Dear Editor, dear reviewers,

We thank warmly the reviewers for the careful reviews and for their comments. We propose a new version of the article taking into account the remarks of the reviewers. We explain in details the reason of our choices.

Sincerely,
Floriane Provost, on behalf of all co-authors,

NOTE: In the following document, the referee comments are in normal fonts and the answers are in blue font.

**

Reviewer 1 comments:

This manuscript reports on the recent calving dynamics of Astrolabe Glacier, a small glacier in Terre Adélie Land, East Antarctic. The manuscript reports of an anomalous advance of the ice tongue which the authors link to strong landfast sea-ice conditions, but they also highlight that fractures can develop during the winter. Sea-ice buttressing is a potentially important but understudied topic, and the detailed inter-annual observations presented in this manuscript have the potential to be useful for the wider community. However, I think major revisions are required here before publication can be considered. My concerns are detailed in the below comments:

Major comments:

"Unprecedented advance": The manuscript states in a few locations that there was an unprecedented advance of the ice tongue up to November 2021. This may well still prove to be correct, but I cannot be certain of this because the study does not show the full time series of available satellite imagery. The manuscript looks in detail between 2000-2022, but what about the earlier satellite imagery? I am pretty sure there is available imagery going back to the 1970s e.g. 1997 RADARSAT mosaic, 1992 ERS data, Landsat4/5 late 1980s, Landsat 1 early 1970s, maybe even the ARGON mosaic from 1963 (Kim et al., 2007) or even aerial photography from the 1940s. I have not checked for each of those satellites, but there is certainly a cloud-free Landsat-1 image from the early 1970s. I appreciate that there are gaps between these images, but they are still important to include to help determine if this really is an unprecedented advance. The ice-front extent from these images should be added to Figure 5a.

We would like to stress that we stated "unprecedentedly **observed** extension" which implies "in the limit of the data considered". We never state that the observed extension in 2021 is for sure unprecedented, and we wrote it in the discussion: "Due to the limited temporal extent of the datasets and sparse

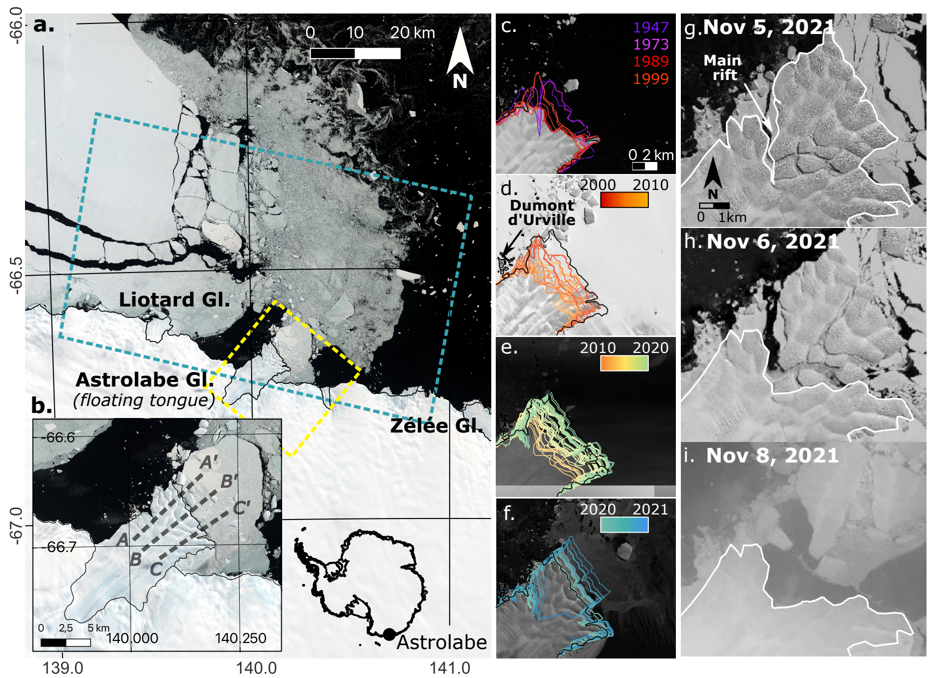
availability of the satellite imagery before the 2000s, it is impossible to conclude if these changes are exceptional or part of a longer cycle" (L230).
The Astrolabe ice front evolution has not been documented since Frezzotti et al., 2002 (this analysis spread from 1947 to 1989). Our goal was to resume this work looking at satellite optical acquisitions freely accessible at high spatial resolution (< 15 m) to distinguish the ice front from the sea-ice or landfast sea-ice. Concerning the datasets mentioned by the reviewer:

- **Radarsat**: we do not have access to raw RADARSAT images. We map the ice front from the RAMP product [Jezek and Barry., 2013] and added it to the dataset.
- **ERS data**: ERS data are available over the Astrolabe from 1996. We mapped the front position from 1996 to 1999 in order to fill the gaps in this period.
- **Landsat 1**: there is only one cloudless image available from Landsat-1 on January 29, 1973.
- **Landsat 4/5**: there are 3 cloudless Landsat 4/5 acquisitions in 1989.
- **ARGON mosaic 1963**: The ice front position is very difficult to determine from this dataset at the Astrolabe glacier due to bad contrast of the acquisition. We attempt to map the ice front with this acquisition (Figure 1b, revised).
- **Aerial photography**: in 1947, one campaign was performed and sketched maps were derived (https://www.archipoles.com/idurl/1/14865). We digitize the sketched map and perform a first order coregistration in order to map the ice tongue ice front (Figure 5a). It should be noted that we observe high distortion in the sketched map, but the trend of our mapping is very similar to [Frezzotti and Polizzi, 2002]. We do not have access to more recent aerial photography.

We also added ice front position from MODIS images from 2000 to 2010 in order to complete the gaps in this period with error bars corresponding to an error of ± 1 pixel in the ice front position. We updated all figures accordingly. In conclusion, it confirms what we stated: for the considered dataset (even extended in the revised manuscript) the extension of the Astrolabe glacier's shelf in 2021 has never been observed before.

Sea-ice concentrations: As I understand, the authors extract mean sea ice concentrations from a 4,000 km box surrounding the glacier, they infer periods of multi-year landfast sea-ice conditions from this analysis. I am not sure this is the case. The dataset the authors use is not the best for determining Landfast sea-ice conditions because the pixels are course and they do not extend all the way to the coastline.

In the new version of the paper, we plot the spatial extent of the box (80 km along the coast x 30 km across the coast) surrounding the glacier that was used for extracting the sea-ice extent. The box comprises the ice tongue (Figure 1 revised) and we checked before the analysis that the sea-ice product encompassed the glacier (it does) and that the coastline was not defined on the glacier (it is not). We chose this dataset because it spans a long time frame: 1979-2021 including the period of the 2021 calving. We assumed that if we look at the coastal areas or to the direct surroundings of the glacier, the sea-ice is likely to be fastened to the coast.



Revised Figure 1.

In order to validate this assumption, we analyzed another product from [Fraser et al., 2020] specifically constructed to map landfast sea-ice but with a more restricted time period: 2000-2018. Figure 1 (below) shows the comparison between the two products for the same area: a) the 4,000 km^2 box and b) for the pixel area surrounding the glacier (Figure 2).

First, one can observe that the [Fetterer and Windnagel, 2017] products do not exhibit major differences between the two considered areas. Secondly, at the vicinity of the glacier, the detection of landfast sea-ice from [Fraser et al., 2020] is in agreement with the general trend of [Fetterer and Windnagel, 2017] (Fig 1b) in terms of absence/presence of landfast sea-ice or sea-ice. The only major

Figure 1: Comparison between the extension of sea-ice from [Fetterer and Windnagel, 2017] and the extension of landfast sea-ice from [Fraser et al., 2020] for the two areas: a) the 4,000 km^2 box (in blue on Figure 2), and b) for the pixel area surrounding the glacier (in yellow on Figure 2).

difference is for year 2013 (Fig 1b) where the [Fetterer and Windnagel, 2017] detects the presence of sea-ice while [Fraser et al., 2020] shows landfast sea-ice free conditions. This may be explained by the difference of spatial and temporal resolution of the two datasets and, by the fact that during January-February 2013 an unusual polynya appeared at the Astrolabe glacier (Figure 2). It seems that the direct surroundings of the Astrolabe ice tongue remained partly trapped in landfast sea-ice during 2013 (Figure 2).

We do agree that a more detailed (at finer spatial resolution) analysis could be conducted in the future to map precisely the type of sea-ice (i.e. ice mélange, polynyas, landfast sea-ice, icebergs, etc.) surrounding the Astrolabe glacier. However, we do believe that the considered product ([Fetterer and Windnagel, 2017]) captures the general trend of landfast sea-ice conditions at the Astrolabe glacier.

Indeed, a quick look at the MODIS imagery shows that actually the glacier is sea-ice free for large portions of nearly every summer, including the period of ice tongue advance. So the claim that multi-year fast ice has forced the advance of the ice tongue is incorrect. It appears that there is no MYFI at any stage over the period 2011-2021. I think a useful figure for any revised manuscript could be a multi-year panel showing a MODIS image showing the sea-ice conditions at the sea-ice minima (roughly March) every year from 2000 (or at least the period of anomalous advance 2011-2022), this would enable the reader to better visualize the sea-ice conditions. (see MODIS imagery on NASA Worldview website; link below).

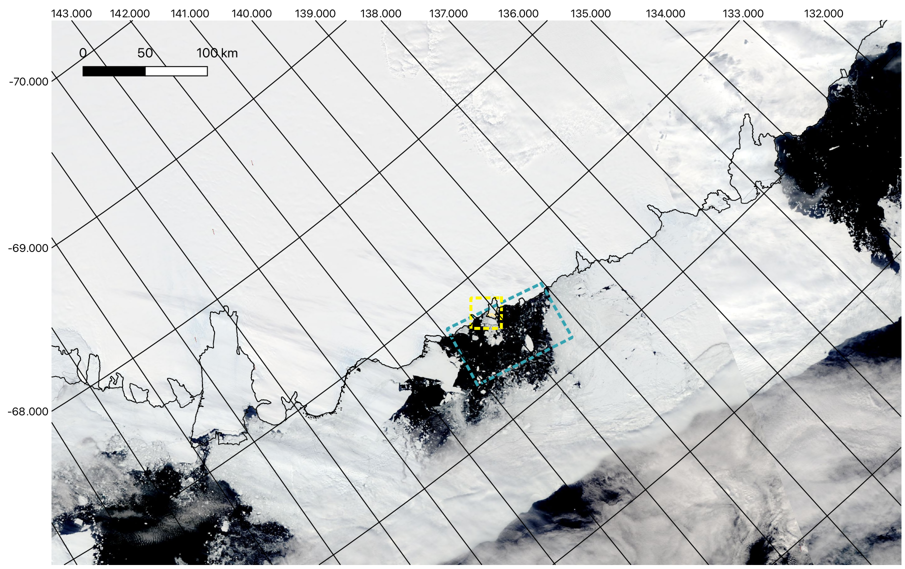


Figure 2: MODIS acquisition of January 10, 2013 centered on the Astrolabe glacier. The acquisition shows the polynya that developed in January-February 2013 at the Astrolabe glacier. The blue square represents the extent of 4,000 km^2 box used to extract sea-ice extent. The yellow square represents the extent of the pixel of the [Fetterer and Windnagel, 2017] product located on the Astrolabe glacier. The area of the pixel is around 600 km^2.

We thank the reviewer for the link to the MODIS viewer. As requested, please find the time series of early-summer (corresponding to late austral summer) MODIS images from 2001 to 2021 in Figure 2. We looked for and show the minimum of sea-ice extent we found for each year.

One can observe that the first two rows (2001-2010) show clear sea ice free conditions every year. Conversely, on the two next rows (2011-2020), the area surrounding the Astrolabe glacier is always occupied totally or partially by sea ice, except for years 2011, 2016 and 2021. In particular, in 2014, 2015, 2017, 2018 it is clear that sea-ice attached to the glacier is visible. This is as well confirmed by the dataset of [Fetterer and Windnagel, 2017] and [Fraser et al., 2020] and by the data presented in Figure 5a.

The definition of Multi Year Fast ice can be defined as "first-year", "second-year" and "multi-year" sea ice [Fraser et al., 2023]. However, [Fraser et al., 2023] is also stating: *"Due to the coarse resolutions of gridded products (e.g., Melsheimer et al., 2022) it is difficult to discriminate between second-year and multi-year*

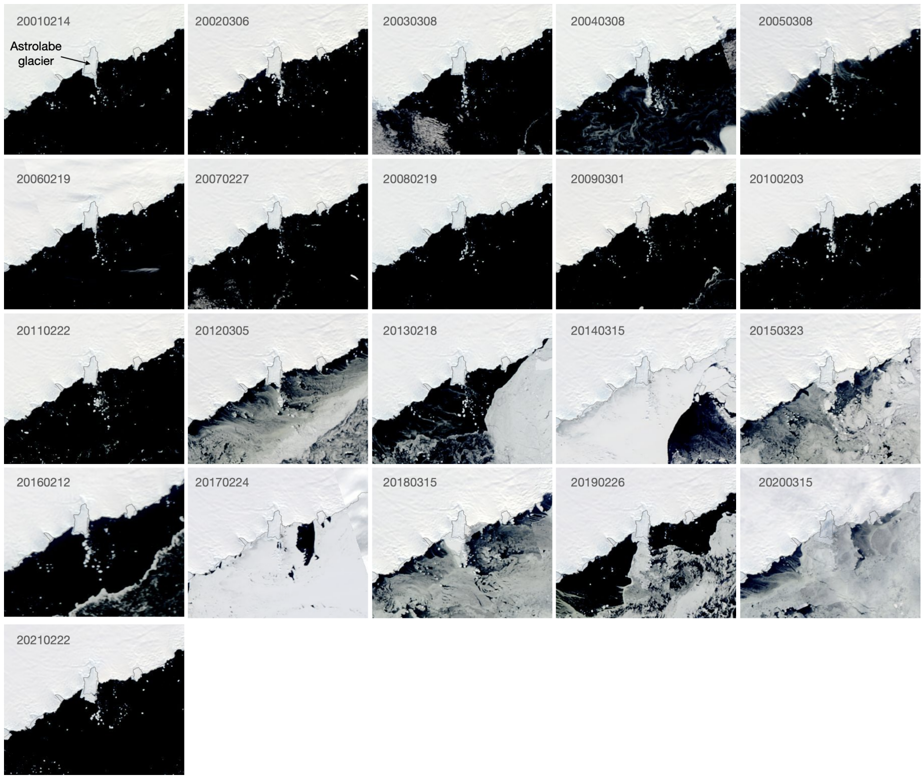


Figure 3: MODIS images at the Astrolabe glacier ice tongue for period 2000 to 2021. One image per year is displayed, corresponding to the observed minimum extent of sea ice.

ice. Hence only the latter term will be used herein."

The screening of all the dataset shows that landfast sea-ice around the Astrolabe does not disappear for two consecutive years in 2014-2015 and in 2017-2018. Hence, we can conclude according to the definition that these periods are MYFI. MYFI is also visible on the [Fraser et al., 2020] product on the period 2014-2015 and 2017 (year 2018 is not available). Hence, we strongly disagree with the reviewer, and we would like to kindly ask the reviewer to indicate precisely the sea-ice periods he/she is referring to as sea-ice free for these years.

Moreover, we derived the main two periods of sea-ice extension from Figure 5a, which is based on monthly analysis of the sea-ice extent. We already stated clearly in the text that these two periods correspond to MYFI **or** very short periods of sea-ice free conditions: "in the period 2011-2021, multi-year landfast sea-ice occurred with no sea-ice free conditions, or very short and/or episodic periods of sea-ice free conditions (Figure 5b) at the vicinity of the Astrolabe ice tongue." (L238-240). We do not mean here that the entire period 2011-2021 is a MYFI.

This is important, the other studies mentioned in the manuscript (Miles et al., 2017 – Porpoise Bay, Gomes-Fell et al., 2020 – Victoria Land and Christie et al., 2022 – Antarctic Peninsula and other studies) link the advance of outlet glaciers to persistent multi-year fast ice, and when the fast ice finally breaks away the ice shelves/tongue calve instantly. A different process is clearly operating here and the differences between the studies mentioned above and the processes operating here should be discussed in any revised version. The increased sea-ice concentrations in the 4,000 km box are clear in the summer post 2011 and Figure 5b is convincing, but the mechanism that the authors hypothesize is driving the changes to the ice tongue needs to be much more clear.

We improved the discussion and attempted to be clearer in the similarities and differences between the cited studies and glacier sites. We observe that the presence of persistent sea ice fasten or at the vicinity of the Astrolabe glacier ice tongue corresponds to period of glacier extension. It remains difficult to prove if that is due to the effect of the buttressing of the sea ice, to the protection it offered against ocean swell, or most probably both. However, this is in line with Miles et al., 2017, Gomes-Fell et al., 2020 or Christie et al., 2022. Conversely, we do not observe a simultaneous fracturing of the ice tongue during the onset of the sea ice free period. We do observe that at the Astrolabe, the presence of fractures prior to sea ice disappearing is key to initiate ice calving, and that sea ice unbuttressing does not generate nor accelerate fissure/rift opening. The Astrolabe calving of 2021 present similarities with the one of Larsen C-A68 of 2017 with fissures propagating during the austral winter (of 2021; [Larour et al., 2021]). [Larour et al., 2021] showed that the thinning of ice mélange within rifts can lead to the acceleration of the rift opening. At the Astrolabe, the sea ice surrounding the ice tongue and within the rift partially melted in 2020, and it is possible that the renewed sea ice was thinner and weaker than prior to 2020 which would have favored the opening of the rift [Larour et al., 2021]. However, we do not observe an opening of the main rift but rather a dislocation of the entire western part of the ice tongue front during austral winter 2021. We hypothesize that this could be due to both the action exerting by the opening of the rift and the resistance of the sea-ice buttressing resulting in a compressional stress within the western part of the ice tongue and hence the opening of fissures in the transverse direction. This hypothesis remains to be tested with a model.

It is also essential that the authors detail the sea-ice concentrations in the methods section of the paper, it has been completely missed out. Including where you have actually extracted the data i.e. show the 4,000 km box on a figure.

We added the bounding box and the pixel location and extent where the sea-ice area and concentration are extracted (Revised Figure 1). We are using an external dataset [Fetterer and Windnagel, 2017], and we do not think one specific paragraph is needed to describe this data. We added a paragraph in the discussion about their quality and possible processing to monitor more accurately the sea-ice around the Astrolabe.

Glacier acceleration and ice break off: 2021: In general I was a little confused in this section, are you refereeing to an acceleration of the entire glacier? Or is this just a local acceleration on the ice tongue near the ice-front?

We refer to the frontal part of the glacier where the network of fractures appears in austral winter 2021. We added a sentence in this section to be more specific.

Title: I feel it could be made more impactful if it included something related to sea-ice, the process that the authors hypothesize is driving change here. Very few glaciologists would recognize Astrolabe Glacier and I fear most would simply skip over the manuscript based on the current lengthy title. I think the title needs to include something relating to sea-ice to entice a much wider readership. Perhaps something along the lines of: 'Anomalous advance of the Astrolabe Glacier Tongue driven by more persistent sea-ice conditions 2011-2021'. (Or something similar)

We thank the reviewer for this suggestion.

Cause of shift in sea-ice conditions: The shift in sea-ice conditions appears is around 2011. This more or less coincides with the calving of the Mertz Glacier tongue, just round the corner from Astrolabe. The calving of the Mertz Glacier fundamentally changed the local sea-ice conditions (see Tamura et al., 2012; Campagne et al., 2015 and several others). Feel free to ignore, but maybe worth briefly investigating and would make an interesting discussion point.

We agree and added a paragraph on the discussion about the influence of the Mertz glacier tongue on the region. We briefly address this point, as we do think it would require a regional investigation and additional dataset to discuss in depth the influence of the Mertz calving on the Astrolabe glacier calving cycle.

Figures

Figure 1: There is no satellite image of the entire glacier at any point in the manuscript. This is an essential requirement and it would make sense for this to be in figure 1. I would recommend replacing the DEM with a Landsat or Sentinel-2 image. You could also add all the mapped ice-fronts to this figure.

We thank the reviewer for this suggestion and modified figure 1 accordingly.

Figure 5: I think panel (a) is a nice figure, but you could consider extending the ice-front position change back to the 1970s. It is difficult to judge panel

(c) because I cannot really distinguish any changes from the color scheme, please consider amending this.

We maintained the time limits of Figure 5a but updated the figure with the additional ice front position described in the answer of the first major comment.

New figure suggestion: A multi panel figure showing a MODIS image of the glacier every sea-ice minima (roughly e.g. Late Feb to March)

Here, we do not agree that this figure is pertinent to the article. Although it provides visual context, it is not representative of the complex sea-ice cycle.

Minor comments

Numerous incidents of Figures or references not bracketed

We carefully reviewed the manuscript to correct this.

Line 19-23: Not sure, I buy this argument. Most of the ice shelves in West Antarctica are actually quite small. There have also now been at least a dozen of East Antarctic focussed studies on individual glaciers. Please revise.

We change the sentence for: "The monitoring of antarctic glaciers remains heterogeneous [Baumhoer et al., 2018]. Studies focus either on continental scale monitoring, which usually lead to commenting the evolution of the largest glaciers of Antarctica [Walker et al., 2013, Rignot et al., 2019, Miles et al., 2022, Millan et al., 2022, Baumhoer et al., 2023] or to certain glaciers or group of glaciers that concentrate most of the attention [Baumhoer et al., 2018]."

Line 32-44: I think it would be nice to explicitly define Landfast sea-ice here and how it differs to sea-ice, some readers of The Cryosphere will not know this. Then clearly go through the mechanisms in which Landfast sea-ice can promote ice shelf advance/delay calving/stabilize ice tongues, but also how sea-ice on the open ocean can be important (e.g. buffering ocean swell) using examples from the literature. This will help set up the paper. A recent review paper on Landfast sea-ice and the references within could be a useful start here: (see [Fraser et al., 2023]; 'Antarctic Landfast Sea Ice: A Review of Its Physics, Biogeochemistry and Ecology').

We have rewritten the introduction to address this comment (L33-50).

Line 43-45: This is an excellent question.

Line 49 – "Landfast sea-ice melting" is awkward because the sea-ice can be melting but still present. Perhaps "sea-ice free conditions" or similar is better. Please revise throughout manuscript.

We corrected accordingly.

Line 58: What is wrong with radar images during this time period?

Our analysis focuses on optical imagery in open access with high spatial resolution (ASTER, Landsat, Sentinel-2) in order to be able to determine precisely the limit between the glacier ice front and landfast sea-ice. We now include some radar imagery when they can complete optical gaps.

Line 103: "ice tongue surface" – this figure does not show changes to the ice tongue surface.

We simplified the sentence: "Changes in the ice tongue front position are presented in Figure 2." (L116)

Line 187: "Figure ?"

We corrected for "Figure 5b".

Line 209: is there any bathymetry data available to confirm this? Are there any pinning points?

The presence of several islands (where the Dumont D'Urville station is located) on the western side of the glacier suggests that the bathymetry is shallower on the West compare to the East. The bathymetry of [Beaman et al., 2011] seems to confirm this, and we now cite this paper. The rift on the western side of the ice tongue always open around the same location (Figure 1 of the article) suggesting a geometrical forcing. No pinning point could be identified.

Line 216: There is little to no MYFI here.

We already answered to this question in the major comments section.

Line 223-240: There is some discussion of sea-ice trends from 1979-2016, but what about 2016-2023? There has been an exceptional decline in sea-ice, particularly this year. As a reader, I am interested what the results from this study might mean for a future with considerably less sea-ice?

We added some discussion on the recovery of the Astrolabe glacier in the future: "Considering the current decrease trend of sea ice extent in Antarctica turner2022, it is unlikely the Astrolabe would experience such an extension in the future as the recovery of the Mertz tongue is highly unlikely. The Astrolabe will most probably resume the stable cycle of yearly calving, as observe in 2000-2010 [Frezzotti and Polizzi, 2002]. It is impossible from the current knowledge on the Astrolabe glacier cycle to conclude on further retreat of the ice tongue."

Line 229-231: Please investigate the availability of imagery; I believe that there are imagery dating back to the early 1970s for the vast majority of East Antarctica that has been used in other studies.

We already answer to this question in the first comment.

Line 235: "while before 2010, 1 to 2 images per year at most are available during summer". This is not correct. MODIS allows a daily viewing of this glacier since 2000, the resolution is sufficient enough to see at least the major calving events.

We do agree that MODIS provides an exceptional dataset since 2000, but in the case of the Astrolabe glacier, it might be very difficult to distinguish between the ice tongue and sea-ice and determine reliably the ice front position because of the spatial resolution of the MODIS images. However, we attempted to monitor the ice front position (see first answer of this review) and modified this sentence to "before 2001".

MODIS link: https://worldview.earthdata.nasa.gov/?v=1524288.6381649177,-2038092.853452241,1794076.1394911779,-1918924.853452241p=antarctict=2019-03-16-T07%3A45%3A59Z

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