High resolution maps of glacier changes.
The Pléiades Glacier Observatory

Etienne **BERTHIER**, LEGOS – CNRS

Importance of glaciers in the climate system

(1) Glaciers = **climate indicators**

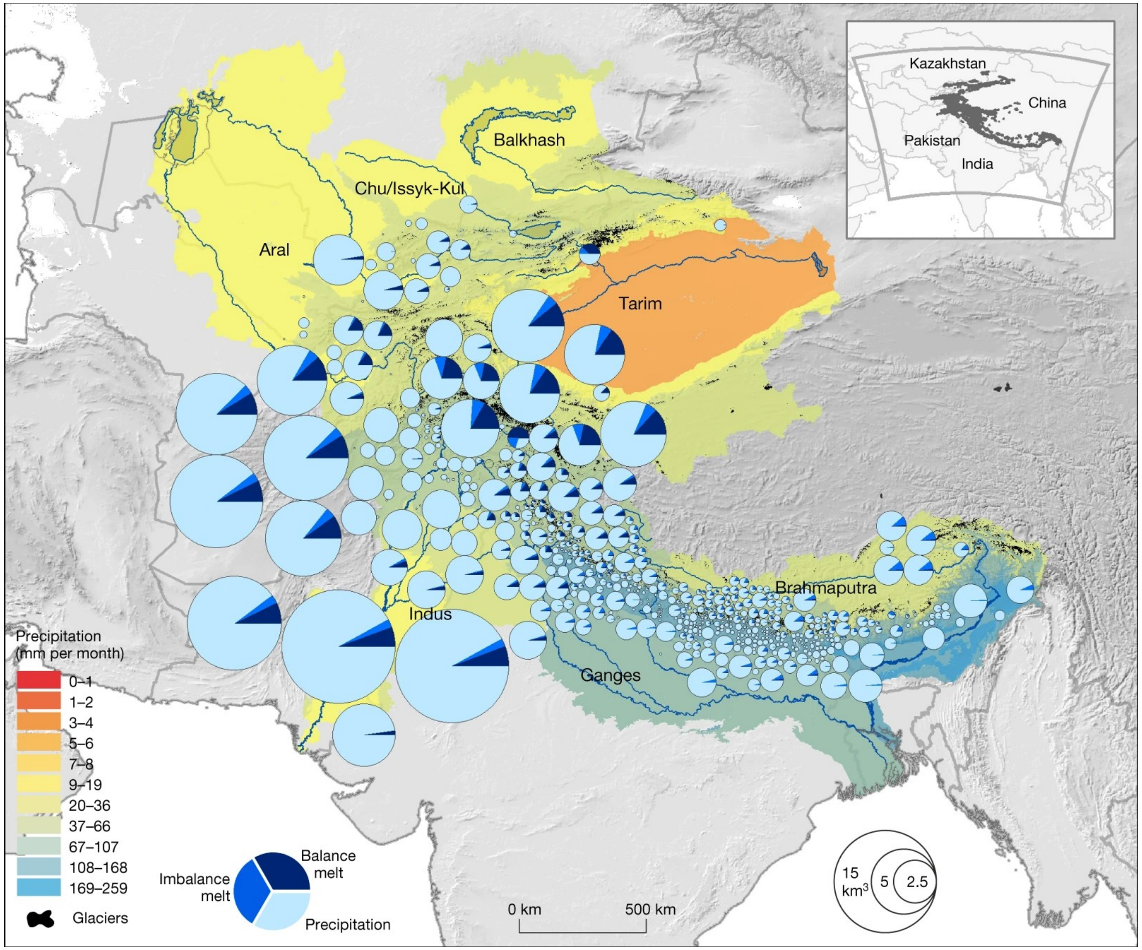
Rapid retreat and mass loss of glaciers since 1850

During the last 2 decades, anthropogenic forcings (GHG) explained 70% of the global glacier mass loss *[Marzeion et al., Science, 2014]*

Retreat of Ossoue glacier between 1911 & 2011
(René, La Météorologie; PhD R. Marti)

(2) Glaciers = natural **water tower**. Important in dry, continental areas especially during years of drought *[Kaser et al., PNAS, 2010; Pritchard, Nature, 2019]*

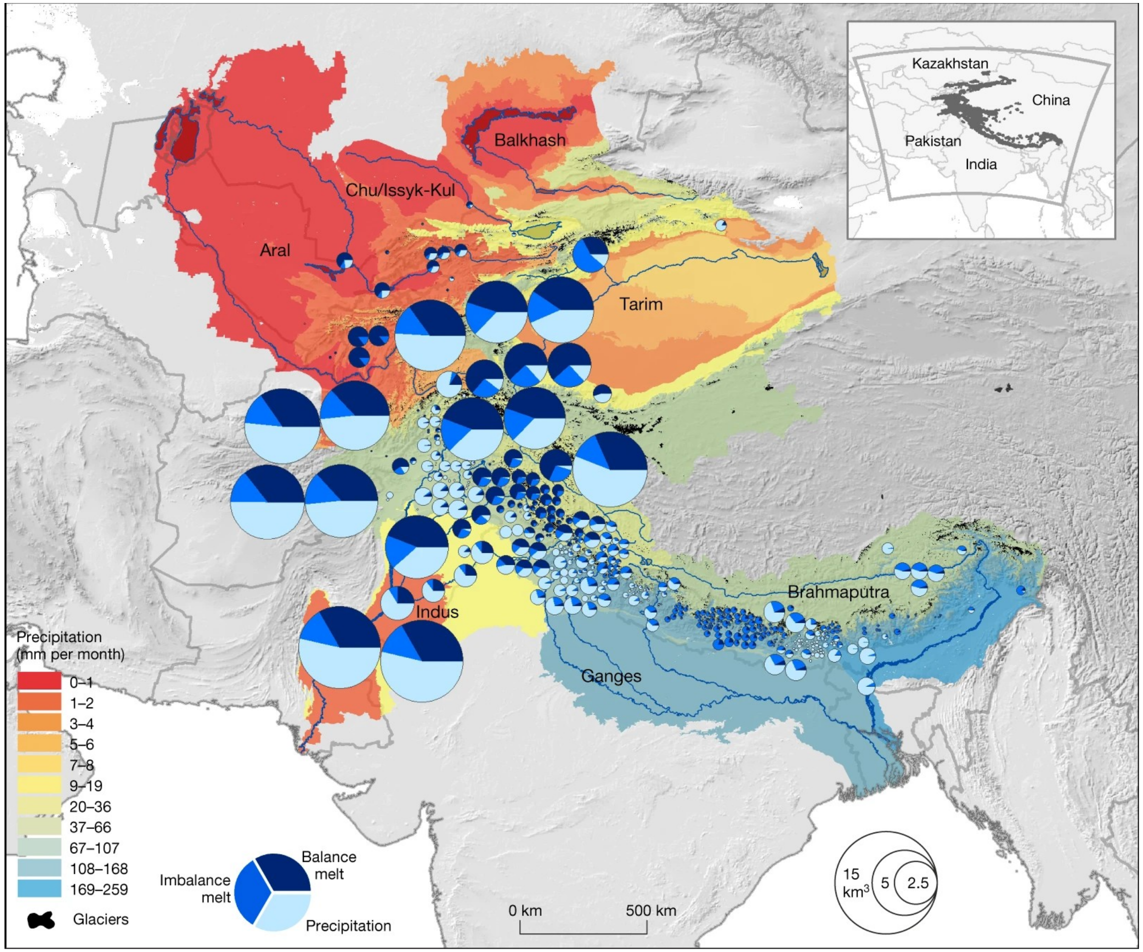
Hydrological significance of glaciers



Relative contribution of glacier melt and precipitation to river discharge in High Mountain Asia for a ***standard*** *year*

[Pritchard, Nature, 2019]

Hydrological significance of glaciers



Relative contribution of glacier melt and precipitation to river discharge in High Mountain Asia for <u>a year of a drought</u>

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Importance of glaciers in the climate system

(1) Glaciers = **climate indicators**

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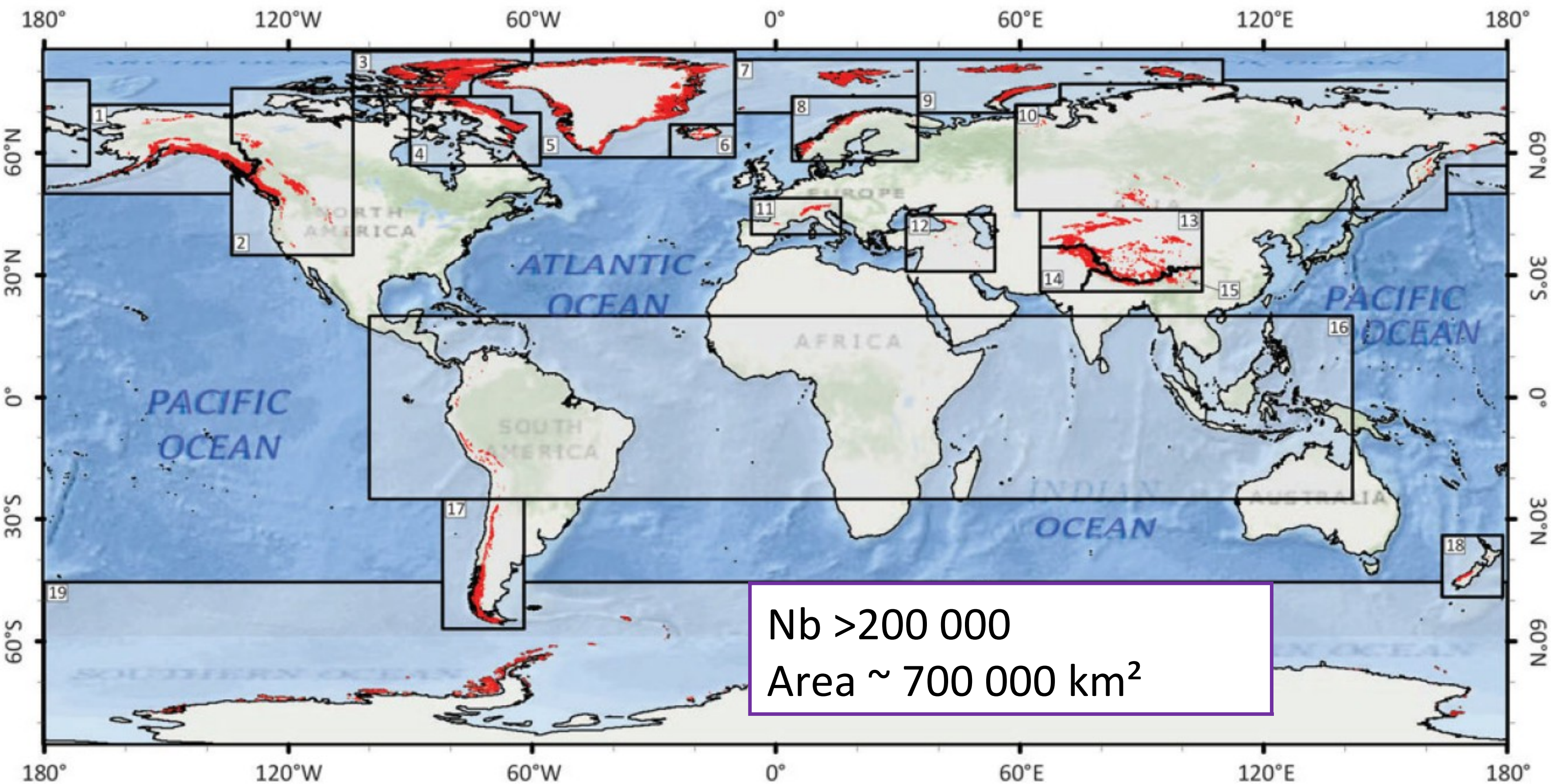
(2) Glaciers = natural **water tower**. Important in dry, continental areas especially during years of drought *[Kaser et al., PNAS, 2010; Pritchard, Nature, 2019]*

(3) Glaciers contribute ~25% to a ~3 mm/yr **sea level rise** *[Cazenave et al., ESSD, 2018]*

Distribution of glaciers & ice caps



→ Spread over the whole Earth.
→ Sparse sampling in the field
→ Mainly models used in sea level budget assessments

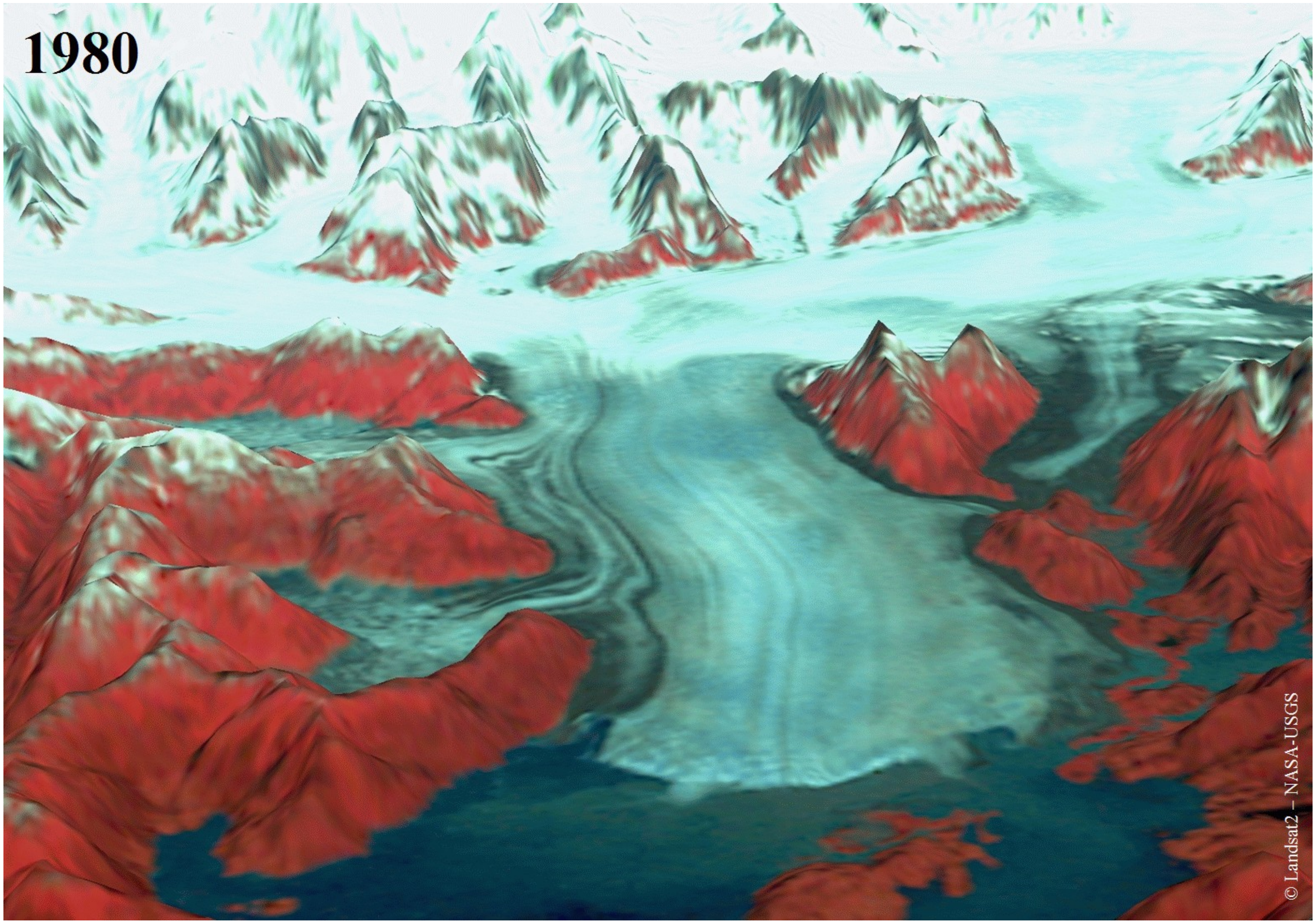
[RGI v6, Pfeffer et al., JGlac, 2014]

Our strategy to estimate regional glacier mass change:

The geodetic method =
Digital Elevation Model (DEM) differencing

Principle of the geodetic method

Step 1: Adjust 2 topographies (DEMs) of the glacier for Yr1 and Yr2 (example for Columbia Glacier, Alaska)



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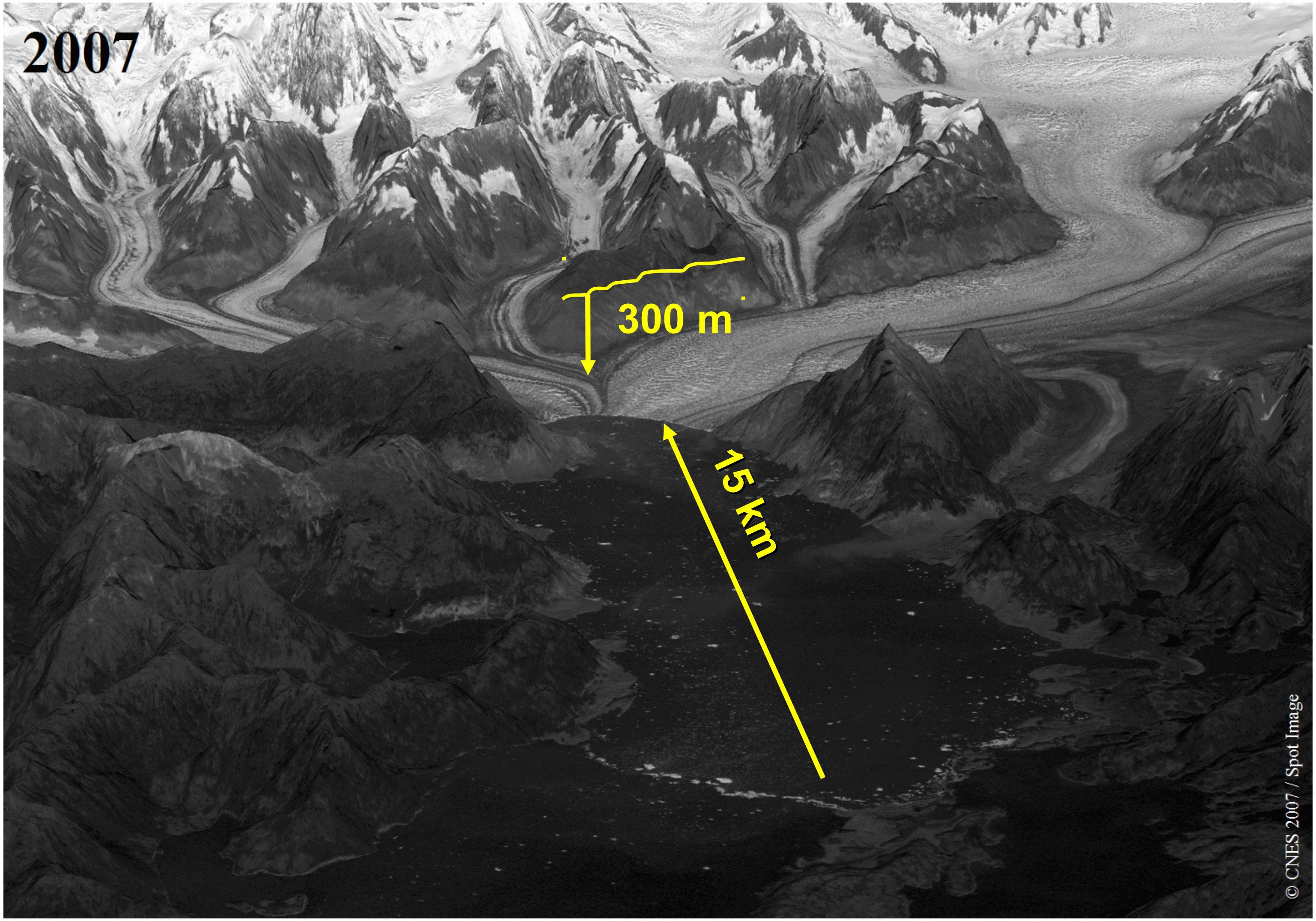
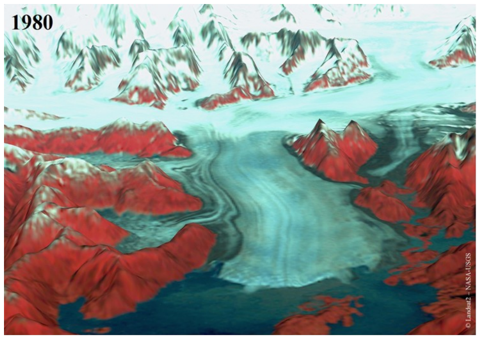
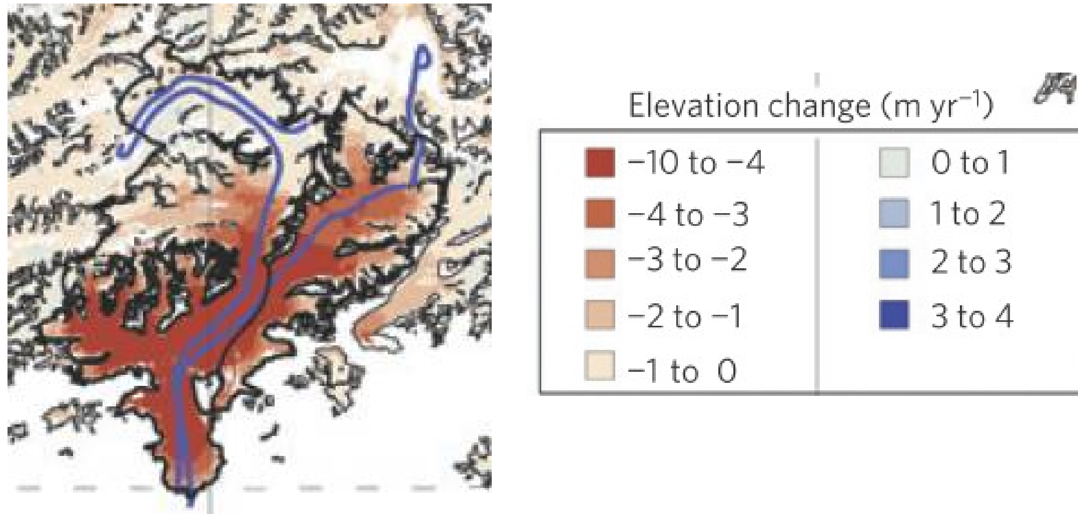


Principle of the geodetic method

<u>Step 2</u>: Create a map of glacier elevation change rate (*dh/dt*)



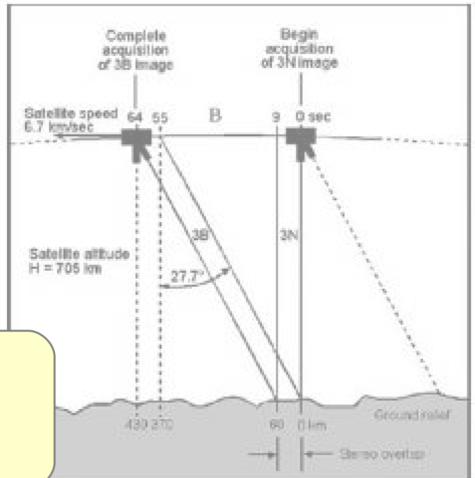


<u>Step 3</u>: Integrate *dh/dt* of the whole glacier area and convert to mass change using a density conversion factor [Huss, 2013]

Mass Balance = $\int_S \rho_i \frac{\partial h_i}{\partial t}$

Equivalent layer of water gained/lost by a glacier/region
Unit : m/yr water equivalent (w.e.) or Gt/yr (large regions)

2 sources of stereo-images/DEMs



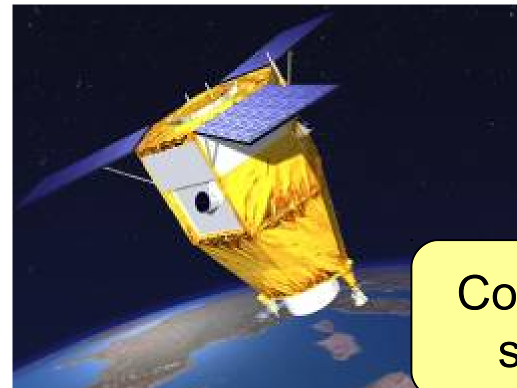
'public data' sensor

ASTER 3N & 3B, 15 m
Along track stereo using two telescopes

↓

30 m DEM
generated using the Ames Stereo Pipeline (ASP)

Raup et al., IEEE, 2000
Shean et al., ISPRS, 2016
Brun et al., NatGeo, 2017



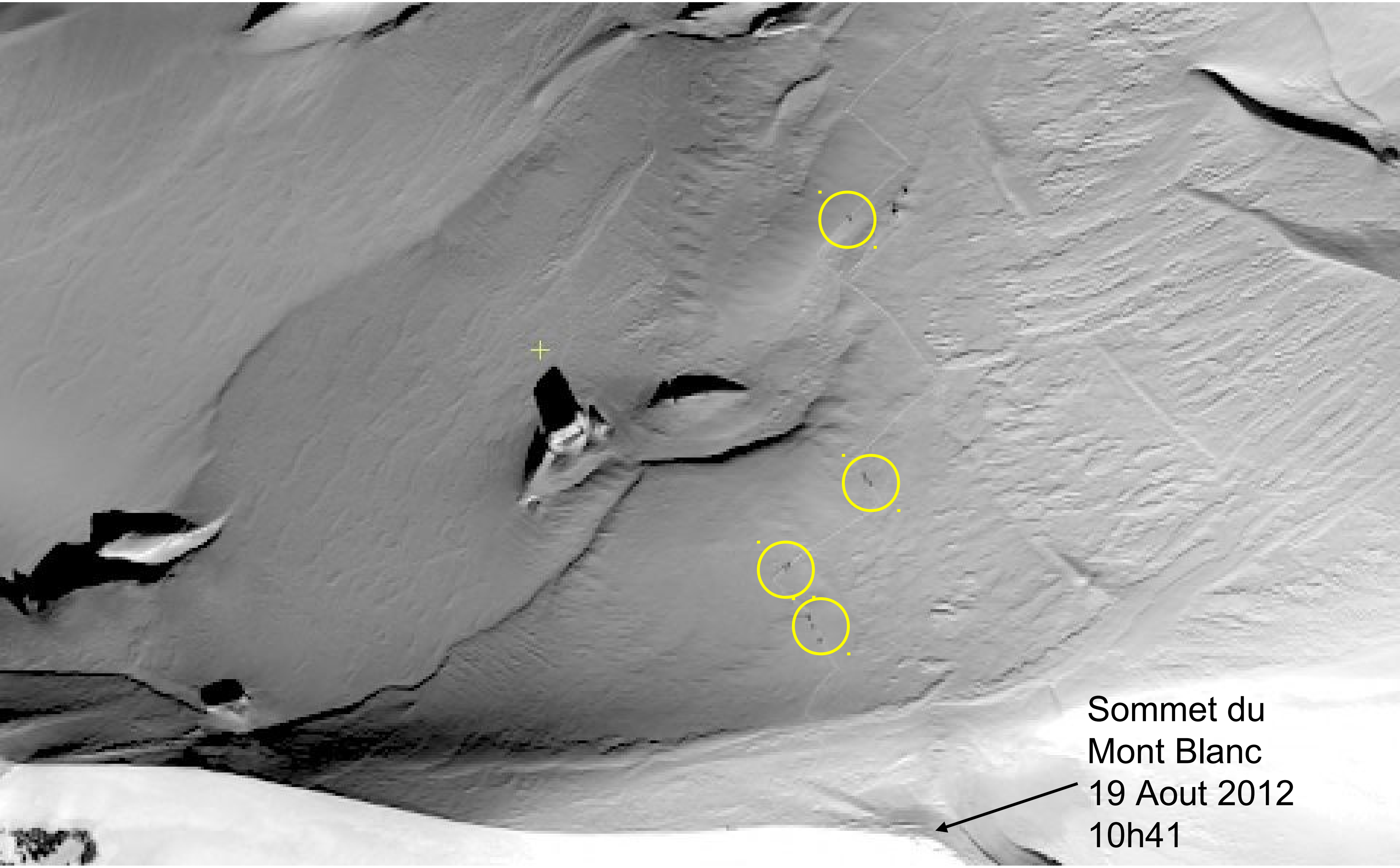
Commercial satellites

Pléiades 1A & 1B, 0.5 m
Along-track stereo
satellite agility

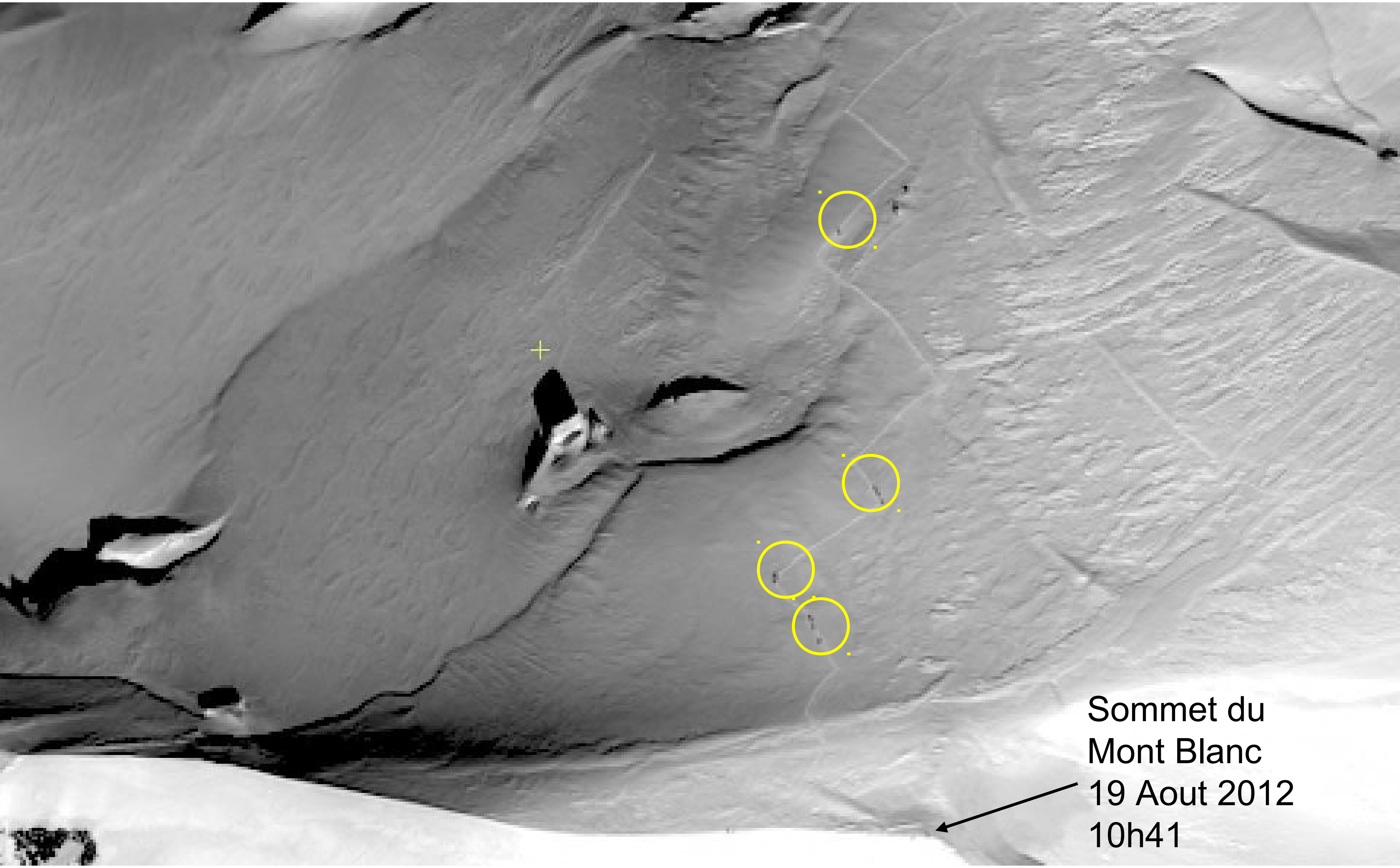
↓

DEM generation using the Ames Stereo Pipeline

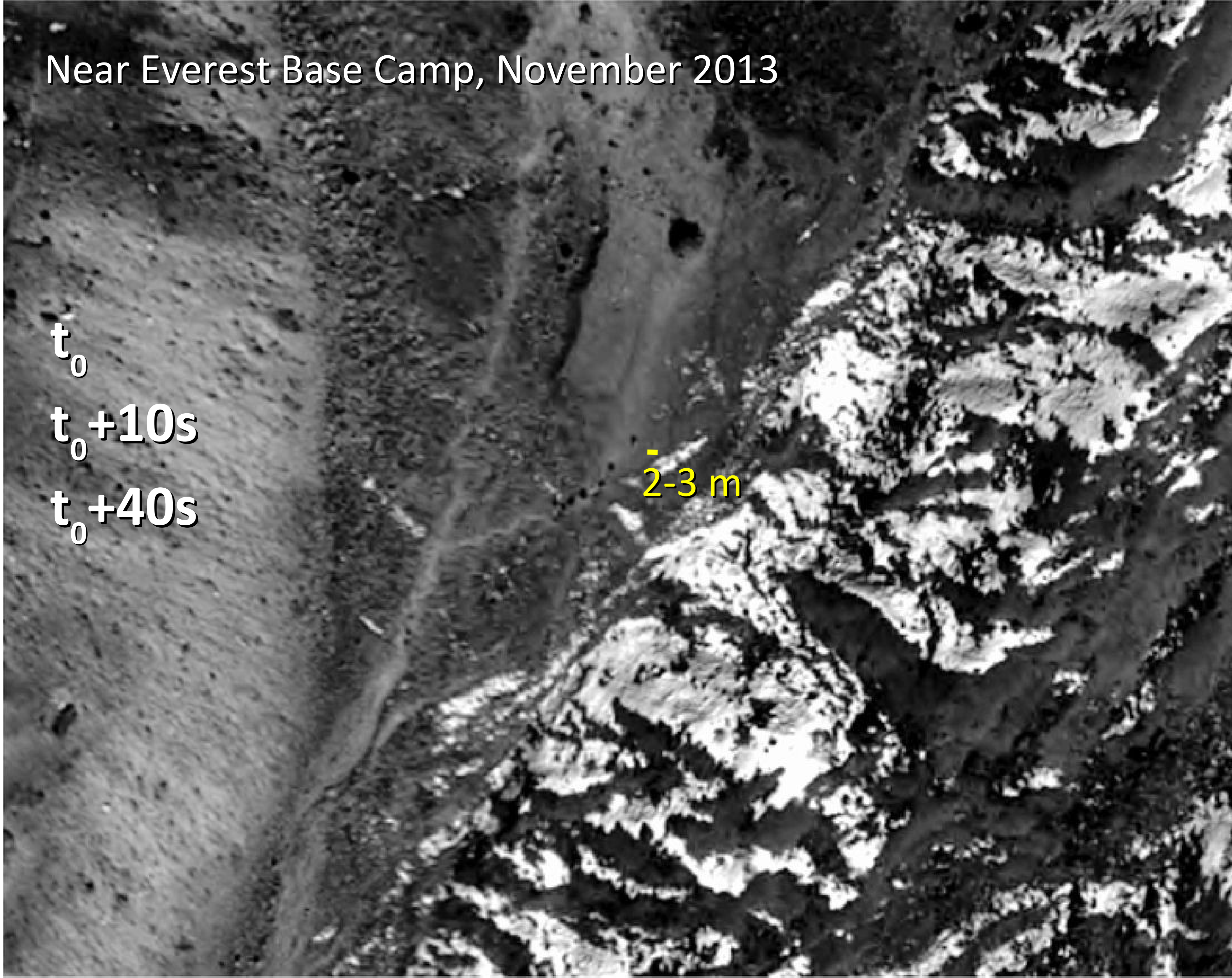
Berthier et al., TC, 2014
Marti et al., TC, 2016



t



t + 27 sec


Near Everest Base Camp, November 2013
t0
t0+10s
t0+40s
2-3 m

Near Everest Base Camp, November 2013

t_0

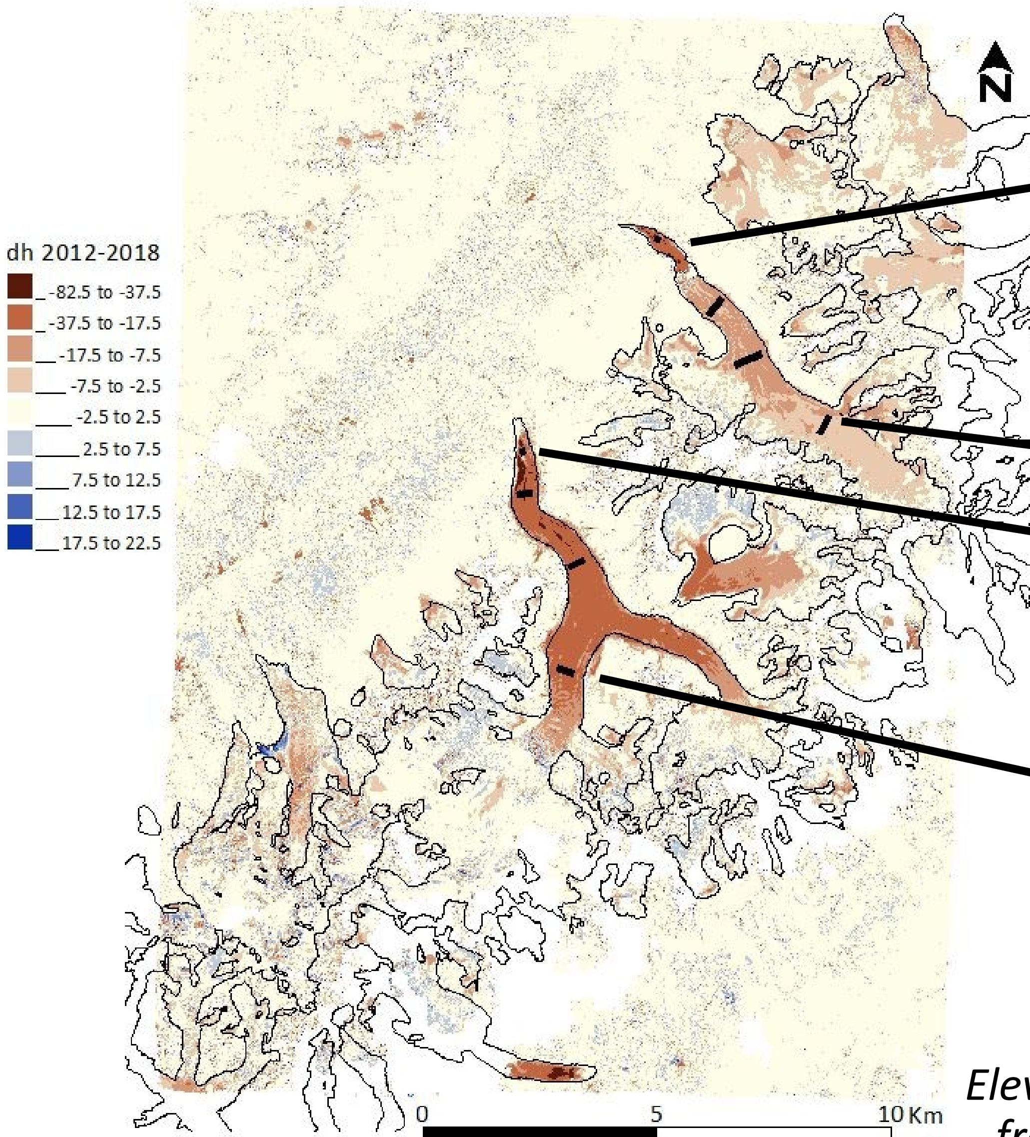
t_0+10s

t_0+40s

Added value of high resolution DEMs?

1. Accurate geodetic mass balance (Mont-Blanc, 2012-2018)
2. Seasonal mass balances (Iceland, J. Belart).
3. A reference for processing of historical imagery (Iceland, J. Belart)
4. Great reactivity of these satellites (Aru collapses)

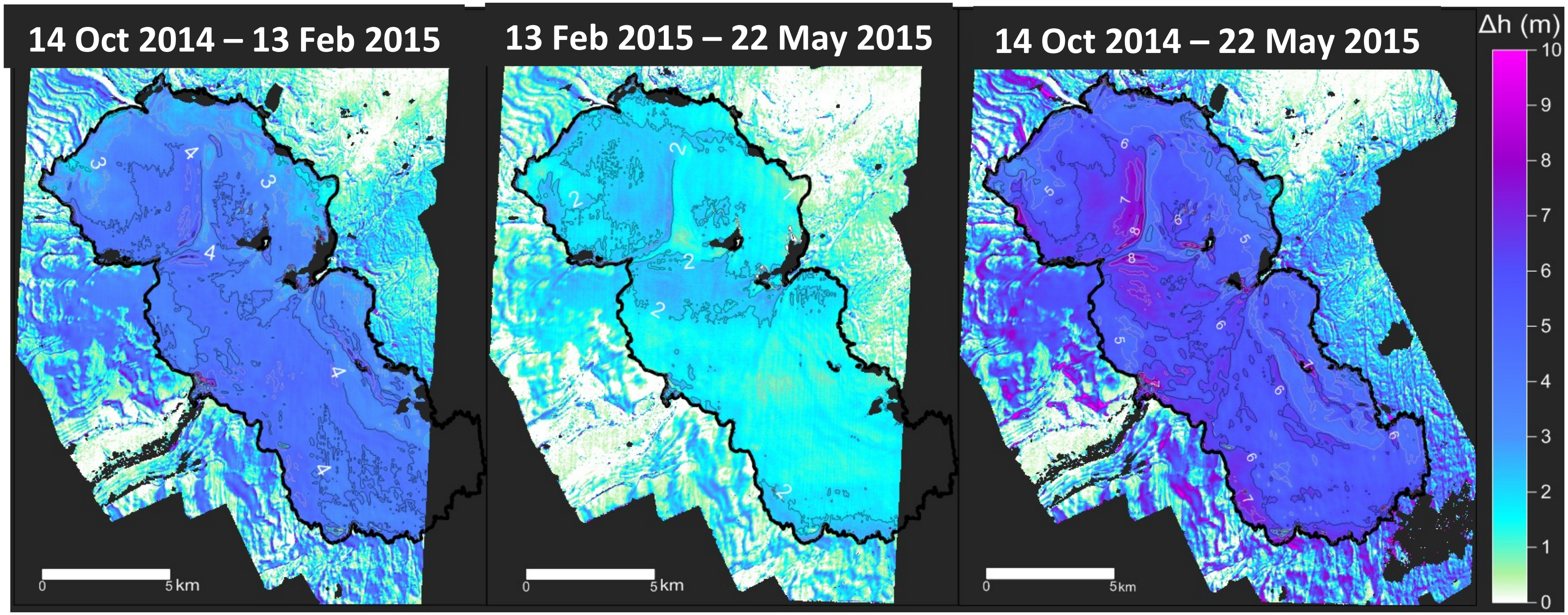
Accurate geodetic mass balance. Mont-Blanc 2012-2018



Profil	GPS	SAT	Diff
P2	-29.8	-29.3	0.5
P4	-7.8	-7.3	0.5
P5	-8.8	-8.3	0.5
P7	-6.5	-6.4	0.1
MON	-15.9	-17.9	-2.0
ECH	-32.1	-31.8	0.3
TRE	-30.5	-31.2	-0.7
TAC	-20.4	-20.0	0.4
Mean_all			**0.0±0.9**
Mean_No MON			**0.2±0.4**

Elevation difference map (4m resolution) from two Pléiades DEM and GPS data

Glacier-wide winter mass balance. Drangajökull. Iceland



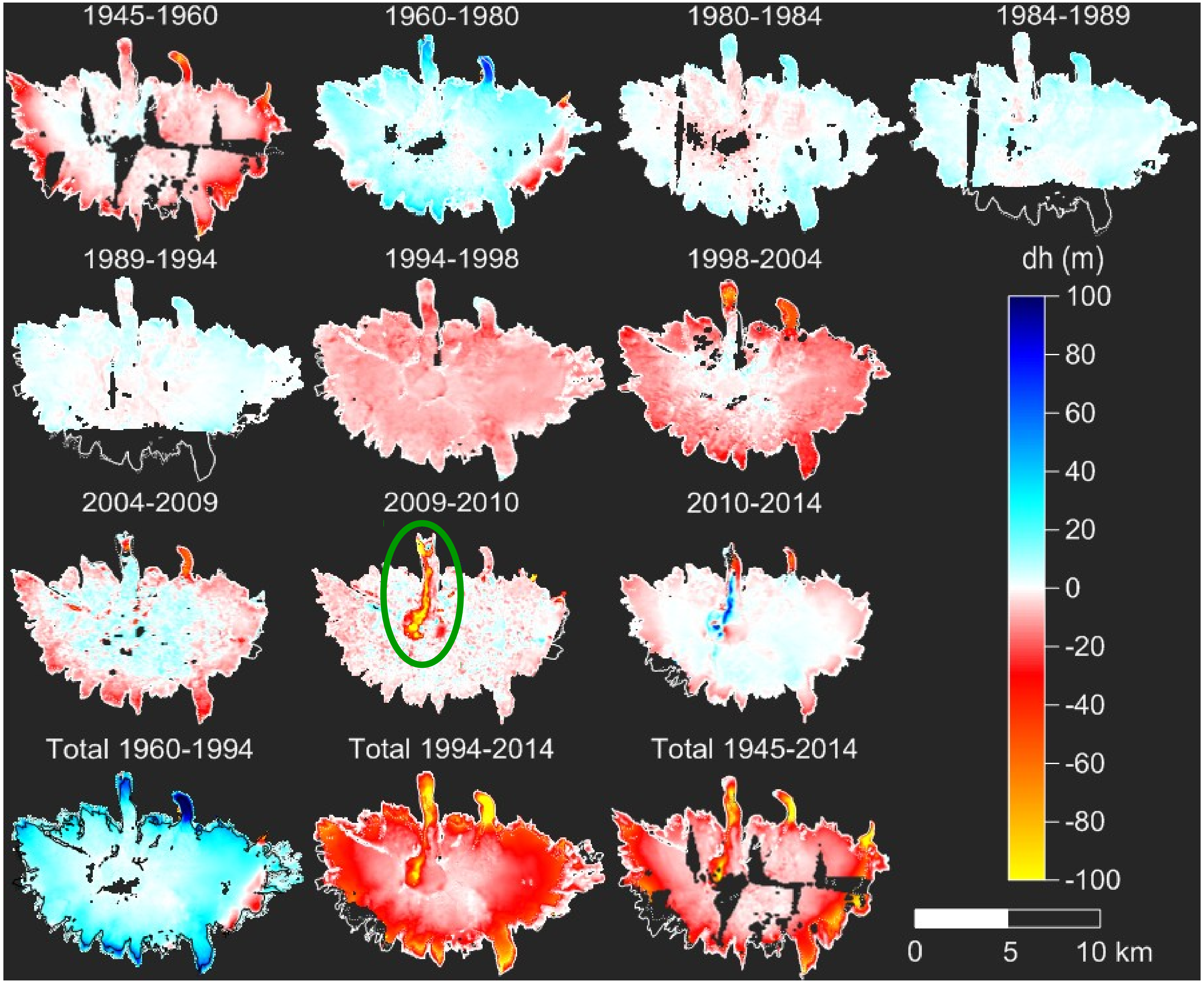
B=2.08 ± 0.28 m w.e. **B=1.26 ± 0.37 m w.e.** **B=3.33 ± 0.23 m w.e.**

Map of elevation differences for three periods during the 2014-2015 winter in Iceland. Pléiades and Worldview DEMs

Co-supervisor Eyjolfur Magnusson (Univ Iceland)

Belart et al., TC, 2017

High resolution DEMs to unlock archives of aerial-images. Eyjafjallajökull



Belart et al., JGlac, 2019

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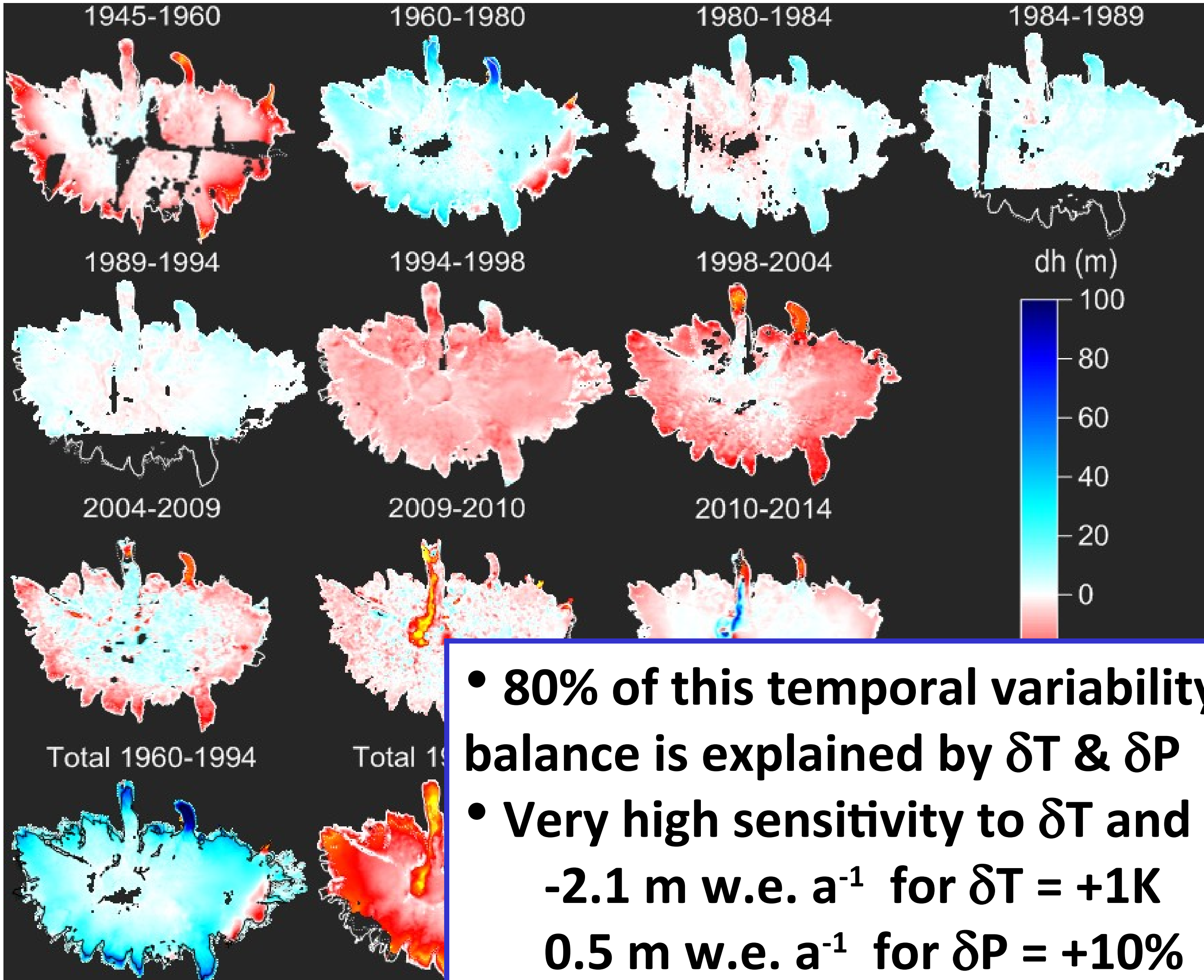
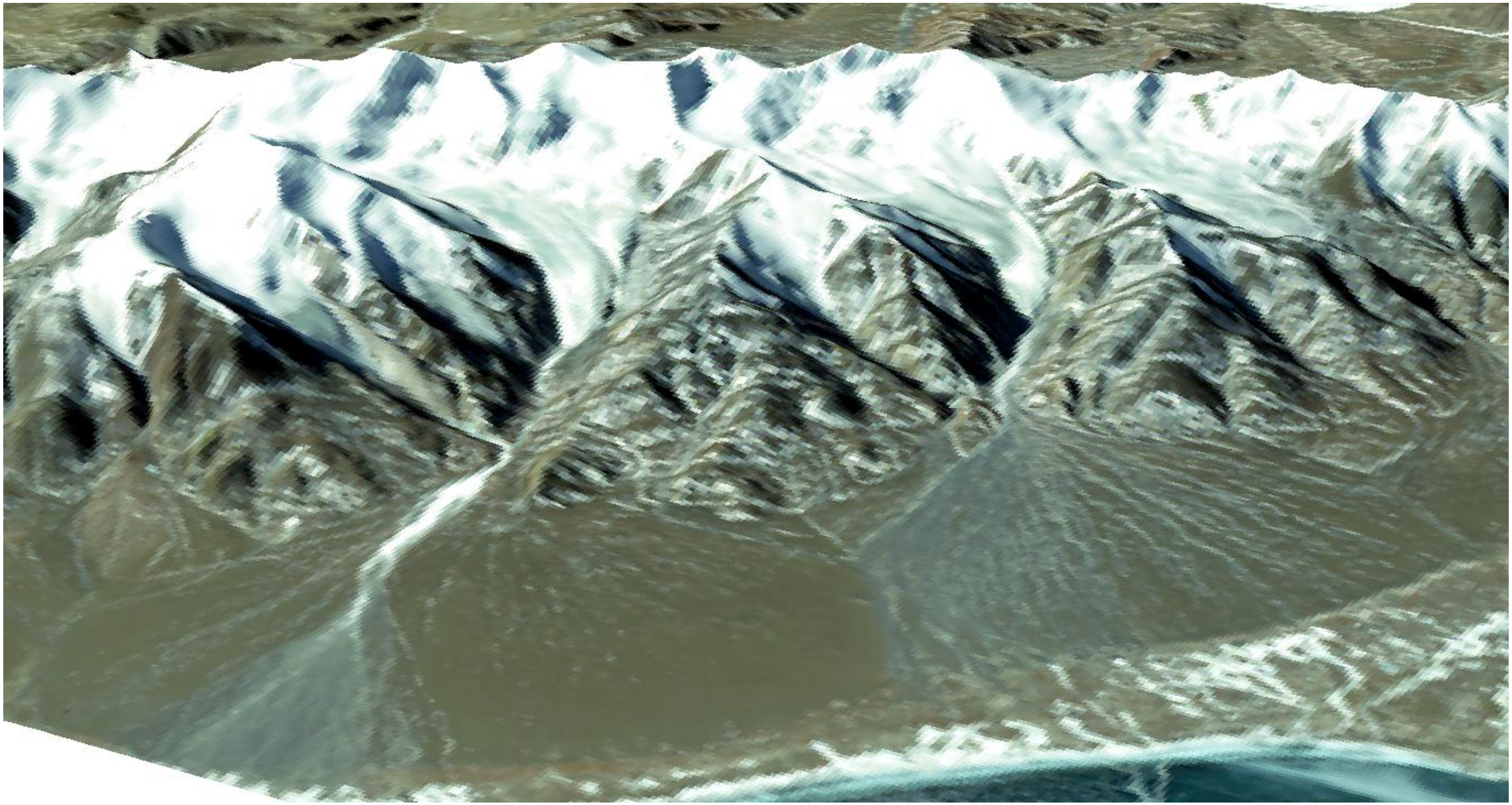


- **80% of this temporal variability in mass balance is explained by δT & δP**
- **Very high sensitivity to δT and δP**
  - **-2.1 m w.e. a^{-1} for δT = +1K**
  - **0.5 m w.e. a^{-1} for δP = +10%**

Great reactivity of these satellites. Aru summer 2016 collapses



3D view of the Aru Range in the remote Tibetan Plateau (Landsat 2015)

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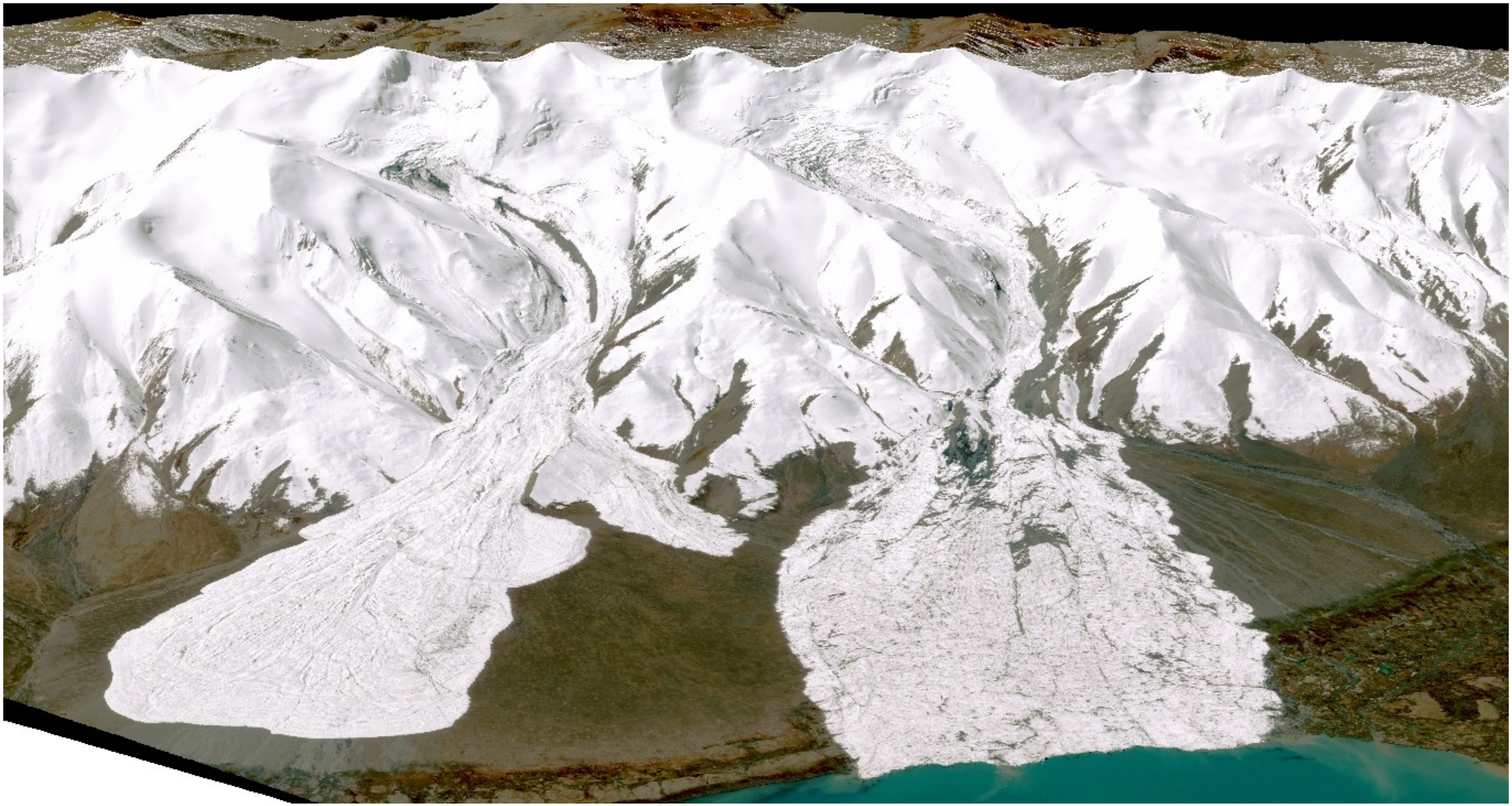

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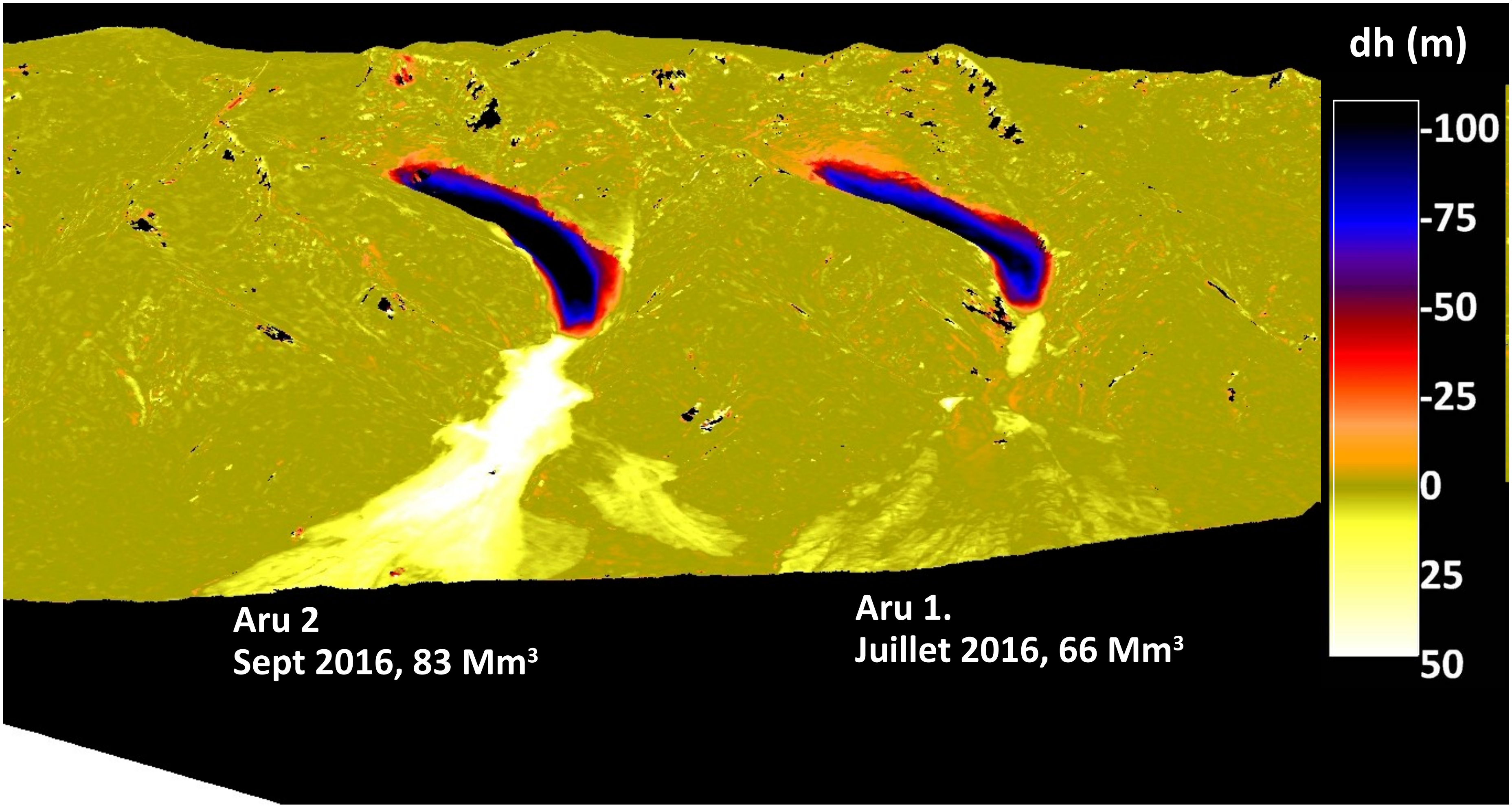
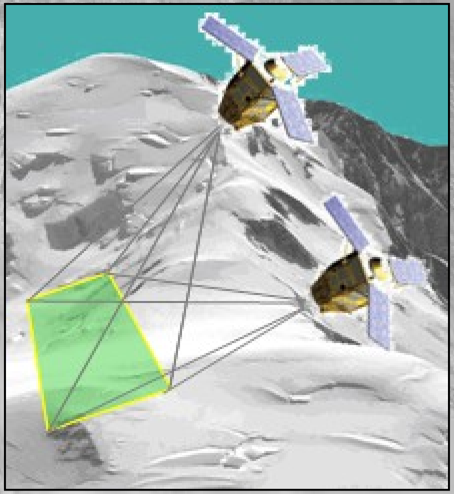


Kääb et al., *NatGeo*, 2018

Pléiades Glacier Observatory

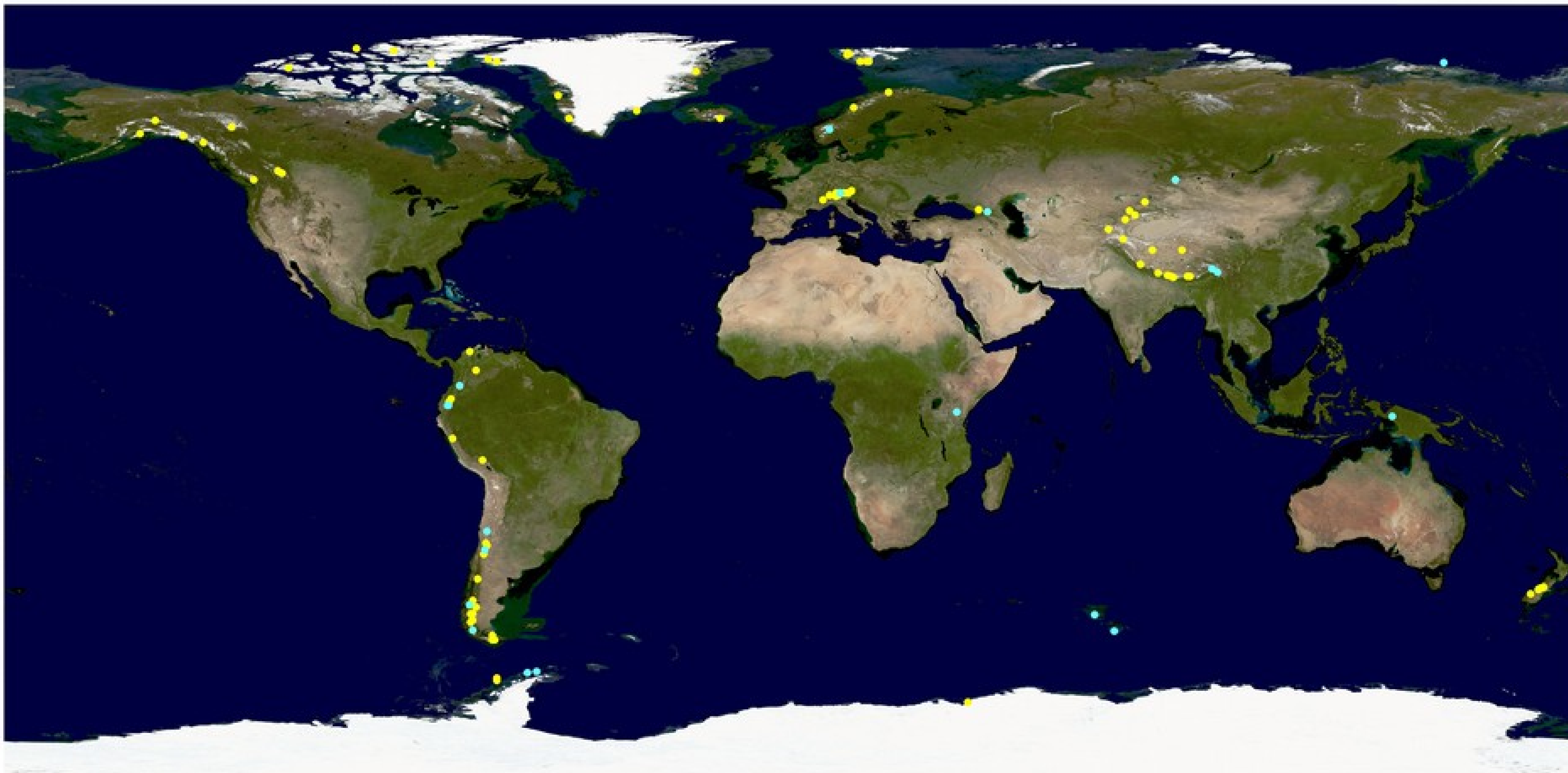
Fontannaz D., Lifermann A., Zemp M.

- Facilitate access to Pléiades satellite stereo-imagery (0.5 m) and DEMs (2-4 m) for the glaciological community
- Acquire imagery at the **right time of the year** (i.e., generally, end of the melt season)
- PGO stereo images are **freely available to all science users**, on the condition that they sign an agreement with CNES (no image catalog yet…)
- Six acquisition campaigns completed, 3 in each hemisphere.
- Repeat surveys after five years

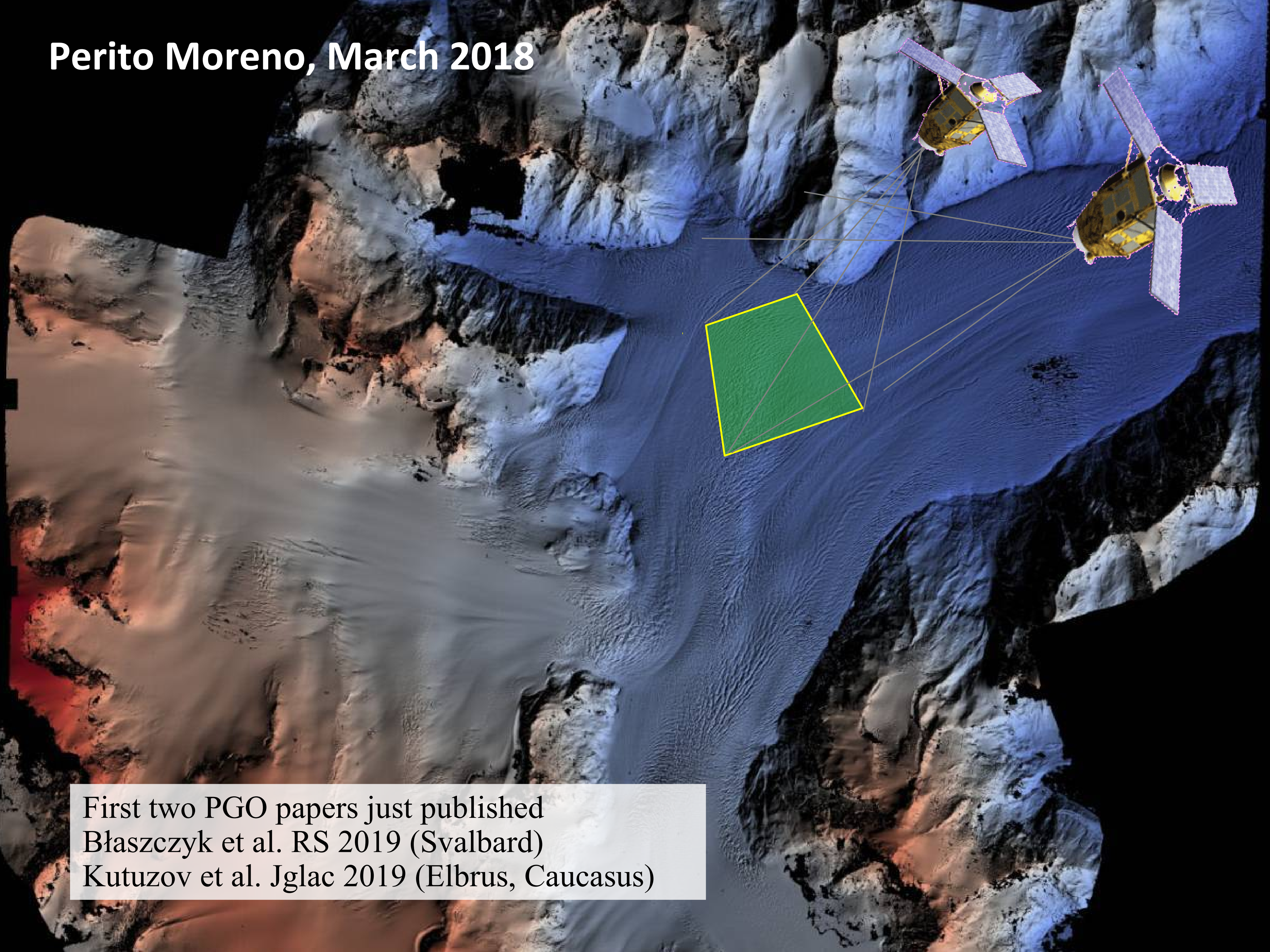


cnes

Sites where Pléiades stereo data have been acquired so far



Perito Moreno, March 2018



First two PGO papers just published
Błaszczyk et al. RS 2019 (Svalbard)
Kutuzov et al. Jglac 2019 (Elbrus, Caucasus)

Conclusions

Using Pléiades DEM diffferencing, dh precised to ~0.5 to 1 m.

Allow measuring seasonal and multi-annual elevation changes (and mass balances) over sites of typically 100-1000 km².

Also a very high potential for seasonal snow depth (PhD Cesar Deschamps-Berger CESBIO, supervisors S. Gascoin & M. Dumont)

Very high demand from the scientific community for repeat, accurate mapping of the constantly evolving Earth surface. See stereo “option” on Sentinel-HR (Hagolle et al.)

Acknowledgments

- → ISIS & TOSCA program from CNES
- → GLIMS project (Raup, Kargel) for the ASTER archive
- → ASP developer team (Oleg, Scott) for their support

The first comprehensive estimate of global glacier mass loss. 2003-2009

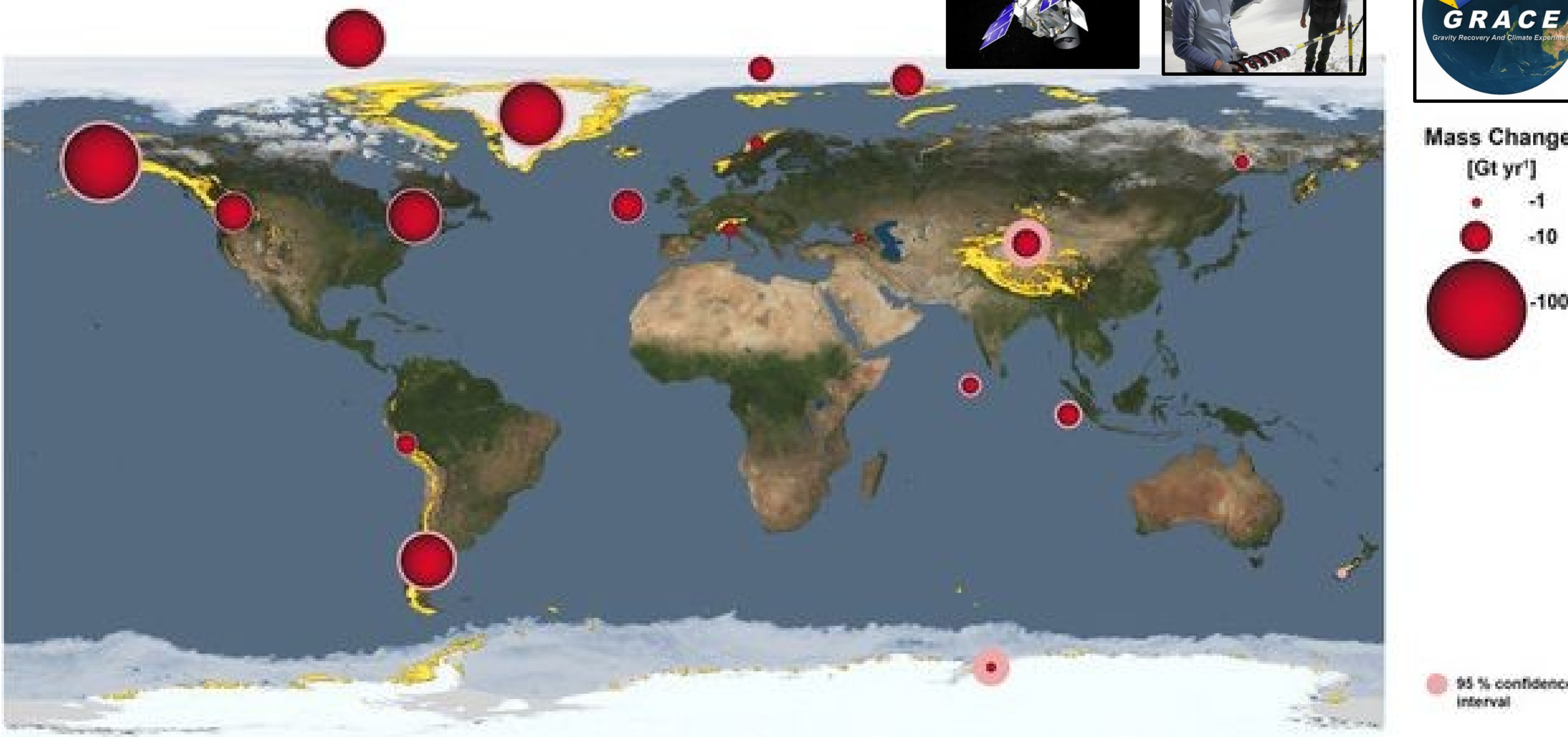


Fig. 1. Regional glacier mass budgets and areas. Red circles show 2003–2009 regional glacier mass budgets, and pale blue/green circles show regional glacier areas with tidewater basin fractions (the extent of ice flowing to termini in the ocean) in blue shading (Table 1). Peach-colored halos surrounding red circles show the 95% CI in mass change estimates, but can only be seen in regions that have large uncertainties.

[Gardner et al., Science, 2013]

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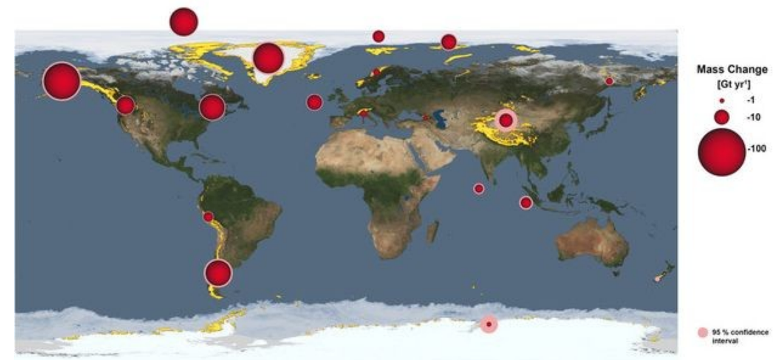


[Gardner et al., Science, 2013]

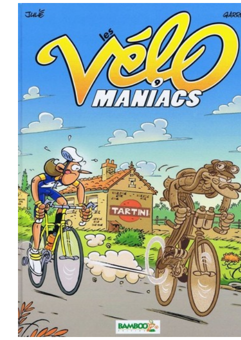
<u>Findings</u>

- Mass loss = 260 Gt/yr (0.7 mm/yr SLE)
- Extrapolation of sparse *in situ* measurements leads to overestimated mass loss
- good agreement between gravimetry and laser altimetry in the Arctic (low GRACE errors, Blazquez et al., 2018)

<u>Limitations</u>

- A short 6-yr time period.
- Individual glaciers or small hydrological basins are not resolved, only large regions (sparse ICESat sampling)
- Disagreement between methods (GRACE/Altimetry) outside the Arctic (Asia, Andes, North America, etc...)

Work/travel differently



PRO-ENVIRONMENTAL BEHAVIOUR

Academic air travel

J. Clean. Prod. **226**, 959–967 (2019).

Air travel is one of the fastest-growing contributors to greenhouse gas emissions. In academia, travel may be required to coordinate research across international teams and conduct fieldwork, and conferences and department visits may provide important opportunities for maintaining visibility, promoting new research and developing collaborations. However, whether air travel is actually related to professional success in academia has not been tested.

Seth Wynes and coauthors, from the University of British Columbia, Canada, analysed data from travel requisition forms provided by 26 academic departments at the University of British Columbia over an 18-month period, as well as publicly available academic profiles. Conferences were the primary purpose for most trips. More senior academics and those with higher salaries were responsible for more air travel emissions. However, there was no association between emissions and productivity, as measured by total citations and *h*-index (adjusted for academic age and discipline). Nor was air travel related to collaborations with other academics, as measured by average number of authors per paper. These results suggest that there is potential for academics to reduce emissions from air travel without compromising their careers. *JR*

https://doi.org/10.1038/s41558-019-0496-7

Nature Climate Change, 2 weeks ago

No relationship between academic productivity and air travels

No relationship between number of collaborations and air travels

Senior academics travel more than young scientists

Train TLS-PARIS

- 4h20 mn entre les centre-villes
- Wifi
- Idéal pour bosser