Delft University of Technology

BACHELOR THESIS

AESB3400

Assessing Land Ice Height Decrease of the Fleming Glacier using ICESat-2 Satellite Data: A 2019-2022 Analysis

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July 6, 2023

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Preface

This project is the final work required to obtain the Bachelor's degree in Applied Earth Sciences at TU Delft. It is already three years ago that I started this study, three years that went by very quickly. It all began with the freshmen excursion to the Blegny mine in Belgium and the huge open-pit mines in Germany. It is a miracle that this excursion was not cancelled, unlike most on-campus classes during the first and second year. Due to Covid-19, we all had to get used to classes through Zoom, online exams and seeing your classmates just once a week during the very few on-campus classes. Fortunately, during the second half of the second year most restrictions were lifted and we were able to go on fieldwork to the Vesc region in France. During this fieldwork there was a remote sensing assignment where we collected polygons to do a semi-automatic classification using QGIS. Although this assignment was a lot of work, I did like the fact that we could use satellite data to analyse the Earth's surface. Therefore, when choosing a topic for my thesis I wondered if I could combine this with something else that I think is fascinating: glaciers. These massive rivers of ice provide a window into past climate conditions, while their melting and disintegration offer an insight into the current climate dynamics. That is why I decided to e-mail Roderik, who was the professor of the Y2Q4 subject *Geostatistics and Remote Sensing* to see if there were any possibilities to write a thesis about this. He reacted enthusiastically and recommended I contact Bert Wouters, his colleague who specialises in ice and glaciers and his PhD student Felix. We met up soon after that and agreed on the final topic: using ICESat-2 data to assess the height decrease of the Fleming Glacier over time.

I would therefore like to take this opportunity to thank Bert Wouters and Felix Dahle for their feedback and advice whenever I ran into any issues during the research and writing of the thesis. Additionally, I want to thank Roderik Lindenbergh for helping me set up the research topic and Sophie de Roda Husman for being the third supervisor for my final presentation. Last but not least I would like to thank my classmates, because without them these last three years would have been way harder and way less fun.

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Project duration:	22 May 2023 – 10 July 2023	
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An electronic version of this thesis is available at http://repository.tudelft.nl/.

Abstract

The following report investigates the land ice height decrease of the Fleming Glacier between 2019 and 2022 using ICESat-2 satellite data. This glacier is located on the Antarctic Peninsula, an area that has been severely impacted by global warming. Using data from the Advanced Topographic Laser Altimeter System (ATLAS) on board ICESat-2, more specifically its ATL06 product, the average land ice heights in 2019 and 2022 could be compared. This was done with the aid of Python and the icepyx library, which allows for an easy extraction of the desired data from the NASA Eathdata website. The raw data had to be processed and filtered to eliminate the NaN values and reduce the noise. The resulting height measurements were then plotted and an average rate of land ice height decrease of 4.40 metres over the 3-year period was found, which corresponds to a 1.47 $m/year$ decrease. The findings of this study indicate a slightly lower value compared to the results reported by Friedl et al. in their 1994-2016 study. However, this discrepancy is plausible, particularly considering the episode of increased ice melting observed in the Fleming Glacier after 2008, which can be attributed to the disintegration of the Wordie Ice Shelf. Crucially though, due to an issue with the Reference Ground Track overlap the amount of common data points found was just 27. This is insufficient to draw definitive conclusions regarding the overall melting of the entire Fleming Glacier. Future research, especially involving the use of the ATL11 product, is therefore recommended for this region.

Contents

1 Introduction

Climate change is one of the biggest challenges humanity is currently facing. Rising temperatures are leading to the melting of land ice, which in turn can cause an increase in global sea levels, as land ice makes up 70% of the total freshwater reserves on earth [2]. Land ice on Earth can be divided into two main categories: ice sheets and glaciers. The ice sheets of Greenland and Antarctica constitute a significantly larger proportion (99.5%) of the total land ice volume. Nevertheless, glaciers, due to their smaller size, will react more rapidly to the global temperature increase [2]. By measuring the rate of melting of glaciers, more knowledge can be obtained about the effects of climate change on land ice and the rate at which it is worsening. With the launch of the ICESat-2 satellite and the publication of its first results in 2019, more accurate data regarding the land ice height has become available. This report will use this data with the aim of measuring the thickness decrease of the Fleming Glacier in the 2019-2022 period.

1.1 The Fleming Glacier

The Fleming Glacier is a glacier located on the West of the Antarctic Peninsula as seen in Figure 1. This is one of the regions most affected by the increase in global temperatures in terms of ice discharge, which is accelerated by the dynamic response of glaciers to the disintegration of several ice shelves [8, 16]. A study from 2014 found that ice melt from the Antarctic Peninsula (North of 70° S) could lead to a sea level rise of 69 ± 5 mm [9]. While this is negligible compared to the potential of the Antarctic ice sheet to increase the sea level by 58 m [7], it is nonetheless of interest due to the short response time of the glaciers on the peninsula [2].

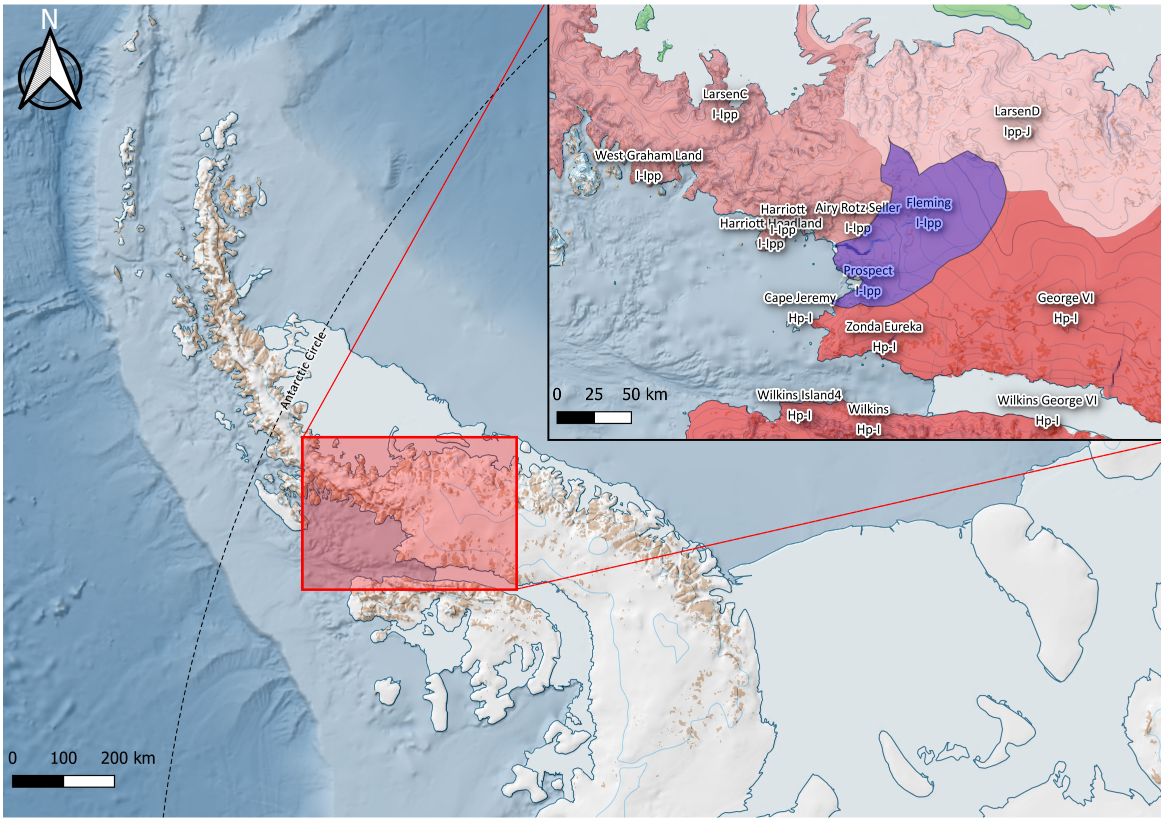


Figure 1: Location of the Fleming Glacier (marked in blue) and surrounding ice boundaries on the Antarctic Peninsula. *Created using the Quantarctica package in QGIS [11].*

The Fleming Glacier is an interesting site within the Antarctic Peninsula. Together with the Airy, Rotz and Seller glaciers it spans the largest catchment area on the peninsula, about 7000 km^2 [5, 8]. It is also the largest glacier in Marguerite Bay, stretching 80 km in length and reaching widths of up to 10 km as of 2018 [8]. It used to feed the Wordie Ice Shelf, however extensive collapse of the ice shelf occurred in the second half of the 20^{th} century, resulting in the formation of Wordie Bay [12]. Notably, the Fleming Glacier is the fastest-flowing Glacier in Wordie Bay, the flow speed in its basin and surrounding glaciers can be seen in Figure 2.

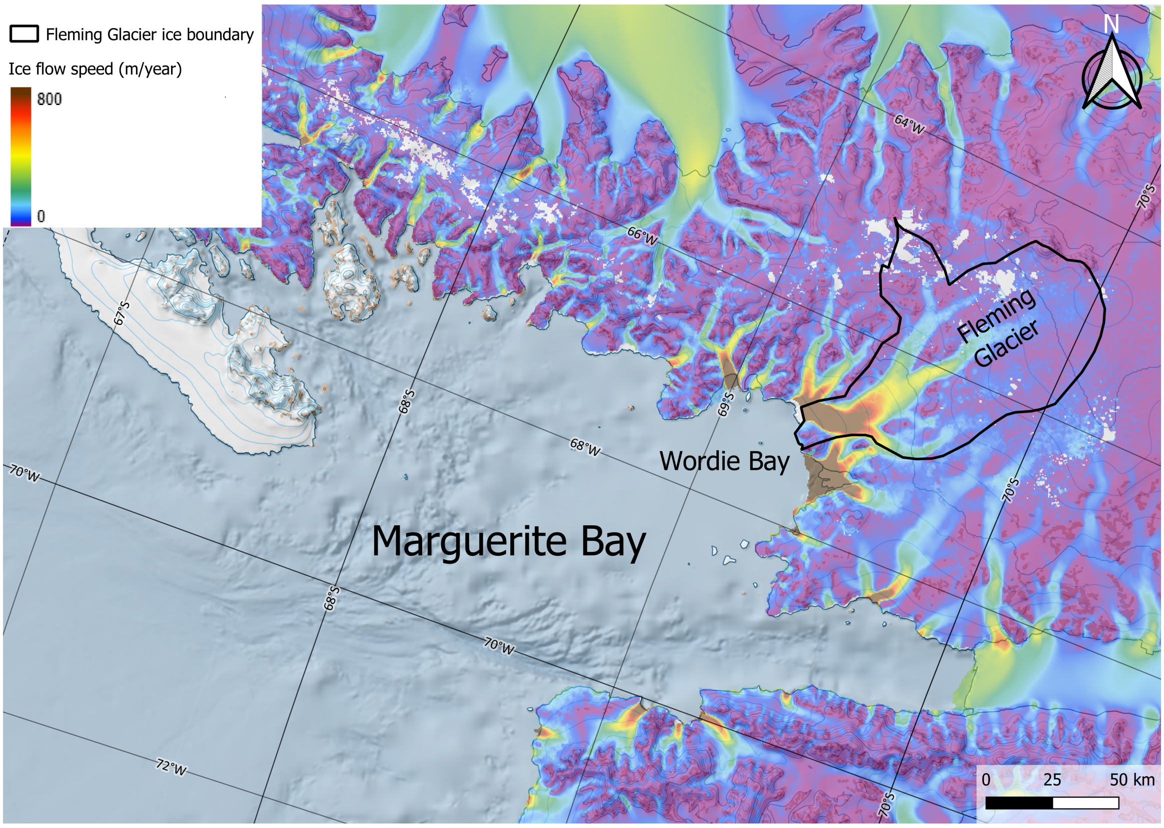


Figure 2: Ice flow speed of the Fleming Glacier and other glaciers in the Marguerite Bay. *Created using the Quantarctica package in QGIS [11].*

1.2 ICESat-2

Since the 1990s, radar and laser altimeters have collected measurements on the thickness and mass change of ice sheets and glaciers [14]. The first real breakthrough however came with the introduction of the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and Land Elevation Satellite (ICESat) mission which was launched in 2003 by NASA [1]. The goal of this first polar-orbiting satellite laser altimeter [14] was to detect ice sheet elevation changes on the centimetre scale. A study from 2019 showed that the overall uncertainty was indeed just 4.0 cm [3]. While ICESat exhibited notable capabilities, it is important to acknowledge that it was not without limitations. Its drawbacks included interlaser biases [3], time-varying biases in radar altimetry [14] and a relatively coarse resolution of elevation data [3]. The launch of ICESat-2 in 2018 was aimed at addressing and overcoming the aforementioned challenges encountered by its predecessor, thereby striving for significant improvements [14].

1.3 Previous Findings

The most relevant previous study on the Fleming Glacier was performed by Friedl et al. in 2018 [8]. In that paper, the influence of the disintegration of Wordie ice shelf on the ice dynamics and land ice height of the Fleming Glacier was studied between 1994 and 2016. The study used both ICESat and Centro de Estudios Científicos Airborne Mapping System (CAMS) measurements, the latter being airborne lidar datasets with a vertical accuracy of 0.2 m [8]. The most extensive ice height measurements were conducted for two time frames: 2004-2008 and 2011-2014. The results have been summarised in Table 1 below.

Table 1: Elevation changes found by Friedl et al. (2018) [8]

Elevation Decrease (m/a)	**ICESat data**	**CAMS data**
Median 2004-2008	1.9 ± 1	1.5 ± 0.6
Maximum 2004-2008	4.6	3.8
Median 2011-2014	3.2 ± 0.8 m	2.6 ± 1.2
Maximum 2011-2014	4.1	3.7

This table shows that the elevation decrease went from an average of under 2 metres in the 2004-2008 period to around 3 metres between 2011 and 2014. Now, using data from ICESat-2 system, the rate of melting of the Fleming Glacier between 2019 and 2022 will be quantified in this paper. A similar result to the elevation changes as found by Friedl et al. between 2004 and 2008 is expected if the glacier has attained equilibrium subsequent to the dynamic response triggered by the disintegration of the Wordie Ice Shelf after 2008 [8]. Has this equilibrium not been reached, the findings are expected to be closer to or even surpass the 2011-2014 results from Friedl et al. Previous studies have yielded insufficient data to draw conclusive findings regarding recent changes in ice dynamics in that region.

In the following chapters, first the methodology used to analyse the data will be presented. Following that, the findings will be presented in a graphical format. The report will conclude with a discussion of the results and implications of the findings.

2 Methodology

This chapter will describe the steps taken to get to the final results in two parts. Chapter 2.1 will briefly discuss how the sensors on the ICESat-2 work and how they gather data on the height of the land ice, while Chapter 2.2 will explain how the data was analysed and visualised.

2.1 Data Acquisition

The improvements in data resolution of the ICESat-2 over its predecessor are for the most part due to the introduction of the Advanced Topographic Laser Altimeter System (ATLAS) which replaced GLAS. The highly improved sampling rate and smaller footprint mean that ICESat-2 produces data with a higher resolution, helping to measure elevation changes of the glacier more accurately [10, 14]. Table 2 below compares several aspects of both satellite systems.

Table 2: A comparison of ICESat and ICESat-2.

Feature	**ICESat**	**ICESat-2**
Sampling rate	172 m	0.7 m
Footprint	± 60 m	± 14.5 m
Latitude coverage	± 86°	± 88°

The big difference in the sampling rate is a result of a very different technique used by ATLAS [10]. The GLAS uses 1064-nm laser pulses which are reflected by the surface and then caught by an optical receiver to measure the two-way travel time [1]. ATLAS meanwhile uses photomultiplier tubes to let the receiver detect single photons reflected from the Earth's surface [10]. This means that the pulses can have a lot less energy, allowing the system to send them out at a way higher frequency of 10 kHz, which is useful for rough terrain such as glaciers [10].

ATLAS uses 3 pairs of beams with a pair width of 90 m and a separation of 3.3 km [10]. This allows for the countering of yet another shortcoming of the GLAS system, which was a single-beam instrument [13]. As seen in Figure 3, ICESat-2 data can be interpolated between two beams of a pair to estimate the slope Ω and calculate the height along a Reference Ground Track (RGT). This is useful for the measurement of elevation change of land ice over time, as this needs to follow a consistent line and since limitations in the laser spot control make it impossible to exactly follow the RGT [10].

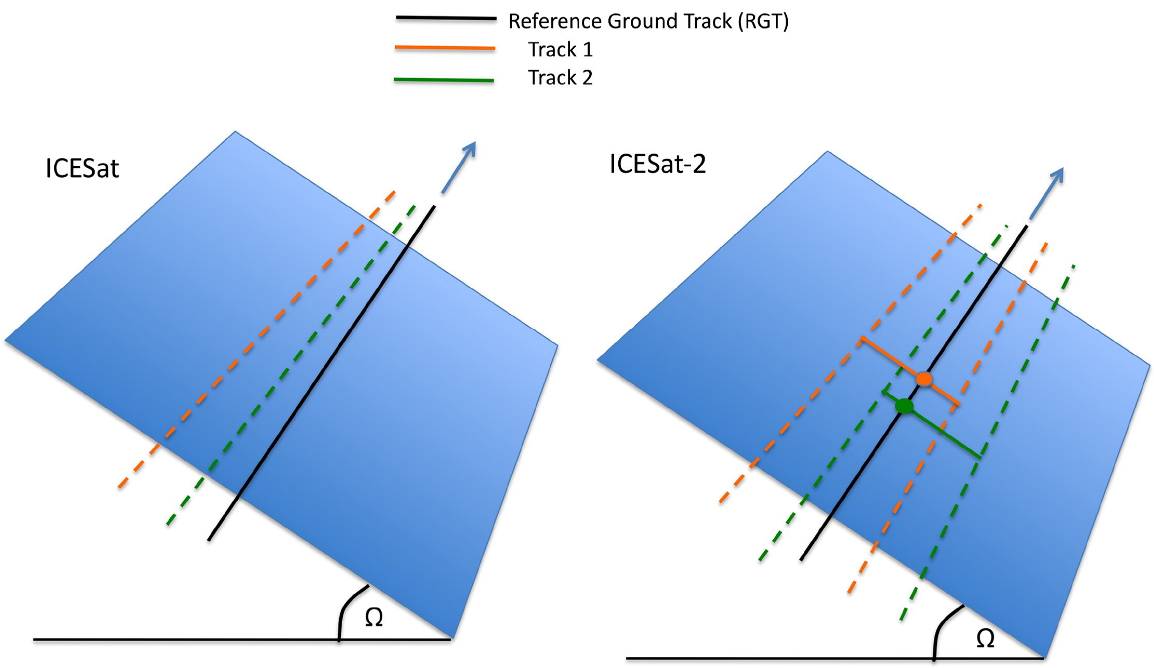


Figure 3: Difference in collection strategies of ICESat and ICESat-2 for an unknown slope Ω. *From [10].*

To better understand how the data collection along RGTs works, it is helpful to know that ATLAS collects several different types of data products. The most relevant one for the purposes of this research is ATL06, which provides geolocated land-ice surface heights [6]. This product encompasses measurements from the three sets of beam pairs, where each pair follows a reference pair track (RPT) parallel to the RGT [13]. As depicted in Figure 4, the middle RPT functions as the RGT with RPT 1 and 3 separated by 3.3 km to either side. The measurements in this ATL06 product are relatively accurate, resulting in beam overlap for most repeat measurements [13]. The correction that can still be applied to this uses a polynomial fit, interpolating the data to the RGT and correcting for the small-scale topography and slope changes as shown before in Figure 3 [13]. The resulting data is stored in the form of the ATL11 product, which can be downloaded from the NASA Earthdata platform [6].

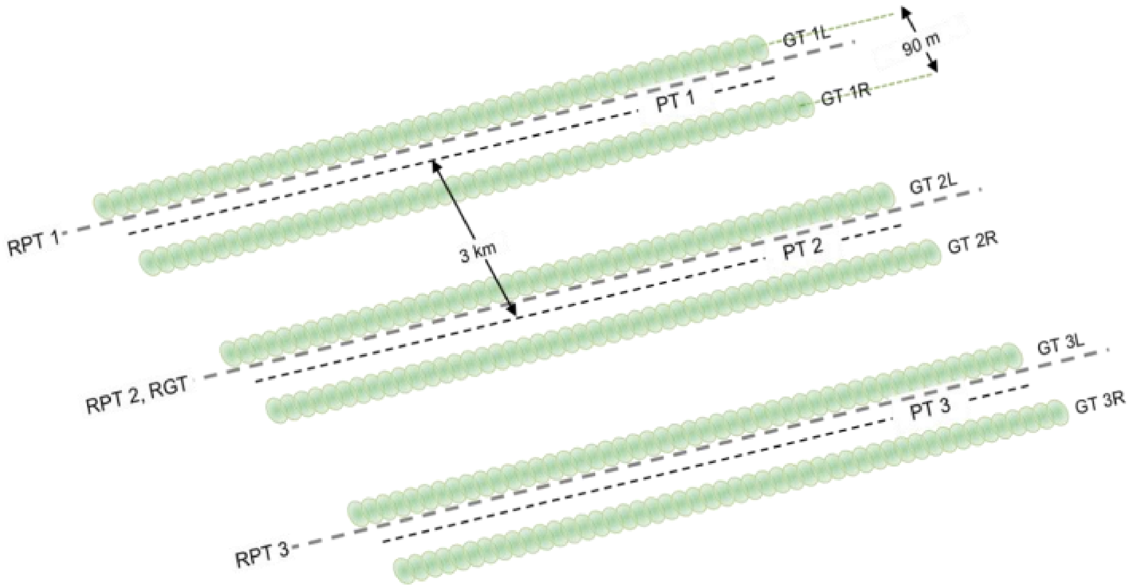


Figure 4: Schematic drawing of the pattern used by ATLAS. The 3 beam pairs follow RPTs with the middle one being the RGT for a given repeat measurement. *From [13].*

Thus, the ATL11 product offers a higher precision for comparing land ice height data at specific locations, enabling more accurate assessments of localised variations. On the other hand, when aiming to measure the average land ice height over a time span of a few years, the ATL06 product is expected to yield satisfactory results. Moreover, the lack of support for ATL11 by the icepyx library [15] would highly complicate the analysis of the ATL11 product, leading to the decision to only analyse ATL06 data in this report.

2.2 Data Analysis

The data from the IceSat-2 was largely analysed using the icepyx software library [15], made to ease the process of querying and analysing ICESat-2 data sets (Appendix B). After choosing a time frame and coordinates outlining a polygon around the Fleming Glacier, the data could be downloaded from the NASA Earthdata website [6]. The available satellite tracks could then be viewed on top of a satellite image of the area of interest as seen in Figure 5. The tracks are slightly distorted but clearly show that the data is collected in 3 parallel beam pairs at once. Due to the relatively small spacing between the beam pairs, each pair seems to show up as just a single track in this image.

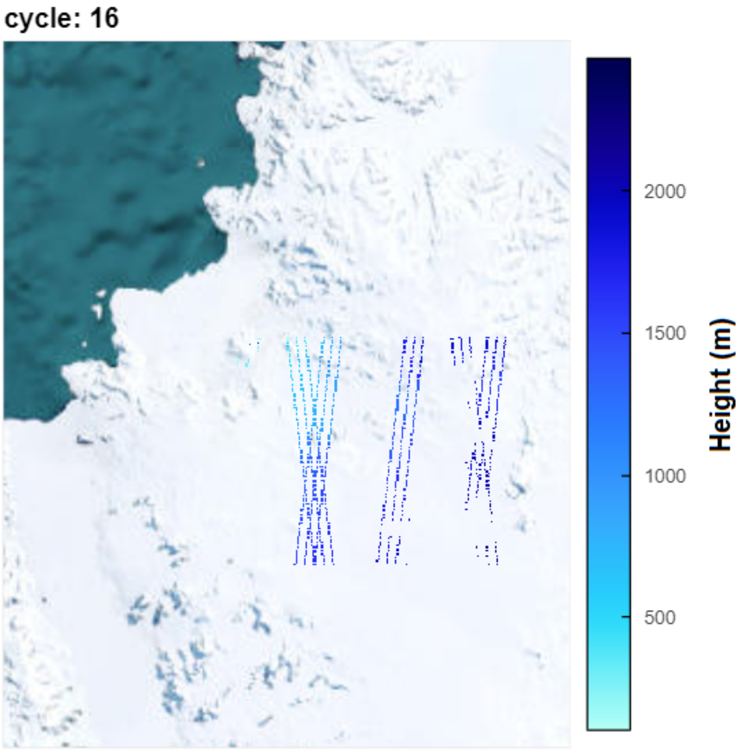


Figure 5: Data tracks gathered by ICESat-2 on the Fleming Glacier in 2022 during one of its cycles. *Obtained using a Jupyter notebook from the icepyx library [15].*

After confirming that the data had been queried for the desired area it could be further analysed. All information was stored in HDF5 files, with each file containing data from all 3 beam pairs for a specific time frame. From these files, two had to be manually removed because they did not contain land ice height information. The remaining files could then be visualised (Figure 10 in Appendix A), however, the resulting figures appear slightly distorted. By removing the NaN values with a filter and flattening the data (Appendix C), much clearer graphs could be obtained, which will be presented in the Results section. The flattening was necessary to convert the 2-dimensional data into a 1D array which is appropriate for plotting. This is because the heights and coordinates were still separated into their corresponding beam pairs.

The next step was to compare the land ice elevations between 2019 and 2022 to answer the question of how much the Fleming Glacier had melted in that time. All coordinates in the HDF5 files were provided in decimal Latitude Longitude format (dLL). Unlike the more traditional coordinate notation (degree, minute, second), dLL can be directly used in digital programs like QGIS or Google Earth [17]. Moreover, the number of decimals in a dLL value specifies the precision of the location with the ICESat-2 data provided up to 8 decimals. At the given latitude and longitude this would result in a degree of precision of about 1 mm N/S and 0.4 mm E/W [18]. Such a high level of accuracy meant that there were no matching coordinates between the 2019 and 2022 data. Only by decreasing the precision to 5 decimals by rounding the data, 27 common coordinate points could be found (Appendix A Table 3). The precision had now been lowered to about 1.1 m N/W and 0.44 m E/W [18].

3 Results

In this chapter, the results will be presented and briefly discussed. The first section will be about presenting the location and elevation of the 2019 and 2022 data while the second section will delve into comparing the two.

3.1 Elevation maps

The filtered and flattened data has been presented in Figure 6. The data in the graph follows a line pattern for the most part, these are the tracks along which the ICESat-2 collected data. The graph for 2022 displays fewer data points compared to the data from three years prior. This can be attributed to the satellite's reduced track coverage across the Fleming Glacier during July and August of 2022. The colour bar indicates the land ice height above sea level. This ranges from 0 metres in the top left to about 2000 metres in the bottom right for both 2019 and 2022. This does not mean that the glacier has a thickness of up to 2 kilometres; the Antarctic continent that lies underneath has a higher elevation as it goes further landwards. As seen in Figure 7 the top left of the graphs indeed corresponds to the terminus of the glacier into Wordie Bay. This map also explains some of the apparent "blank spots" in Figure 6: these are areas outside the ice boundary and have therefore been filtered out when ordering the data.

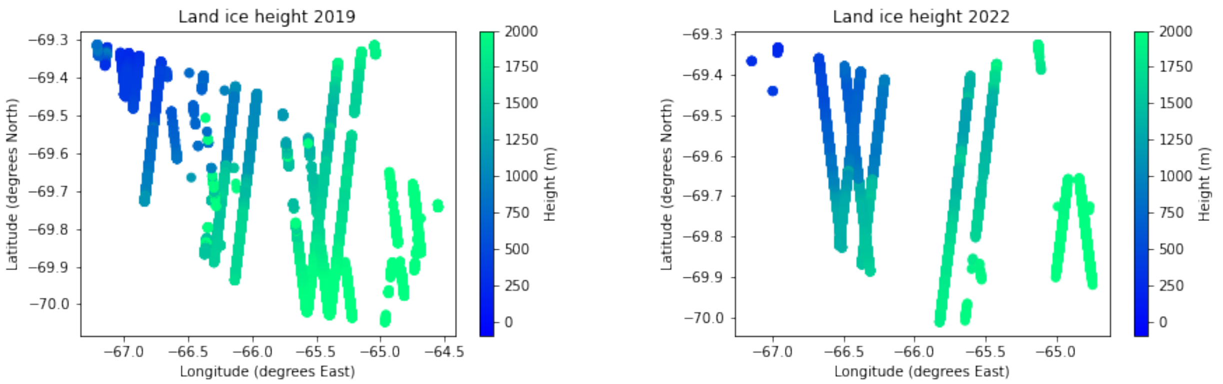


Figure 6: A comparison of datapoints of the land ice height of the Fleming Glacier in 2019 and 2022.

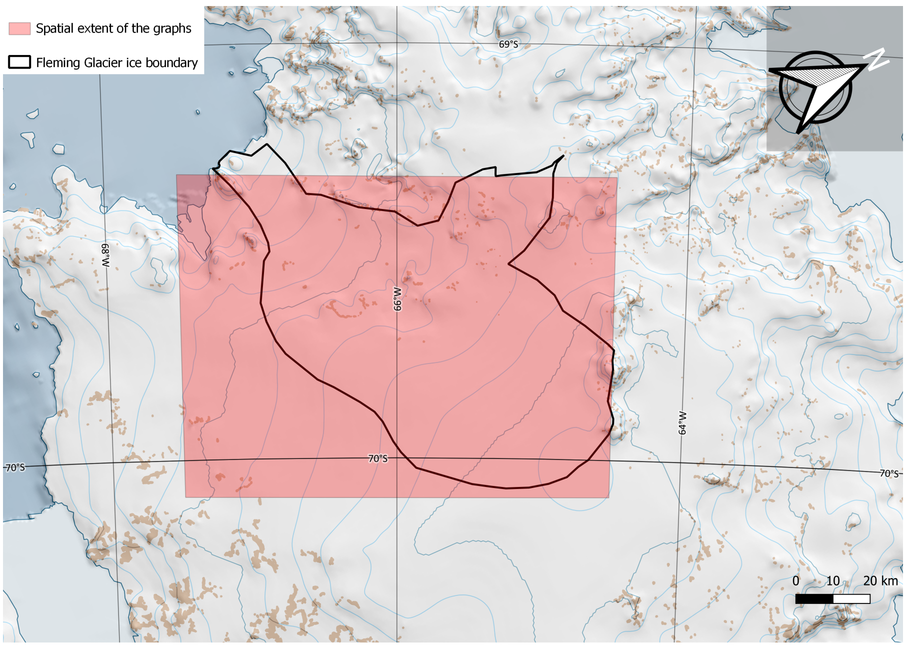


Figure 7: The spatial extent of the graphs above visualised in red over the boundaries of The Fleming Glacier. *Created using the Quantarctica package in QGIS [11].*

3.2 Data comparison

To compare the land ice height between 2019 and 2022, common coordinate points are needed. Even though at first glance it may have seemed like there are many overlapping data points, just 27 coordinates were found with a precision of 5 decimal places in the dLL format, meaning an error of at most 1.1 m. As can be seen in Figure 8, these points are all located in a very small area which is near the terminus of the Fleming Glacier. The satellite tracks from 2019 and 2022 do seem to follow the same pattern in a lot of other places, but with a separation that is too high to reliably compare them.

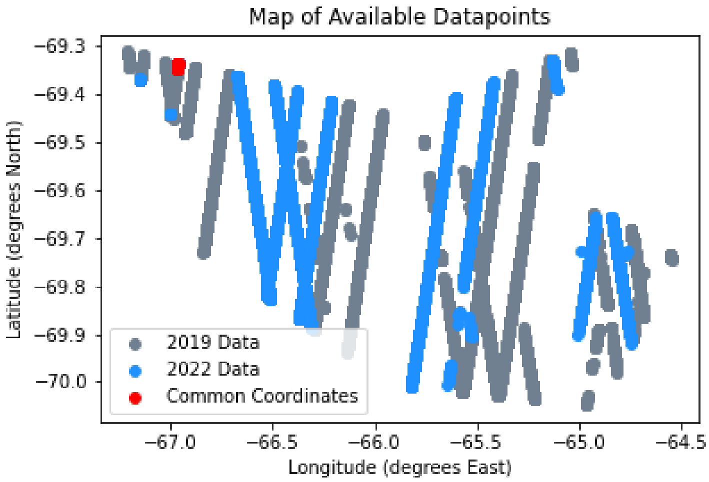
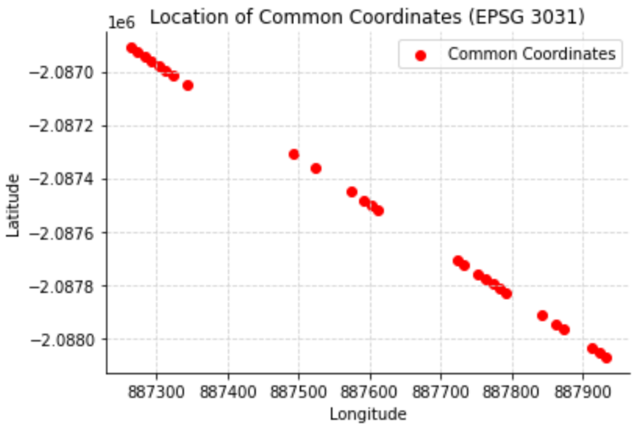


Figure 8: The extent of the data with the common coordinates indicated in red.

Zooming in on the area with shared coordinates it becomes clear that it is a little part of a single track going roughly from South to North. The empty spots along the general trend in the first plot in Figure 9 represent locations with coordinates that were just outside the error limit (i.e. the fifth digit of the coordinates did not match). For this plot the Antarctic Polar Stereographic system (EPSG3031) has been used, a system created for the Antarctic region in which each decimal increase is equal to a one-metre deviation. The second plot in this figure presents the height difference of the glacier between 2019 and 2022. The index on the x-axis corresponds to the common coordinate locations in the graph to the left, with the first one being the point that is furthest South. For this section, the average height difference was found to be 4.40 metres. Considering that the measurements are over a time span of 3 years, the average rate of melting would be 1.47 $m/year$. There are however a few points at which the height in 2022 increased, this is most likely a result of local snow and ice dynamics, since this occurs at a location where the measured elevation in 2019 is lower than would be expected if the general trend would have been followed.



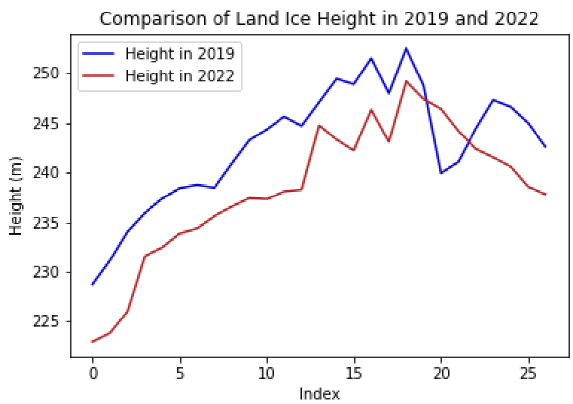


Figure 9: Land ice height at the common locations and their coordinates.

4 Discussion

The data that was analysed in this report is subject to many uncertainties. In this chapter, all these uncertainties will be considered and the usefulness and reliability of the results will be evaluated. Afterwards, potential further research opportunities will be explored.

4.1 Result validation

As mentioned previously, the ATLAS system on board the ICESat-2 mission has a higher sampling rate and spatial resolution than its predecessor [1, 10, 14]. More important than that though for this research is its accuracy. This was estimated in an extensive 2019 study during which highly precise traverse GNSS data was collected by PistenBully vehicles on the Antarctic ice sheet and subsequently compared to ICESat-2 height data along the same track [4]. This research concluded that the ATL06 data (used in this paper) is accurate to better than 3 cm for height measurements with a surface measurement precision of better than 9 cm [4].

The lat/long precision had to unfortunately be decreased to about 1.1 m by rounding the data to 5 decimals in order to compare the data sets. This however still results in just 27 common data points densely concentrated in a small area of the glacier. The restricted sample size raises concerns about the representativeness of these data points in capturing the overall trends. The underlying problem originates from the Reference Ground Tracks (RGTs) which seem to not be consistent. As explained before in Figure 4, ICESat-2 uses pairs of beams following RPTs, which should in theory allow for an easy comparison of height data from different years. Figure 8 clearly demonstrates a notable offset between the 2019 and 2022 data though. Based on this observation, the most tenable conclusion is that there were no common RGTs between 2019 and 2022 in this particular region. This is endorsed by the fact that the magnitude of the offset significantly exceeds the Root Mean Square (RMS) accuracy, which is typically expected to be half of the 90-meter beam spacing within a pair [13]. This is an unexpected result, as the main purpose of ATL06 data is to allow for a comparison of the land ice height at a specific location over time, for which RGTs are crucial.

A comparison between the results of this study and Friedl et al. (2018) [8] reveals that the calculated annual land ice height decrease of 1.47 m/year is plausible. While Friedl et al. found slightly higher values overall (Table 1), that study also found that lower ice thinning rates are present near the front of the glacier, with the biggest elevation changes being observed further upstream [8]. The limited geographic extent of the common coordinates and the fact that they are located near the terminus of the glacier could explain the difference between the results. Furthermore, this result supports the hypothesis that the dynamic response to the disintegration of Wordie Ice Shelf [8] has slowed down or even ceased.

4.2 Future research opportunities

Clearly, this research has a few shortcomings, the biggest one being the limited amount of data. Nevertheless, it shows that ICESat-2 can provide extensive data sets with an accuracy that is unmatched at its scale. By comparing data from a different/longer period, there would be a possibility that more common data points were found, hence improving its reliability. More data and data points more closely following RGTs would potentially allow to round the latitude and longitude to 6 coordinates instead of 5, which would reduce the uncertainty in that aspect tenfold.

Another possibility would be the use of interpolation techniques to map the height of the entire glacier surface. This was not done in this paper due to the complex topography of glaciers with many height changes caused by ice dynamics. Interpolation would probably be more useful to get an idea of the overall glacier topography rather than just a comparison.

Finally, it is strongly recommended to further investigate this area using ATL11 data for future research, especially if icepyx support is added. Although the main issue appears to concern the incoherent Reference Ground Tracks, ATL11 data could nonetheless aid in improving the accuracy of the existing common coordinates. In particular, the fine-scale glacier topography would become more apparent and perhaps more common coordinates would be identified with that data set.

5 Conclusion

The aim of this report was to use ICESat-2 data to measure the amount by which the Fleming Glacier has melted between 2019 and 2022. The data was downloaded from NASA and then analysed using various Python scripts, including the icepyx package. The following approach was implemented:

- The area of ice boundaries of the Fleming Glacier was identified and a time frame to be investigated was chosen. The corresponding ATL06 data was downloaded from the NASA Earthdata website.
- The data was then flattened and the NaN values were removed using a Python script. This resulted in cleaner data which could then be plotted.
- Using various plots data from 2019 and 2022 could be compared. This allowed for a comparison of the land ice height across multiple "common coordinates" and a calculation of the yearly average rate of melting in the 2019-2022 period.

This led to the following conclusions:

- The ATLAS system on board ICESat-2 has remarkable capabilities in acquiring land ice height information in the Arctic region, showing to be a considerable upgrade over its predecessor and still having a promising future ahead of it.
- The study resulted in the finding that between the winter of 2019 and 2022 the land ice height of the Fleming Glacier decreased by 4.40 metres, meaning an average decrease of 1.47 $m/year$. Compared to the findings by Friedl et al. (2018) [8] this means that the rate of melting has slowed down.
- The data from these years has a very limited amount of common points which could be compared within a reasonable accuracy range, just 27.
- The poor beam overlap between 2019 and 2022 can be accounted to an issue with the Reference Ground Tracks.
- Several locations have been found at which the land ice elevation increased rather than decreased, this is most likely due to local snow and ice dynamics.

The results of this report are in line with previous studies. The accuracy of this study is however constrained by the limited number of data points available. Future research should focus on a way to collect data across more common points (which are also more spread out over the glacier surface) as this is necessary to increase the confidence of the results. The use of ATL11 data is strongly recommended for future investigations as well, as this should provide more matching coordinates as well as more detailed surface topography data.

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A Additional graphs and data

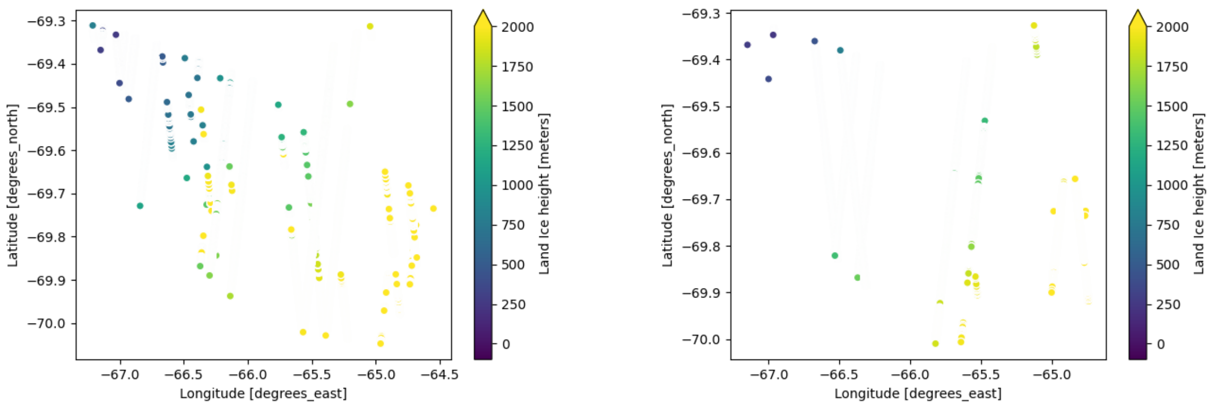

Figure 10: Visualisation of the raw land ice height data of 2019 and 2022.

Table 3: Land Ice Height at the common coordinates

Latitude	Longitude	Height 2019	Height 2022
-69.34577	-66.96667	228.71589661	222.94343567
-69.3378	-66.96392	231.13140869	223.81877136
-69.34612	-66.96679	234.02438354	225.98556519
-69.34595	-66.96673	235.92347717	231.57858276
-69.34098	-66.96503	237.36610413	232.45042419
-69.34187	-66.96533	238.43048096	233.86488342
-69.33478	-66.96289	238.76148987	234.37219238
-69.3362	-66.96338	238.46890259	235.61767578
-69.33726	-66.96374	240.90910339	236.56523132
-69.33461	-66.96283	243.26220703	237.42817688
-69.34541	-66.96655	244.34921265	237.32301331
-69.3463	-66.96685	245.65097046	238.09065247
-69.33567	-66.9632	244.69911194	238.29637146
-69.33496	-66.96295	247.09124756	244.76133728
-69.33744	-66.9638	249.44250488	243.3160553
-69.33815	-66.96405	248.89976501	242.22253418
-69.34559	-66.96661	251.52035522	246.32804871
-69.33585	-66.96326	247.97425842	243.0868988
-69.33709	-66.96368	252.54060364	249.21824646
-69.34045	-66.96485	248.78753662	247.40994263
-69.34028	-66.96479	239.94694519	246.41358948
-69.34648	-66.96691	241.09138489	244.1703186
-69.33833	-66.96411	244.41365051	242.38809204
-69.34063	-66.96491	247.30712891	241.53114319
-69.3424	-66.96551	246.61384583	240.59907532
-69.34506	-66.96643	244.98599243	238.56881714
-69.33762	-66.96386	242.59162903	237.81549072

B Python code to request and download ICESat-2 data

```
import icepyx as ipx

# setting the polygon vertices
short_name = 'ATL06'
date_range = ['2019-07-01','2019-09-01']
spatial_extent = [(-67.27055,-69.30573), (-66.6246,-69.3649), (-65.8852,-69.4503),
(-64.9948,-69.3051), (-65.2556,-69.5423), (-64.5394,-69.7376), (-64.8899,-70.0506),
(-65.9012,-70.0064), (-66.8401,-69.7303), (-66.89406,-69.49974), (-67.27055,-69.30573),
(-67.27055,-69.30573)]

region = ipx.Query(short_name, spatial_extent, date_range)

print(region.product)
print(region.dates)
print(region.start_time)
print(region.end_time)
print(region.product_version)
print(list(set(region.avail_granules(cycles=True)[0]))) #region.cycles
print(list(set(region.avail_granules(tracks=True)[0]))) #region.tracks

region.visualize_spatial_extent()

cyclemap, rgtmap = region.visualize_elevation()
cyclemap

#downliadung data from the NASA Earthdata directory
region.earthdata_login()
region.order_granules()
#view a short list of order IDs
region.granules.orderIDs
path = 'C:julyaugust2019'
region.download_granules(path)
```

Credits
Notebook by: Tian Li, Jessica Scheick and Wei Ji
Source material: READ_ATL06_DEM Notebook by Tian Li and Friedrich Knuth

C Python code to visualise and compare the datasets

```
import icepyx as ipx
import numpy as np
import xarray as xr
import pandas as pd
import h5py
import os,json
from pprint import pprint
import matplotlib.pyplot as plt

path_root2019 = 'C:somedata2019test'
pattern = "processed_ATL{product:2}_{datetime:%Y%m%d%H%M%S}_{rgt:4}{cycle:2}
{orbitsegment:2}_{version:3}_{revision:2}.h5"
reader2019 = ipx.Read(path_root2019, "ATL06", pattern)
reader2019.vars.append(beam_list=['gt1l', 'gt3r'],
var_list=['h_li', "latitude", "longitude"])
ds2019 = reader2019.load()
ds2019

path_root2022 = 'C:julyaugust2022'
pattern = "processed_ATL{product:2}_{datetime:%Y%m%d%H%M%S}_{rgt:4}{cycle:2}
{orbitsegment:2}_{version:3}_{revision:2}.h5"
reader2022 = ipx.Read(path_root2022, "ATL06", pattern)
reader2022.vars.append(beam_list=['gt1l', 'gt3r'],
var_list=['h_li', "latitude", "longitude"])
ds2022 = reader2022.load()
ds2022

ds2019.plot.scatter(x="longitude", y="latitude", hue="h_li", vmin=-100, vmax=2000)
ds2022.plot.scatter(x="longitude", y="latitude", hue="h_li", vmin=-100, vmax=2000)
```

Credits
original notebook by: Jessica Scheick
notebook contributors: Wei Ji and Tian
templates for default ICESat-2 Intake catalogs from: Wei Ji and Tian.

```
The following section of code was created for this project with the
purpose of comparing and visualising the ICESat-2 data more clearly.
```

```
from pykrige.ok import OrdinaryKriging
import gstools as gs
import skgstat as skg
import scipy as sp
#%matplotlib auto
%matplotlib inline


#Flattening and removing nan/0 values from the data


'2019 data'
longitude_flat = ds2019.longitude.values.flatten()
latitude_flat = ds2019.latitude.values.flatten()
h_li_flat = ds2019.h_li.values.flatten()
valid_mask = np.logical_and.reduce((
```

```
    ~np.isnan(longitude_flat),
    ~np.isnan(latitude_flat),
    ~np.isnan(h_li_flat),
    longitude_flat != 0,
    latitude_flat != 0
))
longitude_clean = longitude_flat[valid_mask]
latitude_clean = latitude_flat[valid_mask]
h_li_clean = h_li_flat[valid_mask]
print(longitude_clean)
print(latitude_clean)
print(h_li_clean)

'2022 data'
longitude_flat22 = ds2022.longitude.values.flatten()
latitude_flat22 = ds2022.latitude.values.flatten()
h_li_flat22 = ds2022.h_li.values.flatten()
valid_mask22 = np.logical_and.reduce((
    ~np.isnan(longitude_flat22),
    ~np.isnan(latitude_flat22),
    ~np.isnan(h_li_flat22),
    longitude_flat22 != 0,
    latitude_flat22 != 0
))
longitude_clean22 = longitude_flat22[valid_mask22]
latitude_clean22 = latitude_flat22[valid_mask22]
h_li_clean22 = h_li_flat22[valid_mask22]
print(longitude_clean22)
print(latitude_clean22)
print(h_li_clean22)



#Plot the coordinate/height graphs
plt.scatter(x= longitude_clean, y=latitude_clean, c=h_li_clean,
vmin=-100, vmax=2000, cmap='winter')
plt.colorbar(label='Height (m)')
plt.title("Land ice height 2019")
plt.xlabel('Longitude (degrees East)')
plt.ylabel('Latitude (degrees North)')
# plt.savefig("2019landiceheight")

plt.scatter(x= longitude_clean22, y=latitude_clean22, c=h_li_clean22,
vmin=-100, vmax=2000, cmap='winter')
plt.colorbar(label='Height (m)')
plt.title("Land ice height 2022")
plt.xlabel('Longitude (degrees East)')
plt.ylabel('Latitude (degrees North)')
# plt.savefig("2022landiceheight")

print(h_li_clean22.shape)
print(h_li_clean.shape)
print(latitude_clean22.shape)


#Compile the 'clean' data back together
coordinates19 = np.column_stack((latitude_clean, longitude_clean))
print(coordinates19)
```

```
coordinates22 = np.column_stack((latitude_clean22, longitude_clean22))
print(coordinates22)

# Round the coordinates to '5' decimal places
rounded_coordinates_2019 = np.round(np.column_stack((latitude_clean,
longitude_clean)), decimals=5)
rounded_coordinates_2022 = np.round(np.column_stack((latitude_clean22,
longitude_clean22)), decimals=5)
# Create a set of rounded coordinates from the 2019 dataset
coordinates_2019 = set((lat, lon) for lat, lon in rounded_coordinates_2019)
# Create a set of rounded coordinates from the 2022 dataset
coordinates_2022 = set((lat, lon) for lat, lon in rounded_coordinates_2022)
# Find the common coordinates present in both datasets
common_coordinates = coordinates_2019.intersection(coordinates_2022)
# Convert the common coordinates back to numpy array
common_coordinates = np.array(list(common_coordinates))
print(common_coordinates)

#Match the height data with the common coordinates
indices_2019 = np.where(np.isin(rounded_coordinates_2019,
common_coordinates).all(axis=1))[0]
# Get the indices of common coordinates in the 2022 dataset
indices_2022 = np.where(np.isin(rounded_coordinates_2022,
common_coordinates).all(axis=1))[0]
# Get the height values for the common coordinates in the 2019 dataset
heights_2019 = h_li_clean[indices_2019]
# Get the height values for the common coordinates in the 2022 dataset
heights_2022 = h_li_clean22[indices_2022]
print(heights_2019)
print(heights_2022)

comparisondata = np.column_stack((common_coordinates[:, 0],
common_coordinates[:, 1], heights_2019, heights_2022))
print(comparisondata)


===========================
Plotting comparison graphs
===========================

heights_2019 = comparisondata[:, 2]
heights_2022 = comparisondata[:, 3]
fig, ax = plt.subplots()
ax.plot(heights_2019, color='mediumblue', label='Height in 2019')
ax.plot(heights_2022, color='firebrick', label='Height in 2022')
ax.set_xlabel('Index')
ax.set_ylabel('Height (m)')
ax.legend()
plt.title('Comparison of Land Ice Height in 2019 and 2022')
# plt.savefig("heightcomparison")
plt.show()


fig, ax = plt.subplots()
# Plot the common coordinates
ax.scatter(common_coordinates[:, 1], common_coordinates[:, 0],
color='red', marker='o', label='Common Coordinates')
ax.set_xlabel('Longitude')
```

```
ax.set_ylabel('Latitude')
ax.legend()
plt.title('Location of Common Coordinates')
ax.spines['top'].set_visible(False)
ax.spines['right'].set_visible(False)
ax.grid(color='lightgray', linestyle='--')
# plt.savefig("commonpointlocation")
plt.show()


plt.scatter(x=longitude_clean, y=latitude_clean,
color='slategray', label='2019 Data')
plt.scatter(x=longitude_clean22, y=latitude_clean22,
color='dodgerblue', label='2022 Data')
plt.scatter(common_coordinates[:, 1], common_coordinates[:, 0],
color='red', label='Common Coordinates')
plt.xlabel('Longitude (degrees East)')
plt.ylabel('Latitude (degrees North)')
plt.legend()
plt.title("Map of Available Datapoints")
# plt.savefig("commononrestofdata")
plt.show()
```