Morphological and ice dynamic changes induced by the formation of proglacial lakes in Exploradores Glacier, Patagonia

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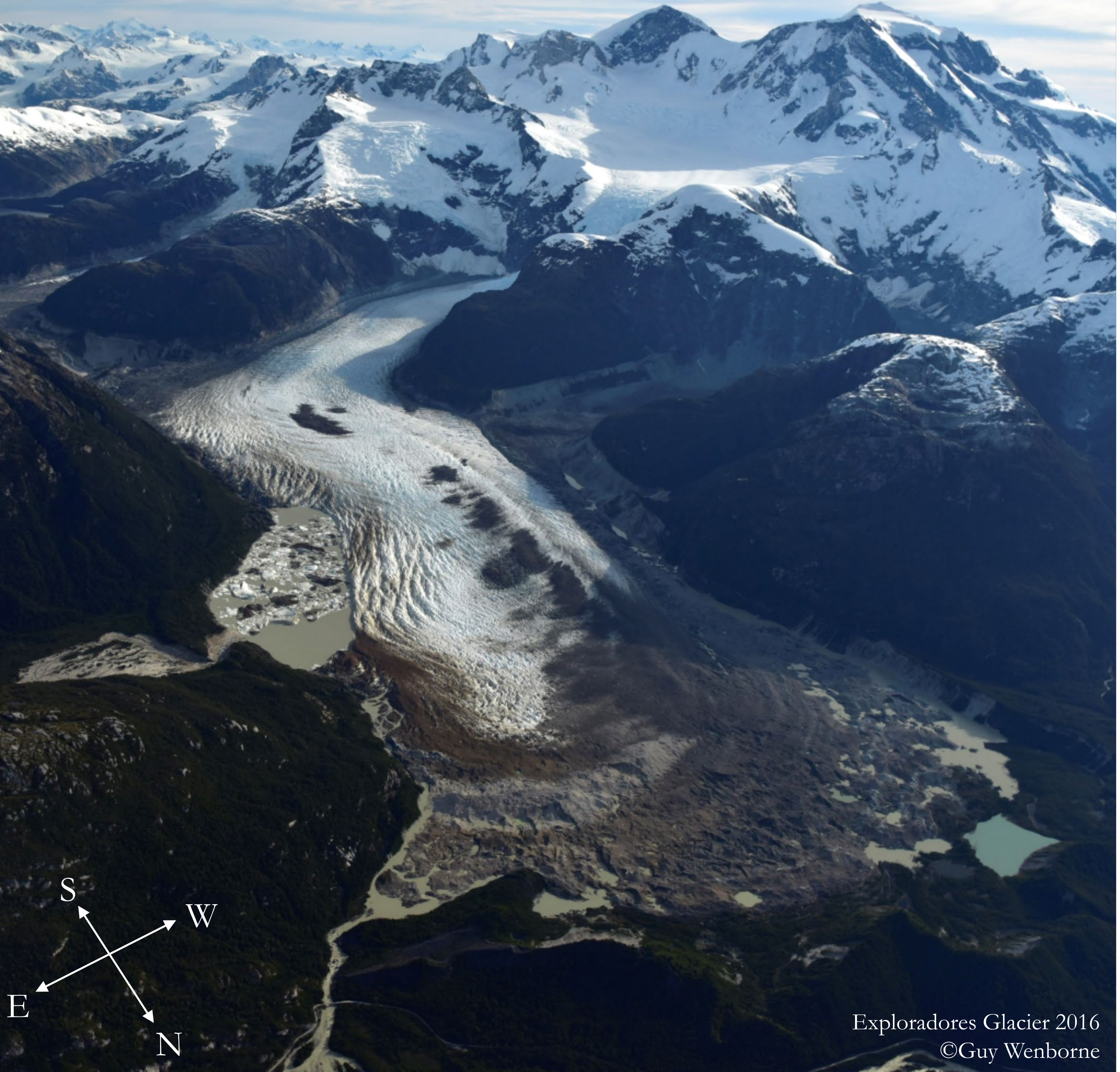
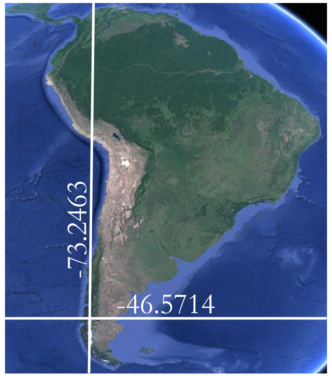


MOTIVATION

Glacier dynamics are sensitive to the formation and expansion of proglacial lakes. Proglacial lakes development can accelerate glacier retreat rate by flotation of the terminus, formation of a calving front, and increased ice flow (e.g., Tsutaki et al., 2019). Understanding the impacts of proglacial lakes formation and development, which are reported to be growing in number in Patagonia (Wilson et al., 2018) and other regions, is relevant to improve the understanding and prediction of glacier response to climate change.
Several studies have observed dynamic changes induced by the formation of proglacial lakes: in Alpine glaciers (e.g., Tsutaki et al., 2013), in the Himalayas (e.g., King et al., 2018) and in the New Zealand Alps (e.g., Quincey & Glasser, 2009). In Patagonia, previous studies have pointed out that the significant downwasting of Exploradores Glacier is leading to the formation of a proglacial lake (Aniya et al., 2011). What are the implications of a transition from land- to lake-terminating glacier? In what time frame? Can we observe, quantify, and model (some of) the dynamics/processes involved?

OBJECTIVES

Characterize and monitor recent spatial and temporal changes in the lower section of Exploradores Glacier and their relationship with lake development at the glacier terminus. Deploy for the first time, a monitoring strategy mainly based on sequential UAV surveys on the lower section of a glacier in Patagonia.



CHALLENGES

Few historical/past data available makes difficult to setup and calibrate/validate models. Many of the processes have non-linear feedbacks. On top of that, several glacial lake outburst floods (GLOFs) have affected Exploradores Glacier in recent years which could mask the overall dynamic trend.

EXPLORADORES GLACIER

Exploradores Glacier is located at the north face of Monte San Valentin (4058 m a.s.l.), with an elevation range ~180-4000m a.s.l, an area of 85 km^2 (RGI), and an Acc. Area Ratio of 0.66 (Aniya et al., 2017). The study area is located at the lower section of Exploradores Glacier with an elevation range between ~180 to 220 m a.s.l.

On the image:

1. Ice-dammed lake started to develop in 2003 (Aniya et al., 2011).

2. Debris-covered area has been expanding in the last decades (Aniya et al., 2011).

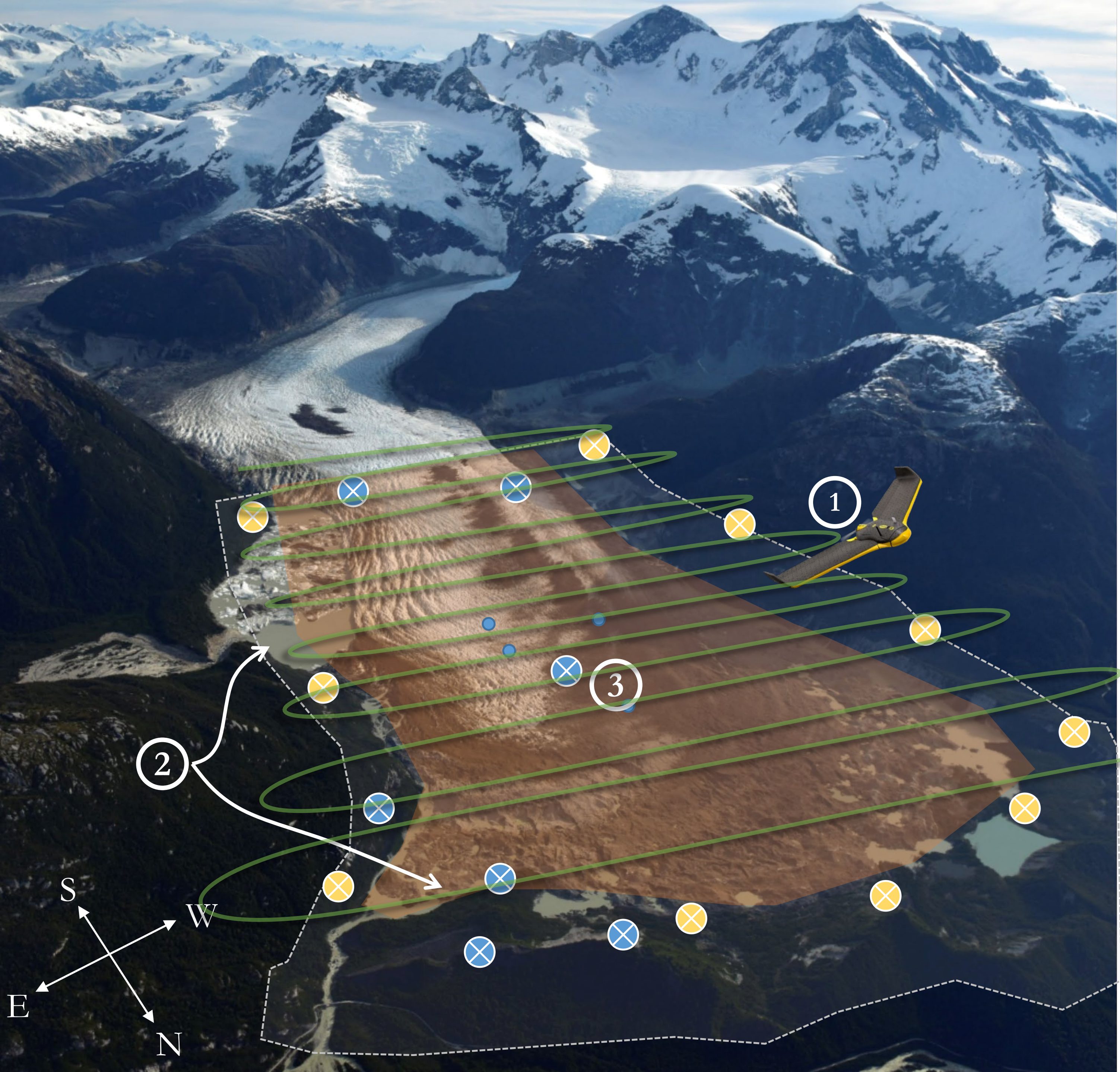
3. Supraglacial ponds and lakes near the glacier termini have grow and coalescence.

4. A GLOF from Chileno Valley occurred in 2015 (Wilson et al., 2019)

5. Hiking tours up to 100 person per day visit the glacier during summer. The preferred tour area is nearby the calving front.

6. In 2018 the collapse of a moraine dammed lake of a tributary glacier produced a GLOF, damaging the access bridge, National Park and Parque Exploradores infrastructure. No one was on the glacier that day.

7. GLOF risk from ice-dammed lake?



DATA COLLECTION

1. UAVs surveys.

07.03.2019 — 21.03.2019 — 24.11.2019 — 17.12.2019 — 20.01.2020 — 21.02.2020 — 09.03.2020 — ??.??.2020

Ground control points — Tie-points. GCPs for co-registration — Validation points

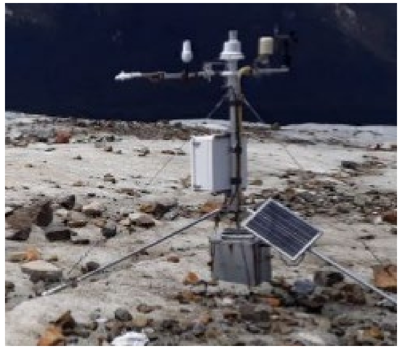
Seven UAVs surveys have been carried out, each of them covering an area of ~15km². The images were processed using an SfM workflow in PIX4Dmapper Pro. A "reference" UAV survey was generated using GCPs collected simultaneously with UAV survey. Based on this reference dataset, and additional tie-points, multitemporal co-registered orthomosaics and DEM were generated (see Benoit et al, 2019). The surveys have dGPS validation points on the glacier to assess accuracy of the ortho-images and dsm. Preliminary results indicate that uncertainties are 0.2m horizontal and 0.5m vertical.

2. Lake level.

Four water level sensors have been installed. Two sensors with recovered data indicated in (2).

3. Meteo-data.

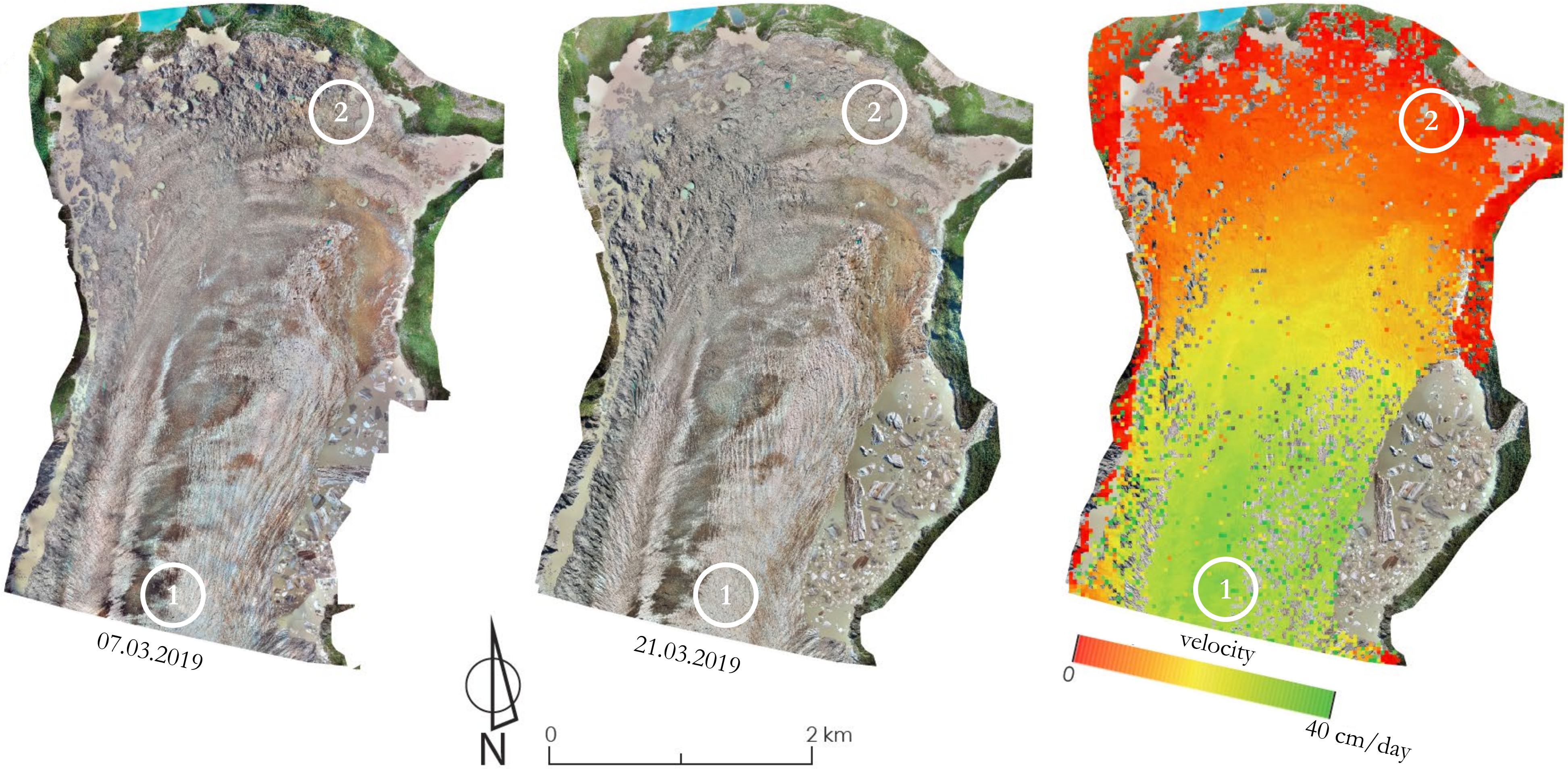
Water directorate AWS located near (3) in addition to 5 ablation stakes in the study area.



RESULTS Surface velocity
(preliminary)

1. & 2. Horizontal displacements were computed using a feature tracking algorithm (IMCORR). Preliminary results show that surface velocity ranged from ~40 cm/day in (1) located ~4.6 km from the terminus and, ~3 cm/day in (2) located ~200 m from the terminus. The velocities where computed between four dates and did not vary significantly across the year.

The results are similar to Aniya et al., 2005 who measured boulder displacements in 2003-2004 with resulting in velocities of 39 cm/day near (1) and, 4 cm/day near (2). Similarly, no significant differences where found between summer-winter velocities.



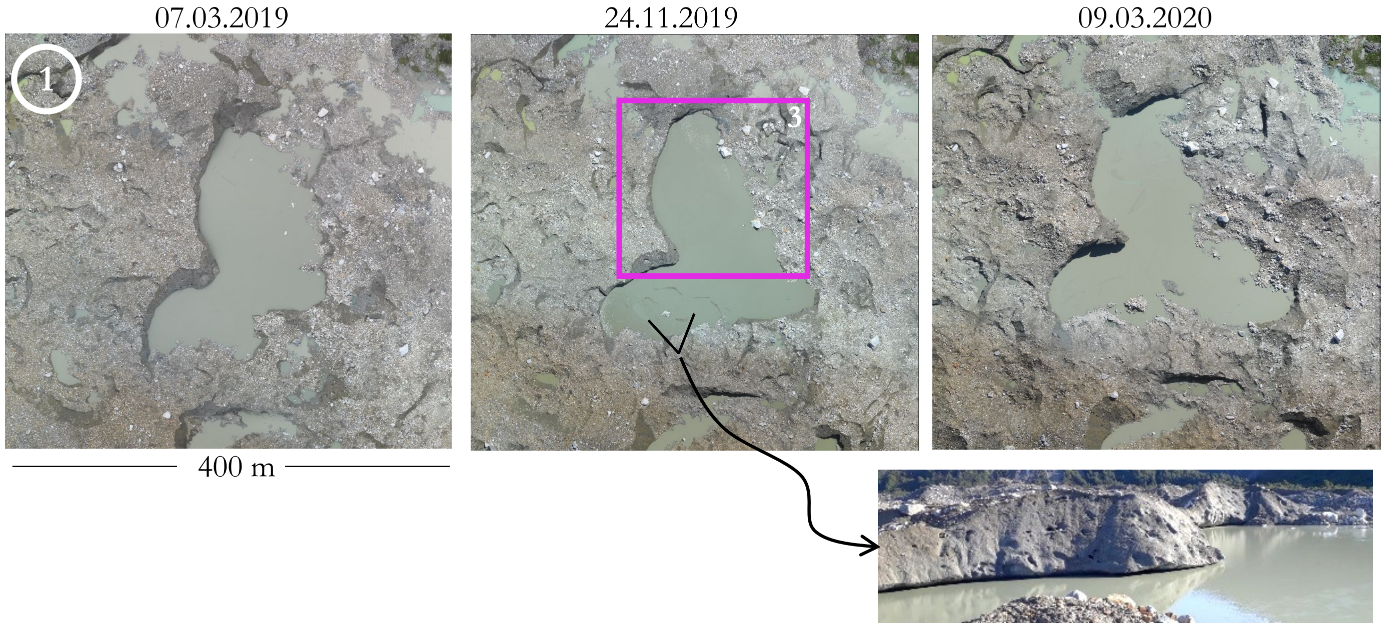
Computed velocities (cm/day)
in (1), (2)

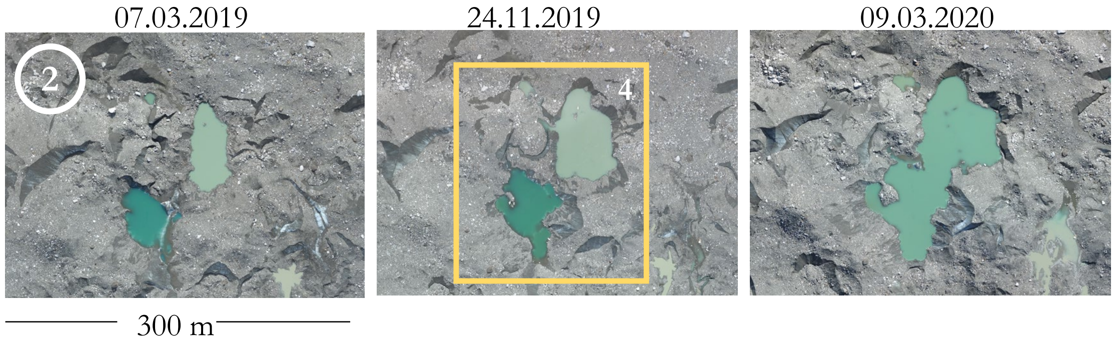
07.03.2019
21.03.2019 — 3, 40 (07.03.2019 – 21.03.2019)
24.11.2019 — 3, 40 (21.03.2019 – 24.11.2019)
17.12.2019
20.01.2020
21.02.2020
09.03.2020 — 3, 40 (24.11.2019 – 09.03.2020)
??. ??.2020

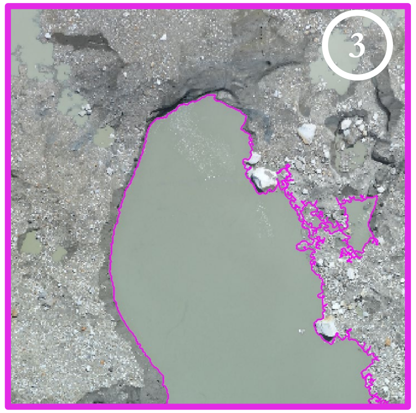
RESULTS Ponds coalescence and expansion

(preliminary)

1 & 2. Pond expansion/coalescence. Generally ponds are delimited by ice-cliffs of several meters where waterline melt form notches (see oblique image in (1)). We carried out a survey to reference (dGPS) ponds water level near the terminus. To minimize diurnal oscillations the survey was conducted in a time span of two hours. Results indicate that the ponds have a similar (+/- 5 cm) water level elevation with respect to the glacier outlet. No evident surface drainage has been observed near the glacier terminus. These suggest that water level correspond to hydrological base level and ponds connect by englacial/subglacial hydraulic pathways.

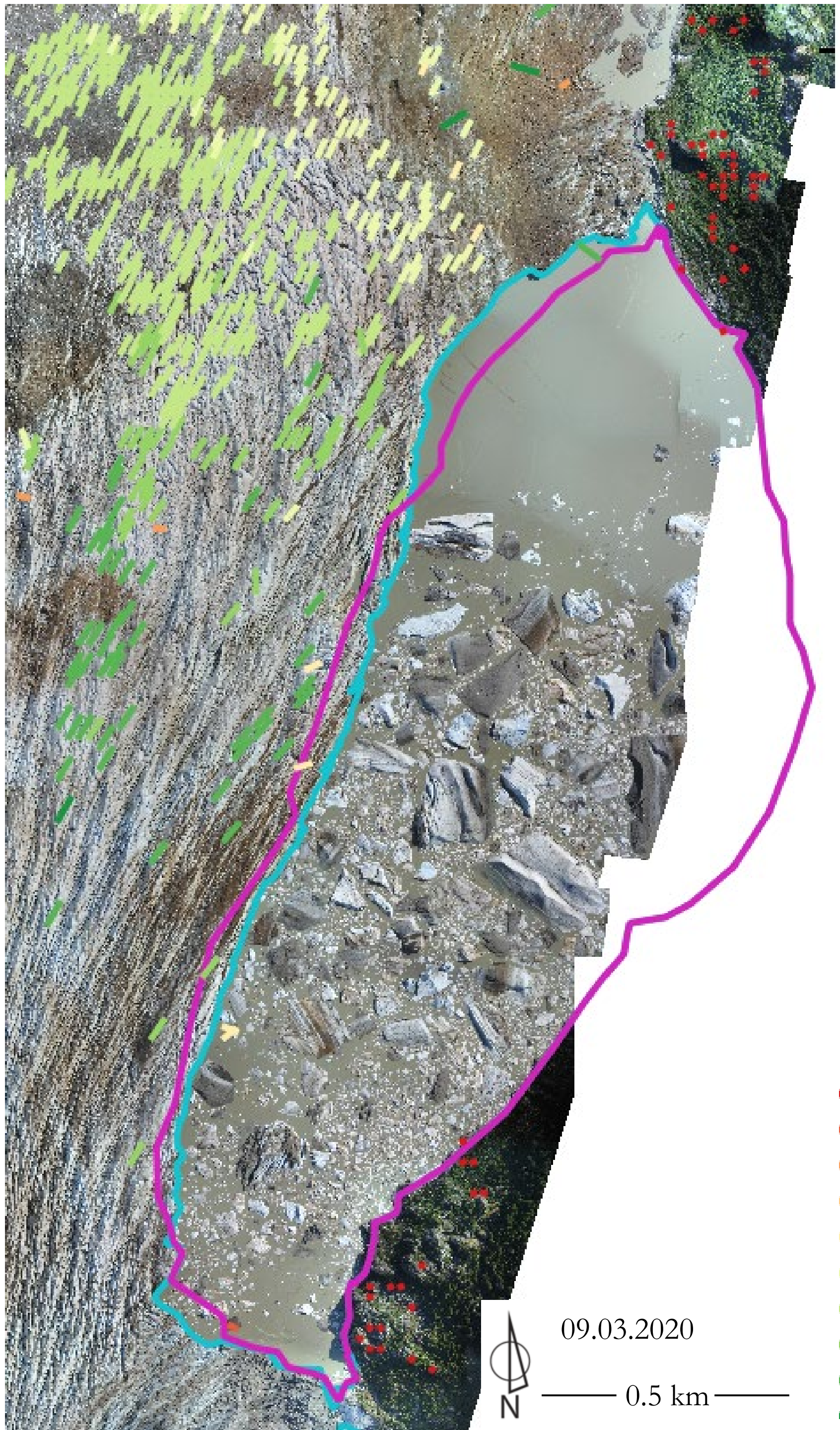






3 & 4. Lake/ponds semiautomatic classification. Working on a lake/pond semiautomatic classification for RGB images. Based on texture analysis & region growing. Three challenges: 1. No infrared , 2. lakes in dem present artifacts (not flat areas) and, 3. relatively small size for satellite images resolution. Any idea to share?

Examples 3 & 4 were generated using region growing. First step assign a pixel inside the pond. Second step, dilate region if similar pixels (threshold parameter) are found in the vicinity.



(preliminary) **RESULTS Lake expansion/calving**

East marginal lake (or ice-dammed lake) started developing in 2003, and expanded considerably between years 2007 and 2011 (Aniya et al., 2017). In 2016 had an area of 1.15 km^2 (Wilson et al., 2019). During the monitored period, lake area did not significantly change from March-2019 with an area of 1.405 km^2 to March 2020 with an area of 1.397 km^2.

1. **& 2.** In zone (1) the glacier advanced, and in zone (2) retreat. A large calving event was detected in zone (2) in mid-February 2020.

3. Surface velocity vectors (between 24.11.2019 and 09.03.2020) are in an angle of ~10º-15º with respect to the calving front. The ice flux has been sufficient to compensate calving and maintain the lake area over the last year.

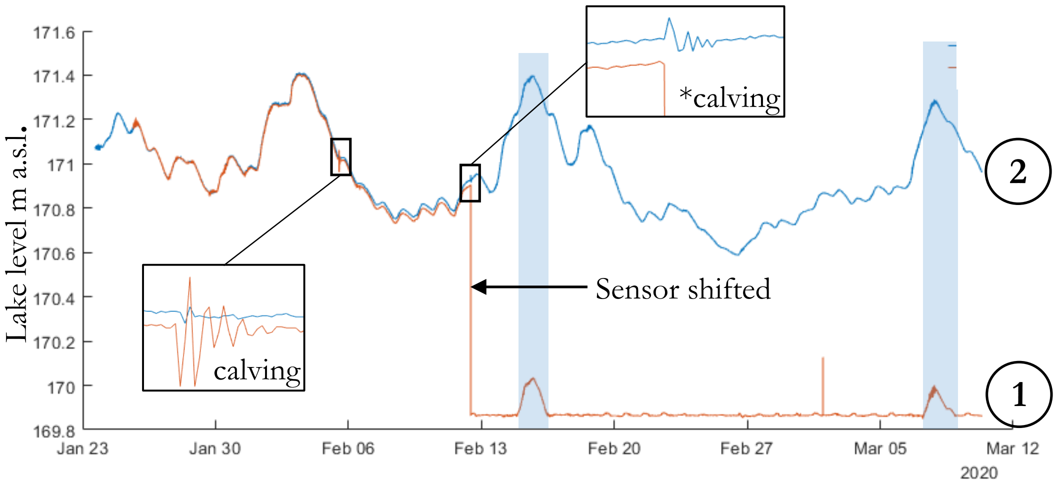
4. Approximate location of water level sensor.

5. Note the large iceberg (~450x130m) in the 21.03.2019 image. What's a safe distance from the calving front for glacier hiking tours?

Surface velocity (cm/day)

- 0 - 4.7
- 4.7 - 9.3
- 9.3 - 14
- 14 - 18.6
- 18.6 - 23.3
- 23.3 - 27.9
- 27.9 - 32.6
- 32.6 - 37.3
- 37.3 - 41.9
- 41.9 - 46.6

DISCUSSION Lake connectivity



1. & 2. Lakes levels where obtained correcting the sensor pressure to atmospheric pressure variations and referenced with dGPS. Preliminary results show that the ice-dammed lake level (1) and the outlet lake level (2) have a synchronous match between them, indicating a clear hydraulic connection. On the one hand, up to date there has not been reports of GLOFs caused solely by the ice-dammed lake (1). Moreover, during year 2005-2012 aerial images showed a surface channel connecting the ice-dammed lake to the outlet (see Aniya et al., 2017). On the other hand, the short time span of the data is not conclusive and potentially the subglacial channel could be blocked or closed.

* 12-Feb calving event caught on camera. Images are 10 minutes apart.

Thanks for taking your time to read these slides.
. Questions/comments/suggestions are welcomed.
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CONCLUSIONS

We provide a data set composed of seven high-resolution UAVs orthoimages and dsm from Exploradores Glacier across one year period. In addition to lake level measurements and in-situ observations, providing a novel data set for a glacier in Patagonia.

The ice-dammed lake levels (or marginal lake) showed a clear hydraulic connection with the lake at the outlet. However, observations are restricted to a short time span, and a larger observation period is needed to assess GLOF risk.

FURTHER WORK

Here we presented preliminary results of an ongoing project. Further work will include linking present UAVs images with past aerial/satellite images in order to obtain a larger time span of observations. To finish integrating mass balance data, surface velocity and hydraulic potential levels into a glacier dynamic model.

Which other processes/dynamics should be further analyzed? Any advice on modelling some of these processes?

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