

## Seasonal glacier surface velocity fluctuation and contribution of the Eastern and Western Tributary Glaciers in Amery Ice Shelf, East Antarctica

Shridhar Digambar Jawak<sup>1,2</sup>, Shubhang Kumar<sup>3</sup>, Alvarinho Joaozinho Luis<sup>1</sup>, Prashant Hemendra Pandit<sup>4\*</sup>, Sagar Filipe Wankhede<sup>1</sup>

<sup>1</sup>*Earth System Science Organization (ESSO), National Centre for Polar and Ocean Research (NCPOR), Ministry of Earth Sciences (MoES), Headland Sada, Goa 403804, India*

<sup>2</sup>*Svalbard Integrated Arctic Earth Observing System (SIOS), SIOS Knowledge Centre, Svalbard Science Park, P.O. Box 156, N-9171, Longyearbyen, Svalbard, Norway*

<sup>3</sup>*Centre for Land Resource Management, Central University of Jharkhand, Ranchi 835205, India*

<sup>4</sup>*National Bureau of Soil Survey and Land Use planning (NBSS & LUP) - Indian Agriculture Research Institute (IARI), New Delhi 110012, India*

### Abstract

Glaciers play a crucial role in the study of the climate change pattern of the Earth. Remote sensing with access to large archives of data has the ability to monitor glaciers frequently throughout the year. Therefore, remote sensing is the most beneficial tool for the study of glacier dynamics. Fed by many tributaries from different sides, the Amery Ice Shelf (AIS) is one of the largest ice shelves that drains ice from the Antarctic ice sheet into the Southern Ocean. This study focuses on the eastern and the western tributaries of the AIS. The primary objective of the study was to derive the velocity of the tributary glaciers and the secondary objective was to compare variations in their velocities between the summer and winter season. This study was carried on using the European Space Agency's (ESA) Sentinel-1 satellite's Synthetic Aperture Radar (SAR) data acquired from the Sentinel data portal. Offset tracking method was applied to the Ground Range Detected (GRD) product of the Sentinel-1 interferometric wide (IW) swath acquisition mode. The maximum velocity in summer was observed to be around 610 m/yr in the eastern tributary glacier meeting the ice shelf near the Pickering Nunatak, and around 345 m/yr in the Charybdis Glacier Basin from the western side. The maximum velocity in the winter was observed to be 553 m/yr in the eastern side near the Pickering Nunatak whereas 323 m/yr from the western side in the Charybdis Glacier Basin. The accuracy of the derived glacier velocities was computed using bias and root mean square (RMS) error. For the analysis, the publicly available velocity datasets were used. The accuracy based on RMS error was observed to be 85-90% for both seasons with bias values up to 25 m/yr and root mean square error values up to 30 m/yr.

**Key words:** Antarctic, glacier velocity, offset tracking, synthetic aperture radar

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\*Corresponding author: P. H. Pandit <sh.prashantpandit@gmail.com>; <alvluis@ncaor.gov.in>

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**Abbreviations:** AIS – Amery Ice Shelf, CGB – Charybdis Glacier Basin, CM – Clemence Massif, ESA – European Space Agency, PN – Pickering Nunatak, SAR – Synthetic Aperture Radar, GRD – Ground Range Detected, IW – Interferometric Wide, POD – Precise Orbit Determination

## Introduction

The cryosphere is one of the most important parts of the Earth's ecosystem. The interest in the study of glaciers has increased rapidly in the past decades as glacier dynamics are affected due to the change in the climatic patterns (Schellenberger *et al.* 2016). Recent advancement in the studies has increased our understanding of the mass balance of the ice sheets, their contribution to the sea level rise, and the flow dynamics (Rignot 2006, Schellenberger *et al.* 2016). Regular monitoring and understanding the glacier flow dynamics helps in the assessment of the changes that occur in the glacier throughout the year (Joughin 2002). Unfortunately, regular assessment of glaciers through field visits is limited in remote regions of the Earth such as Antarctica and Himalayas, due to various factors including harsh weather and high logistical costs, *etc.* (*e.g.* Tong *et al.* 2018). The remote location of Antarctica makes remote sensing the best available technology that could be used for regular monitoring and assessment of glaciers and its parameters (Pandit *et al.* 2018a, Jawak *et al.* 2018a).

During the last decades, the progress in the remote sensing technology has allowed major advancement in the cryosphere study by providing complete and precise observation of the complex pattern of the ice sheets and has significantly improved our understanding of the science of ice flow. The glacier velocity mapping has been accurately estimated (Fan *et al.* 2019, Pandit *et al.* 2018b, Jawak *et al.* 2018a, b; Liu *et al.* 2017, Jawak *et al.* 2017). Remote sensing-based observations, in particular, have made it possible not only to detect changes

in ice dynamics but also to estimate and map the ice motion.

Glacier velocity has been estimated from space using sequential images captured by multiple satellites, by either optical technology or the synthetic aperture radar (SAR). Although this work was initially started with the launch of optical sensor satellite Landsat, the SAR sensor has been the method of choice to map ice velocity. The reason was its ability to operate in all weather conditions, higher temporal and spatial correlation compared to optical sensors, winter and summer alike, and finer spatial resolution available at the time (Mouginot *et al.* 2017a). The continuous acquisition and the free distribution of the datasets of Landsat satellite series along with Sentinel satellite programme have offered a novel opportunity to study the velocity of polar and Alpine glaciers and the ice sheets motions.

One of the significant parameters for examining the variations in the dynamics of glaciers and ice streams is the glacier surface velocity, which facilitates mass transport from ice sheets to the oceans (Hanna *et al.* 2013, Mouginot and Rignot 2015, Wuite *et al.* 2015). The mass balance of the East Antarctic ice sheet over the past two decades remains unclear (Liu *et al.* 2017). A study conducted by Golleger and Levy (2011) suggests that the ice velocity of outlet glaciers of East Antarctica have a dynamic response to environmental changes. Thus, the study of surface ice flow velocity and its seasonal changes needs to be conducted (Liu *et al.* 2017).

The Amery Ice Shelf (AIS), East Antarctica is among the largest ice shelves of Antarctica. Various studies (Joughin 2002, Tong et al. 2018, Manson et al. 2000, Pittard et al. 2015, King et al. 2007) have been performed to estimate the annual velocity of the AIS and the tributary glaciers contributing to its flow from the western and eastern side, as well as the head of the glacier. Unfortunately, very few studies have focused on the estimation of seasonal glacier velocity variations in the AIS and its surrounding glaciers. Since outlet glaciers are more susceptible to variations in climatic patterns than the inland glaciers (Scambos et al. 2004, Zhou et al. 2014), understanding the seasonal variations in surface velocity of these outlet glaciers helps in better assessment of the changes that occur in the glaciers as inland glaciers are less affected by the climate change as compared to outlet glaciers.

Several methods have been used in the past to estimate glacier velocity such as *e.g.* Interferometric SAR (Joughin 2002, Tong et al. 2018) (InSAR), Differential

InSAR (Tong et al. 2018), speckle tracking (Tong et al. 2018, Gray et al. 2001) and offset tracking (Sánchez-Gómez and Navarro 2017, Strozzi et al. 2002) on SAR data, feature tracking (Fukuda et al. 2014) on optical data, and many more. Of these methods, velocity estimation using offset tracking has been previously carried out in various regions including mountain glaciers such as the Andes (Riveros et al. 2013), the Himalayas (Satyabala 2016) and continental glacier of Antarctica (Gomez et al. 2019). The study conducted by Sánchez-Gómez and Navarro (2017) in Canadian Arctic included both offset tracking as well as DInSAR method and concluded that both the techniques resulted in good accuracy and complemented each other.

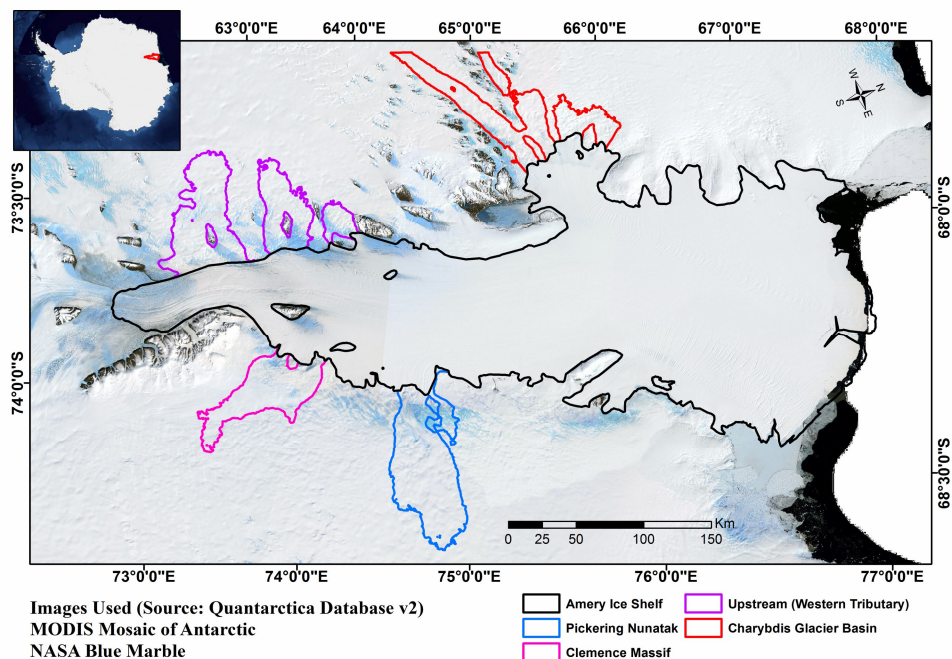
The objectives of the current study were (1) to estimate the ice flow velocity of the eastern and western tributary glaciers of the AIS, East Antarctica and (2) to compare the variation in the summer and winter season velocity of the tributary glaciers using offset tracking method on SAR data.

## Material and Methods

### *Study Area*

The AIS represents one of the fastest glaciers in Antarctica. The glacier is typical by high surface velocities and drains 16% of the mass from the interior of Antarctica (Gray et al. 2001, Jawak et al. 2019). The temperature variation ranges between 0°C to 10°C within single a day during summer. In winter, the daytime temperature varies between -15°C and -18°C (Jawak et al. 2019, Pendlebury and Truner 2004). The precipitation observed in the region is mostly in the form of snow and ice crystals near the coastal area (Jawak et al. 2019, Pendlebury and Truner 2004, Hodgson et

al. 2001). The current study (Fig. 1) was conducted on the four major tributary glacier that contributes to the flow of the AIS both from the eastern and the western side of the ice shelf. The two major glaciers from the eastern side meet the AIS near the Clemence Massif (CM) region and the Pickering Nunatak (PN). The other two glaciers meet the AIS from the western side of the ice shelf, one flowing near the upstream region and the other in Charybdis Glacier Basin (CGB) region. The four tributary glaciers contribute to the flow of the AIS.



**Fig. 1.** Map of the Amery Ice Shelf and location of the tributary glaciers contributing to the Amery Ice Shelf.

**Data Used**

This study uses Sentinel-1a and Sentinel-1b satellite data. These satellites form part of European Space Agency’s (ESA) Copernicus program’s first series of satellites, which orbit 180° apart and have a temporal resolution of 6 days. The Sentinel-1 satellite series carries radar instrument that acquires data during day and night and in all weather conditions. This mission ensures the continuity of C-band SAR data provision by ESA, following up the SAR sensors operating on ERS-1, ERS-2, and ENVISAT (ERS and ENVISAT have a lower temporal and spatial resolu-

tion and do not provide free data), with significantly enhanced capabilities in terms of duty cycle and coverage. The Sentinel-1 operates in the C-band SAR with the frequency of 5.405 GHz and the wavelength of 5.547 cm. The Ground Range Detected (GRD) product used for the study is captured in the Interferometric Wide (IW) swath mode of acquisition.

The whole area of study is covered in four different frames of acquisition within two different paths. The details of the data used for the study are mentioned in Table 1.

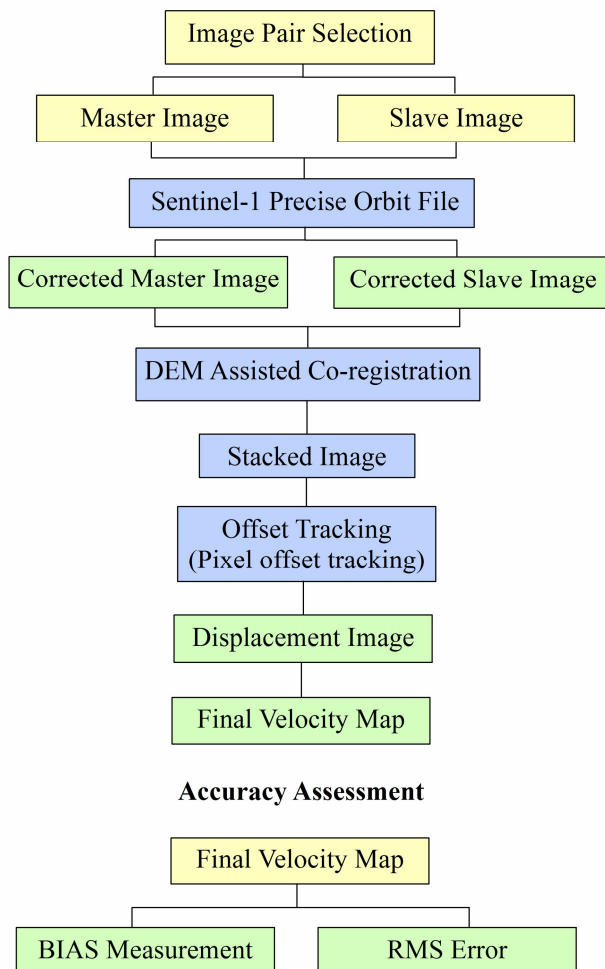
**Method Adapted**

The step-by-step methodology is shown in Fig. 2. The first step for the velocity estimation was the selection of suitable image pairs from the archives of the data.

The selected pair was then used to mark the master and the slave image (or the pre- and post-event image) that would be considered for the study.

Season Path/Frame	Summer		Winter	
	Acquisition 1	Acquisition 2	Acquisition 1	Acquisition 2
3/844	23-06-2017	29-06-2018	21-01-2018	27-01-2018
3/839	23-06-2017	29-06-2018	21-01-2018	27-01-2018
134/848	24-06-2017	30-06-2017	08-01-2017	24-01-2017
134/853	24-06-2017	30-06-2017	08-01-2017	24-01-2017

**Table 1.** Data used in the study.



**Fig. 2.** Flowchart showing the step-by-step method adapted for velocity estimation and accuracy assessment.

After the selection of suitable images, the images were spatially corrected using sentinel-1 POD (precise orbit determination) data provided by the European Space Agency. The POD data is auxiliary to the pre-existing orbital data of the imagery. The images are then stacked and co-registered using the Digital Elevation Model (DEM) generated by the Radarsat Antarctica Mapping Project (RAMP). The co-registration is an important step for velocity estimation as it ensures that the ground targets from a stationary scene contribute to the correct pixel in both, the master and the slave images in the range as well as the azimuth direction. Co-registration is then followed by the pixel offset tracking technique that measures the displacement between the pixels (features) and produces the displacement image of the area. The im-

age obtained after processing provides the displacement that occurred within the time of acquisition of both images. The obtained displacement image is then converted into a velocity map. The final velocity map is then used for the accuracy assessment of the obtained results. The results are compared with previous stable data of velocity (Rignot *et al.* 2011, Mouginot *et al.* 2017b, Jeong and Howat 2015). The MEaSURES (Making Earth System Data Records for Use in Research Environments) yearly velocity at 450 m and 1 km resolution provided by National Snow and Ice Data Center are used for measuring the accuracy. The results were compared using the Root Mean Square error (RMSE) method and the bias of the derived results was estimated using the publicly available stable velocity data.

## Results and Discussion

The final results were obtained for the velocity of the four major tributaries contributing to the AIS from the eastern and the western side. The results were generated, summer (Fig. 3) and winter (Fig. 4) season. The maximum velocity observed during the summer season reached 610 m/yr in the eastern tributary glacier near the PN. The maximum velocity during the winter was also seen near the PN with maximum value of 553 m/yr. The maximum velocity in the western tributaries was found in the CGB region having 345 m/yr during the summer and 310 m/yr during the winter season.

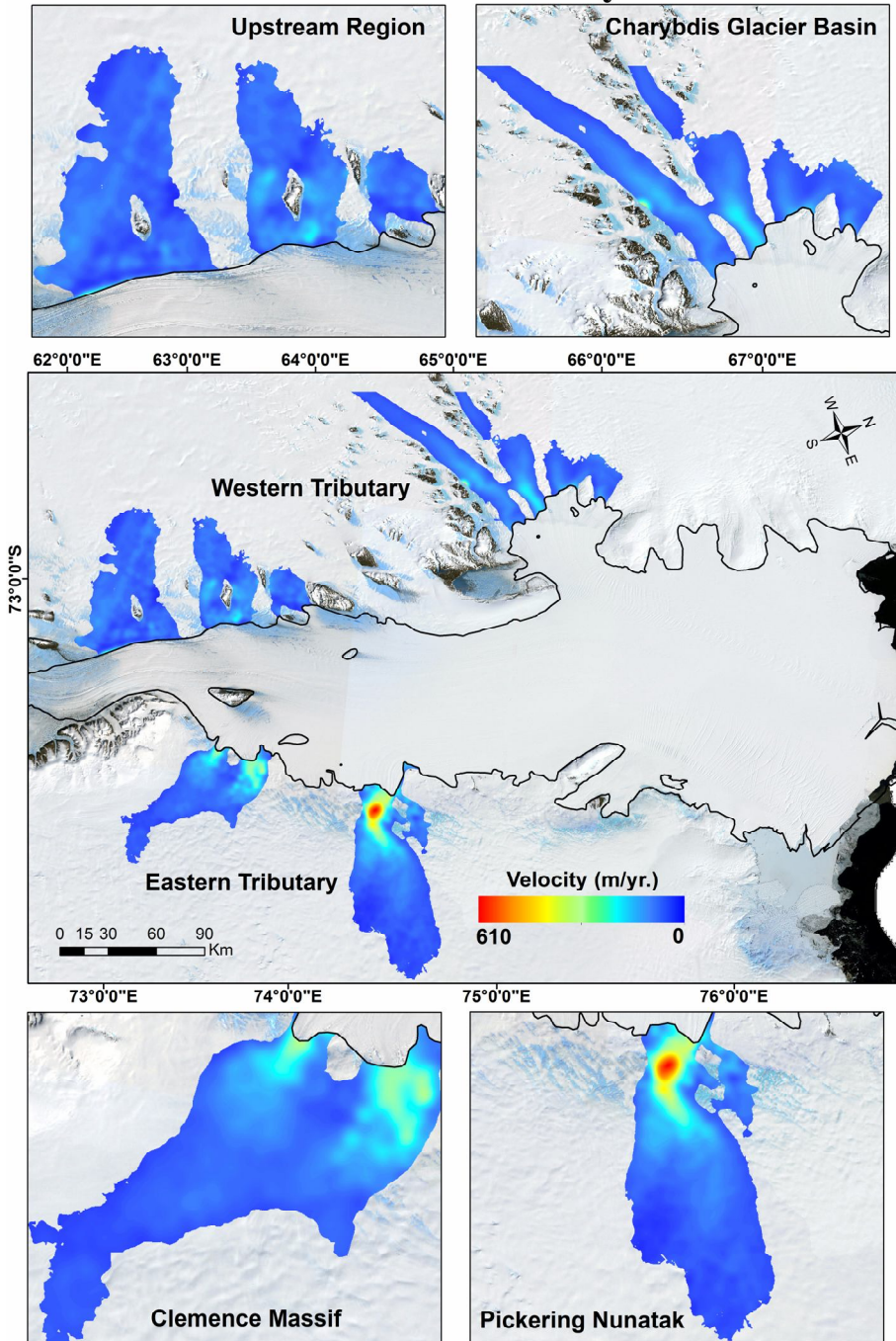
Fig. 3 shows the summer velocity of the eastern and western tributary glaciers contributing to the AIS. The major contribution was observed from the eastern tributaries of the AIS as compared to the western tributary glaciers. Higher velocity is ob-

served at the mouth of the glacier where it meets the ice shelf.

Fig. 4 shows the winter velocity of the tributary glaciers of the AIS. A similar trend in the velocity was observed in the winter season with the velocities from eastern tributaries contributing more than the western tributaries to the ice shelf.

Fig. 5 shows the maximum and minimum velocity difference in the summer and winter season of the four tributary glaciers of the AIS. Major differences were not observed in both the eastern glacier tributary glaciers and the CGB, whereas, the glacier meeting the ice shelf near the upstream area was observed to possess almost double the maximum velocity in the summer than in winter season. The minimum velocity did not change much in all the four tributary glaciers joining the ice shelf.

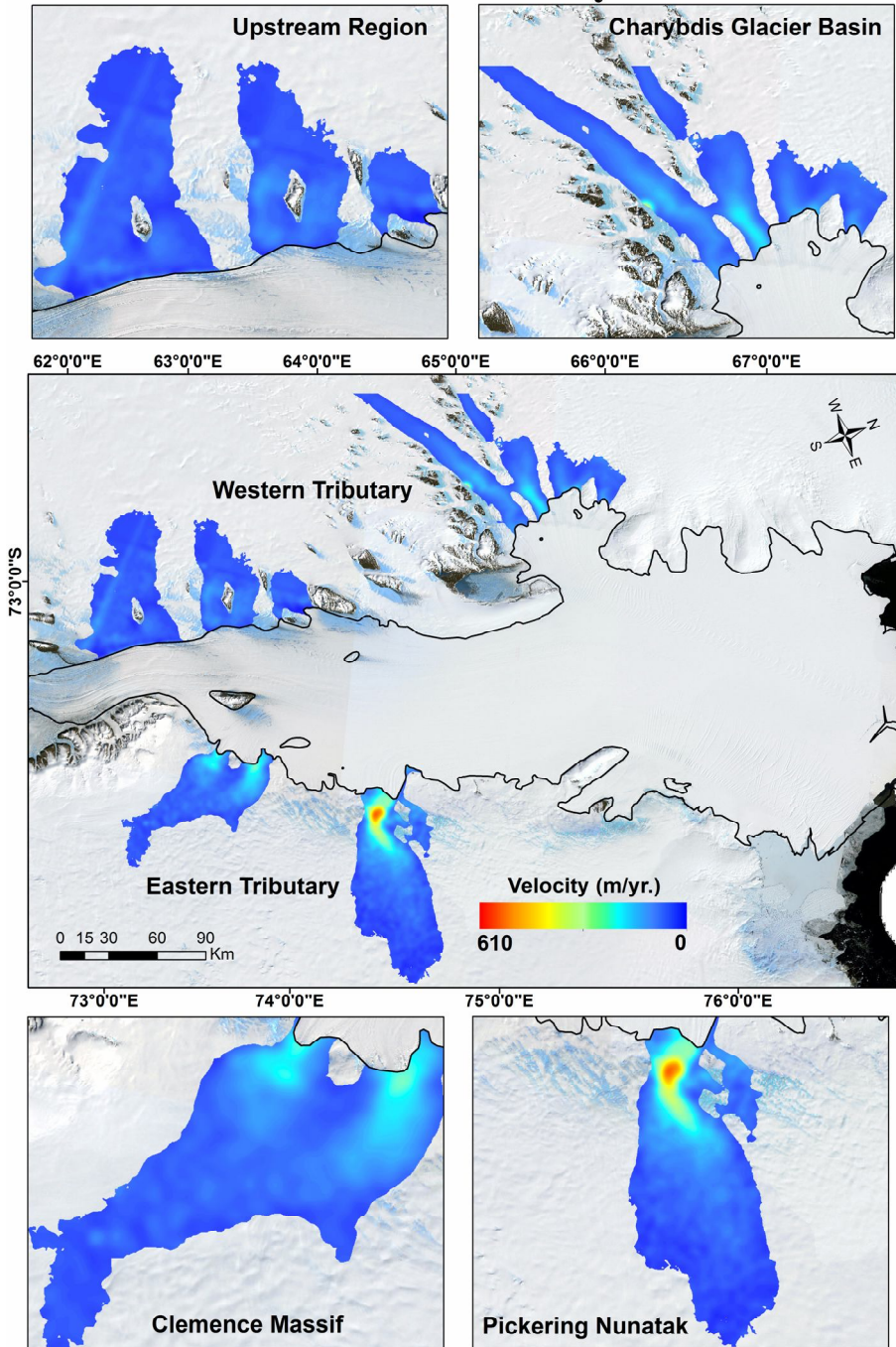
### Summer Velocity



**Fig. 3.** Map showing velocity of the eastern and western tributary glaciers during the summer season.



## Winter Velocity



**Fig. 4.** Map showing velocity of the eastern and western tributary glaciers during the summer season.



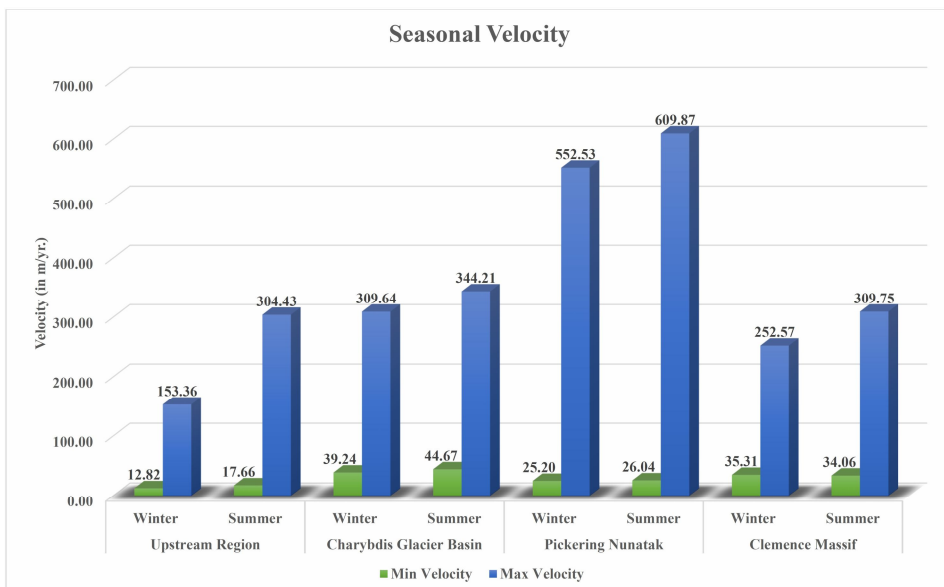


Fig 5. Graph representing maximum and minimum velocity during summer and winter season.

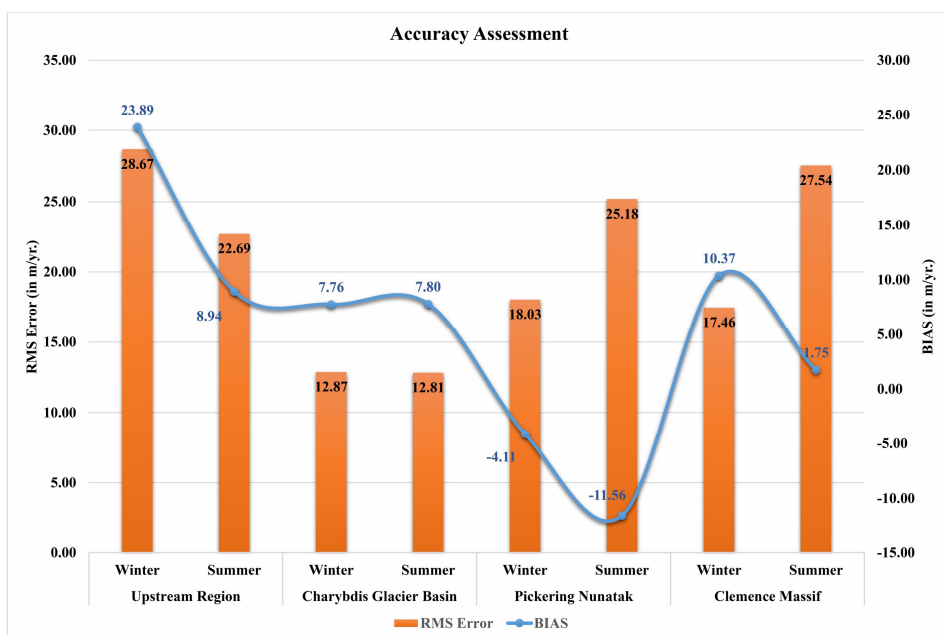


Fig. 6. Graph showing the root mean square error for each derived result and bias of the estimated velocity.

The higher velocity in the summer season was observed more spread throughout the glacier area compared to the winter when the velocity was concentrated near the mouth of the glacier where it meets the ice shelf. The eastern tributary glaciers showed higher difference between the summer and winter velocities as compared to the western tributary glaciers. The upstream region was found with some variation in the velocity whereas very minor variation was found in the CGB region.

The accuracy assessment was carried out on the basis of the bias of the results, in comparison to the previous stable velocity map as well as estimating the RMSE (Fig. 6). The maximum bias was found out in the upstream region with errors upto 24 m/yr during the winter, whereas the other glaciers in both seasons and the summer

velocity of the upstream region did not have an RMSE of more than 12 m/yr. The accuracy based on the RMSE was estimated to be around 85-90%. The bias of the results was observed to be within 30 m/yr for all the four glaciers. The accuracy with respect to bias was also found to be around 85%.

Since the AIS is one of the fastest flowing glaciers of the Antarctic, accurate velocity estimation is much sought for the precise study of the glacier dynamics. The results derived using the offset tracking method on GRD product of Sentinel-1 ensued very comparable output with respect to the previous stable data derived using other methods. The accuracy obtained for the offset tracking method matched well with the accuracy of the InSAR and offset tracking using optical remote sensing data.

## Conclusion

The study carried out to derive the glacier surface velocity using the offset tracking method for eastern and western tributary glaciers of the AIS using the GRD product of the Sentinel-1 SAR data was found out to be efficient and comparable to the velocity previously derived by using the Interferometric SAR (InSAR) method (Yu *et al.* 2010, Wen *et al.* 2014). The results were observed to be accurate to 85-90%. The offset tracking method was useful for estimating glacier surface flow in the regions having moderate to high surface flow velocity. The decorrelation in the offset tracking method is less as compared to InSAR even if the temporal gap between the two acquisition periods is large.

The difference in summer and winter velocity in the tributary glaciers was not very large except for the western tributary glacier meeting the ice shelf near the upstream region. The maximum velocity in summer was observed to be almost double than in winter. Since, almost the entire AIS is covered with ice throughout the year, the difference in velocity is not very high. The final results obtained were comparable to the results of several other methods previously used for study in various regions such as Lambert-Amery Ice Shelf (Yang *et al.* 2018), Antarctica Ice Shelf (Mouginot *et al.* 2017a, b). Offset tracking method could be utilized for velocity mapping in various regions with a great level of accuracy.

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