Estimation of surface melt induced melt pond depths over Amery Ice Shelf, East Antarctica using Multispectral and ICESat-2 data

Geetha Priya M.[1*], Deva Jefflin A.R.[1], Alvarinho J. Luis[2] and Bahuguna I.M.[3]
1. CIIRC, Jyothy Institute of Technology, Bengaluru, Karnataka, INDIA
2. National Centre for Polar and Ocean Research, Ministry of Earth Sciences, Headland Sada, Goa, INDIA
3. Space Application Centre, ISRO, Ahmedabad, Gujarat, INDIA
*geetha.sri82@gmail.com

Abstract
Surface melting is increasing over the Antarctica continent, with unknown impacts on glacier and ice sheet dynamics at the ice-bed interface. Surface meltwater drains to the bed of Antarctica ice sheets and outlet glaciers, causing accelerations in ice flow (up to 100% greater than the annual mean). Because melt occurrences are currently erratic (also Antarctica surface melt refreezes), effective subglacial drainage cannot be maintained, resulting in repeated short-lived ice flow disturbances and calving of ice shelves. Long-term exposure to strong surface melting promotes the formation of melt ponds and subsequently Supraglacial lakes and therefore there is possibility of hydrofracturing.

The present study aims to estimate the volume of surface melt-induced melt ponds over the Amery Ice Shelf (AIS) using a physically-based radiative transfer model. The AIS, located on Antarctica's east coast, is one of the world's biggest glacier drainage basins. The ICESat-2 geolocated photon data were used to validate the depth estimates of melt ponds derived from Landsat-8 and Sentinel-2 multispectral datasets based on the model. The average depth estimated is around 1.9±0.6 m for the melt ponds adopted for the present study. The present study aims to quantify surface melt over the Antarctica continent (AIS region) in the context of India's scientific credentials in polar science. We recommend monitoring extensive surface melt and subsurface refreezing which might result in more ponding above impermeable ice layers in the coming years.

Keywords: Antarctica, ICESat-2, Amery Ice Shelf, Surface melt, Melt pond.

Introduction

The retreat of ice sheet in Antarctica is related to the warming ocean that causes a retreat of Antarctica ice sheet grounding lines by gradually accelerating the ice sheet outflow and through extensive summer melt ponds produced by a warm atmosphere.

**** Author for Correspondence***

Increased melting has occurred in regions of Antarctica, particularly on the east Antarctica Peninsula, as a result of atmospheric warming and surface meltwater is prevalent along the continent's border.[7] Surface meltwater can impact ice dynamic processes in a variety of ways, but it is uncertain whether these changes will accelerate, stabilize, or have no effect on future ice losses.[5,21] The surface melt over ice sheets and glaciers has the following impacts:

• Primarily, they reduce ice surface albedo and increase absorption of incoming solar radiation, resulting in positive feedback that may further accelerate melting.[8]
• The fast drainage of meltwater has been linked to the collapse of floating ice shelves which can lead to increased ice flow from tributary outlet glaciers.[9]
• Supraglacial lake (SGL) draining to the bed of grounded ice in Greenland and West Antarctica has been related to transitory increases in ice velocity.[11] This mechanism has yet to be detected in East Antarctica, while future warming may increase the interconnectedness of surface and basal hydrological systems.[6]

Topographic depressions on the ice surface have the first-order control over lake placement with ponds and lakes forming in the same depressions in repeated summers. [13] At the end of the melt season, melt ponds and supraglacial lakes refreeze, although some have been reported to drain into the ice.[16] This creates a positive albedo-feedback loop that governs the growth of ponds and lakes, in which the lower albedo of surface waters promotes radiative-driven melting.[17] The unpredictable availability of significant amounts of ponded surface water raises the chances of sudden draining to the bed, a shift in basal lubrication and a quick rise in ice velocity.[10] Thousands of blue lakes and ponds emerge along the borders of the Antarctica ice sheet throughout the summer when higher temperatures force snow and ice to melt and accumulate in depressions on the surface.[2]

Recently, satellite datasets used by researchers have recorded over 65,000 of these lakes along East Antarctica's coast.[19] Though periodic meltwater lakes have occurred on the continent for decades, lakes in such large numbers have never been observed in East Antarctica's coastal zones.[20] This means parts of the world's largest ice sheet may be more vulnerable to a warming climate than previously thought. The proposed research is an attempt to quantify the surface melt by estimating the melt pond/SGL volume to gain a better understanding of surface melts. In literature, the surface melt-related studies over Antarctica from Indian researchers focus on distribution and duration mapping, making the present study significant in quantifying the melt.

Study area

The Amery Ice Shelf is a vast mass of floating ice located west of the American Highland in a depression in Antarctica's Indian Ocean shoreline. It stretches more than 320 kilometers inland from Prydz and MacKenzie bays to the Lambert Glacier which feeds it. After the Ross Ice Shelf and the Filchner-Ronne Ice Shelf, the Amery Ice Shelf is Antarctica's third-biggest ice shelf. Studies carried out using satellite data indicate that the melt ponds and SGL are present over the Amery Ice Shelf. The melt events in the form of ponds are sporadic and short-lived before their drainage which is difficult to be recorded by satellite images due to coarser resolution, cloud cover and larger revisit times.

Also, melt ponds and supraglacial lakes are vulnerable to Katabatic winds, which can result in significant short-term snowmelt occurrences.[12] Two melt ponds (MTP-1 and MTP-2) over the Amery Ice shelf have been selected for the present study and the details are given in table1 and figure 1.

Data used

For estimating the depth of the two selected melt ponds, both Sentinel-2 and Landsat-8 datasets were used (table 2). Landsat-8 is an Earth observation satellite launched by the United States on February 11, 2013 with Thermal Infrared Sensor (TIRS) and Operational Land Imager (OLI) instruments. Landsat -8 has a revisit period of 16 days with a swath coverage of 185km

Table 1
Extent of the study area

Parameters	MTP-1	MTP-2
Area (sq.km.)	71.0	1.3
Length (km)	39.0	1.6
Perimeter(km)	88.0	5.7
Extent	71.5475S, 69.3786E to 71.8441S, 68.7975E	71.6319S, 67.8413E to 71.6472S, 67.8630E

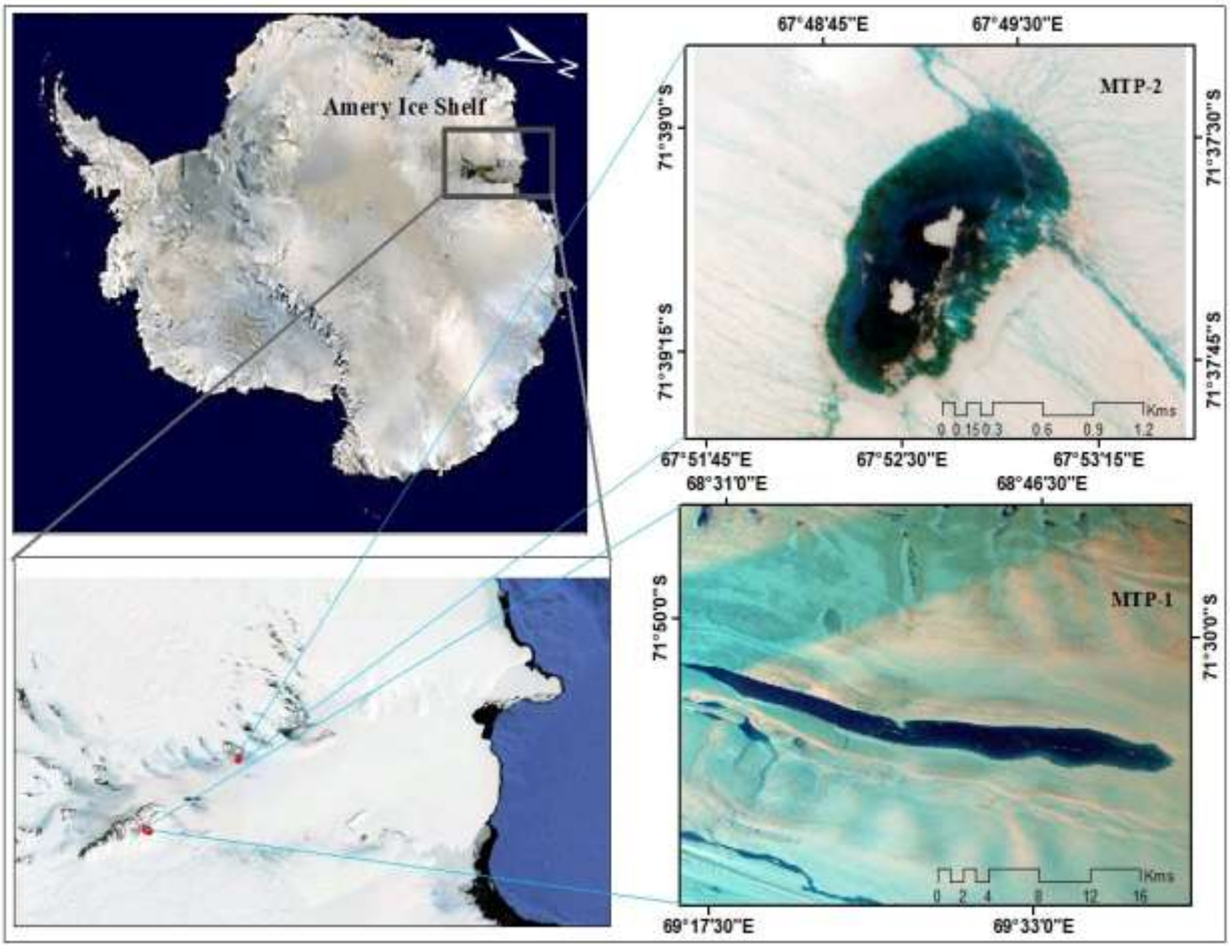

Figure 1: Study area map

Table 2
Data sets used for estimating the depth

Parameters	MTP-1	MTP-2
Data used	Landsat-8	Sentinel-2
Date of acquisition	27/01/2019	02/01/2019
Bands used	Panchromatic (band-8)	Red (band-4)
Resolution	15m	10m

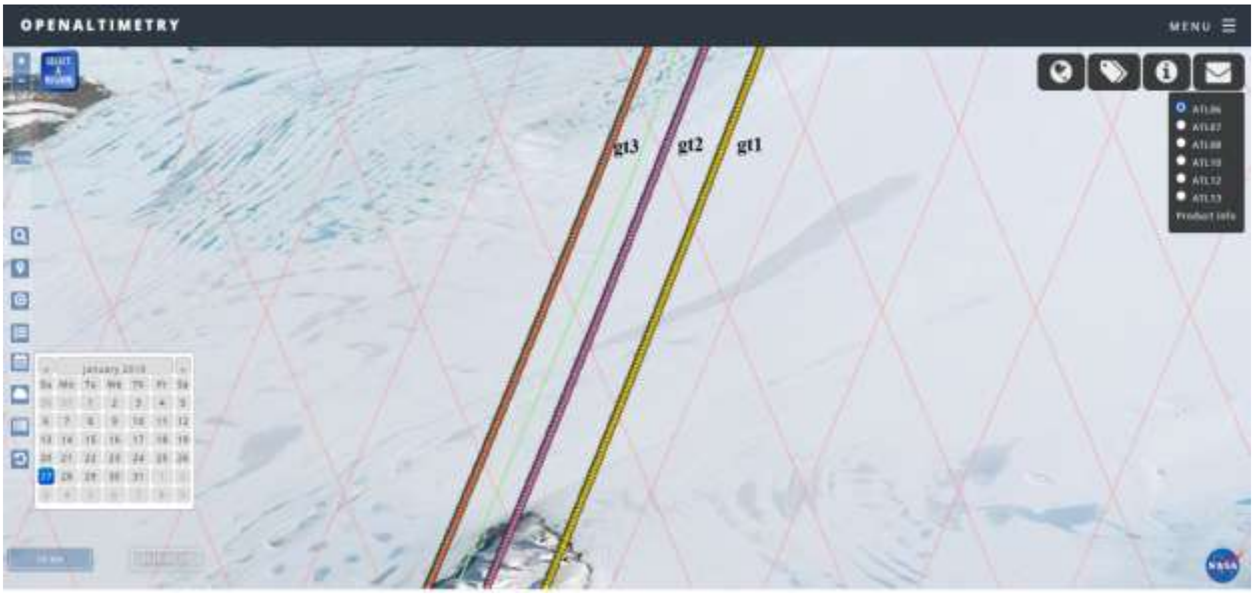

Figure 2: ICESat-2 track-462 over the selected Melt pond showing the beams gt1, gt2 and gt3 on 27/01/2019 from openaltimetry.org for ATL06 and ATL03 datasets

The Sentinel-2 mission from the European Space Agency (ESA) launched on June 23, 2015 consists of a constellation of two polar-orbiting satellites with multispectral sensors. Its huge swath width (290 km) and short revisit time (5 days combined) make it ideal for monitoring variations in land surface conditions. The data with minimum cloud cover (<10%) has been used.

ICESat-2 is a satellite mission that measures ice sheet elevation and sea ice thickness as well as land topography, vegetation features and clouds are part of NASA's Earth Observing System launched on 15 September 2018. ICESat-2 contains a laser altimeter called ATLAS (Advanced Topographic Laser Altimeter System) which acquires data with 6 beams (±3 km swath) as shown in figure 2. ICESat-2 provides data in a 17m wide swath with a revisit period of 91 days. To compare the estimated depth results, ATL03 (Global Geolocated Photon Data) and ATL06 (Land Ice Elevation) datasets of ICESat-2 acquired on the dates January 27, 2019 and January 02, 2019, with track numbers 462 (beam gt1l) and 81 (beam gt2l) have been used for SGL1 and SGL2 respectively.

Material and Methods

The surface melt-induced melt ponds and SGL form refreeze and drain quickly whereas few ponds and lakes exist for a longer time. During the austral summer (November to February) of the hydrological year 2018-2019, Landsat-8, Sentinel-2 and ICESat-2 data over Amery Ice Shelf were obtained from USGS Earth Explorer and Openaltimetry websites based on same date availability. Landsat-8 (band-8) and Sentinel-2 (band-4) datasets available in digital numbers (DN) are converted to top of atmosphere (ToA) reflectance as a preprocessing step.

The ToA products have been used for delineation and depth estimation of the selected melt ponds (MTP-1 and MTP-2) which are approximately 39km and 1.6km long and present over the Amery Ice shelf. Alternatively, normalized difference water index (NDWI) can also be used for covering a large number of water bodies. The present study is limited to the selected melt ponds based on the ICESat-2 track availability and coverage.[15,18] The radiative transfer model (RTM) given in equation 1 has been applied to the subset image of melt ponds for depth estimation.

$$z = [\ln(A_d - R_\infty) - \ln(R_w - R_\infty)] / g \quad (1)$$

where Ad is lake bed reflectance, R∞ is optically deep water reflectance, Rw is the reflectance of observed water, z is water depth and g is a two-way attenuation coefficient. The values of Ad, R∞ and g depend on the imagery and band used. The photon and elevation data from the ICESat-2 tracks across the selected lakes have been extracted for comparison analysis. The entire process flow has been shown in figure 3.

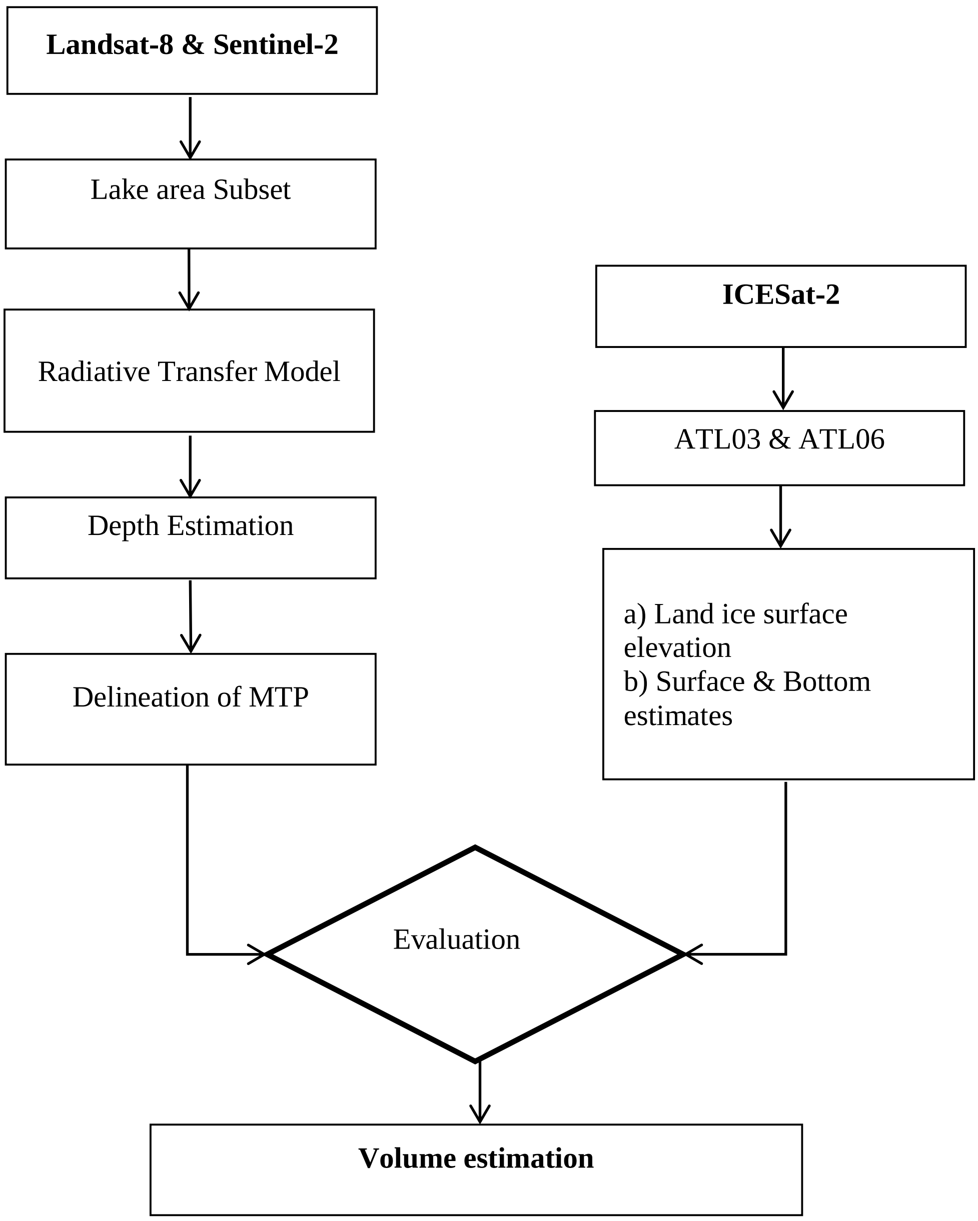

Figure 3: Process flow

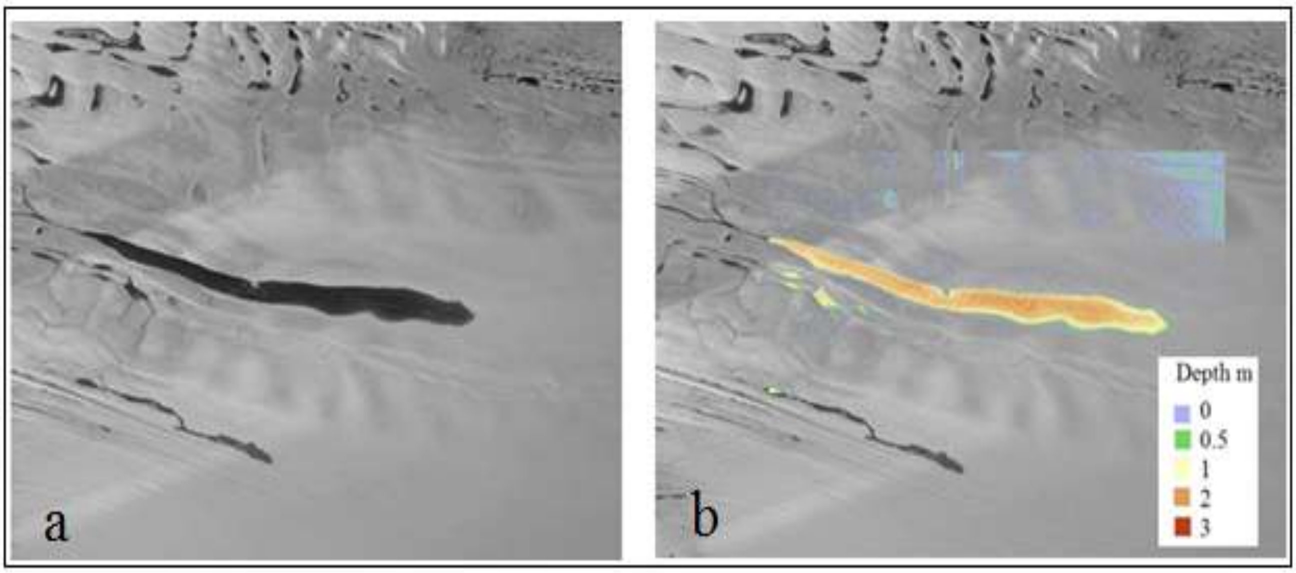

Figure 4: MTP-1 (a) Landsat-8 band-8 data on January 27, 2019 (b) RTM based depth estimates

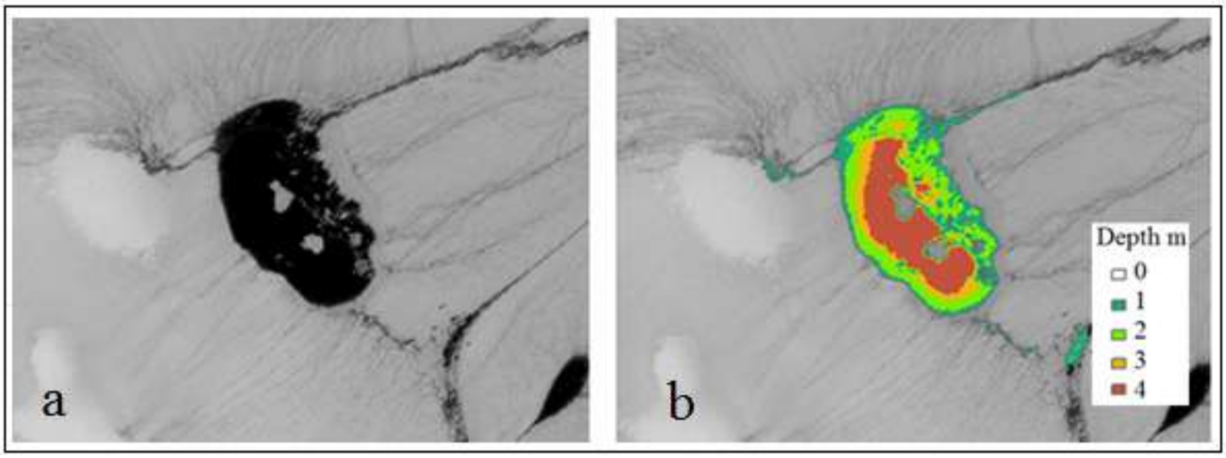

Figure 5: MTP-2 (a) Sentinel-2 band-4 data on January 02, 2019 (b) RTM based depth estimates

Results and Discussion

Depth estimations for two selected melt ponds on two different dates of the same melt season with 25 days intervals have been carried out using the process flow discussed earlier (figure 3). The ICESat-2 datasets are limited to a specified footprint providing depth estimations as points along the tracks over the melt ponds. The RTM model is an image-based approach for depth estimation that provides spatially distributed estimates.

Image-based depth estimation: To compute the water depth of all pixels categorized as ponds/lakes, we used a physically based radiative transfer model. Using the rate of light attenuation in water, lake-bottom and optically deep water reflectances, this approach determines lake water depth.[3,14] The results obtained from the model for the two melt ponds are shown in figures 4 and 5. From the image-based model, the spatially estimated depth for the melt ponds MTP-1 and MTP-2 was observed to be in the range of 3 to 4 m. The estimations around the melt pond regions were found to be zero indicating the potential of the proposed model in measuring the depths. Small melt water channels around the pond region had a depth of around 0.5 -1m.

ICESat-2 based depth estimation: For ICESat-2-based results, the ATL03 return signal photons (figure 6) from the surface and bottom of the melt ponds are considered. Every ATL03 photon event downloaded from ICESat-2 ATLAS, gives time, latitude, longitude and ellipsoidal height. Several geophysical processes such as atmospheric influences and solid ground deformation are taken into account while calculating heights. ATL06 offers geolocated measurements of land ice heights as well as supplementary information for interpreting and evaluating the results. The ATL06 land ice height has been used as a reference for the surface estimates from ATL03.

The average of the return photons from the bottom of the melt ponds was manually calculated to delineate the depth and is shown in table 3 for sample points in comparison with the image-based results. When compared to other places, the track covers a modest amount of lakes or a smaller region of a lake. Because ICESat-2 has a 91-day repetition cycle, the tracks accessible for research were either in October and July when the lakes are frozen or in April when they drained or refroze. For the selected melt ponds, only January data is available which is during the melt time. The track data was difficult to estimate and identify in locations where the lakes are shallow (i.e. lakes with a depth of less than 1m).

Melting and ponding: For the melt ponds MTP-1 and MTP-2, on average, the difference in depth estimates from ICESat-2 and the image-based model was found to be around 0.2m. This represents that the image-based model can be used for ponds/lakes depth estimation due to the high spatial and temporal resolution of the multispectral sensor-based satellites. On average, the depth of the melt pond MTP-1 was observed to be twice that of the melt pond MTP-2 (figure 7). Ponds / lakes vanish or drain in one of three ways: supraglacial drainage via channels across the ice surface, englacial drainage into the firn, or surface refreezing and/or snow burial.[1,4]

Melt pond MTP-2 is only 1.6 km long and exhibited a maximum depth of 4m which is deeper in comparison with the melt pond MTP-1 which is larger in area and length. This is because melt pond MTP-1 resembled an elongated supraglacial lake-type structure with a meltwater channel. The meltwater accumulated in the form of melt ponds for MTP-1 and MTP-2 estimated from the present study is $18x10^9$cu.m. and $16.9x10^5$cu.m. on January 27, 2019 and January 02, 2019 respectively.

Average 2m (near-surface) air temperature data recorded by Amery G3 AWS (Automatic Weather station) is shown in figure 8 for the melt season during Nov 2018-March 2019. Amery G3 AWS has been installed at an elevation of 84m at Amery Ice Shelf (70.8919S, 69.8725E) by the Mawson research station of Australia. It is observed from the (sub-zero) temperature data that other influences such as localized albedo interactions may be predominantly inducing the surface melt resulting in melt ponds and lakes. Blue ice regions have a lower albedo than refrozen snow which has positive feedback on surface melting by increasing solar radiation absorption.[9,19] For quantifying the surface melt over Amery Ice Shelf, all the melt ponds and supraglacial lakes of a given melt season have to be considered and monitored at a high temporal resolution to understand the melt evolution and drainage events and calving mechanisms.

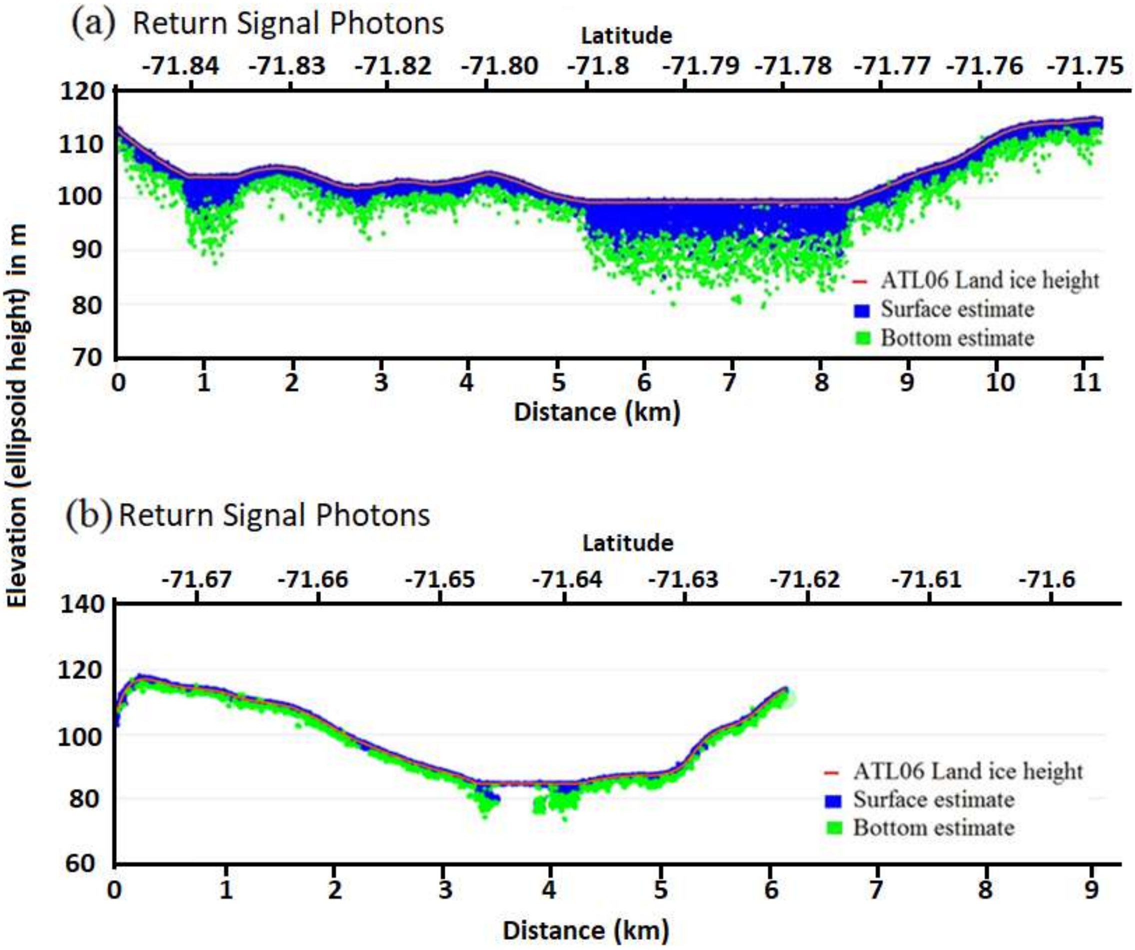

Figure 6: ATL03 Photon data showing the surface and bottom estimates from (a) MTP-1 (b) MTP-2

Table 3
Data sets used for estimating the depth

Samples	MTP- 1			MTP-2		
	Latitude in decimal degrees	ICESat-2 depth in m	RTM depth in m	Latitude	ICESat-2 depth in m	RTM depth in m
Point 1	-71.80	1.57	2.30	-71.64	3.83	3.91
Point 2	-71.78	1.18	1.80	-71.63	3.84	3.30

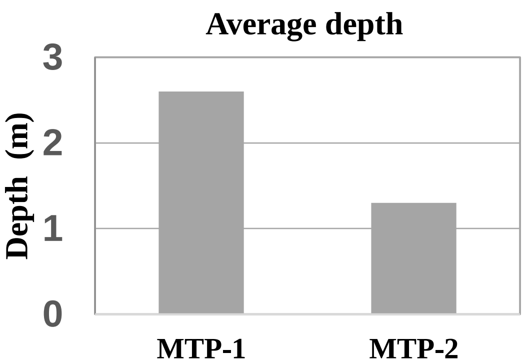

Figure 7: Average depth estimation for the selected lakes using RTM model

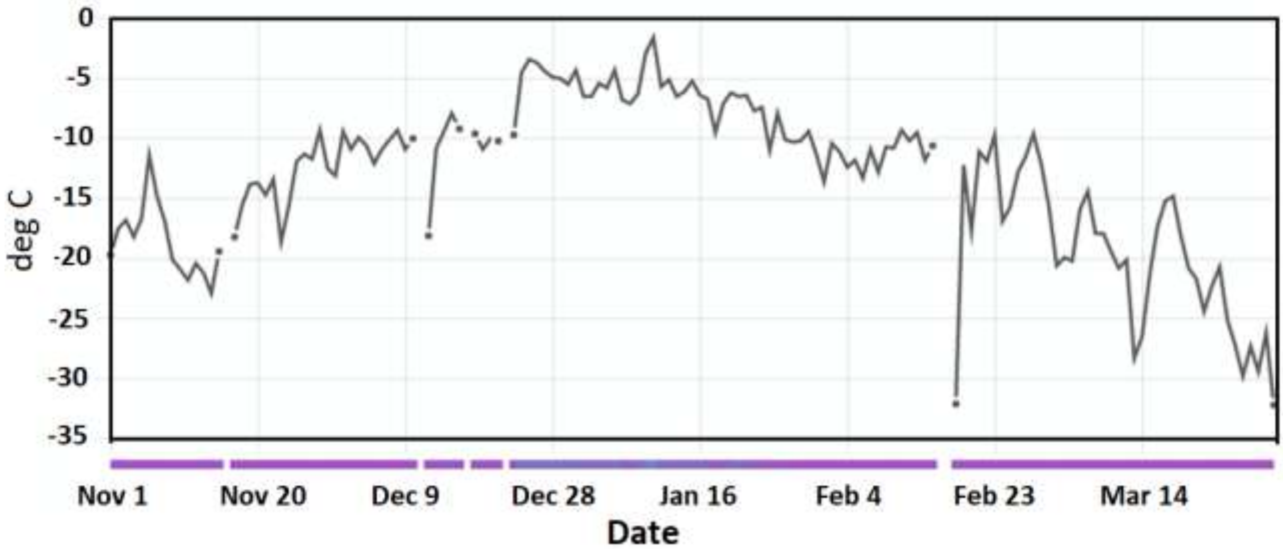

Figure 8: Daily mean 2-m air temperature over Amery ice shelf during the melt season 2018-2019

Conclusion

Surface melting measurements are useful for studying glacier and ice sheet dynamics and monitoring climate changes in the polar areas. Downward percolation of meltwater from the firn surface followed by refreezing at deeper depths carries heat significantly faster than thermal conduction and diffusion. Less is known about the water trapped in snow or firn. Additionally, pools of melted snow and ice darken the surface of the ice, generating melt ponds and lakes, increasing the amount of solar radiation absorbed by the glacier/ice sheet and speeding melt, resulting in positive feedback. Furthermore, meltwater pools in surface lakes are known as supraglacial lakes (SGL), they can weaken an ice shelf, allowing it to break apart. When meltwater pools in depressions on the surface of a glacier or ice sheet, supraglacial lakes (SGL) occur. They range in size from a few meters to tens of kilometers in area and play an essential role in the mass balance of an ice sheet.

The present study is an attempt to estimate the volume of melt ponds formed due to surface melting over the Amery Ice shelf region of East Antarctica using Landsat-8 and Sentinel-2 datasets. From ICESat-2, ATL03 photon data and ATL06 Land ice elevation measurements were also utilized for corroborating the image-based depth estimations. Results of selected melt ponds reveal intensified surface melting over the shelf region. Approximately, more than $18x10^9$cu.m. of meltwater has been estimated for two melt ponds with an area of 72.3 sq. km. with an average depth of 3.5m during the melt season in January 2019. Continuous monitoring of meltwater is required to access the potential of destabilizing the ice shelf.

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