# INVESTIGATING THE UTLITY OF ICESat-2 TO MONITOR SEA ICE EXTENT IN THE BEAUFORT SEA

A Directed Research Project

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# 1.0 INTRODUCTION

## 1.1 Background

Monitoring sea ice extent can be viewed as a precursing identifier of climate change impacts. Climate change is a very pertinent issue and one that has a direct effect on our society. Understanding this effect is of upmost importance so that we can be prepared however is necessary for a potentially existential problem. Depleting ice levels are the main contributor to rising sea levels and subsequent changes in oceanic cycles and processes. These oceanic cycles and processes are the drivers of our weather patterns and climate as a whole. If we can understand how much sea ice is physically changing in the polar regions, as well as how quickly it's changing, we can start to analyze the effects sea ice extent has on Earth's systems.

ICESat-2 stands for Ice, Cloud, and land Elevation Satellite and is the second iteration of this sensor. The first ICESat was operational from 2003 to 2009 and provided multi-year elevation data needed to determine ice sheet mass balance as well as cloud property information, especially for stratospheric clouds common over polar areas. It also provided topography and vegetation data around the globe, in addition to the polar-specific coverage over the Greenland and Antarctic ice sheets. ICESat-2 was launched in 2018 and operates by transmitting laser pulses from the satellite at a rate of 10,000 Hz. Each laser pulse releases about 20 trillion photons though only about a dozen of these photons reflect from the surface and return to the sensor. ICESat-2 provides scientists with height measurements that create a global portrait of Earth's 3rd dimension; gathering data that can precisely track terrain changes associated with glaciers, sea ice, forests, and more.

The satellite was launched with four main objectives: 1) measure melting ice sheets and investigating effects on sea level rise, 2) measure and investigate changes in the mass of ice sheets and glaciers, 3) estimate and study sea ice thickness, and 4) measure the height of vegetation in forests and other ecosystems.

## 1.2 Problem Statement

According to the study titled, "*Changing state of Arctic sea ice across all seasons*", performed by Julienne Stroeve and Dirk Notz in 2018, the Beaufort Sea ranks second in total ice loss experienced during times of low ice extent at the end of the summer season (end of September/beginning of October). This region has lost roughly 68% of its total ice during the specified season compared to averages between 1979-1989 (Stroeve, Notz 2018). Because of this fact, it would be beneficial to understand every tool available to monitor the changing conditions. Thus, I will look to answer the question of whether or not the ICESat-2 sensor can be used to monitor sea ice extent in the Beaufort Sea.

## 1.3 Objectives

The overall goal of this study is to determine if ICESat-2 can be used to accurately monitor sea ice extent. Although not directly purposed to measure sea ice extent, it may be possible to use ICESat-2 in this manner.

## 1.4 Justification

A multitude of studies have been done using this sensor to measure ice thickness, ice sheet topography, freeboards (portion of ice above the water line)., etc., but very little has been published to determine sea ice extent. This study will help provide clarity on whether ICESat-2 can be used for this purpose in the future.

## 2.0 LITERATURE REVIEW

### 2.1 Historic background of the cryosphere

The depletion and augmentation of ice present on the surface of the Earth has been in a cyclic process for millions of years. Times where glaciers and ice extents are large and widespread are termed “glacial periods” (or ice ages). On the contrary, times where glaciers and ice extents are small and isolated are known as “interglacial periods”. The most recent glacial period on the Earth’s surface was between 120,000 and 11,500 years ago (NOAA). This period in colloquial terms is known as extending from the Eemian period to the end of the Younger Dryas (NOAA). It is since then, that that Earth has been in an interglacial period known as the Holocene (NOAA).

Changes in Earth's angle on its axis, as well as its orbit, have caused the amount of solar radiation it receives in each season to change over time. Times of greater, more direct, solar radiation in the northern hemisphere tend to lead to interglacial periods. Vice versa, extended times where there is less intense solar radiation in the northern hemisphere seem to lead to glacial periods. These cycles between glacial and interglacial periods have persisted over the past 2.6 million years. Since the middle of that span, these cycles have occurred with a rough frequency of about 100,000 years (Lisiecki and Raymo, 2005). In the historical time series of solar radiation, there are cycles of 100,000 years, known as eccentricity, and cycles of 23,000 years known as the precession of the equinoxes. The cycles of 100,000 years tend to be weaker than those cycles lasting just 23,000 years. Be that as it may, periods of full interglacial activity only occur at roughly every fifth peak in the precession cycle. This reality is still very much an active area of research, and we are yet to have an entirely complete explanation for why the climatic pattern forms this way. Another area of research that’s important to understand why glacial and interglacial periods occur when they do is the full understanding of positive feedbacks within the climate system. Positive feedbacks are reinforcing and compounding contributions such as climate warming leading to more water vapor being present in the air, which then lends its hand to greater warming of the climate. Questions needs to be answered such as what positive feedbacks influence glacial and interglacial periods the most and how much exactly do they influence them?

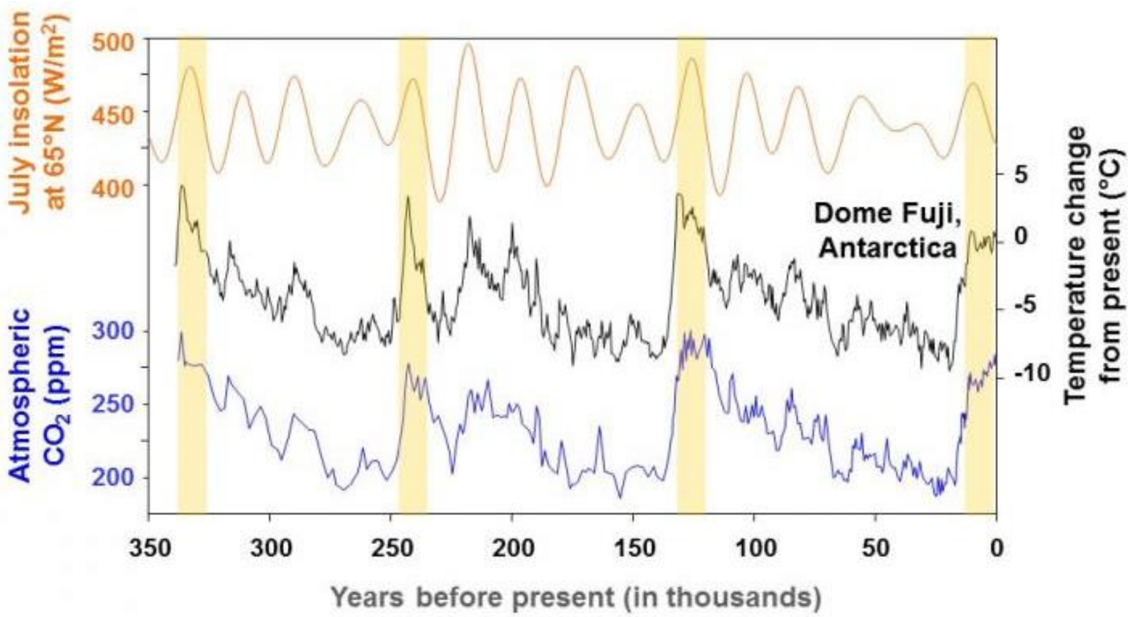


**Figure 1:** Solar radiation varies smoothly through time (top, orange line) with a strong cyclicity of ~23,000 years, as seen in this time series of July incoming solar radiation at 65°N (Berger and Loutre 1991). In contrast, glacial–interglacial cycles last ~100,000 years (middle, black line) and consist of stepwise cooling events followed by rapid warmings, as seen in this time series inferred from hydrogen isotopes in the Dome Fuji ice core from Antarctica (Kawamura et al. 2007). Atmospheric $CO_2$ measured from bubbles in Dome Fuji ice (bottom, blue line) shows the same pattern as the temperature time series (Kawamura et al. 2007). Yellow columns indicate interglacial periods.
Image Credit: NOAA, Glacial-Interglacial Cycles

Figure 1 provides a summary of trends in atmospheric CO2, summer insolation and temperature change over the last several hundreds of millennia. In this figure, the black line is the Antarctic temperature record and the yellow sections denote rapid warming followed by more subtle cooling (Kawamura 2007; Jouzel 2007). The shape of these factors forms a clear and noticeable pattern. Interestingly, towards the end of a given glacial period, temperature seems to rise more quickly and distinctly than the solar radiation line (orange line). Again, climatic positive feedbacks can be the explanation for this. First, the ice-albedo feedback. The less ice there is present, the less incoming solar radiation can be reflected. Second, the feedback involving atmospheric $CO_2$. It is proven that the amount of atmospheric $CO_2$ decreased in glacial periods as proven by bubbles trapped in ice cores (Kawamura 2007; Siegenthaler 2005; Bereiter 2015). This can be explained because the ocean is known to be a carbon sink of sorts, and with much greater amounts of ice covering and trapping it, less $CO_2$ is able to escape into the atmosphere. In turn, these lower $CO_2$ levels in the atmosphere diminish the greenhouse effect and contribute further to lower temperatures overall. On the opposite side of this is at the end of glacial periods, warming decreases the amount of ice coverage, heats up the ocean, and extricates trapped $CO_2$. A continuation of this contributes to a stronger and stronger greenhouse effect and warmer temperatures. As we are currently in a stage of global warming, these effects are ever-present and understanding their impacts and implications on our current climate and species is imperative.

### 2.2 Current Ice Extent Monitoring Practices

One way of studying the effects of being in the midst of an interglacial period is by monitoring the extent of ice present on the Earth's surface. Because the amount of ice is so vast, and the effects of its depletion are spread out over such a long time, we as humans have an innate inability to comprehend subtle changes or the grand implications of them. The most obvious and effective way to visualize this issue to a point of understanding is to monitor changes over time. This method is clear cut and provides an obvious visualization of ice extent from thousands of years ago compared to present day. Peltier (1994) performed this method by creating a model to recreate past climates and compared ice coverage to present day. This model consisted of variables such as surface temperature, extent and albedo of land and sea ice, and paleotopography. Their method and variations of it, is essentially the only way to provide side-by-side visual comparisons of past ice extent and present-day ice extent for such time scales.

Another way of monitoring the issue of ice extent is by reducing the time scale to something relatively more compact and recent. For example, there are many studies that look at glacial extent over shorter time intervals. I have gathered a collection of six recent studies that all meet the criteria of monitoring glacial extent from roughly the mid to late 1900's to the early 2000's and into the 2010's. They are performed over a broad geographic extent including India, Canada, Mexico, Pakistan, Turkey, and Tibet (Burgess and Sharp, 2004; Kaushik et al., 2020; Kutuzov and Shahgedanova, 2009; Li et al., 2016; Naeem et al., 2016; Viola et al., 2019). Each of these studies utilize satellite observations (primarily Landsat). They each prepare their gathered images however is needed, georeferenced them using geographic control points, and calculated the area differential using some sort of raster overlay techniques, whether it be from ArcGIS or other geospatial software. Furthermore, they all come to the conclusion that glaciers around the world are in fact losing ice volume and retreating. The rate of which they are retreating varies from study to study. Each study has a slightly different time period, but they all do come to the same base level findings that glaciers are retreating and are doing so relatively quickly. They also share similar reasons for why their respective glaciers are retreating whether it be albedo levels, warming temperature, etc. Where these studies differ is their reason for performing it in the first place.

### 2.3 Current ICESat-2 Utilization Examples

Opposed to the traditional method of monitoring ice extent retreat using passive optical satellite images, my study will attempt to use the Ice, Cloud and land Elevation Satellite (ICESat-2) lidar sensor aboard the International Space Station (ISS). ICESat-2, launched Sept.

15, 2018, uses lasers and a very precise detection instrument to measure the range to the Earth's surface. By timing how long it takes laser beams to travel from the satellite to Earth and back, we are able to calculate the height of glaciers, sea ice, forests, and lakes (NASA). There have been a multitude of studies performed in the past using this same sensor for various ice-related monitoring. The majority of these studies seem to focus on sea ice altimetry, thickness, topography, and freeboards.

Some examples of studies using the ICESat-2 sensor to determine sea ice thickness include the following. Xiaoyi Shen et al., performed a study in 2021 aimed at determining ICESat-2's ability to measure sea ice thickness. In this study, they estimated sea ice thickness using three different methods and compared the results to previous measurements from other sensors. Two of the methods (BMA and BME, buoyancy method with the AWI snow depth and the buoyancy method with the empirical snow depth respectively) are considered buoyancy methods. The difference between them is BMA uses Alfred Wegener Institute (AWI) snow depth which is gathered by a passive microwave radiometer combined with a climatology model while BME uses empirical snow depth measurements. The final of the three methods (Empirical Estimation Method, EEM) uses the linear relationship between in-situ measurements of total freeboard and sea ice thickness. They concluded that most methods were viable, but the BMA buoyancy method performed the best. In 2021, Ron Kwok et al., studied arctic snow depth and sea ice thickness to determine how much of the freeboard was covered by snow. They used lidar and radar to calculate snow thickness and sea ice thickness, respectively for the entire Arctic Ocean. They determined that, on average, roughly 50% of the freeboard is covered in snow. This helps contribute to the understanding of the insolating role snow cover plays on ice growth rates. Another study performed by Alek Petty et al., in 2020 focused on determining snow depth and ice thickness using ICESat-2. This study built upon the previously mentioned Ron Kwok study by examining the seasonal evolution of ice through the first winter of their study. They used those measurements and compared them to ICESat's measurements from 2008 to determine the change across an 11-year time period and determined that by their estimates, sea ice across the inner Arctic Ocean domain had diminished in thickness by roughly 20% from 2008 to 2019.

There were a few studies that used ICESat-2 for proposes other than estimating sea ice thickness. For example, in 2019 Beata Csatho et al., examined ice sheet elevation mapping and change detection. In this study they were able to describe the computation of surface elevation change rates from ICESat-2 data using the Surface Elevation Reconstruction and Change detection (SERAC) algorithm. They focused on how they calculated a time series of elevation change rates but did face one drawback. The drawback is since real ICESat-2 data suitable for generating time series of several time epochs were not yet available, they had to use simulated data for their study.

Ron Kwok et al., also performed a study in 2019 that used two ICESat-2 datasets, one from winter and one from summer. Their research describes and tests procedures that were devised to separate lidar returns of ice from open water which is a crucial step for the estimation of local sea levels for freeboard calculations. This study helps my pursuits because it shows that ICESat-2 does have the capability of determining the extent of ice.  Finally, in 2020, Nan Xu et al., focused on monitoring annual changes in water levels in Lake Mead from 1984-2018. Their study used both Landsat imagery and ICESat-2 data. They determined that ICESat-2 has a great potential to accurately characterize the Earth's surface topography and reported that ICESat-2 can capture signal photons reflected from underwater bottoms up to approximately 10 m in Lake Mead.

These studies all contribute to a great body of knowledge that stems from ICESat-2. They cover very important areas of research such as the ones I listed before, sea ice altimetry, thickness, topography, and freeboards. They do however show an area of study that hasn't yet been explored to my knowledge. I couldn't find any studies that directly searched specifically for sea ice extent change over time using ICESat-2. This is the niche I will seek to fill with my study.

## 3.0 DATA

ICESat-2's waveform LiDAR data are available via the NASA Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC). The actual data itself is described as "containing science unit-converted, time-ordered telemetry data, calibrated for instrument effects, downlinked from the Advanced Topographic Laser Altimeter System (ATLAS) instrument on board the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) observatory. The data are used by the ATLAS/ICESat-2 Science Investigator-led Processing System (SIPS) for system–level, quality control analysis and as source data for ATLAS/ICESat-2 Level-2 products and the Precision Orbit Determination (POD) and Precision Pointing Determination (PPD) computations" (NSIDC). The data are free and can be acquired from a simple download. The interface where the data are found allows you to specify the time frame in which you are searching and provides you with the spatial resolution, temporal resolution, and spatial coverage. Furthermore, it also displays the physical parameters of the dataset you're analyzing (i.e. glacier elevation/ice sheet elevation/sea ice elevation/sea surface height/terrain elevation/freeboard/backscatter/etc.). The specific dataset of interest will be the ATL07 –

ATLAS/ICESat-2 L3A Sea Ice Height, Version 5. This dataset specifically provides heights for sea ice and open water leads.

## 4.0 METHODS

### 4.1 Study Area

The ICESat-2 sensor has global coverage capability, so I was not restricted by the instrument. However, the Arctic lends itself to being a pertinent area of study since the region is experiencing the greatest change in sea ice extent. The area where I focused was the Beaufort Sea. This marginal sea is located north of the Northwest Territories, the Yukon, and Alaska, and west of Canada's Arctic islands. It ranks second in total ice loss experienced during times of low ice extent at the end of the summer season (end of September/beginning of October) and has lost roughly 68% of its total ice during the specified season compared to averages between 19791989 (Stroeve, Notz 2018).


**Figure 2:** A figure showing the location of the Beaufort Sea

This study's design is to visualize the difference in sea ice extent between ICESat-2 and 30 m Landsat 8 satellite imagery to determine if ICESat-2 data can accurately characterize sea ice extent.

### 4.2 Data Processing and Analysis

Using OpenAltimetry, I evaluated ATL07 (ATLAS/ICESat-2 L3A Sea Ice Height) data to determine data availability in the study area at the end of the summer season, when sea ice extent is at its lowest (e.g., September/beginning of October). First, I found data along a tract that met the criteria for 2021 and then matched the same tract for a similar date in 2019. At the extent of the data returns for each date, I used the "select a region" tool to isolate the data points of interest. Once the data points were isolated for each year, I exported them into a csv file that included attributes such as latitude and longitude, thus giving me the ability to place the data into a GIS.

Using ArcMap, I imported each year's data points from their csv file based on their latitude and longitude. I then exported that data into its own shapefile in order to gain the ability to edit and standardize the data. I did so by ensuring the data for each year covered roughly the same surface area so that later visualization scales would be as similar as possible. Next, I traced the outline of the previous shapefile and created a new one that consisted of a polygon as opposed to point features. Further preparation of each year's point features was still necessary. I then interpolated the features to create an estimated surface to compare with the Landsat 8 data. To do this, the natural neighbor interpolation tool was used in ArcMap.

Using EarthExplorer (earthexplorer.usgs.gov), I input my previously created polygon shapefile to determine the area of interest and filter the datasets. I also specified additional search criteria such as a two-week date range (09/25 - 10/8) and a 75% cloud cover threshold. In my case, Landsat 8 was the dataset of most interest to me because its range of spectral capabilities suited the need to search for sea ice best. Once a suitable image was discovered for each date, I downloaded them and used ArcMap to display the images underneath the ICESat-2 data returns.

Within ArcMap I was able to reproject the ICESat-2 data and Landsat images to the projected coordinate system North American Equidistant Conic. This projection preserves distances within the area in which the data is located. After that, I simply used the measure tool to determine the difference between ice extents for each date of ICESat-2 data and then subsequently each Landsat 8 image. Measuring the difference between ICESat-2 and Landsat 8 ice returns serves an obvious purpose. It is important to measure the datasets from the same sources across the two dates as well because this will help inform some of the data's reliability. This difference informs the answer to whether or not ICEsat-2 can be used to measure ice extent accurately.

## 5.0 RESULTS

The figures below provide a visual description of the locations of the measurements between the interpolated ICESat-2 data surfaces and isolated NIR Landsat 8 images for each respective date of interest.

- Distance between ICESat-2 data extents: 187.51 km
- Distance between Landsat 8 nearest visible ice return along ICESat-2 tract: 163.07 km

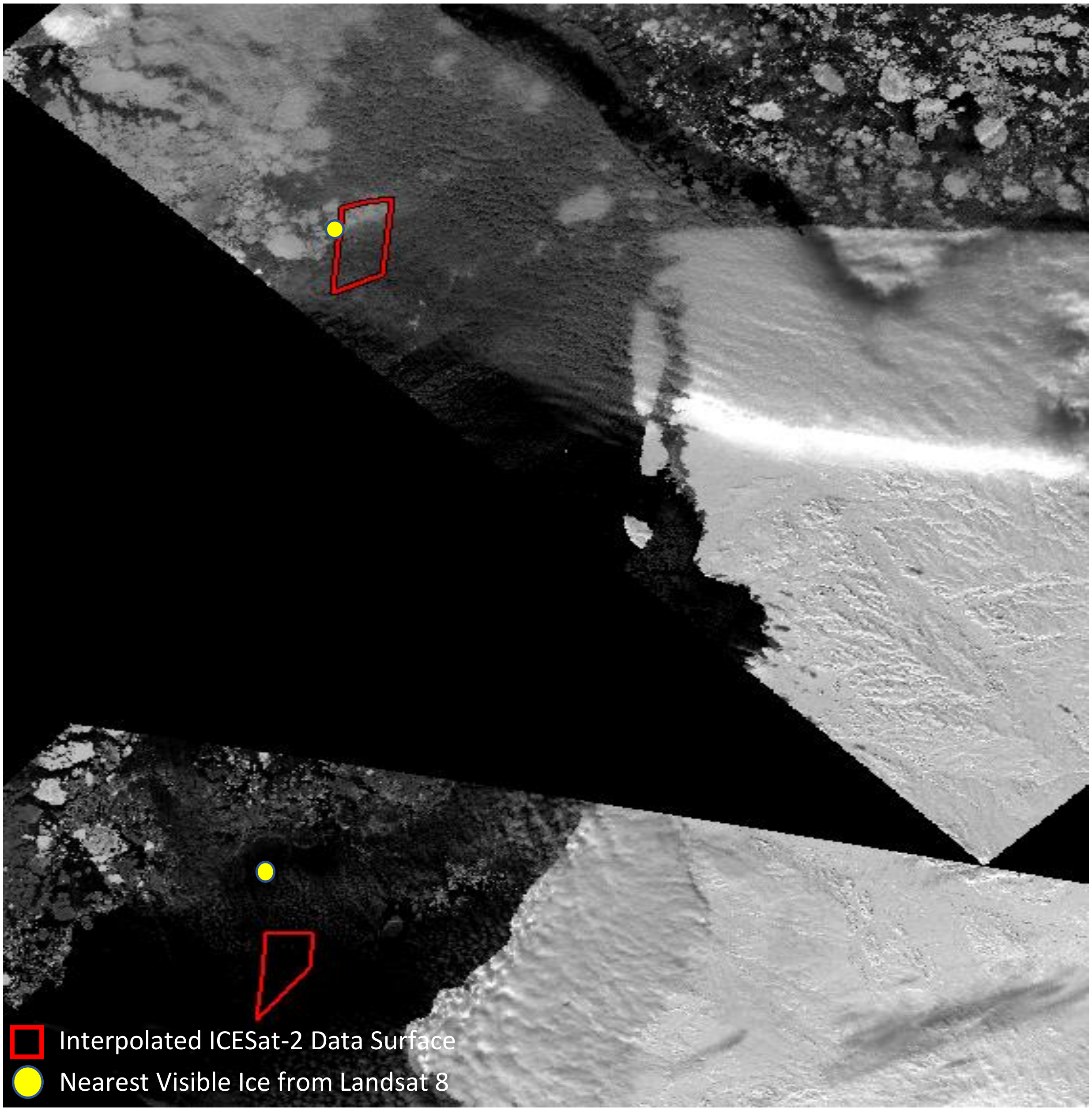


**Figure 3:** An overall image showing both dates for Landsat 8 NIR images, interpolated ICESat-2 surfaces, and nearest visible ice from Landsat 8 along the ICESat-2 tract.

- ICESat-2 data extent to nearest visible Landsat 8 ice return along ICESat-2 tract:

- October 6, 2019: 39.14 km

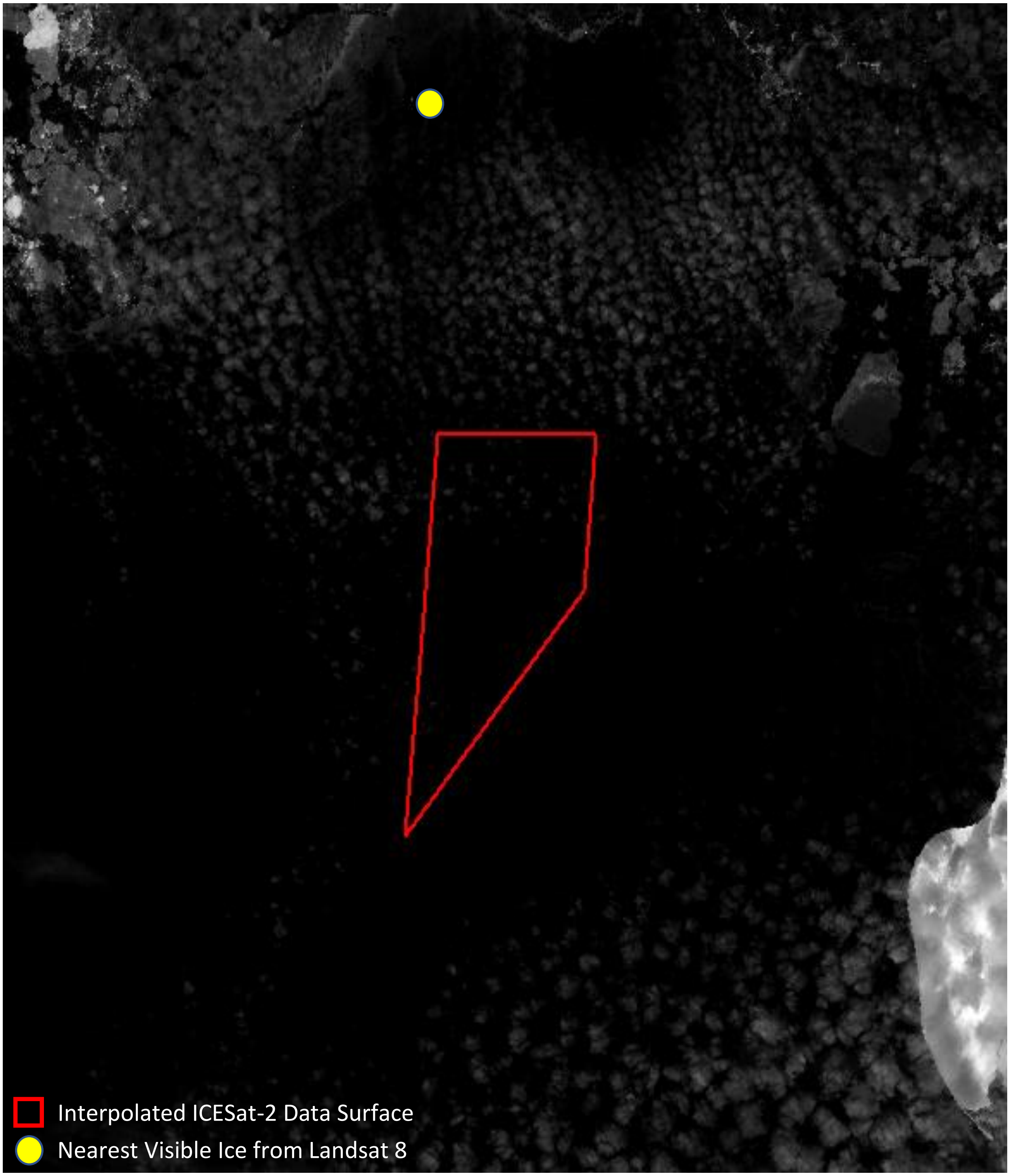


**Figure 4:** An image showing October 6, 2019, Landsat 8 NIR image underneath the corresponding interpolated ICESat-2 data surface and the point of the nearest visible ice return

- October 1, 2021: 14.37 km

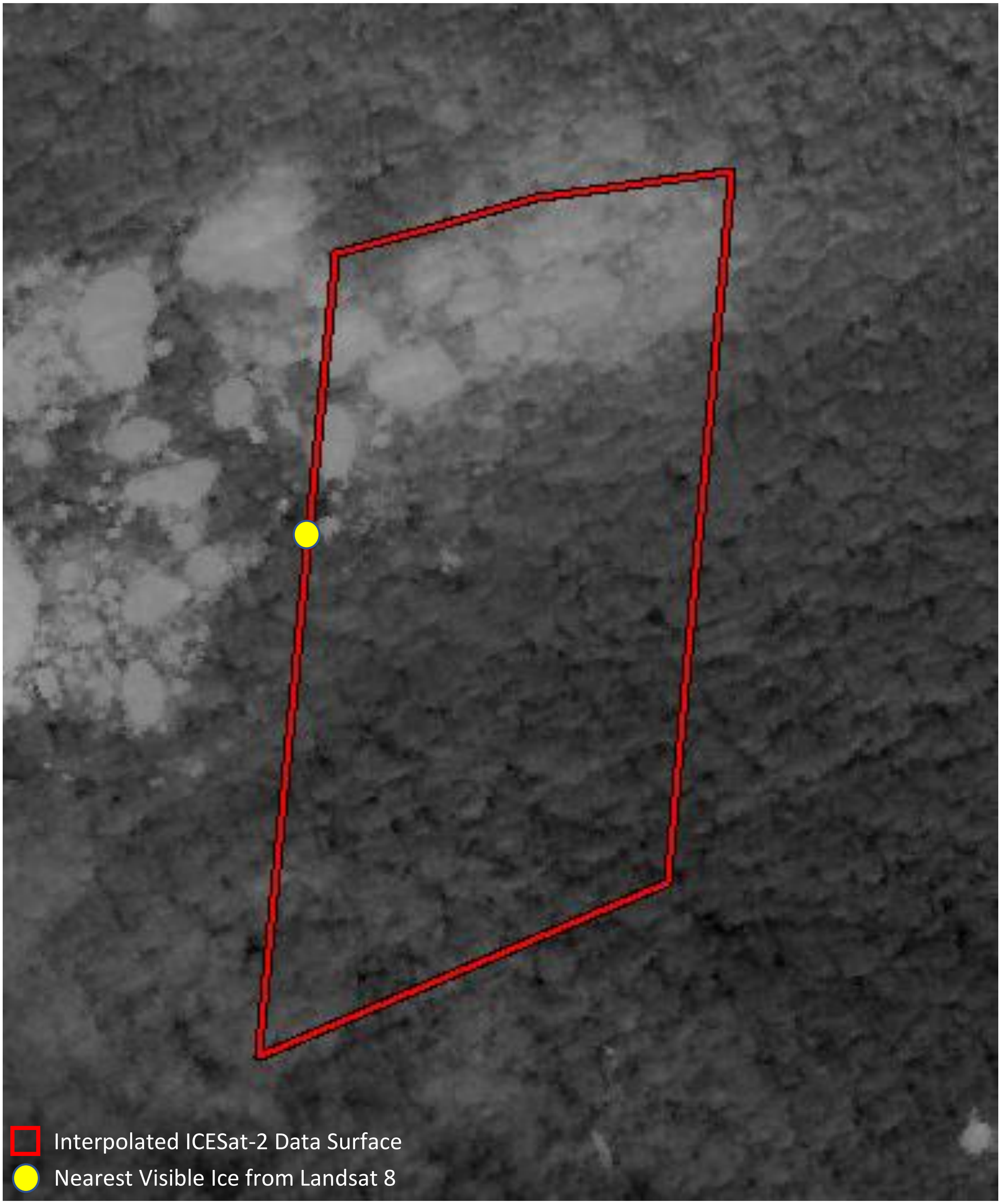


**Figure 5:** An image showing October 1, 2021, Landsat 8 NIR image underneath the corresponding interpolated ICESat-2 data surface and the point of the nearest visible ice return

## 6.0 DISCUSSION

The results from my method do not imply that ICESat-2 can be confirmed to be a reliable tool to measure sea ice extent, for multiple reasons. First, there may be an inherent issue with validating ICESat-2 data returns in this way, because the only Landsat 8 imagery available for my study area/time period covers such a large land area that visualizing the ice itself is an issue. Zooming in as much as possible on the raster display did not allow me to see any ice in the location of the ICESat-2 data points. There may be data returns from ICESat-2 that are reflecting off pieces of ice that are simply too small to see in a satellite image at this scale because of the issue stated in the following paragraph. This forced me to acquire my measurements based on the nearest visible sea ice whereas in reality, there may be sea ice present in the exact spot in the image that the data references. The fact that the ice extent distance between ICESat-2 data returns and the Landsat imagery differs between the two dates, influenced me to believe this is the case here.

Another issue is the nature of sea ice and how fluid, broken up, and dispersed it is in this location and at this time of year. There is no clear continuous shelf, boundary, or extent that could be used to infer any broader information or conclusions, other than where the furthest sliver or small piece of ice is at the precise time the data was recorded (Figure 5). With how often ICESat-2's sensor sends pulses and how small those pulses are, it is entirely possible that miniscule pieces of sea ice or even slush are responsible for the return.


**Figure 6:** A visual example of the dispersed and limited sea ice as discussed in the previous paragraph. Arctic Ocean, Greenpeace Arctic Sunrise expedition.

The last inherent issue is the nature of ICESat-2 data being along tracts and in point format, as well as the neighboring tracts not having the corresponding subsequential date of coverage. Figures 6 and 7 below provide visuals for the nature of ICESat-2's data collection footprint. This is an area of concern because of the broken up, dispersed sea ice. The tracts are wide, but it is still possible to have dispatched sea ice just outside of the field of view of the sensor. This would mean the ice extent overall is greater than the collected data suggests. This is also a concern because it becomes harder to depict a real picture of ice extent over an area wider than a single tract. This narrows down the usefulness of this practice to almost exclusively finding the ice extent in a very specific area or region and I am unsure if that is a frequent need.

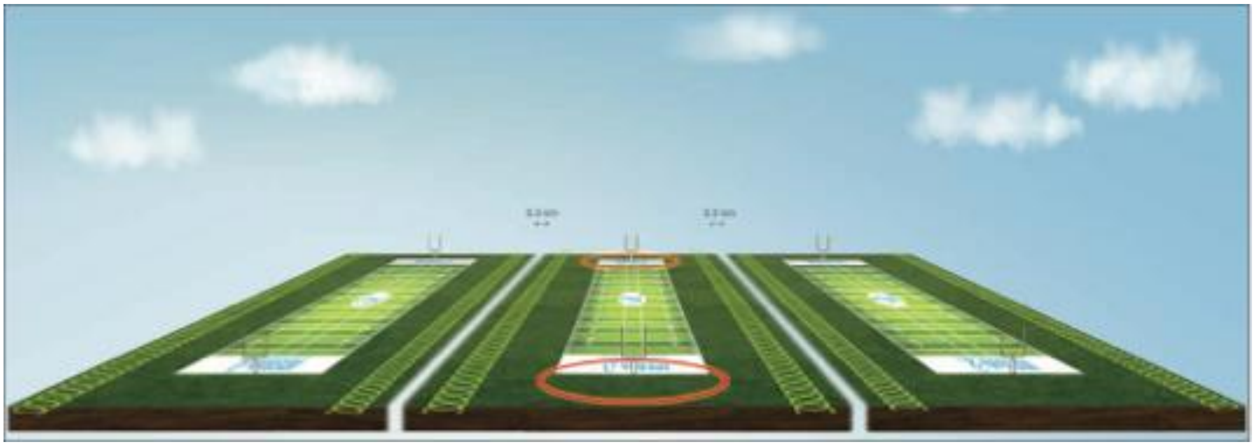

**Figure 7:** A figure showing the data collection footprint of ICESat-2 compared to ICESat. The first ICESat would have taken a single measurement in each end zone where you see two red circles; ICESat-2 takes measurements within each yard line where you see green circles. Furthermore, while ICESat had one laser beam, ICESat-2 has three pairs of beams which equals six beams total. This means that at the same time two laser beams are collecting data on one field, the other two pairs of beams can gather data on two parallel football fields 2.1 miles (3.3 kilometers) apart. (ICESat-2 Mission Brochure)

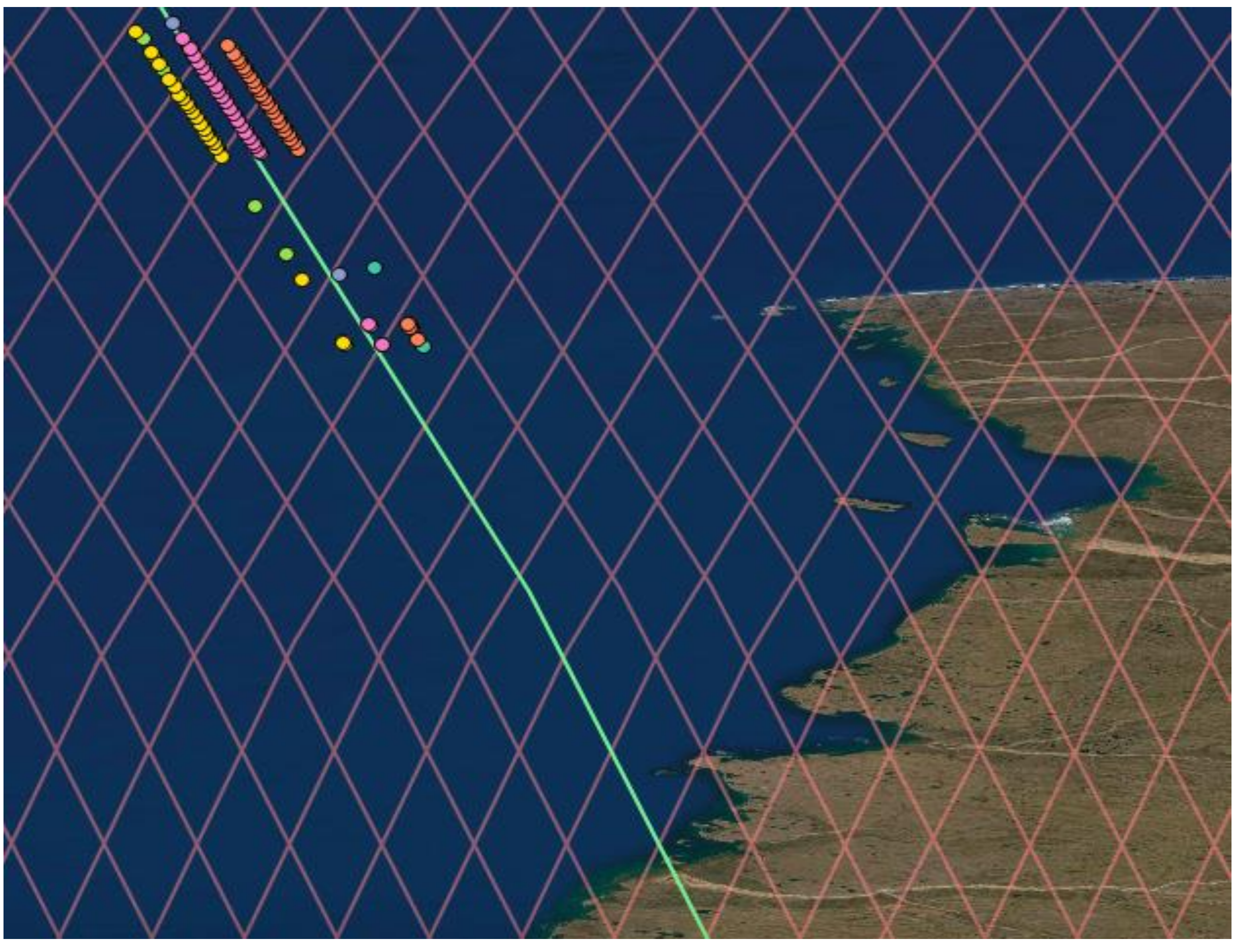

**Figure 8:** A figure showing a different perspective of the data collection footprint of ICESat-2. The red lines are each tracts and the color coded points are the ICESat-2 data returns. At this scale, only 1.56% of data return points are visible. The neighboring tracts are not flown on subsequent dates. October 1st, 2021, data is shown. October 2nd's data is located 22 tracts over to the east. The neighboring tract to the east is not flown until October 30th, 2021.

Based on the results, the answer to my research question would be no. ICESat-2 should not be used to monitor sea ice extent. An average error of 26.76 km between ICESat-2 data and the Landsat imagery is not acceptable. The primary reason for the result of this research is due to the factors listed above. It is difficult to confirm its accuracy and reliability in the way this directed research is presented.

## 7.0 CONCLUSION

In conclusion, I reiterate that solely based on my results, I do not believe ICESat-2 should be used to monitor sea ice extent. However, I also do not believe that ICESat-2's data returns are irrelevant, incorrect, or that its sea ice returns are in locations where there is no ice present. Unfortunately, it became clear that the only way to validate the returns in the way I hypothesized (based on imagery), would be to acquire very specific georeferenced imagery showing only the area of the ICESat-2's data return boundary.

There could hypothetically be a way for future work to explore this topic using the same exact methods as I presented. It would be to narrow down the goal even further from finding the furthest reaching ice return to the finding the furthest reaching area with a clear, dense ice presence (most resembling an ice shelf). This would require a greater knowledge of ICESat-2 elevation data and how that corresponds to locating the boundary of an ice shelf. That point then lends itself to requiring an understanding of the location and behavior of sea ice in the region of interest and at the time of year of interest. Lastly, it would require a fair amount of trial and error with imagery which may be inefficient enough to make the result not worth the process. These three points are what I believe caused the answer to my research question to result in a no. However, with this goal in mind, the worry of having a data return from a small piece of ice would be eliminated and the idea of having the ability to verify the data with imagery could be more readily explored.

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