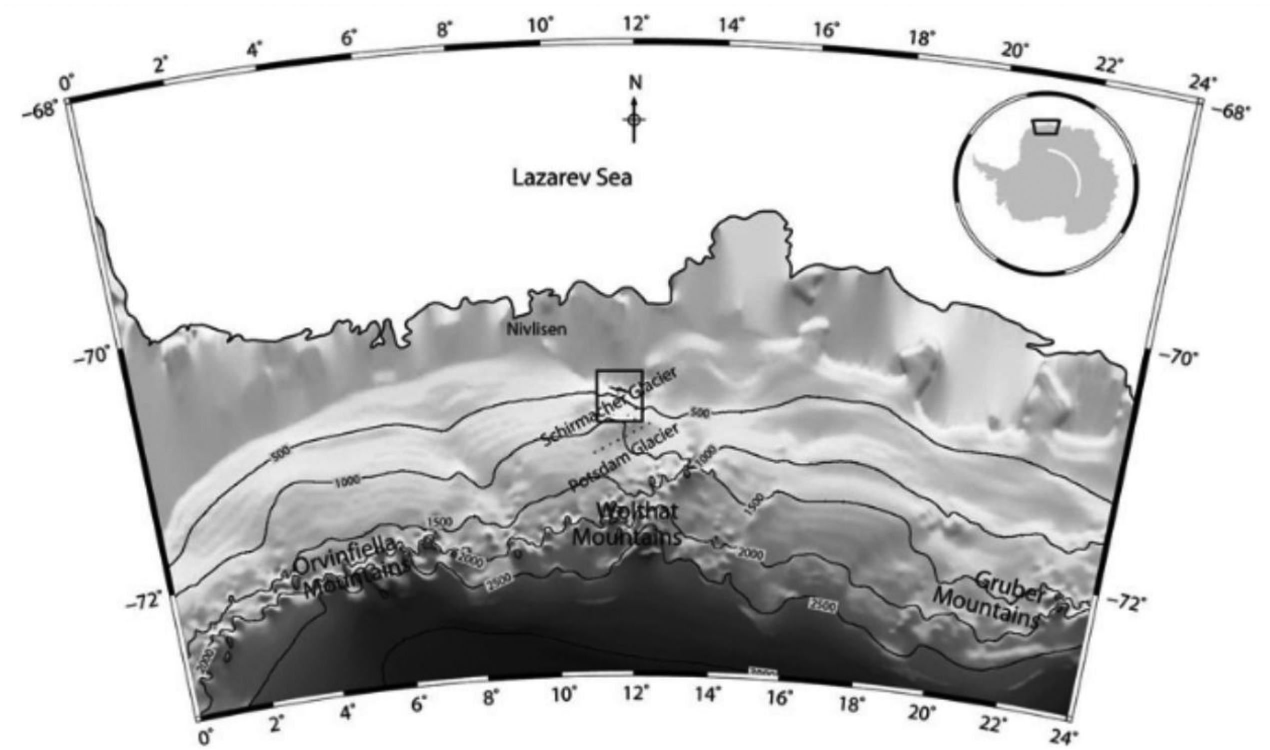

Fig. 3: Location map of central Dronning Maud Land, East Antarctica, showing the study area of Schirmacher Glacier (rectangle) superimposed on a shaded relief map of GTOPO30 digital elevation model with 500m elevation contour interval. Sunil *et al.* (2007)

During Indian Antarctic Expeditions, monitoring of iceberg is an important programme of GSI since very beginning (GSI, 2015). Iceberg monitoring in the Antarctic waters done by Asthana *et al.* (2013) during onward voyage of 24th Indian Antarctica Expedition has revealed concentration of icebergs in two well defined zones separated by an iceberg free zone. They found large variations in the size and shape of the icebergs. They also observed a continuous shift of icebergs position in north-east direction between 50°S to 54°S latitudes and can be related with the Sub-Antarctic front (SAF) and Antarctic Circumpolar Current (ACC).

Melt-Freeze Study of Antarctic using Moderate Resolution Satellite Data

Scientists from ISRO, Ahmedabad and Hyderabad studied the spatiotemporal dynamics of surface melting over Antarctica and developed a methodology to detect and monitor snowmelt and freeze from microwave scatterometer data as this is of importance in understanding the response of ice shelves to climate change (Oza *et al*., 2011; Bothale *et al*., 2015). The association of scatterometer backscatter observations with the snow-pit observations helped in the investigation of inter-annual variations in surface melting was first carried out using space-borne scatterometer data (Oza *et al*., 2011). In next study, K_u band scatterometer based normalised radar backscatter was used, which is sensitive to the water content of snow. In this study, QuikSCAT and OSCAT Enhance Resolution Image data available at, http://www.scp.byu.edu/, in slice mode at 2.225 km resolution were studied. All passes of HH resolution data has been used in the study. Analysis has been done for data from 2001 to 2014. Both the sensors provide daily data for Polar Regions in 13.6GHz. The crossing time for QuikSCAT is 10:30 AM for descending and 10:30PM for ascending pass. Similarly the crossing time for descending pass of OSCAT is 11:30AM and 11:30PM for ascending pass. With the increase in the liquid water content in the snow, there is a sudden decrease in the backscatter from radar. This was used as the basis of melt detection. An adaptive threshold based classification using austral winter mean and standard deviation of HH polarization radar backscatter data is considered. Spatiotemporal dynamics of snow melt in Antarctica from 2001 to 2014 using microwave scatterometer data from OSCAT and QuikSCAT is generated at 2.25 km resolution at daily interval, and derived snow melt and freeze maps. The high correlation between melt duration, obtained from satellite data and the Positive Degree day (PDD) calculated with in-situ data from Automatic Weather Stations at Antarctica, validates the efficacy of the melt algorithm used in the analysis and sensitivity of scatterometer data in detecting presence of water due to melt (Bothale *et al*., 2015).

Conclusions

With the growing concern about the global climate change and its impact, study of the physical and environmental parameters in Polar Regions has become crucial. The Indian Antarctic programme has been established for long-term monitoring of Antarctic glaciers and ice sheet features by establishing 3 stations with advanced facilities. This program is strongly supported by remote sensing community in India. Some of the recent studies carried out with very-high-resolution optical and microwave sensor data depict their potential in identifying and mapping many unique ice sheet and glacier features.

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