



**Remote Sensing of Lava Lake Activity at Mount Erebus
Using SWOT Altimetry Data, Ground Based Thermal Data and ICESat-2
Altimetry Data**

by

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Background

The ambition of this project is to understand the capabilities and limitations of the SWOT satellite and also ICESat-2 satellite in their ability to measure volcanic activity at one of the most inhospitable regions in the world.

Monitoring active volcanoes in polar environments presents distinctive challenges for volcanologists, geophysicists, and climate scientists alike. Mount Erebus, located on Ross Island in Antarctica, is the southernmost active volcano on Earth and one of the very few to host a long-living convecting lava lake. Since its discovery in the 1970s, this lava lake has provided a rare natural laboratory for observing continuous open-vent degassing, magmatic convection, and explosive activity within the extreme environment that is the Antarctic.

Conventional monitoring of Erebus is restricted by the environment Mount Erebus finds itself in. The volcano is situated in one of the most remote and inhospitable regions on Earth. Physical access to the volcano is only possible during short windows of the austral summer. Severe weather, logistical expense, and the risks associated with operating at high altitude in extreme cold all limit the feasibility of long-term ground-based monitoring. These limitations are themselves evident in the thermal dataset used for this research. The ‘MODVOLC’ data shown in **Fig 1** demonstrates clear gaps during the Antarctic winter when polar darkness prevents continuous infrared observations. This seasonal data scarcity further underscores the importance of testing alternative remote sensing methods such as satellite altimetry.

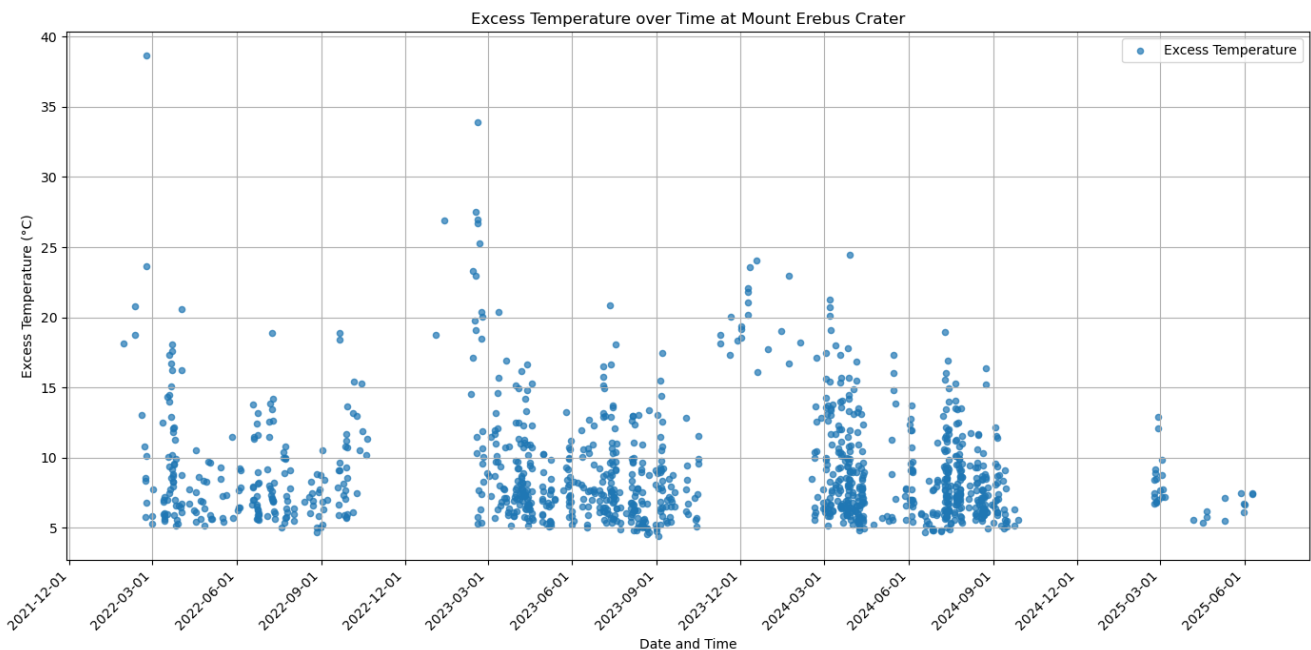


Figure 1: MODVOLC Excess Temperature analysis at Mount Erebus

This monitoring deficit makes Erebus an ideal target for satellite remote sensing. Satellites provide regular, global coverage, often at spatial and temporal resolutions sufficient to resolve signals from small-scale features such as craters.

Altimetry has historically been developed for oceanography and cryospheric science. Radar altimeters and laser altimeters have revolutionised our understanding of sea-level rise, ice sheet mass balance, and hydrological change. The launch of new missions such as **SWOT** (Surface Water and Ocean Topography, 2022) and **ICESat-2** (Ice, Cloud, and land Elevation Satellite-2, 2018) marks a significant advance in our ability to measure Earth’s surface. SWOT’s Ka-band Radar Interferometer provides swath-based mapping of

water surface height at ~250 m resolution, while ICESat-2's photon-counting laser altimeter achieves centimetre-scale vertical precision along narrow ground tracks. It is important to emphasise that these instruments were **not** designed with volcanology in mind.

Applying altimetry to volcanology raises important questions that this research attempts to solve or at least begin to address. The first is can SWOT's swath coverage capture statistically meaningful changes over the small footprint of not simply a crater but a lava lake? Can ICESat-2's sparse but precise transects resolve short-term variations in lava lake elevation? And crucially, can these height changes be meaningfully related to other indicators of volcanic activity, such as thermal output as seen in the **Fig 1** MODVOLC data? This project seeks to address these questions by pairing SWOT and ICESat-2 altimetry data with thermal observations of Erebus's lava lake.

The Satellites:

SWOT

The Surface Water and Ocean Topography (SWOT) mission is a joint project between NASA and CNES, launched in December 2022. Its primary scientific goal is to measure variations in global sea surface height and to provide high-resolution data on freshwater bodies such as lakes and rivers. SWOT's core instrument is the Ka-band Radar Interferometer (KaRIn), which operates by transmitting radar pulses from two antennas mounted on a deployable boom and measuring the phase difference of the returned signal. This configuration allows SWOT to map water surface elevation across a swath approximately 120 km wide, with a spatial resolution on the order of 250 m.

For volcanology, SWOT presents significant challenges. The 250 m footprint is small compared to a volcanic crater but is large when compared to Erebus' lava lake. SWOT's repeat cycle and swath orientation mean that direct observations of a small target such as Erebus's lava lake are rare, and interference from surrounding crater topography produce readings that are inconsistent with the true physical elevation of the lava lake. Nevertheless, SWOT represents a step-change in our ability to monitor surface height in inaccessible locations with wide spatial coverage.

ICESat-2

The Ice, Cloud and land Elevation Satellite-2 (ICESat-2), launched in September 2018, is designed to measure changes in ice sheet elevation, sea ice freeboard, and vegetation canopy height. It carries the Advanced Topographic Laser Altimeter System (ATLAS), which fires 10,000 laser pulses per second towards Earth's surface. The instrument produces six beams in total, three strong and three weak, each with a footprint of roughly 11 m in diameter and spaced about 90 m apart.

ICESat-2 offers vertical precision at the centimetre scale, making it an exceptionally powerful tool for detecting subtle elevation changes. Its limitation is spatial and temporal coverage because the beams are narrow and orbital repeat times are longer than for SWOT. For Erebus, ICESat-2 therefore complements SWOT by providing highly precise height data at the cost of sparse spatial sampling.

Methodology

Three key data sets were used in conducting this investigation. The first was SWOT (Surface Water and Ocean Topography) data. The second was MODVOLC ground based thermal data. The third was ICESat-2 data.

SWOT data was obtained from the NASA earth data search website online, the link for which is as follows:

[http://search.earthdata.nasa.gov/search/granules?p=C2799438306-POCLOUD!C2799438306-POCLOUD&pg\[1\]\[v\]=t&pg\[1\]\[gsk\]=-start_date&pg\[1\]\[m\]=download&pg\[1\]\[cd\]=f&q=karin&sb\[0\]=166.9744%2C-77.59735%2C167.30065%2C-77.43506&tl=1712253035.197!4!!&lat=0.06648990000000055&long=243.91075971289203&zoom=1.341665149213433](http://search.earthdata.nasa.gov/search/granules?p=C2799438306-POCLOUD!C2799438306-POCLOUD&pg[1][v]=t&pg[1][gsk]=-start_date&pg[1][m]=download&pg[1][cd]=f&q=karin&sb[0]=166.9744%2C-77.59735%2C167.30065%2C-77.43506&tl=1712253035.197!4!!&lat=0.06648990000000055&long=243.91075971289203&zoom=1.341665149213433)

For SWOT, the specific data product used was the level 2 KaRIn Low-Rate Sea Surface Height Data Product, Version C. Within this data product are 4 types of files for each individual overpass. Basic, Unsmoothed, Windwave, and Expert. For this experiment, all files used were Unsmoothed. Sometimes for an overpass, there were 8 files in the cases where there were both PGCO and PICO files. (4x PGCO and 4x PICO) Although most of the SWOT files used were PICO in some cases, PGCO and PICO were downloaded out of curiosity for how they both plotted for the same overpass.

To isolate Mount Erebus and reduce the number of files to choose from, a bounding box was drawn over the mountain of SW: -77.59735,166.9744 and NE: -77.43506,167.30065. Although SWOT began collecting data in December 2022, this specific data product has data since August 2023.

The second key data set was MODVOLC thermal data with activity at the crater of Mount Erebus from January 2022. From this data set temperature, excess temperature, and brightness temperature (B31) were used.

Given the abundance of SWOT files and thermal data points, respectively, SWOT files to extract data from were chosen based on whether they corresponded in date and time to a thermal data point from the MODVOLC data. Given volcanic activity at Erebus can change so quickly, it was important to pair a data point that fell within the time range of the SWOT overpass of the defined bounding box. In some cases, there is an up to 2-hour time gap between the SWOT overpass and the thermal data point for the sake of extracting as much information as possible, but this is the exception not the rule.

In total, 49 SWOT files were downloaded and plotted from Earth data search. This is the maximum number that could be downloaded given the SWOT data only began in August 2023 and given the need to pair the SWOT pass to a temp data point. In some cases, two SWOT files were downloaded from the same time and day, reflecting the availability of both PGCO and PICO products. Therefore, in terms of the number of unique MODVOLC data points used there were 45.

The third data set, ICESat-2 was used to confirm or reject findings using SWOT. The bounding box drawn was (S: -77.56, W: 167.05, N: -77.48, E: 167.35). All available ATL03 ICESat-2 data was obtained since 2018.

ICESat data was obtained from the National Snow and Ice Data centre Online, the link for which is as follows:

<https://nsidc.org/data/data-access-tool/ATL03/versions/6>

Unlike SWOT, there were an abundance of files that hit the lava lake but there were few that scored hits while the MODVOLC data was extracted making the pairing of both ICESat and MODVOLC to establish any form of causation impossible.

Study Area

To precisely investigate the lava lake and crater on Mount Erebus coordinates for both were taken from Google Earth. The lava lake centre was given the coordinates, lat:-77.526777, lon: 167.165218. From there a radius of 0.001° was applied which represents a circle with diameter 220m.

While this exceeds the diameter of the lava lake, given SSH and Sigma0 data were extracted based on whether the centre of the SWOT measurement point fell within our lava lake circle, a slightly wider study area could accommodate the scenario where the centre of the SWOT measurement point fell outside the lava lake but still recorded data from within the lava lake area given its 250m diameter. Initially a radius of 0.0005° was applied which yielded no results.

The crater itself was centred on the point lat -77.5272, lon 167.1633. This is not actually the physical centre of the crater. Given curiosity about a potential second lava lake on Mount Erebus just next to the existing one, this 'crater centre' is actually directly between these two hot spots. The crater was given a radius of 0.007° .

In addition to these two study areas, 'peripheral' areas around the lava lake and crater were used to extract additional data. These had a radius of 0.007° centred on the lava lake and 0.014° with the crater centre coordinates.

Data Processing

For each SWOT file, three CSVs were created.

One CSV contains four SSH readings representing the average SSH over the area of the lava lake, lava lake peripheral, crater centre and crater peripheral.

The second csv contains all the data for points that fell within the lava lake centre. This includes not just SSH but also Sigma0 with their corresponding coordinates. Only three of these files were created because only three SWOT files had a measurement point that fell within the defined lava lake circle.

The third type of CSV contains all the points that fell within the defined crater circle with 0.007° diameter. Like the lava lake csv files these contain the coordinates of the points and their corresponding SSH and Sigma0 values.

Additionally, for each SWOT file a visualisation of the swath was created (**Fig 2**, **Fig 3**, **Fig 4**). Displayed are the SSH and Sigma0 of a zoomed out or wide perspective of Ross Island and a zoomed in plot with the lava lake highlighted. Each plot was given the same axis so wide and zoomed in plots from different SWOT files can be directly compared to one another.

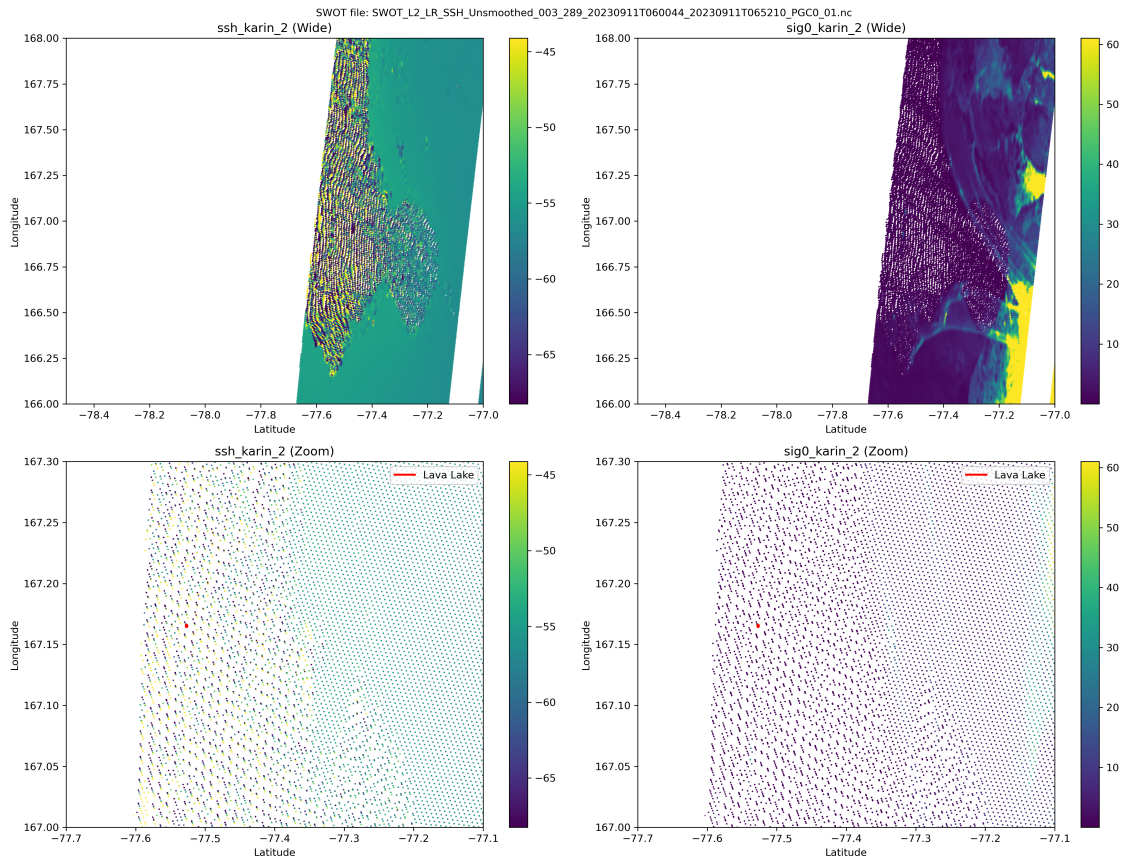


Figure 2: SWOT KaRIn swath over Ross Island showing sea surface height (SSH) values. The wider view highlights the spatial extent of the overpass, with Mount Erebus crater and lava lake location marked. (11/09/2023)

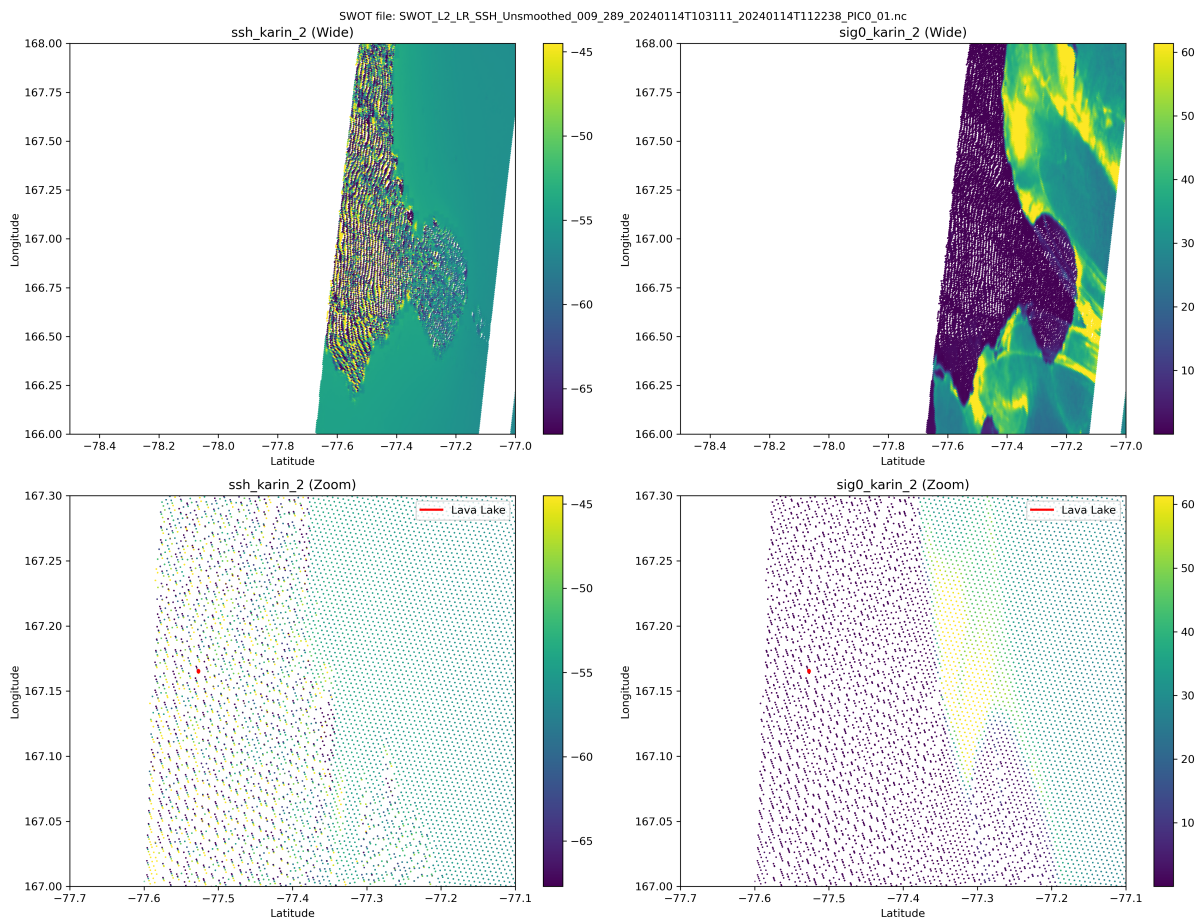


Figure 3: SWOT KaRIn swath over Ross Island showing sea surface height (SSH) values. The wider view highlights the spatial extent of the overpass, with Mount Erebus crater and lava lake location marked. (14/01/2024)

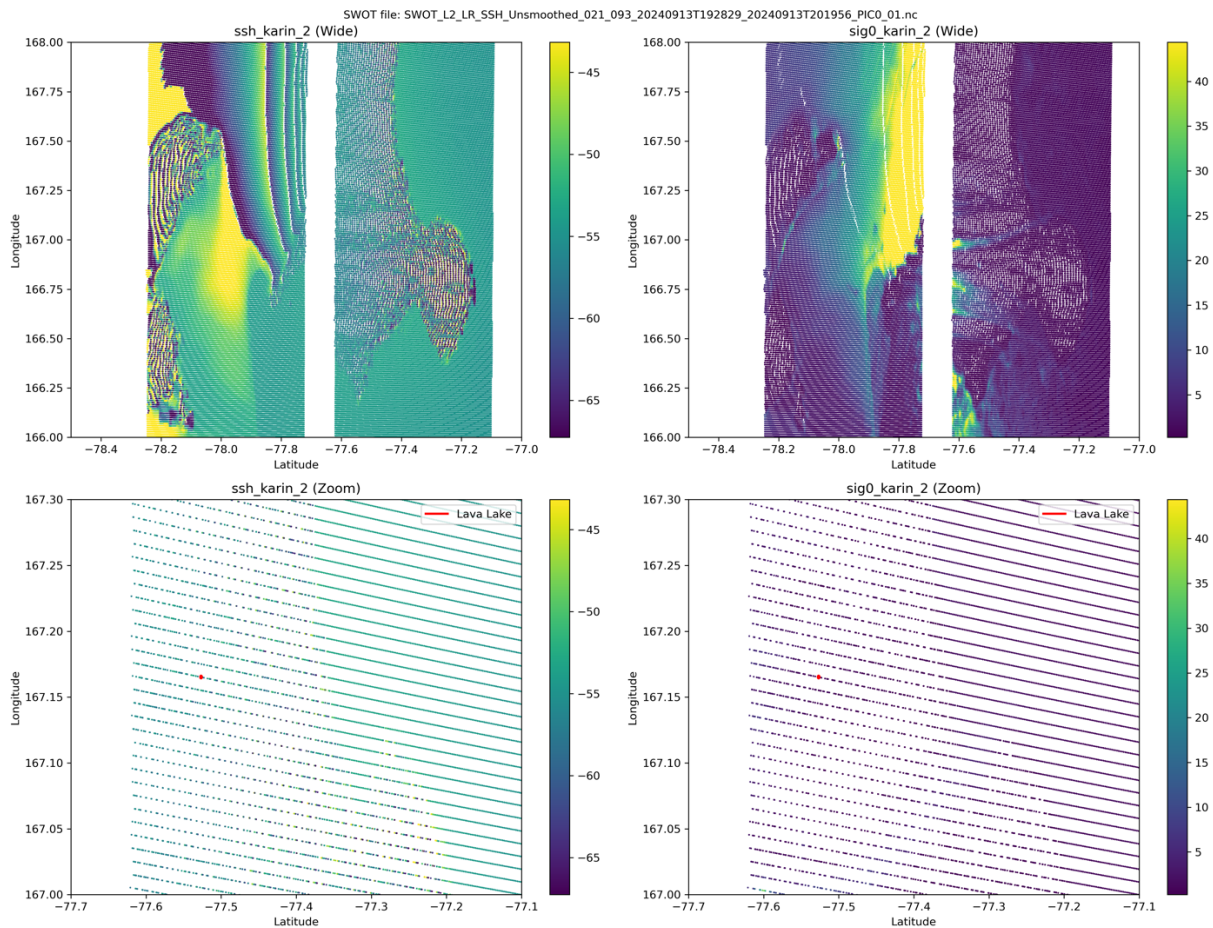


Figure 4: SWOT KaRIn swath over Ross Island showing sea surface height (SSH) values. The wider view highlights the spatial extent of the overpass, with Mount Erebus crater and lava lake location marked. (13/09/2024)

The MODVOLC temp data was then manually paired to its corresponding SWOT file to see SSH/sigma0 vs MODVOLC excess temperature, SSH/sigma0 vs MODVOLC temperature and SSH/sigma0 vs date. (**Fig 10, Fig 11**). Excess temperature vs date was also plotted at the top of both plots for contextual analysis.

ICESat-2 data was used once the limitations of SWOT became clear. The limited temporal and spatial coverage directly over the lava lake and the potential for crater wall interference led to the inclusion of ICESat-2 data as a complementary dataset. By overlaying the ATL03 photon data within the bounding box of the SWOT analysis, ICESat-2 measurements served as a means of validating and refining interpretations of lava lake behaviour. Although ICESat-2 transects are temporally sparse, they provide snapshots of elevation change that can confirm whether anomalous SWOT readings reflect genuine volcanic dynamics or artefacts of resolution.

In this way, ICESat-2 was used not as a standalone dataset but as a critical tool for testing and contextualising the preliminary findings drawn from SWOT. **Fig 5, Fig 6, Fig 7, Fig 8** represent ICESat-2 (ATL03) beams that hit the lava lake. They show the North-East corner of the crater of Mount Erebus where the lava lake is located. **Fig 5** is a zoomed-out version of **Fig 6**. Similarly, **Fig 7** is a zoomed-out version of **Fig 8**.

ICESat-2 ATL03 3D Photon Heights — ATL03_20220714221910_03511610_006_02.h5 — gt2r

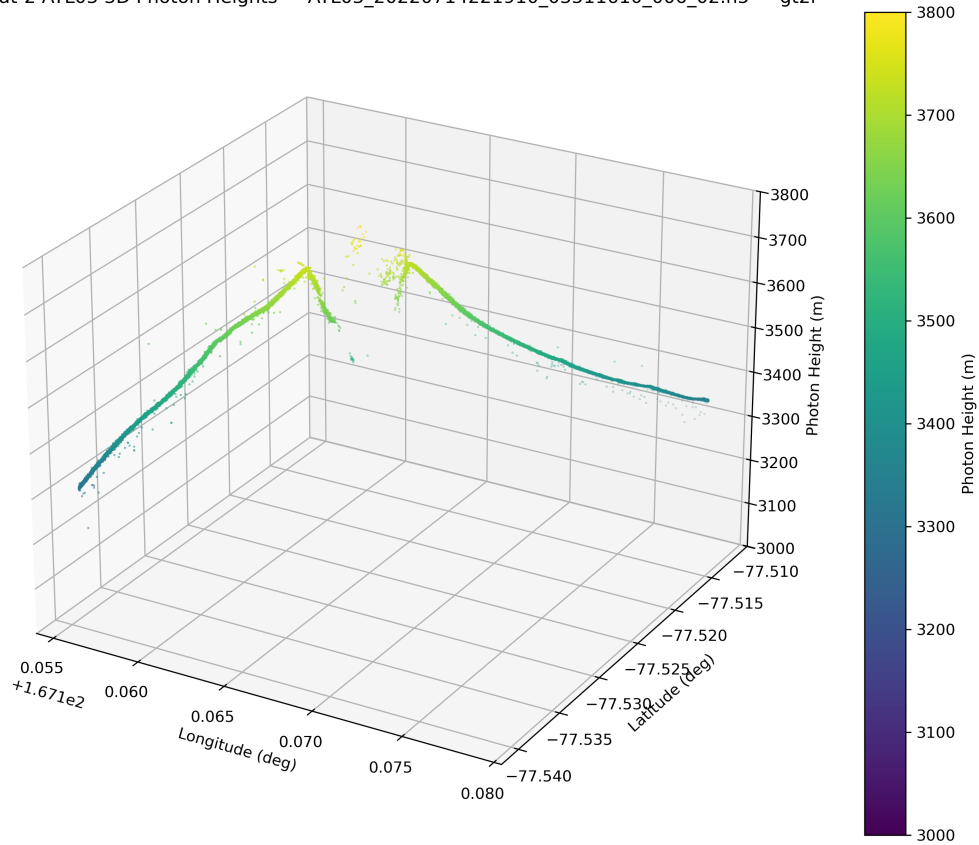


Figure 5: ICESat-2 ATL03 photon returns across Mount Erebus crater (zoomed out). Colours represent photon elevation relative to mean sea level. (14/07/2022)

ICESat-2 ATL03 3D Photon Heights — ATL03_20220714221910_03511610_006_02.h5 — gt2r

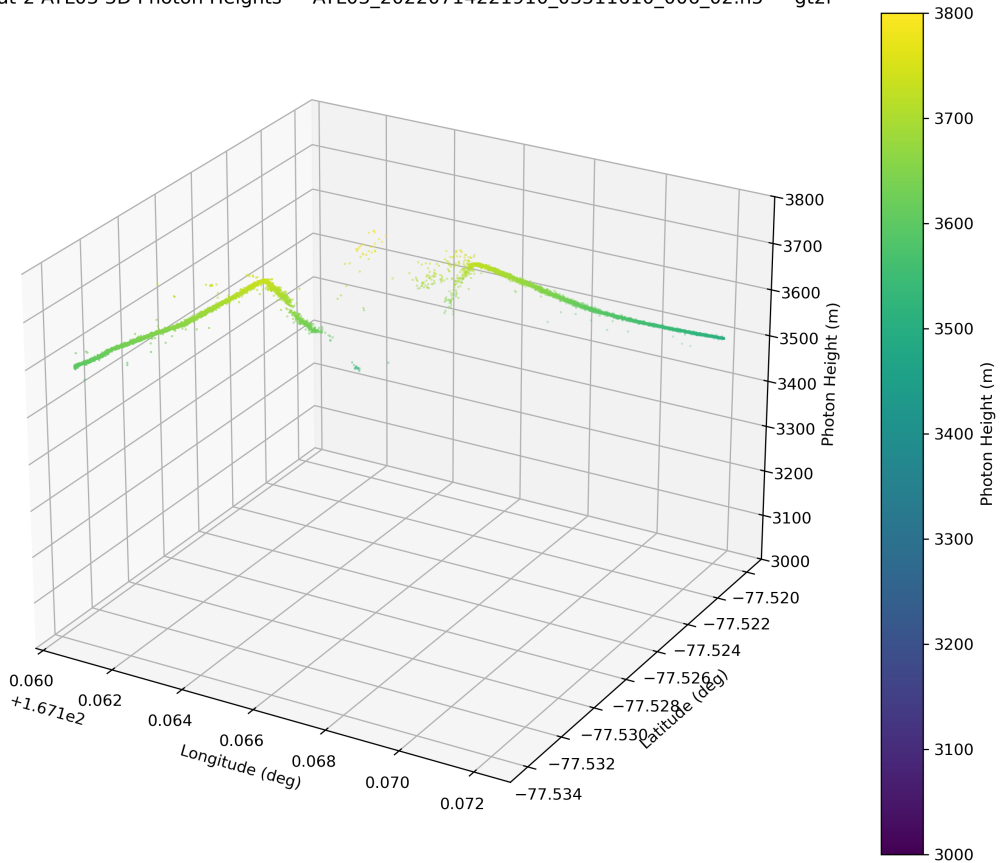


Figure 6: ICESat-2 ATL03 photon returns across Mount Erebus crater (zoomed in). Colours represent photon elevation relative to mean sea level. (14/07/2022)

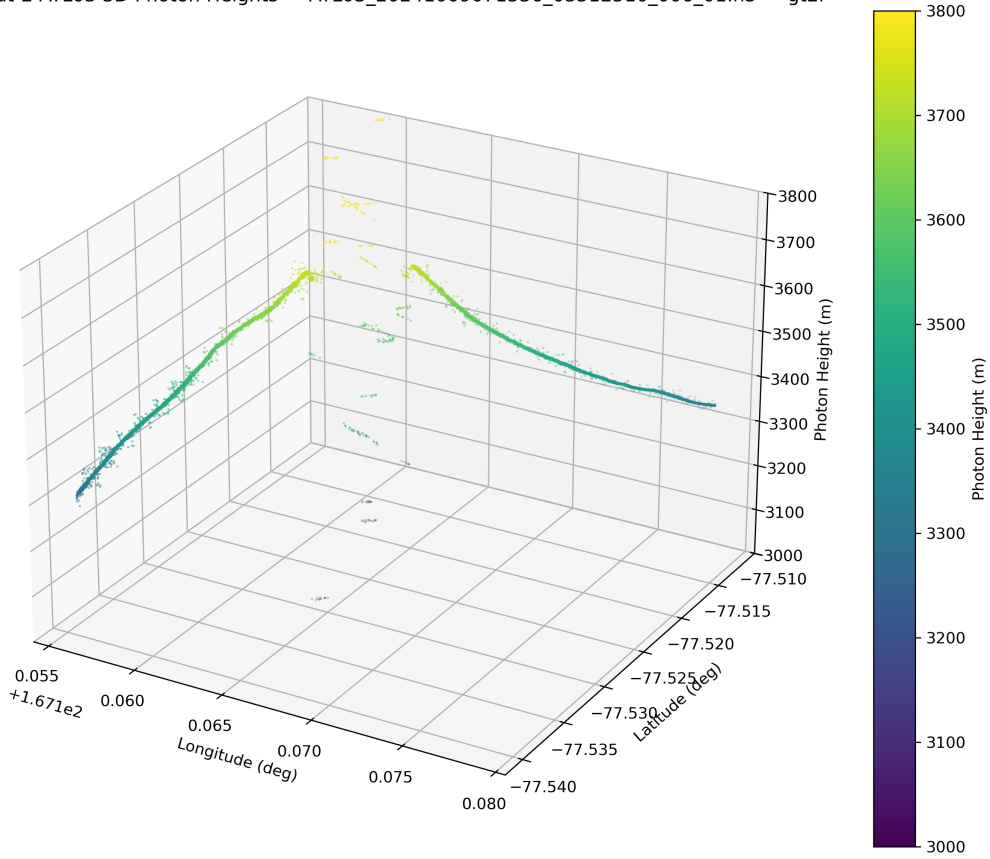


Figure 7: ICESat-2 ATL03 photon returns across Mount Erebus crater (zoomed out). Colours represent photon elevation relative to mean sea level. (09/10/2024)

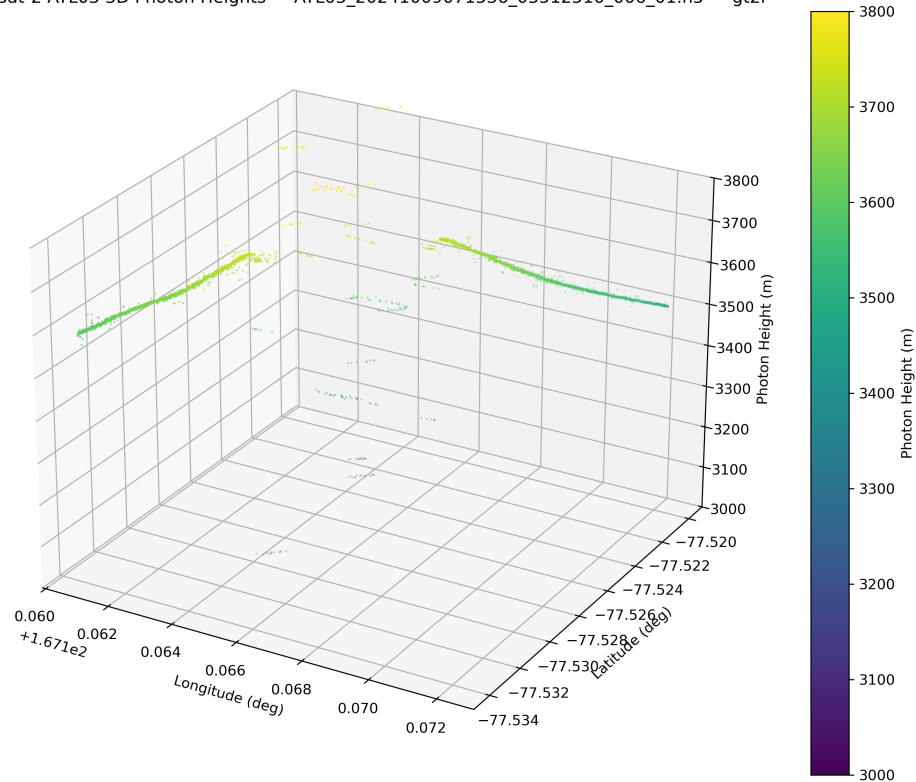


Figure 8: ICESat-2 ATL03 photon returns across Mount Erebus crater (zoomed in). Colours represent photon elevation relative to mean sea level. (09/10/2024)

Results

Relationship between MODVOLC data and SWOT data

After plotting all 49 SWOT files and plotting the relationship between the MODVOLC data and SWOT data no definitive conclusions can be drawn regarding the relationship between SSH and excess temperature at the Lava Lake on Mount Erebus

Out of all 49 SWOT files only 3 returned readings over the Lava Lake. The plots of the 3 files that returned values are displayed as **Fig 2**, **Fig 3** and **Fig 4** and the relationship between the readings from these files and the MODVOLC data is displayed on **Fig 11**. Not only is having three data points statistically insignificant but the reliability of these swaths remains uncertain due to inconsistencies in their structure.

The relationship between readings of the crater as a whole and temperature is displayed in **Fig 10** where there is also a lack of correlation between temperature and SSH

A clear trend throughout the SWOT plots made is the swaths that moved horizontally across the displayed plots are very different in nature to the swaths that moved vertically. The plots where the swath is observed to have more vertical movement has high variability in SSH and sigma0 for points that geographically are very close to each other.

For the 3 files that picked up readings over the lava lake, all 3 gave SSH readings that would suggest the lake sits above the rest of the crater. This is either because the lava lake surface may be bounded by a raised rim formed through successive lava emplacement or these elevated readings could represent crater wall interference which is possible given our 0.001° radius circle exceeds the lava lake area.

Use of ICESat-2 data

With the use of ATL03 ICESat-2 data we find that the elevated readings found on the three SWOT files represent wall interference. **Fig 5,6,7** and **8** all demonstrate that the lava lake sits in a depression relative to the crater wall as opposed to being level with it or elevated with a lip.

This indicates that while SWOT is precise enough to achieve readings over the lava lake area, it is unable to discern the precise SSH value of the lava lake indicating crater wall interference and/or errors as a result of the SWOT satellite itself when it is comparing the return beam between the two antennas.

Figs 7 and **8** illustrate that even ICESat-2's highly precise laser altimetry struggles to resolve sharp elevation changes at the crater rim, with photon returns spreading across the steep gradient. Indeed, when layering multiple ICESat-2 passes on top of each other in **Fig 9** we can see the spread of photons over the depression above the lava lake as evidence of the limits of ICESat-2 when it comes to harsh terrain.

Conclusion

Although there are clear limits to the capabilities of both satellites in harsh terrain, this study has demonstrated several valuable conclusions.

While SWOT is unable to accurately measure SSH over the lava lake of Mount Erebus, it is accurate enough to get readings of the crater despite variation in terrain found there. The principal limitation of SWOT, as with ICESat-2, lies in the rate of change in elevation of terrain as seen with the shape change in elevation between the lava lake surface and the crater walls. This leaves room for the possibility that revisions to how the return beam is read between the two antennas on SWOT could yield more accurate SSH readings for even the harshest of terrain. This is encouraging given the inaccessibility of Mount Erebus year-round, and the rate of change in temperature in Antarctica (three times global average), giving impetus to the need to understand not just volcanic activity but snow and ice coverage year-round in its harsh terrain.

The utility of these datasets will also improve with time. As SWOT's archive grows and more coincident MODVOLC and ICESat-2 passes become available, longer time series will hopefully enable the detection of subtle but systematic changes in lava lake elevation or at the very least increase the likelihood of detecting changes at the lava lake using these instruments.

In a broader sense, this project demonstrates how altimetry missions originally designed for oceanography and cryospheric science have the potential of being repurposed for monitoring hazardous and inaccessible volcanoes, providing a valuable complement to thermal, seismic, and ground-based observations.

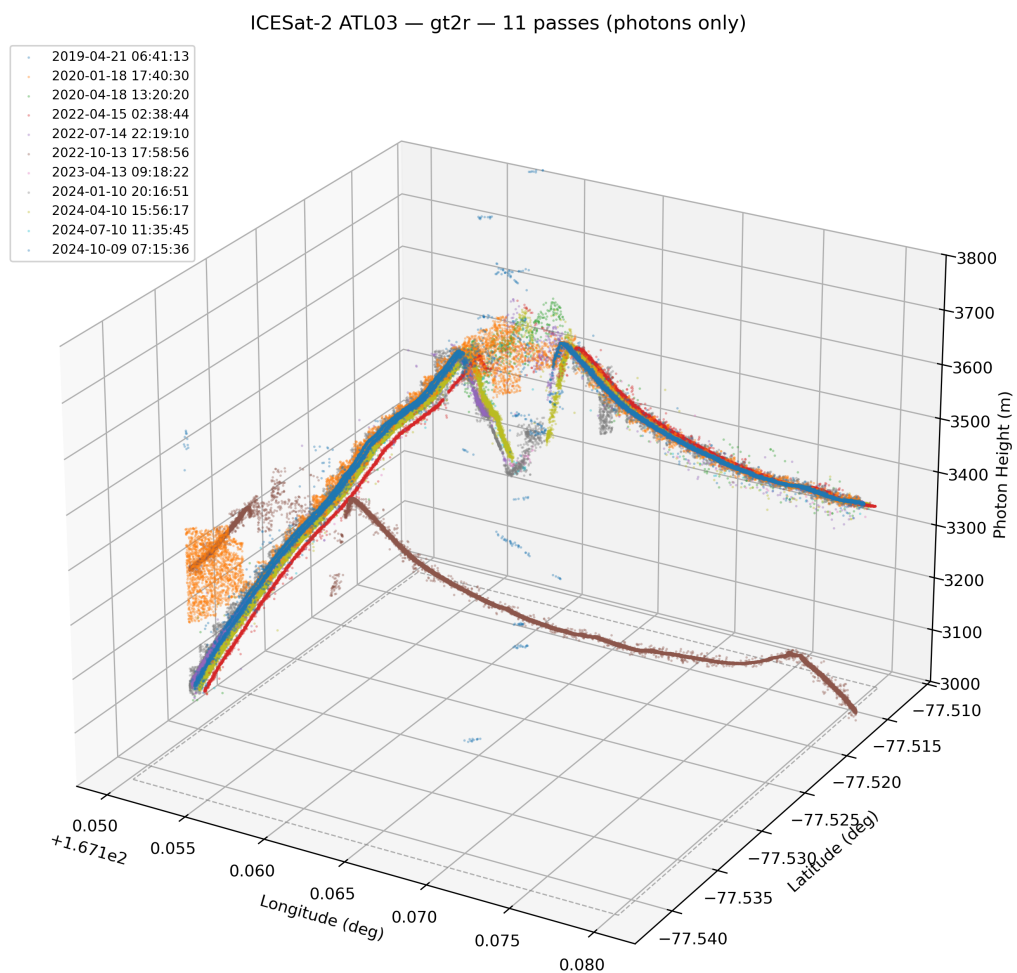


Figure 9: ICESat-2 ATL03 photon returns across Mount Erebus crater (zoomed out). Colours represent the different beam paths over the lava lake and crater.

Crater: SSH & Sigma0 Summary

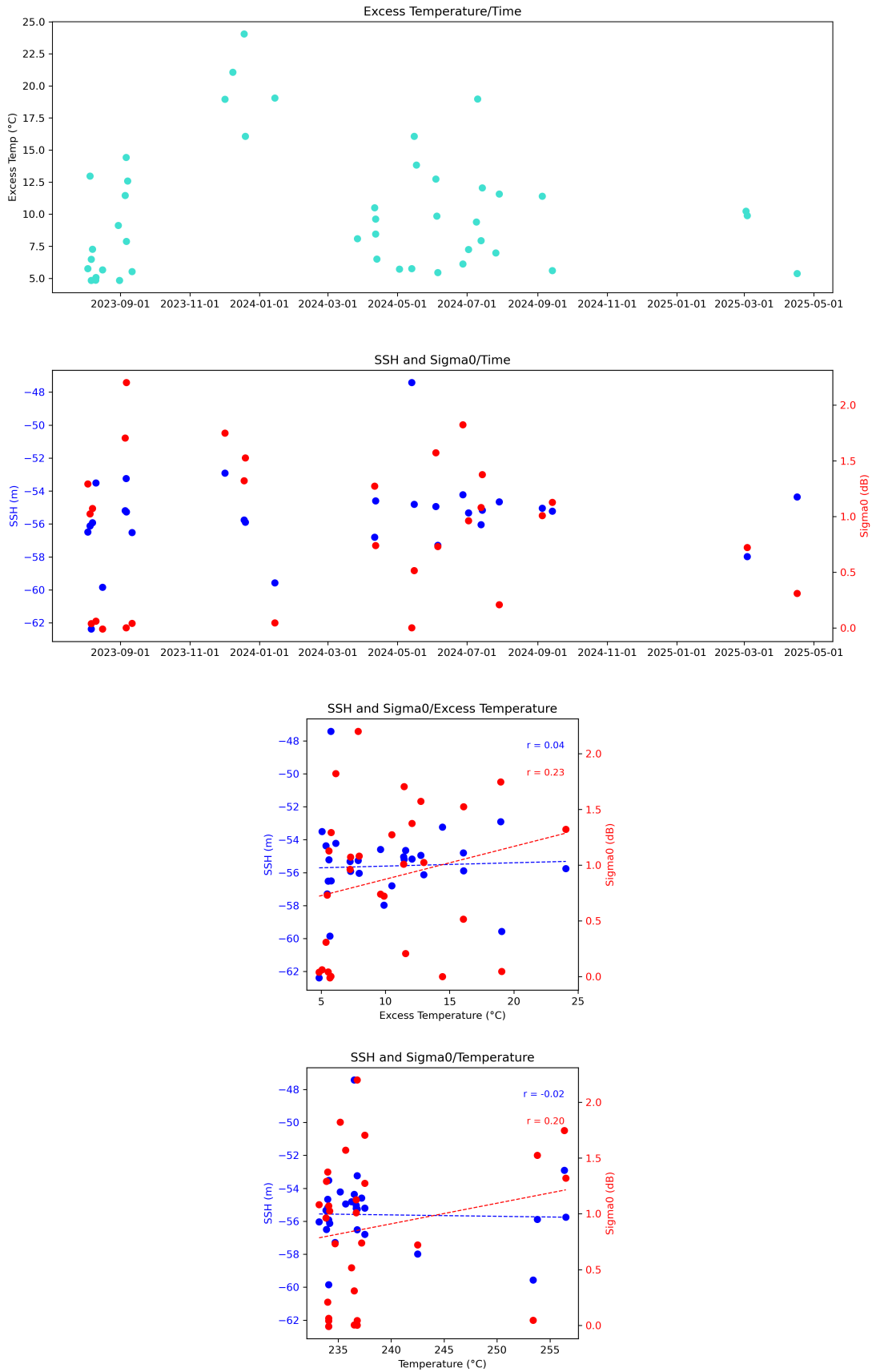


Figure 10: Relationship between MODVOLC excess temperature values and average SWOT sea surface height (SSH) measurements extracted from the crater study area. Each point represents a paired SWOT–MODVOLC observation within a two-hour window. The lack of a clear correlation highlights the difficulty of linking thermal anomalies to altimetric signals at Erebus.

Lava Lake: SSH & Sigma0 Summary

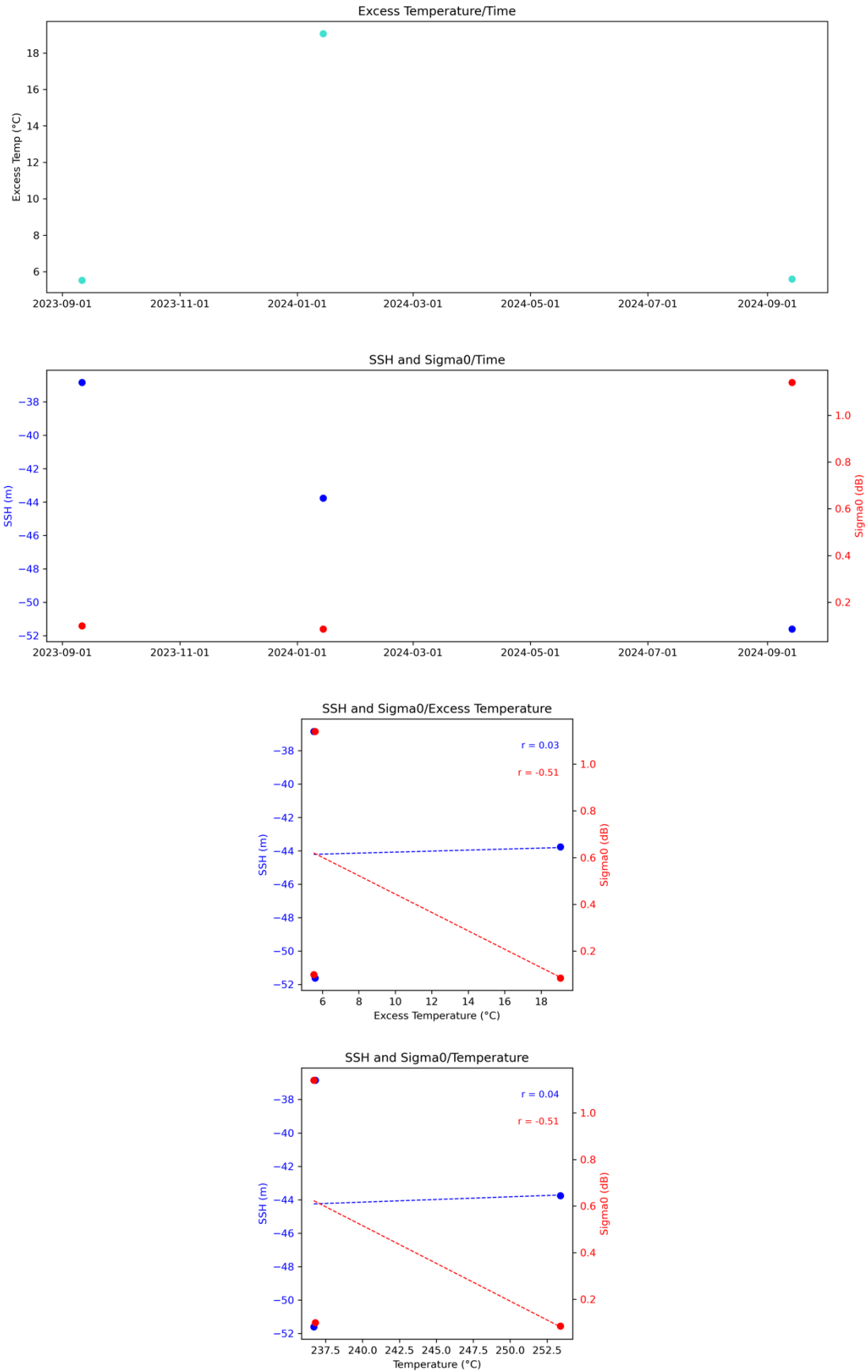


Figure 11: Relationship between MODVOLC excess temperature values and SWOT SSH measurements extracted directly from the lava lake study area. Only three paired observations were available, underscoring the scarcity of direct SWOT detections over the lava lake and the statistical limitations of this dataset.

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