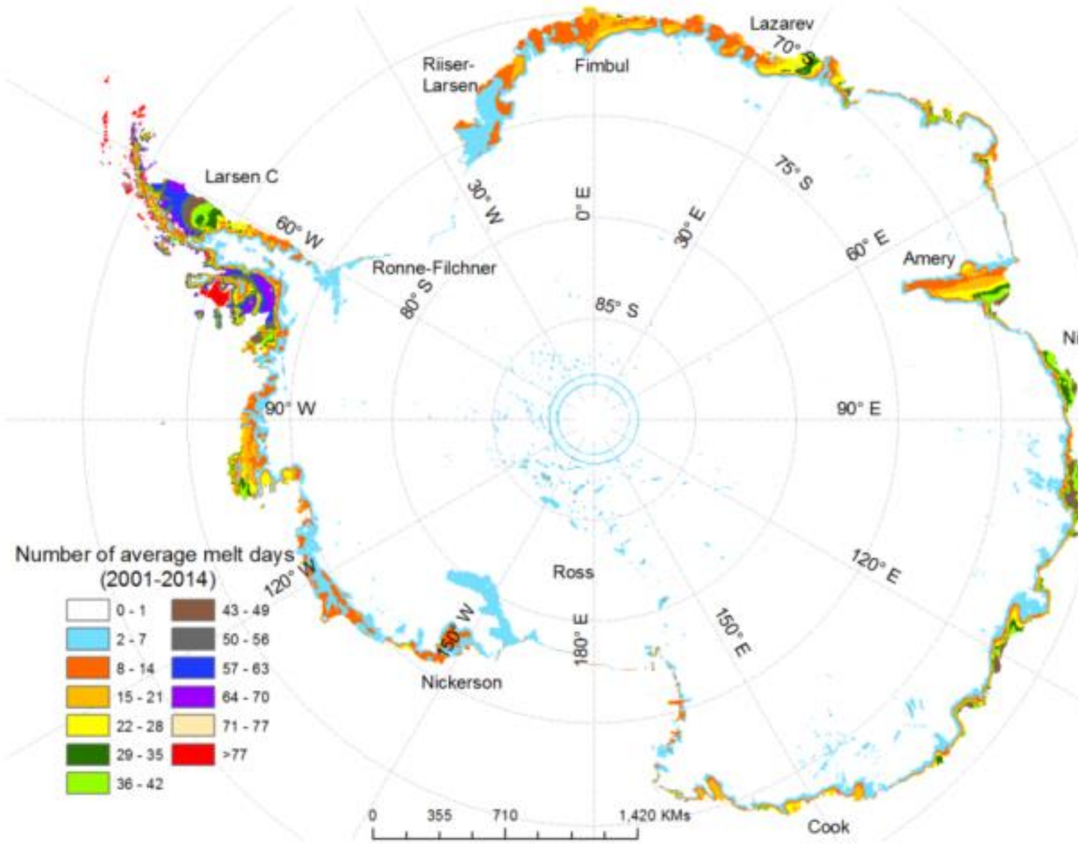
Spatiotemporal dynamics of surface melting over Antarctica using scatterometer data



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Key Words: OSCAT, QuikSCAT, Scatterometer, snow melt/freeze, Antarctica</td></tr>
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Contents

Abstract

Spatio-temporal dynamics of surface melting over Antarctica is of importance in understanding the response of ice shelves to climate change. A methodology to detect and monitor snow melt and freeze from microwave scatterometer data is presented here. Normalised radar backscatter is sensitive to the water content of snow. With the increase in the liquid water content in the snow, there is a sudden decrease in the backscatter from radar. This is 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 2.2.5 km resolution at daily interval. Matlab programme is used to compute and map snow melt and freeze. 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.

Acknowledgement

Authors are grateful to Dr. V.K. Dadhwal, Director NRSC for providing continuous guidance, encouragement and motivation to take up the study and completing the task.

OSCAT and QuikSCAT high resolution data is freely available on http://scp.byu.edu/data/OSCAT/SIR/OSCAT_sir.html. We thankfully acknowledge the providers for making the data available.

Authors also wish to acknowledge the Automatic Weather Station (AWS) data of AMRC, SSEC, UW-Madison in Antarctica.

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1. Introduction

Antarctica ice sheets play an important role in influencing the climate system. An increase in the western continent melt activity has been observed in the recent past which resulted in breaking of ice shelf from the continent (www.antarcticglaciers.org). Continent has many ice shelves off the fringes, which respond to exposure to warming air above and warming polar ocean below. Global climate change has a great impact on ice shelves, because they are sensitive to changes in air and ocean temperature or circulation near Antarctica (Wen *et al*., 2010). Increased atmospheric temperatures lead to surface melting and ponding on the ice surface. Catastrophic ice-shelf collapse tend to occur after a relatively warm summer season, with increased surface melting (Scambos *et al.*, 2009). 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).

2. Cryosphere

Cryosphere describes elements of the Earth system containing water in frozen state and comprises of snow, freshwater ice, sea ice, ice sheets, ice shelves, ice caps and glaciers, solid precipitation, seasonally frozen ground and permafrost. It covers a significant portion of the Earth's land and ocean surfaces. Snow is one major component of cryosphere with winter and summer extents of approximately ~47 million sq km and 26 million sq km (Barry & Gan, 2011). Sea ice is the third extensive component of cryosphere with maximum winter extent of ~14–16 million sq km in the northern hemisphere and ~17–20 million sq km in the southern hemisphere (Tedesco, 2015). Ice sheets cover areas more than 50000 sq km and hold 77% of the world's fresh water out of which Antarctica and Greenland account for 90% and 10% respectively. Winter ice is formed on lakes and rivers whose effect is mostly local.

Cryosphere plays a major role in the climate system through its impact on water cycle, energy budget, primary productivity and sea level (Barry & Gan, 2011). As it is sensitive to temperature change, cryosphere provides some of the most visible signatures of the climate change(Vaughan *et al*., 2013). Sea ice extent has impact on ocean circulation, ocean productivity and regional climate and direct impact on shipping and exploration. Decline in snow cover and sea ice will tend to amplify regional warming through snow and ice-albedo feedback effects.

Details about the satellite missions launched for cryosphere are given in Table 1.

Table-1 Satellite missions for cryosphere

Satellite	Launch	Sensors and resolution	Objective
ICESat	2003-2009	The Geoscience Laser Altimeter System (GLAS). Spatial resolution: 170 m. Temporal resolution: 91 days.	For measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics, ultimately, predict how ice sheets and sea level respond to future climate change.
ICESat-2	Scheduled launch 2017	Advanced Topographic Laser Altimeter System with improved spatial and temporal resolution.	Continuation to ICESat in 2003.
Cryosat-2	2010-present	SIRAL-2, the SAR/Interferometric Radar Altimeters, DORIS receiver, Laser retroreflector, Spatial resolution: 250m, Temporal: 369 days with 30 day sub-cycle	Aims to build a detailed picture of the trends and natural variability in Arctic sea ice and the trend in the thinning rate of the Antarctica and Greenland ice sheets.
GRACE	2002-present	hyper-sensitive microwave range finders Spatial resolution: 300km. Temporal resolution: 15 days	Observe and measure the gravitational field of the Earth, shape and composition of the planet and the distributions of water and ice.
GRACE-FO	(Scheduled launch 2017)	Laser Ranging Interferometer. With improved spatial and temporal resolution.	GRACE-FO will carry on the extremely successful work of its predecessor while testing a new technology designed to dramatically improve the already remarkable precision of its measurement system.
Sentinel	1A-03 April, 2014 1B – Scheduled for 2016	C Band SAR	S1-Monitoring sea ice zones and the arctic, global sea ice, snow cover, ice sheet/glacier monitoring S-3 – Sea ice elevation/thickness, land ice elevation, snow/ice extent

3. Microwave remote sensing and snow melt/freeze

The backscatter response σ^0 from a snow covered surface is a function of numerous interrelated factors including the dielectric properties of snow, snow temperature, density, age, and snow structure. The backscatter received from a snow covered surface includes contributions from snow pack surface component (1), underlying ground surface component (2), snow volume component (3) and ground volume interaction component (4) as shown in Figure 1.

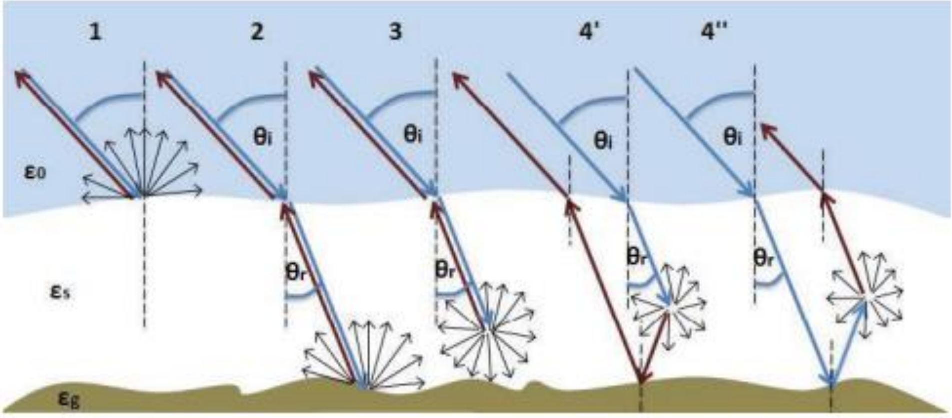


Figure 1: Snow pack backscattering mechanism

Source: Uluby *et al.*, 1981

For dry snow cover the backscattering from the snow surface may be neglected and the total backscattering is a combination of volume scattering from snow and surface scattering from the ground. In wet snow, the absorption loss is high and the scattering from the snow/ground interface may be neglected. The presence of liquid water content increases the absorption coefficient, there by reducing the backscatter response form snow (Tedesco, 2015). In passive microwave, as the liquid water content in the snow pack increases, there is rise in microwave brightness temperature. Brightness temperature recorded from dry snow is lower than that recorded from wet snow (Figure 2a left), because the presence of dry snow on soil attenuates the microwave radiation emitted by the soil. When liquid water forms in the snow, the wet snow layer absorbs the radiation from the bottom snow layer and soil and emits a signal stronger than that of the dry snow covering soil or ice (Figure 2b right). Figure 2b shows brightness temperature over two pixels over Antarctica. The continuous line refers to data measured over an area where melting occurs during summer, while the dashed line and black dots refer to an area where no melting is occurring (Tedesco, 2009).

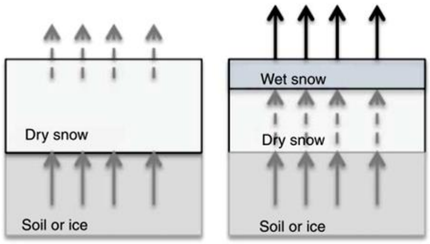


Figure 2a. Brightness temperature response over dry snow and wet snow Source: Tedesco, 2009

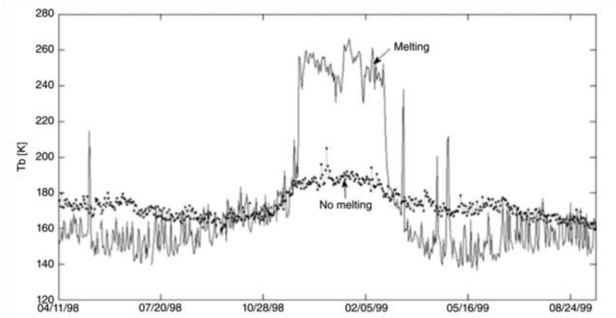


Figure 2b. Annual time series of 19.35 GHz, horizontal polarization, SSM/I brightness temperature for two pixels over Antarctica.

All regions of the electromagnetic spectrum provide useful information about the snowpack and its conditions. Table 2 gives the sensor band response relative to various snowpack properties (Rango, 1993).

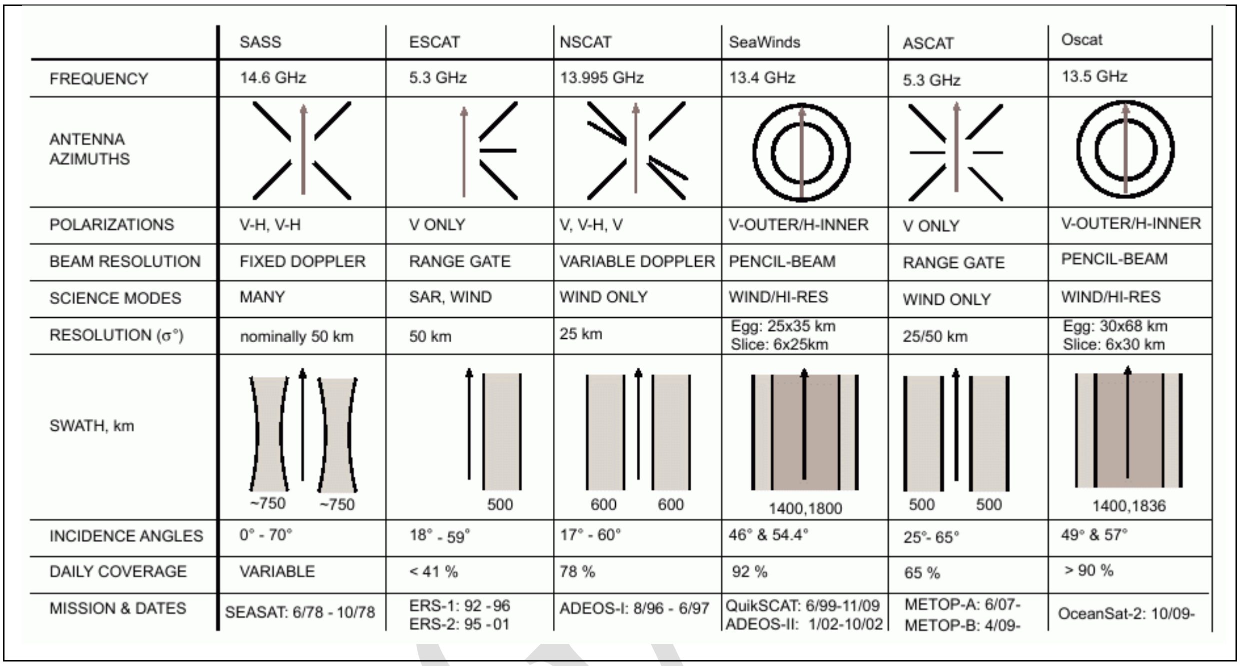
Table-2 Sensor band response relative to various snowpack properties

Snow property	**Visible/NIR**	**Thermal IR**	**Microwave**
Snow covered area	High	Medium	High
Depth	Shallow only	Low	Medium
Water equivalent	Shallow only	Low	High
Stratiography	No	No	High
Albedo	High	No	No
Liquid water content	Low	Low	High
Temperature	No	Medium	Low
Snowmelt	Low	Low	Medium
Snow-soil interface	No	No	High
All weather capability	No	No	Yes

(Source: Rango, 1993)

4. Scatterometry

Scatterometry is useful for identifying and locating the snow melt due to its extreme sensitivity to the presence of liquid water, broad areal coverage, high temporal resolution and all weather, day/night capability of mapping. The key parameter of microwave remote sensing is σ^0, the normalized radar cross-section. It is a function of incidence angle and is sensitive to the surface roughness and the surface's electrical properties. The scatterometer missions and their comparison is shown in Figure 3.



	SASS	ESCAT	NSCAT	SeaWinds	ASCAT	Oscat
FREQUENCY	14.6 GHz	5.3 GHz	13.995 GHz	13.4 GHz	5.3 GHz	13.5 GHz
ANTENNA AZIMUTHS						
POLARIZATIONS	V-H, V-H	V ONLY	V, V-H, V	V-OUTER/H-INNER	V ONLY	V-OUTER/H-INNER
BEAM RESOLUTION	FIXED DOPPLER	RANGE GATE	VARIABLE DOPPLER	PENCIL-BEAM	RANGE GATE	PENCIL-BEAM
SCIENCE MODES	MANY	SAR, WIND	WIND ONLY	WIND/HI-RES	WIND ONLY	WIND/HI-RES
RESOLUTION (σ°)	nominally 50 km	50 km	25 km	Egg: 25x35 km Slice: 6x25km	25/50 km	Egg: 30x68 km Slice: 6x30 km
SWATH, km	~750 ~750	500	600 600	1400,1800	500 500	1400,1836
INCIDENCE ANGLES	0° - 70°	18° - 59°	17° - 60°	46° & 54.4°	25°- 65°	49° & 57°
DAILY COVERAGE	VARIABLE	< 41 %	78 %	92 %	65 %	> 90 %
MISSION & DATES	SEASAT: 6/78 - 10/78	ERS-1: 92 -96 ERS-2: 95 -01	ADEOS-I: 8/96 - 6/97	QuikSCAT: 6/99-11/09 ADEOS-II: 1/02-10/02	METOP-A: 6/07- METOP-B: 4/09-	OceanSat-2: 10/09-

Figure 3: Comparison of scatterometer missions

Source: http://www.scp.byu.edu/

OSCAT scatterometer is similar in characteristics to SeaWinfds from QuikSCAT (Figure 3). OSCAT scatterometer is launched onboard Oceansat-2 on 23rd September, 2009. With orbit altitude of 720 km and inclination 98.28^0, it has orbit ascending node time of 11:30 PM. The orbit revisit cycle is 2 days with approximately 14.5 orbits / day. It operates in Ku band with frequency of 13.6 GHz or wavelength of 2.21 cm. Incidence angle of HH polarisation is 49^0 and for VV polarisation is 57^0. Due to their similarity QuikSCAT and OSCAT data is used here.

5. Datasets

The present study used QuikSCAT and OSCAT Enhance Resolution Image data available at http://www.scp.byu.edu/ in slice mode at 2.225 km resolution which are generated by Scatterometer Image Reconstruction (SIR) algorithm with filtering (SIRF). All passes 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 descending pass. For Julian days 309 to 327, both the datasets were available over Antarctica. Time series graph plotted over few points selected, so that there is average difference of 0.9dB between QuikSCAT and OSCAT data with QuikSCAT data showing higher values (Figure 4).

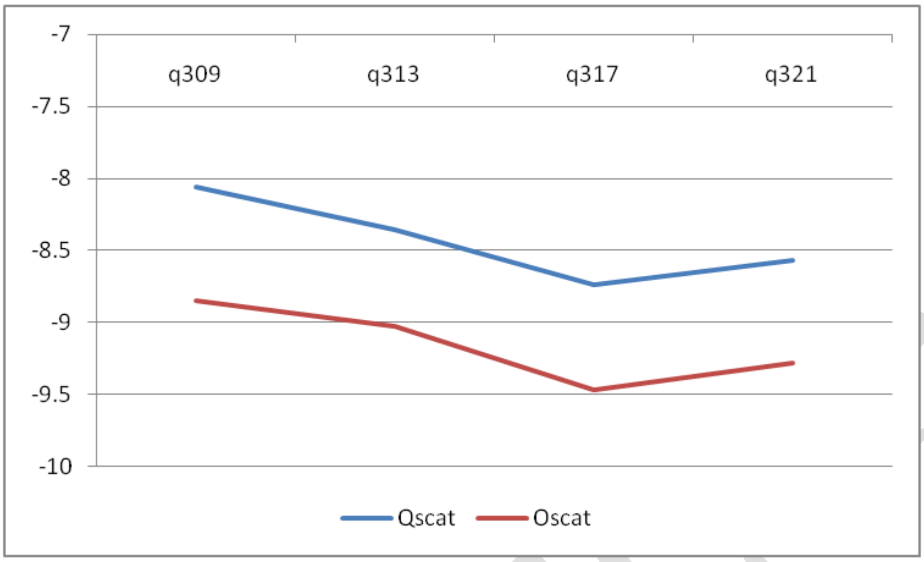


Figure 4: Comparison between OSCAT and QuikSCAT data

The data pertaining to Davis station (-68.5760, 77.9670), which is the nearest AWS station to Amery ice shelf, was obtained from the Australian Antarctica Division for the years 2001 to 2014. AWS data for Ross ice shelf (Elaine station, -83.0940(Lat) & 174.2850 (Long)) and Larsen shelf (Larsen station, -67.020 (Lat) and -61.560 (Long)) was obtained from UW, Madison for the period of 2001 to 2013.

6. Study area

The present analysis is carried out in Antarctica which has ice in three different forms, viz., sheet ice, shelf ice and sea ice. Continent is covered with glacial ice that reaches up to an average of 2,450m. The average altitude of the Continent is 2,300m. Average temperature is -10^{0}C along the coast, -60^{0}C inland, and lowest is less than -80^{0}C . East Antarctic & West Antarctic are separated by Transantarctic mountains and Antarctic peninsula. It is highest, coldest and driest continent on the Earth. Antarctic has ice sheet, ice shelf and sea ice and all the three components play important role in influencing the climate system. Continent has many ice shelves of the fringes which respond to exposure to warming air above and warming polar ocean below. Increased atmospheric temperatures lead to surface melting and ponding on the ice surface. Figure 5 shows the location of AWS stations (Triangles) and test sites (Filled circles) on Amery, Ross, LarsenC and Ronne shelves on Antarctica.

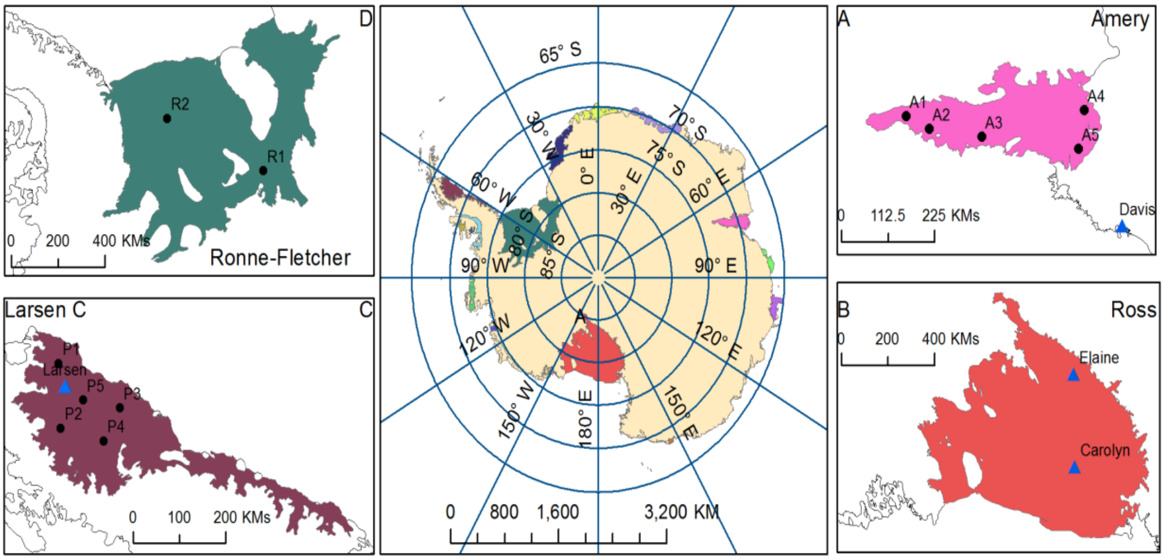


Figure 5. Location of AWS stations (Triangles) and test sites (Filled circles) on Amery, Ross, LarsenC and Ronne shelves on Antarctica.

7. Methodology

Based on the austral winter mean (σ^0_{HHMW}), standard deviation (σ^0_{HHSDW}) and drop in σ^0 for austral summer (σ^0_{HHDS}) (Table 1), looking to the spatio-temporal variability in σ^0_{HH}, an adaptive threshold based classification methodology is used for identification of melt / freeze over the continent.

$$MG = \text{true, if } \sigma^0_{HHn} < (\sigma_{HHMW} - 2{*}\sigma^0_{HHSDmax}) \;\ldots\ldots\ldots\; (1)$$

$$MG = \text{False, if } \sigma^0_{HHn} \geq (\sigma_{HHMW} - 2{*}\sigma^0_{HHSDmax}) \;\ldots\ldots\ldots (2)$$

Where σ^0_{HHn} is the HH backscatter for nth day and $\sigma^0_{HHSDWmax}$ is the maximum standard deviation of austral winter HH backscatter for the study area. An adaptive threshold helps in capturing the backscatter characteristics of individual grid caused by its location in the ice shelf area in comparison to other methods where fixed threshold was used (3.5dB and 5dB)(Sharp & Wang, 2009)or (2.0 and 3.0 dB)(Wang et al., 2007) (Figure 6). Location of the points are shown in Figure 5.

Table 3: Winter mean, standard deviation and drop in backscatter during summer for Amery, Larsen and Ross shelf sites

	Average Backscatter coefficient (dB)			
Amery	2010	2011	2012	2013
σ^0_{HHMW}	-4.12	-4.91	-4.75	-4.46
σ^0_{HHSDW}	0.63	0.57	0.37	0.58
σ^0_{HHDS}	13.72	10.69	15.53	22.19

Larsen	2010	2011	2012	2013
σ^0_{HHMW}	-4.42	-4.35	-4.77	-7.35
σ^0_{HHSDW}	0.42	0.56	0.25	0.37
σ^0_{HHDS}	6.56	10.18	8.79	7.35

Ross	2010	2011	2012	2013
σ^0_{HHMW}	-8.79	-9.58	-9.44	-9.55
σ^0_{HHSDW}	0.31	0.31	0.31	0.31
σ^0_{HHDS}	1.86	1.11	0.97	1.32

A melt grid (MG) is that grid which satisfies the criteria:

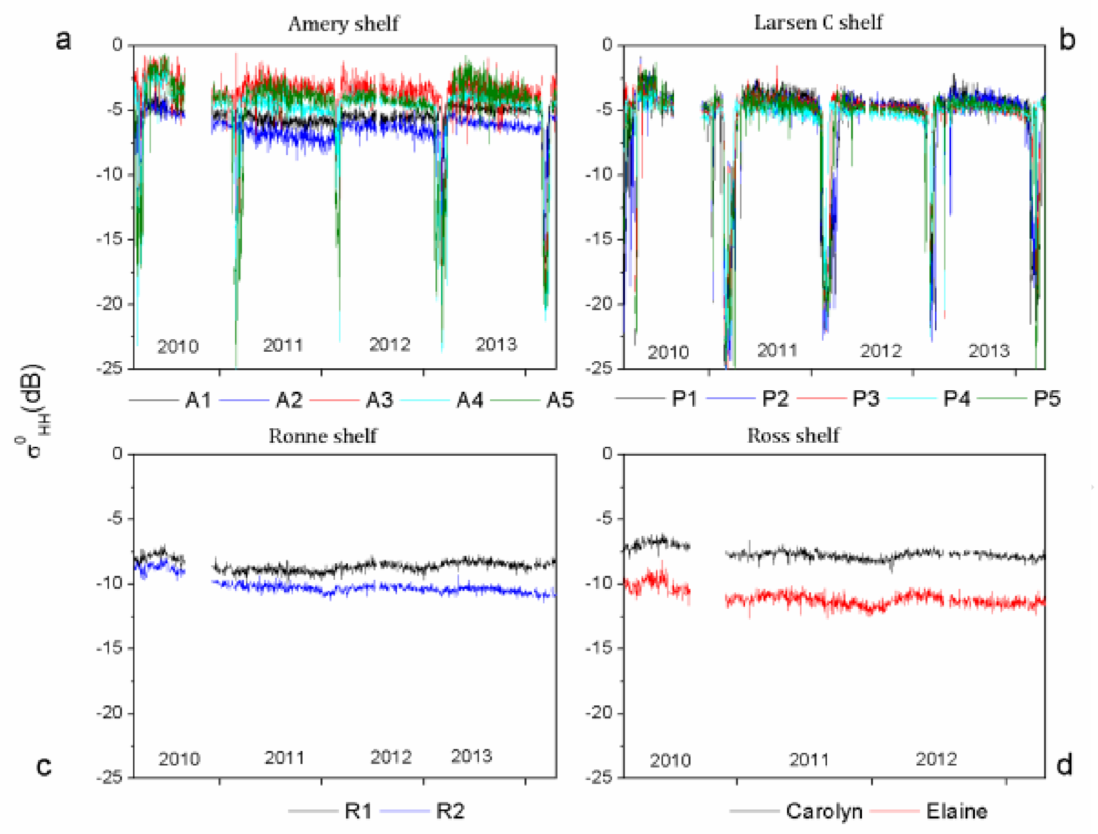


Figure 6. Time series of σ^0_{HH}(dB) for January 2010 to February 2014 over (a) Amery shelf, (b) Larsen C shelf, (c) Ronne shelf and (d) Ross shelf using OSCAT data.

8. Validation

In order to understand the melt behaviour, a Degree Day concept is used (Finsterwalder, 1887). A Positive Degree Day (PDD) assumes that for every 1^0C above 0^0C, a certain amount of melt will take place. Although surface snowmelt is not directly proportional to air temperature due to non-linear interactions between components of the surface energy balance, the PDD approach gives robust empirical relationship between melt and air temperatures. A connection is studied between monthly average temperature(Tmm) and Positive Degree Day(PDD) to understand the melt dynamics over the continent. A relation is developed between monthly melt days (MD) and the positive degree day (PDD) which shows a positive linear relationship between MD and PDD for Amery and Larsen. The high correlation indicates the effectiveness of melt algorithm used in the analysis. Figure 7 shows the relation between melt days (MD) and PDD for Amery and Larsen shelves.

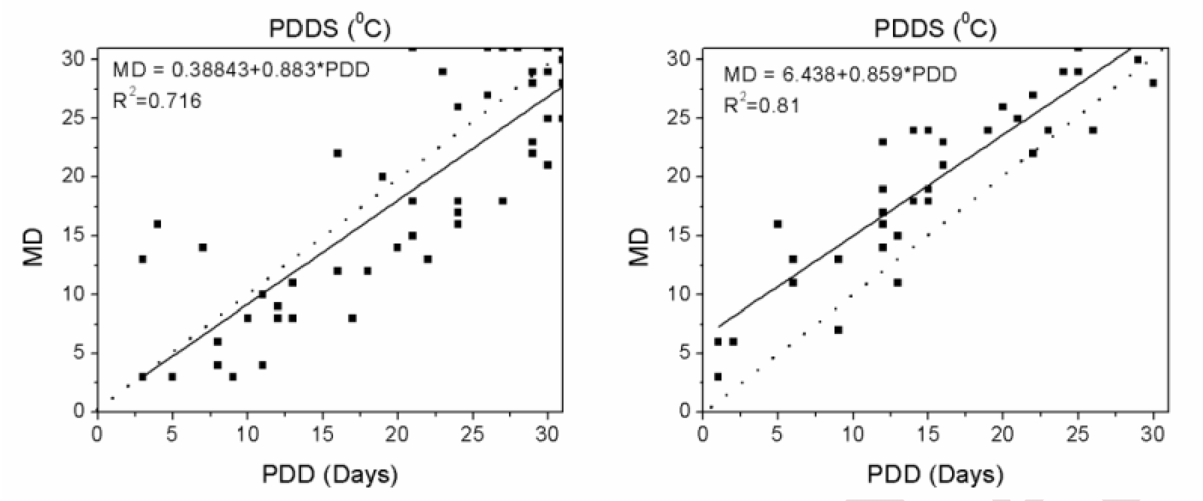


Figure 7: Relationship between Positive Degree Days and Melt Days (Through satellite data) over Amery and Larsen shelves.

To further understand the backscatter response of different snow/ice features of the continent, ground based observations of different geophysical properties are planned in November – February 2015-2016 during Indian scientific expedition to Antarctica.

9. Output

Figure 8 shows the sample output for 10th January 2002 and 10th January 2014. Blue colour indicates the area under melt condition.

A paper on 'Spatiotemporal dynamics of surface melting over Antarctica using OSCAT and QuikSCAT scatterometer data (2001 – 2014)' by Bothale *et al.*(2015) has been published in Current Science. The detailed paper is attached for reference.

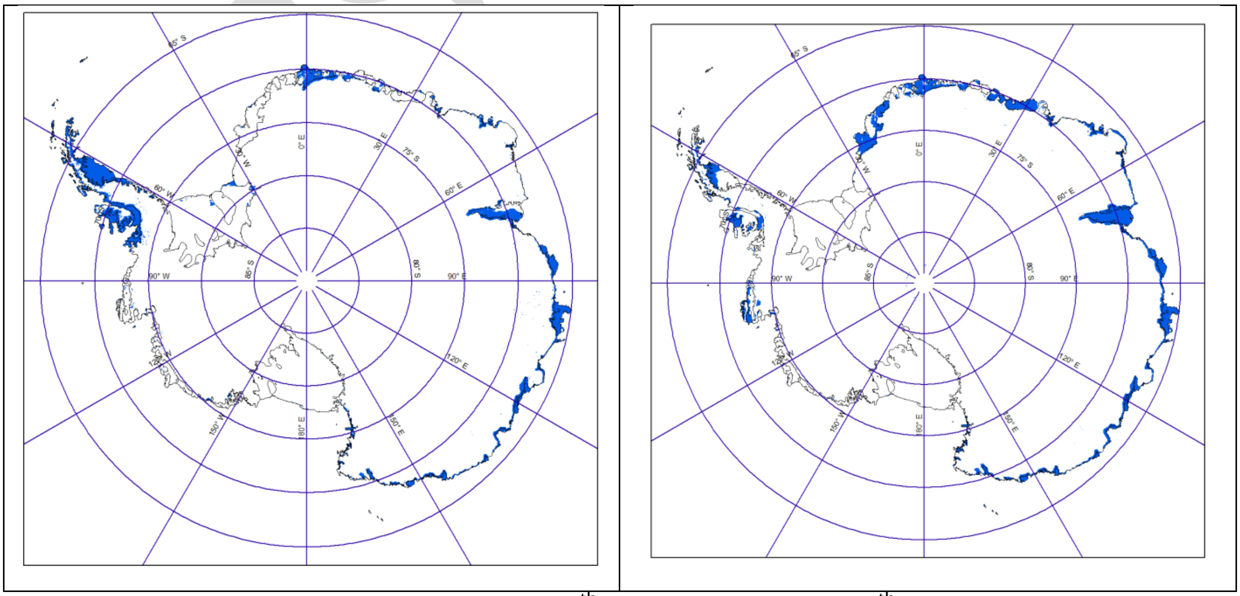


Figure 8: Snow melt status on 10th January, 2002 and 10th January 2014.

The output data is named as SNOW-MELT-DDMMYYYY.tif

Where DD is Date, MM is month and YYYY is year

10. Summary and Conclusions

Melting and freezing of snow/ice affects the exchange of heat between the land and atmosphere. Melt over Antarctica, particularly the trend over ice shelves is of great importance because it is sensitive to the changes in air and ocean circulation near Antarctica. Excessive melting results in ice shelf collapse. Although breaking of ice shelf does not lead to rise in sea water level, collapse of ice shelf speed up the flow of glaciers feeding the shelf. Since the glaciers rest on land, their flow on sea contribute to sea level rise. The melt and freeze status is highly dynamic, hence it is necessary to monitor it at regular interval.

A methodology for the snow melt/freeze using 13.6 GHz scatterometer data is presented here. An adaptive threshold method is used to identify melt and freeze status. Validation of the methodology is done by correlating melt days obtained from satellite data and positive degree days obtained from temperature data of Automatic Weather Stations.

The version 1.0 product of snow melt has been generated for the period of January 2001 to February 2014 using QuikSCAT and OSCAT data. Due to non availability of OSCAT data beyond February 2014, possibility of using ASCAT data will be explored. For better understanding of the backscatter response of snow / ice features, ground based observations of different geophysical properties are planned in November – February 2015-2016 during 35th Indian scientific expedition to Antarctica.

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Spatio-temporal dynamics of surface melting over Antarctica using OSCAT and QuikSCAT scatterometer data (2001–2014)

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In this article, spatio-temporal dynamics of snowmelt in Antarctica from 2001 to 2014 using OSCAT and QuikSCAT scatterometer data is presented. Melting over Antarctic ice sheet can influence shelf dynamics and stability. Here, we have utilized the sensitivity of scatterometer data to detect the presence of liquid water in the snow caused due to melt conditions. After analysing decadal data, a spatial and temporal variation in the average backscatter coefficient was observed over the shelf areas. An adaptive threshold-based classification using austral winter mean and standard deviation of HH polarization is used which takes into account the spatial and temporal variability in backscatter from snow/ice. Significant spatio-temporal variability in melt area, duration and melt index was observed. Around 9.5% of the continent experienced melt over the study period. Larsen C and George VI shelves had maximum melt duration. The high correlation between melt duration obtained from satellite data and the positive degree day validates the efficacy of the melt algorithm used in the analysis and sensitivity of OSCAT data in detecting presence of water due to melt. There is seasonal and spatial variation in melt onset. Based on MI, 2004–05 was the warmest summer over the continent with 2011–12 being the coldest summer. Consistent and intensive melting was observed over Amery, Larsen C, George VI, Lazarev and Fimbul shelves. Melting of sporadic nature was observed over Ronne–Filchner, Ross and Riiser–Larsen shelves. The East Antarctic shelves experienced large melt during the study period. This article presents the suitability of OSCAT in melt identification and status of melt over the continent.

Keywords: Ice shelves, scatterometer data, spatio-temporal dynamics, snowmelt.

ANTARCTICA ice sheets play an important role in influencing the climate system. An increase in the western continent melt activity has been observed in the recent past, which has resulted in the breaking of the ice shelf from the continent (www.antarcticglaciers.org). The continent has many ice shelves at the fringes which respond to exposure to the warming air above and the warming polar ocean below. Global climate change has a great impact on the ice shelves, because they are sensitive to changes in air and ocean temperature or circulation near Antarctica[1]. Increased atmospheric temperatures lead to surface melting and ponding on the ice surface[2]. Catastrophic ice-shelf collapse tends to occur after a relatively warm summer season, with increased surface melting[2]. 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[3].

In situ measurements also indicate melting conditions in Antarctica, but to get the spatial distribution of melt, researchers have used active as well as passive microwave data for identification and mapping of surface melt over the continent[4–7]. Studies based on passive microwave radiometry have used brightness temperature data obtained at different channels[8–12]. Estimation of the extent, onset date, end date and duration of snowmelt in Antarctica from 1978 to 2004 was done using scanning multichannel microwave radiometer (SMMR) and special sensor microwave imager (SSM/I) data. The results indicate periodic melting over Amery ice shelf and occasional melting over Ross Ice shelf[6].

Extensive work has been done in the past using scatterometer data to identify snowmelt[3,4,6,13–18]. Owing to the similarity between Quik Scatterometer (QuikSCAT) and Oceansat Scatterometer (OSCAT), OSCAT is viewed as a continuity mission for QuikSCAT[17]. An empirical, grid cell-specific thresholding method using QuikSCAT data (2000–2004) has been used to identify melt/freeze over Eurasian Arctic ice masses[19]. QuikSCAT data for the period 2000–2009 with wavelet detection algorithm have been used to identify melt over Antarctica and it has been suggested that the ability to classify melting based on relative persistence is a critical aspect of the wavelet-based algorithm[20]. QuikSCAT data have been used to derive Melt Index (MI) and observed correlation between MI variation and rift propagation over Amery shelf[17].

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