Examples of remote sensing applications for the study of glaciers and ice sheets

A. Rabatel[1], J. Mouginot[1], E. Berthier[2], A. Dehecq[3]
et al.

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2 – LEGOS, Univ. Toulouse, CNRS, IRD, CNES, Toulouse, France
3 – J.P.L. Caltech, Passadena, California, USA

Main focuses

Evolution of mountain glaciers (Alpes, Andes, Himalaya)

Changes in glaciers volume (mass balance)

- Surface elevation changes (dh/dt)
- Equilibrium-line Altitude (ELA)

Changes in glaciers surface states

- Geometry (area, length) = multi-temporal inventories
- Surface albedo
- Debris cover (extent, thickness)
- Surface flow velocities

Modelling

- Estimations of glacier thickness from surface velocities and dh/dt
- Simulations of glacier evolution

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Mostly from optical remote-sensing in our cases

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- Surface elevation changes (dh/dt) ⟸ **Examples**
- Equilibrium-line Altitude (ELA) ⟸ **to come**

Changes in glaciers surface states

- Geometry (area, length) = multi-temporal inventories
- Surface albedo
- Debris cover (extent, thickness)
- Surface flow velocities ⟸ **Talk by R. Millan**

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- Estimations of glacier thickness from surface velocities and dh/dt
- Simulations of glacier evolution

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Ice sheets and ice shelves (Antarctica & Greenland)

Mass balance / contribution to sea level rise
- Surface elevation changes (dh/dt)
- Surface flow velocities

Monitoring of physical processes
- Ice shelves fracturing
- Seasonal variability: calving, ice melange, supra-glacial hydrology

Modelling
- Assimilation of surface velocities, dh/dt time series
- Dynamics, ice discharge
- Interaction between ice sheets and ocean

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} **Mostly from SAR**

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Example to come

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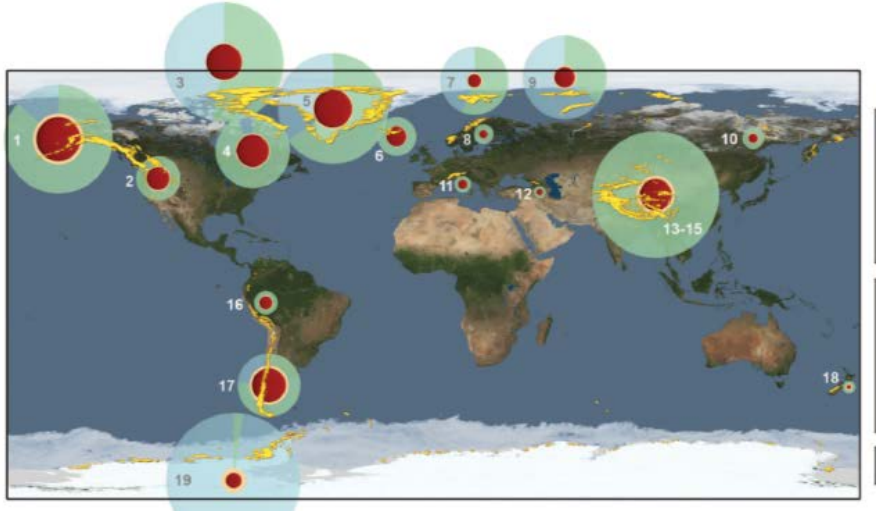
Towards a global estimate of glacier mass loss since 2000

Etienne **Berthier**, LEGOS – CNRS, Univ. Toulouse
with Fanny **Brun**, Ines **Dusaillant**, Romain **Hugonnet**

Example 1

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



Gardner et al., Science, 2013

Limitations

- A single, short 6-yr time period.
- Individual glaciers or small hydrological basins are not resolved (sparse sampling of ICESat)
- Annual variability is not resolved
- Disagreement between methods (GRACE/Altimetry) outside the Arctic

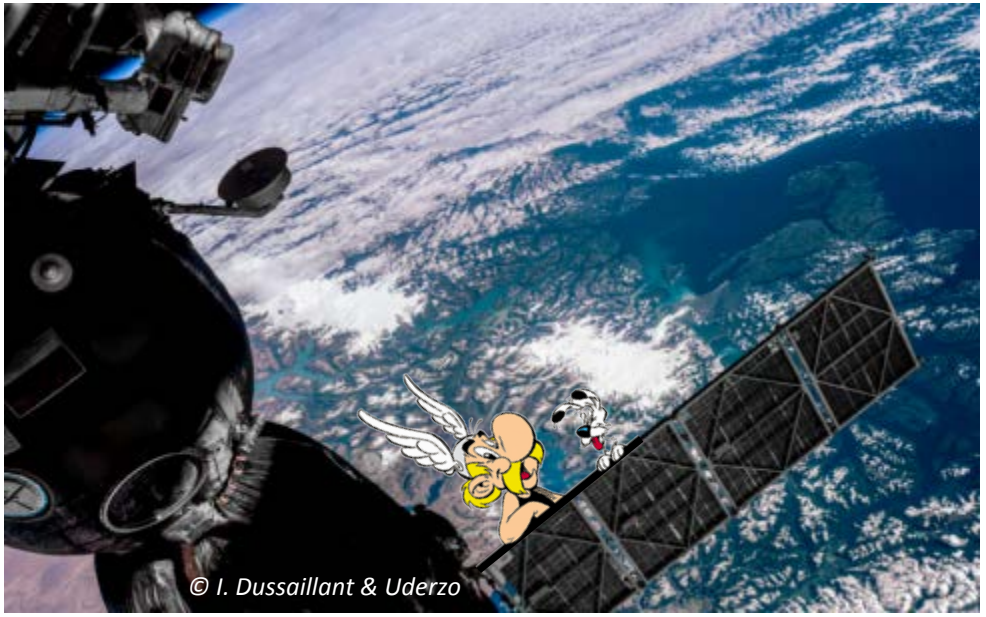
Example 1

Proposed strategy to estimate regional glacier mass change:

The geodetic method = Digital Elevation Model (DEM) differencing

Taking advantage of the vast archive of ASTER stereo-images acquired since 2000

ASTERiX method
ASTER monitoring of
Ice towards e**X**tintion



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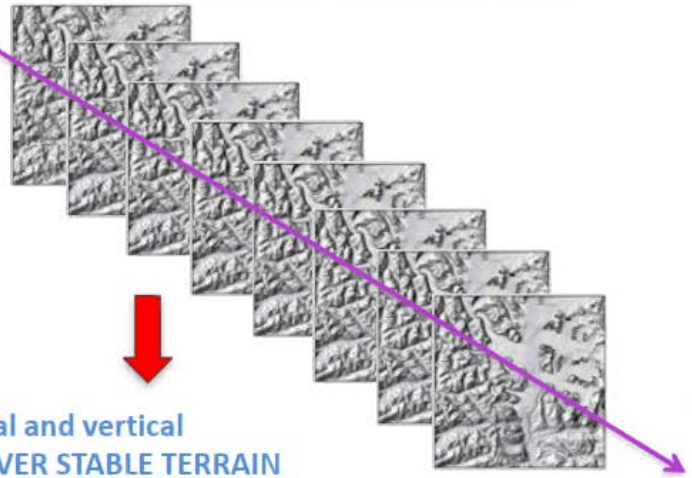
Example 1

ASTERiX method (ASTER monitoring Ice eXtintion)

Time series of ASTER DEMs

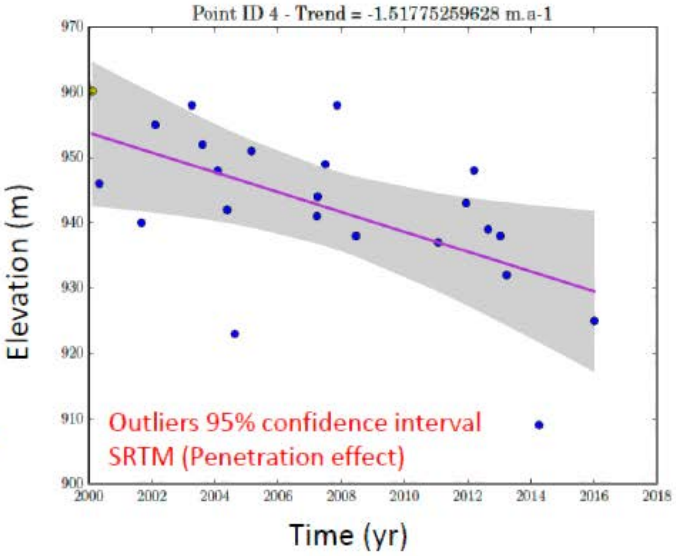
Inicial year



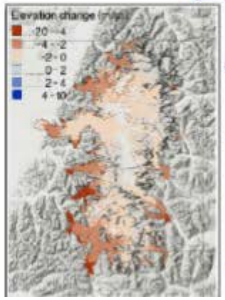
Final year

Horizontal and vertical
ADJUSTMENT OVER STABLE TERRAIN
SRTM DEM as reference

Elevation values for 1 pixel



Fit a linear trend through all elevation values (*dh/dt*)



Map of elevation change rate (*dh/dt*)

Conversion to mass
DENSITY assumption
(Huss, 2012)

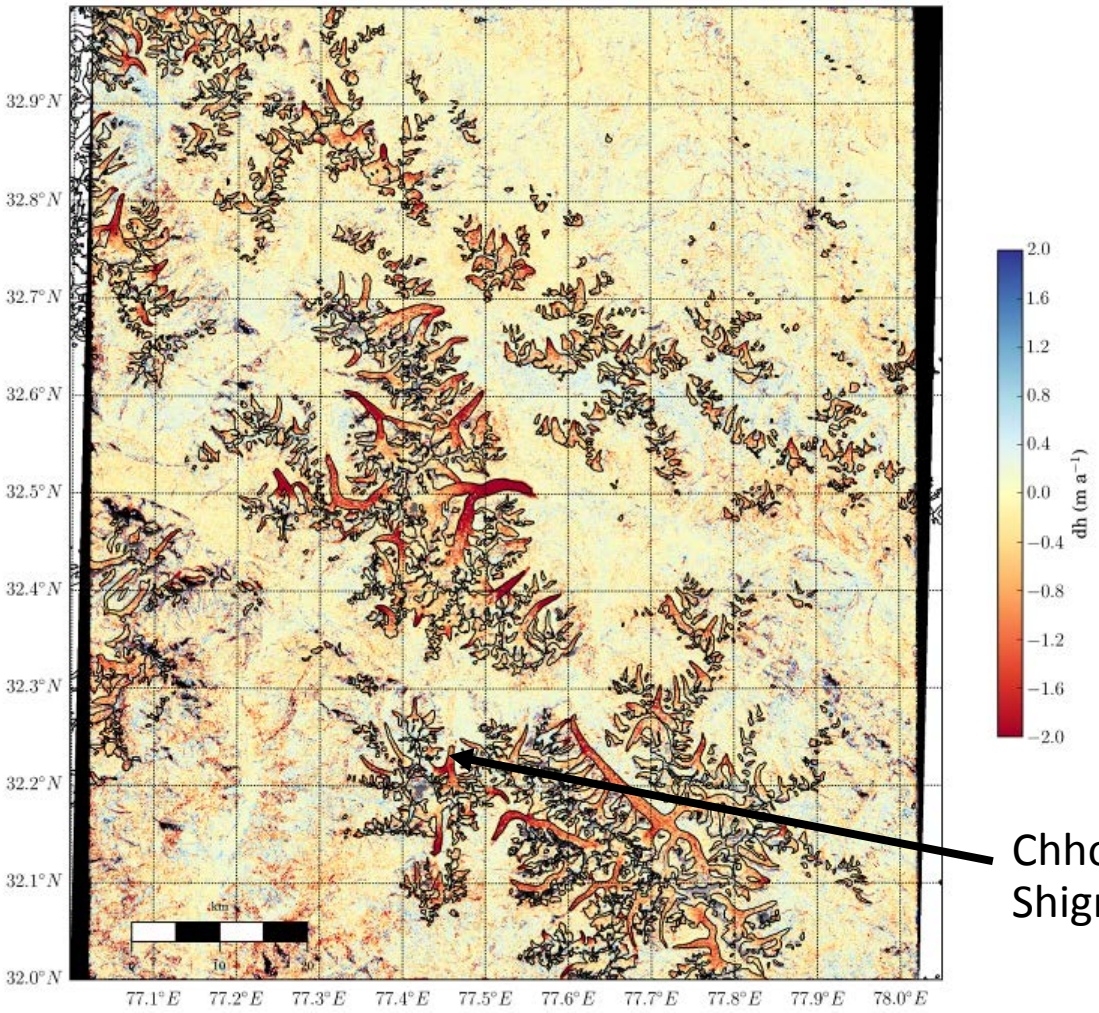
Glacier or regional MASS BALANCE
(m w.e./yr or Gt/yr)

Berthier et al., 2016; Brun et al., 2017 Inspired by: Nuimura et al., 2012; Melkonian et al, 2013, 2014; Wang and Käab, 2015

Example 1

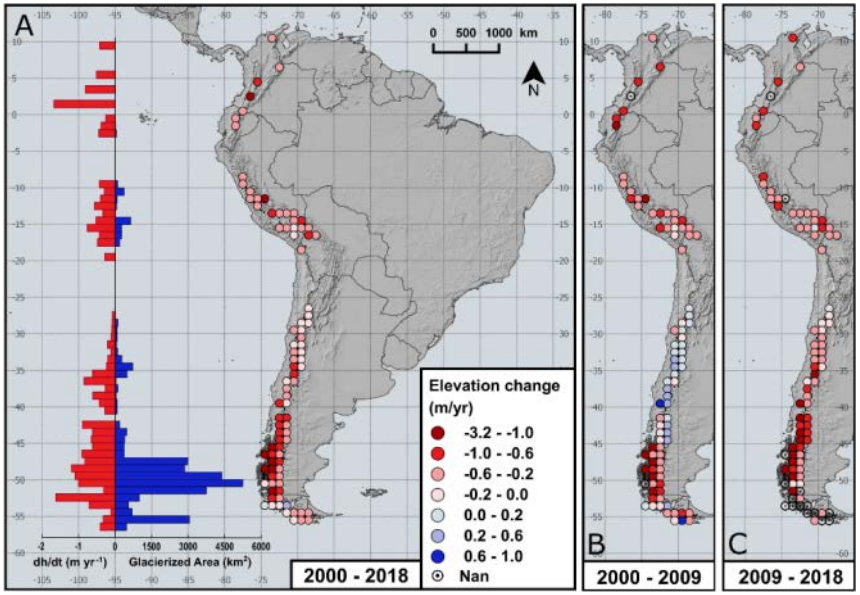
Map of average dh/yr from ASTER DEM time series [2000-2016]
India, Chhota Shigri Glacier catchment

Individual glaciers are now resolved (threshold 1 km²)



Example 1

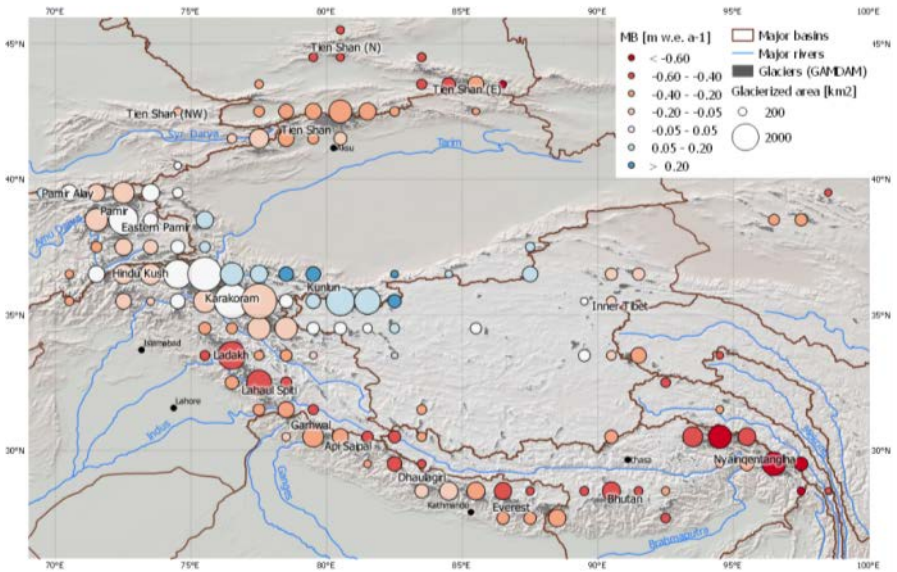
Andean glaciers



PhD Ines Dusaillant
32 000 km² of glaciers
Loss of 19.8 ± 6.3 Gt/yr [2000-2018]
Increased glacier imbalance in the central Andes after 2009

Annual variability is not resolved

High Mountains of Asia



50 000 km² of glaciers
Loss of 16.3 ± 3.5 Gt/yr [2000-2016]
Regional contrast: strong imbalance to the East, steady state in Karakoram - Kunlun

Brun et al., Nat. Geosc., 2017

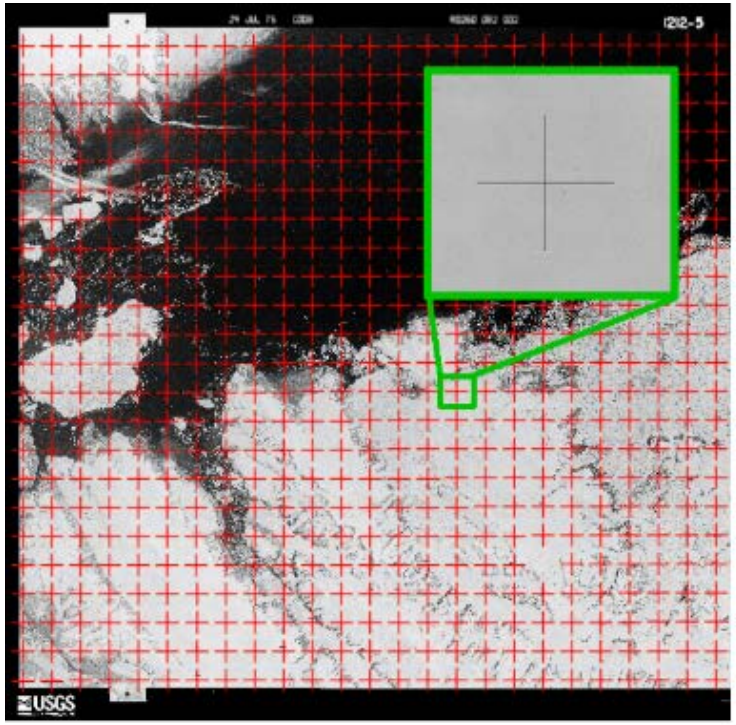
Back to the 1960s – 70s

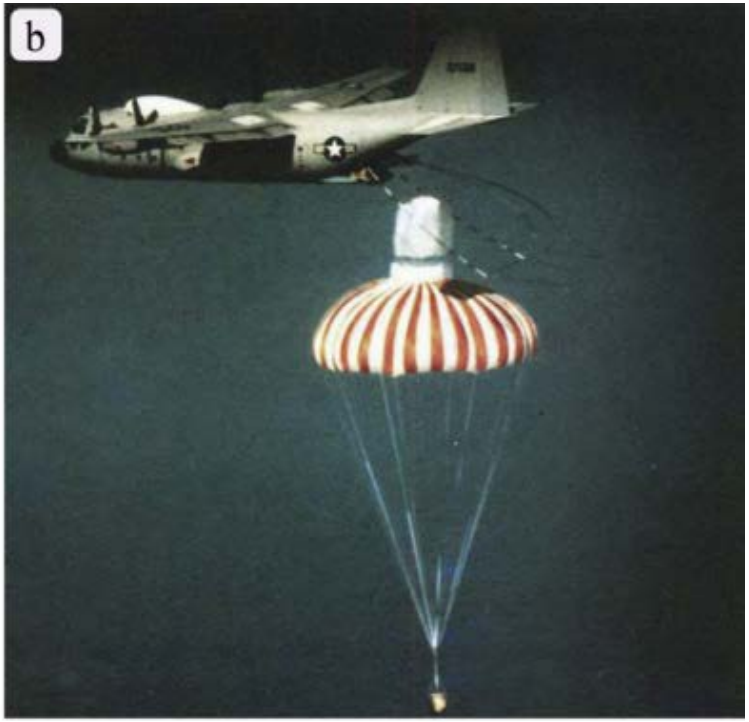
Amaury **Dehecq**, J.P.L. – Caltech – California

Example 1

Automatic processing of « Spy images » (e.g. Hexagon, Corona) available for the 1960s, 1970s and 1980s.

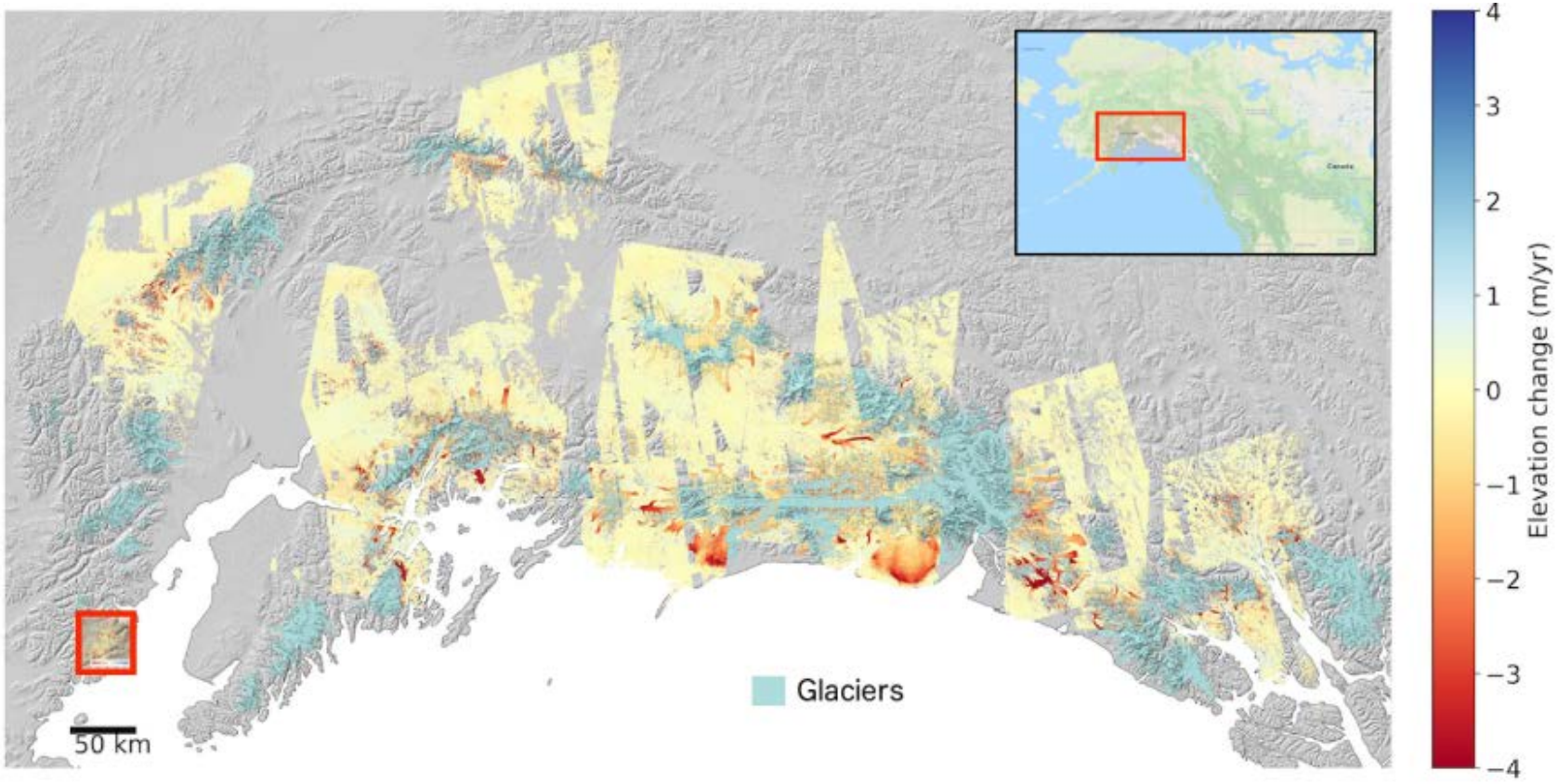
Challenges:
- Scans of « paper » archives (not adquired numerically)
- Need of georeferencing (automatic identification of fiducial markers), distortion corrections
- Unkonwn orbital parameters
- …





Example 1

Alaska – glacier mass changes [1977-2015]



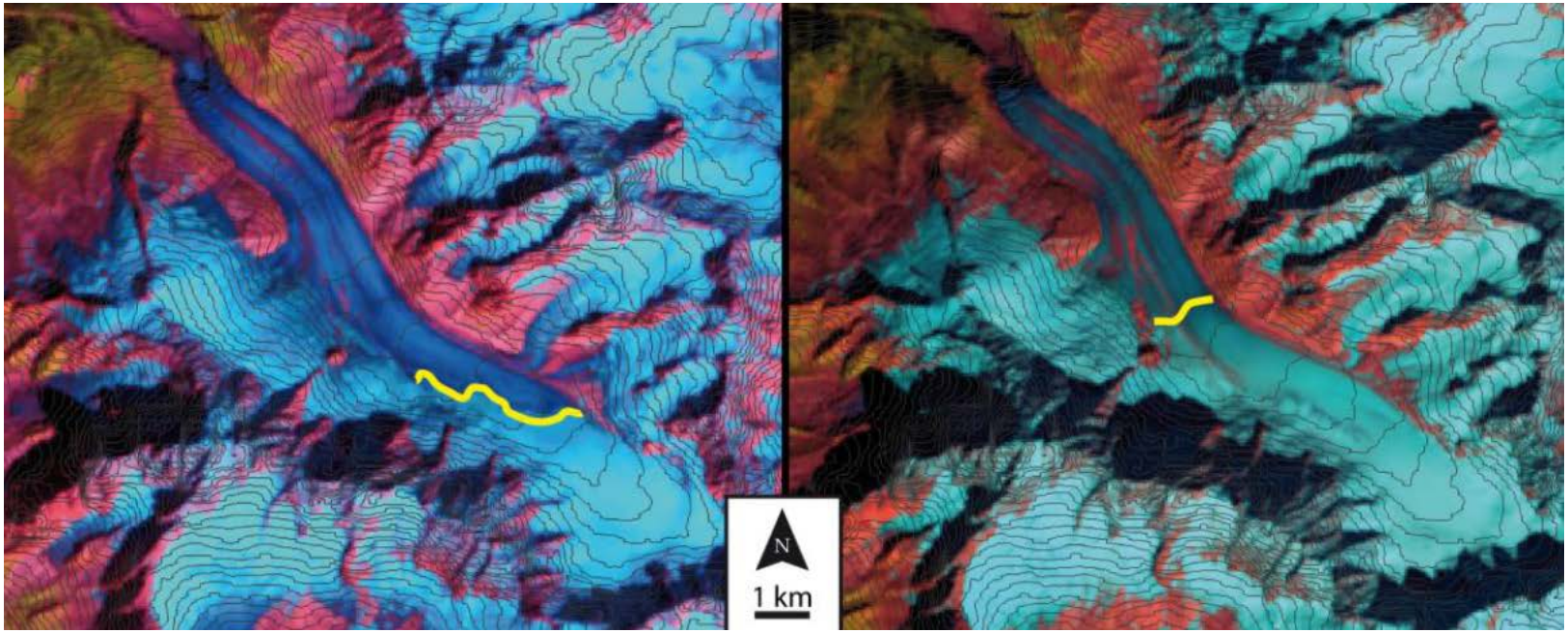
Dehecq et al., in prep.

Getting annual mass balance from the ELA

Antoine **Rabatel**, IGE – Univ. Grenoble Alpes, CNRS, IRD
with Lucas **Davaze**, Léna **Gurriaran**, Jean Pierre **Dedieu**, Yves **Arnaud**

Example 2

Monitoring of the equilibrium-line altitude as a proxy of the surface mass balance

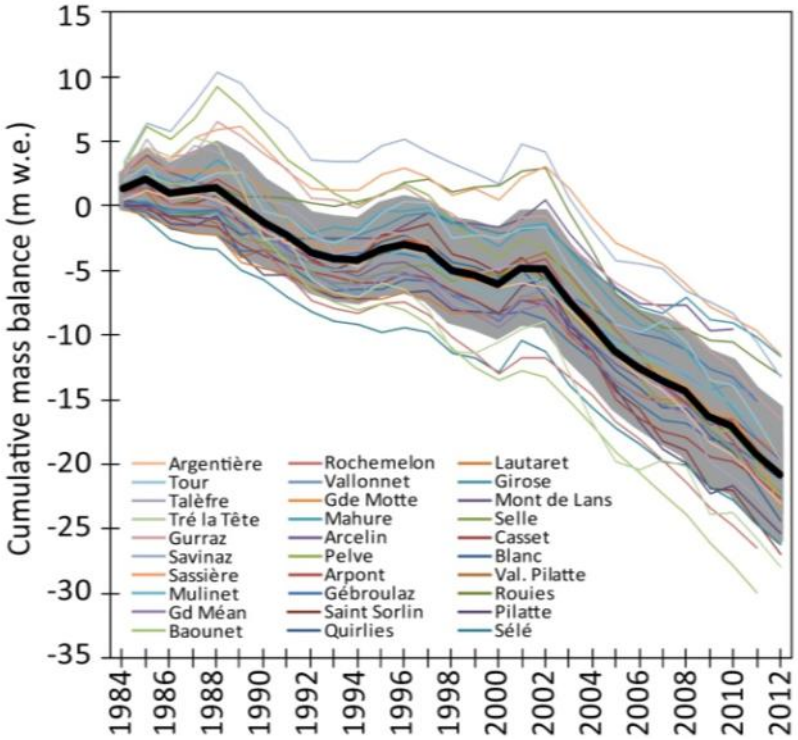


Glacier d'Argentière (Alpes FR), from optical images (e.g., LANDSAT, SPOT, ASTER, Sentinel)
Rabatel *et al.*, 2005, 2008, 2012, 2013, 2016

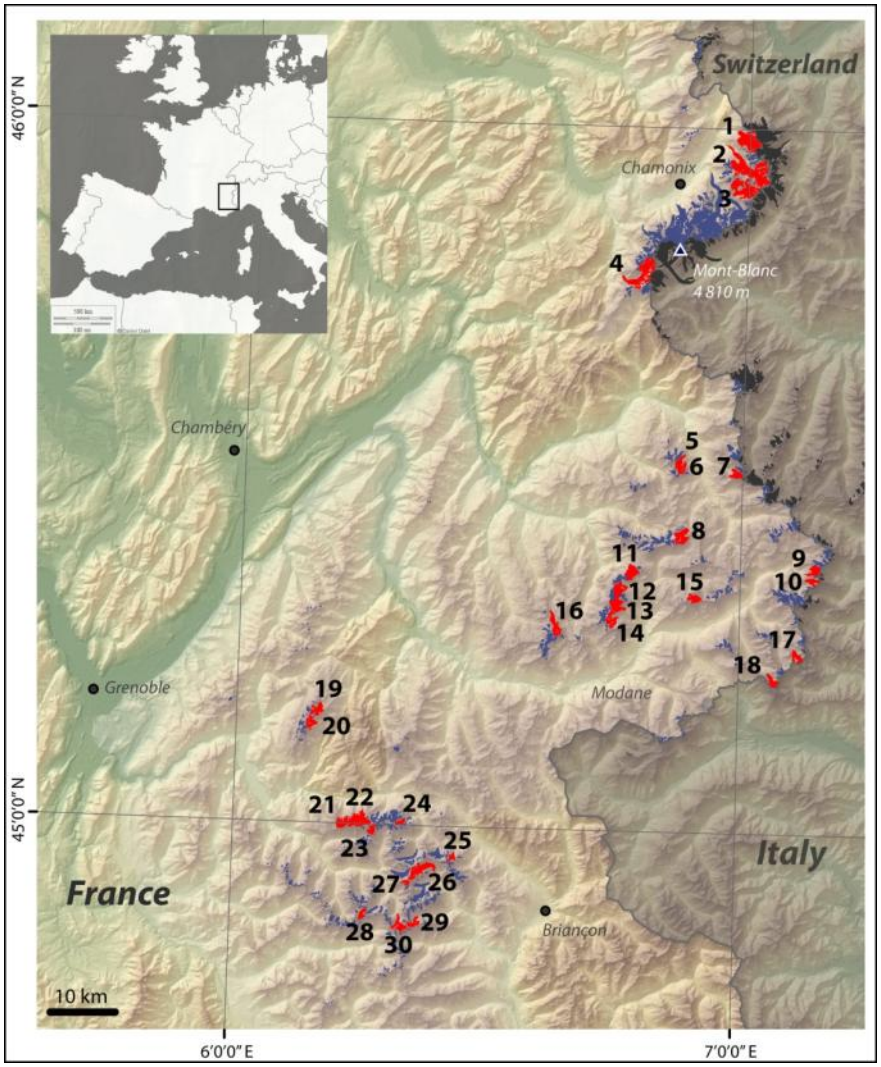
Example 2

Annual surface mass balance [1984-2012]
30 glaciers (French Alps)

Only 4 glaciers have *in situ* measurements over this period



Rabatel et al., J. Glaciol., 2016

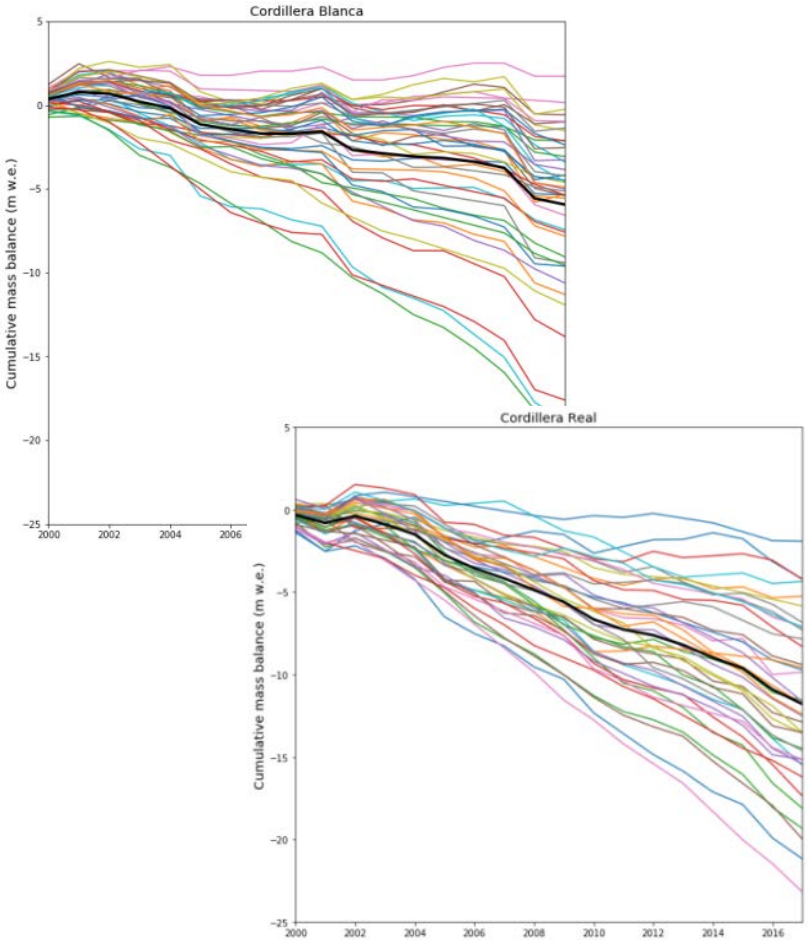


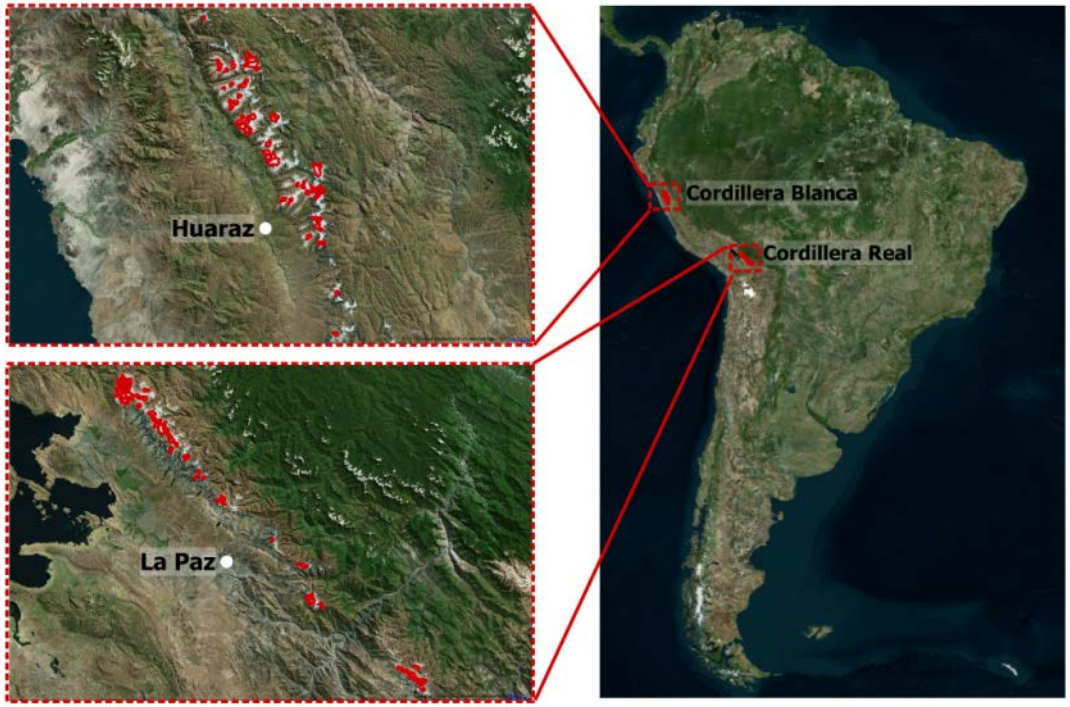
Example 2

Annual surface mass balance [1999-2017]
82 glaciers (Peruvian & Bolivian Andes)

PhD L. Davaze (2016-19), M1 L. Gurriaran (2018-19)

Only 4 glaciers have *in situ* measurements over this period





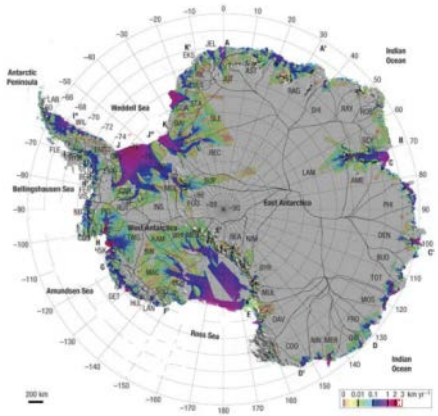
Example 3

Spaceborne observation of ice flow and mass changes over Antarctica and Greenland

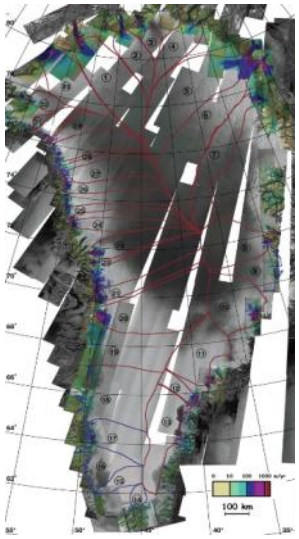
Jérémie **Mouginot**, IGE – Univ. Grenoble Alpes, CNRS, IRD

with Anna **Derkacheva**, Eric **Rignot**, Romain **Millan,** Mondher **Chekki**

Example 3



Rignot et al., 2008

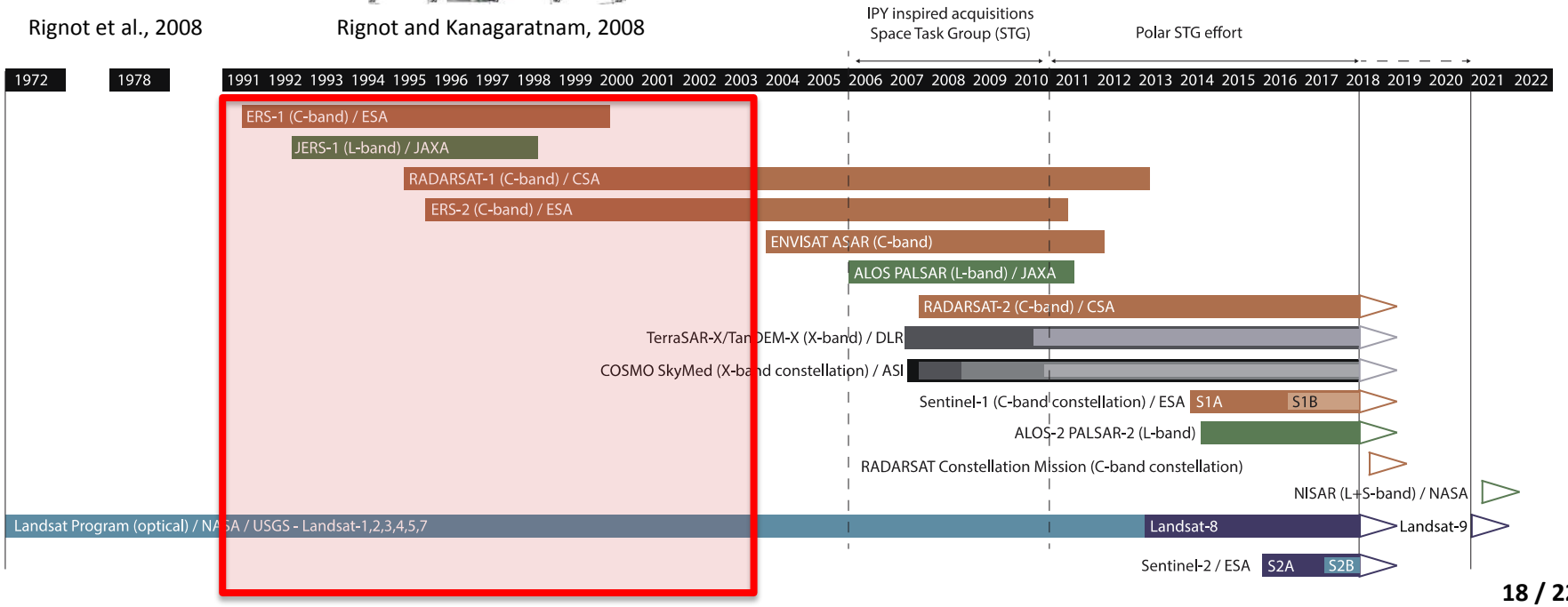


Rignot and Kanagaratnam, 2008

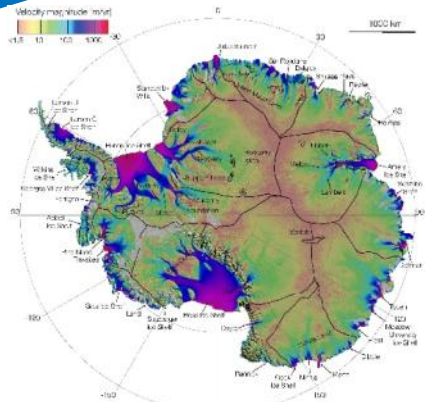
\+ **Ice speed mapping from space (mostly SAR)**

* Feature tracking, speckle tracking, InSAR algorithm
* 1st estimates the mass balance of the ice sheets

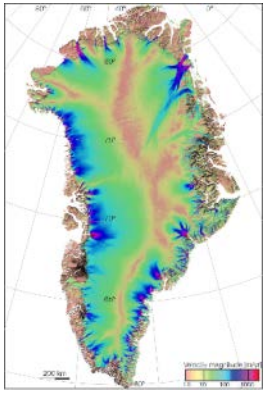
\- **Limited coverage and temporal information**



Example 3

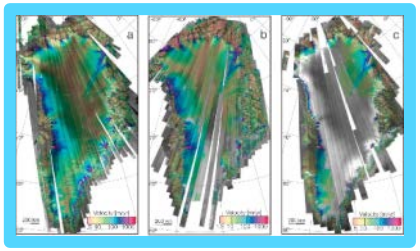


Rignot, Mouginot and Scheuchl 2011
Mouginot et al. 2012

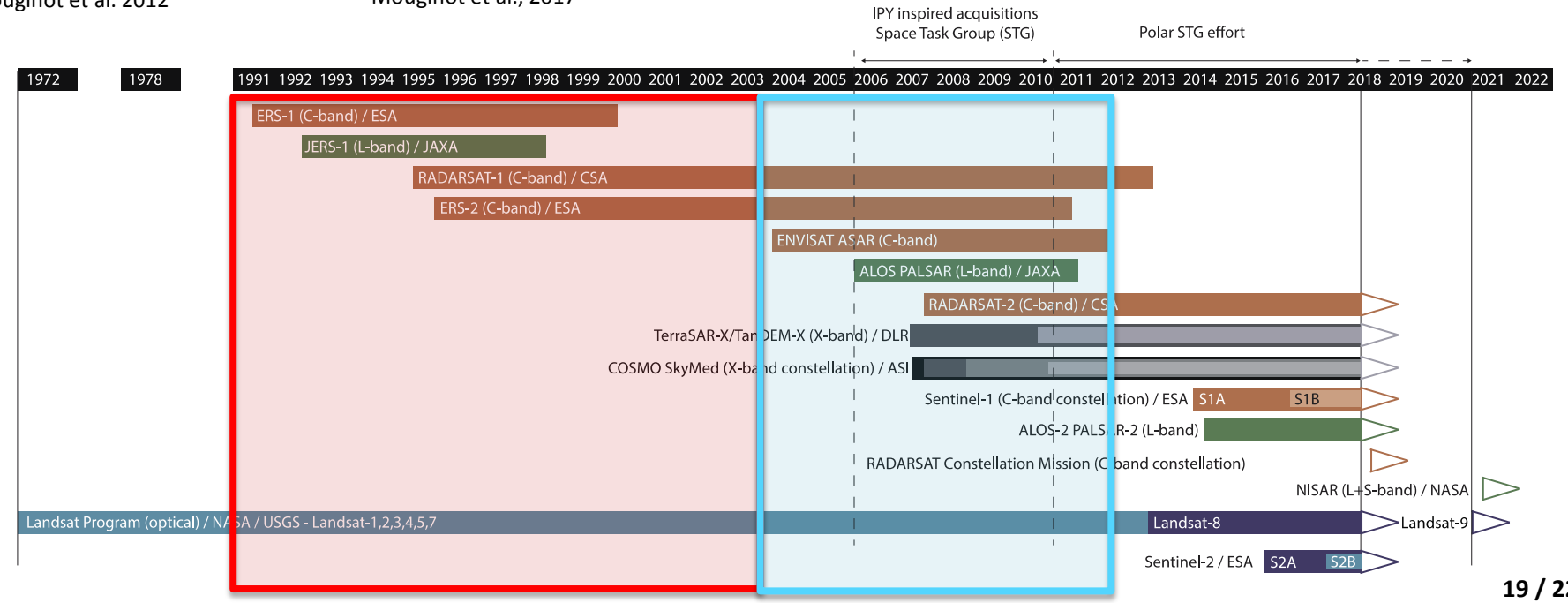


Rignot and Mouginot 2012
Mouginot et al., 2017

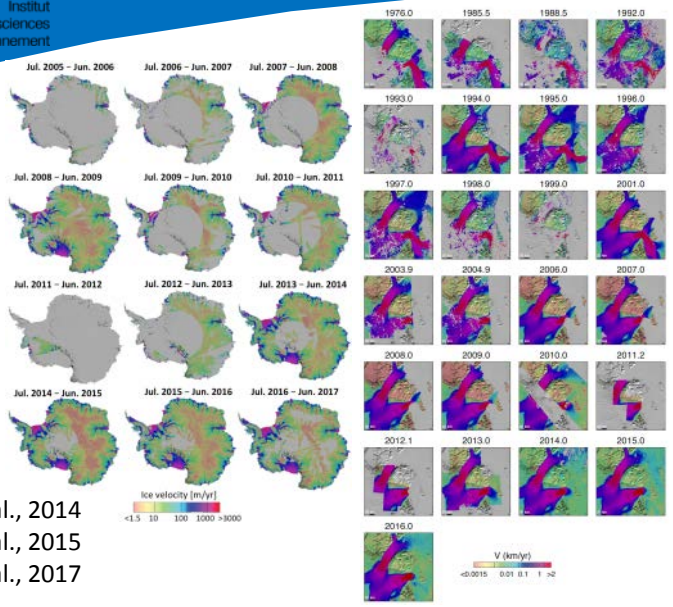
\+ **1st comprehensive maps from multi-sensor campaigns**



\- **No temporal information** (1996-2011)

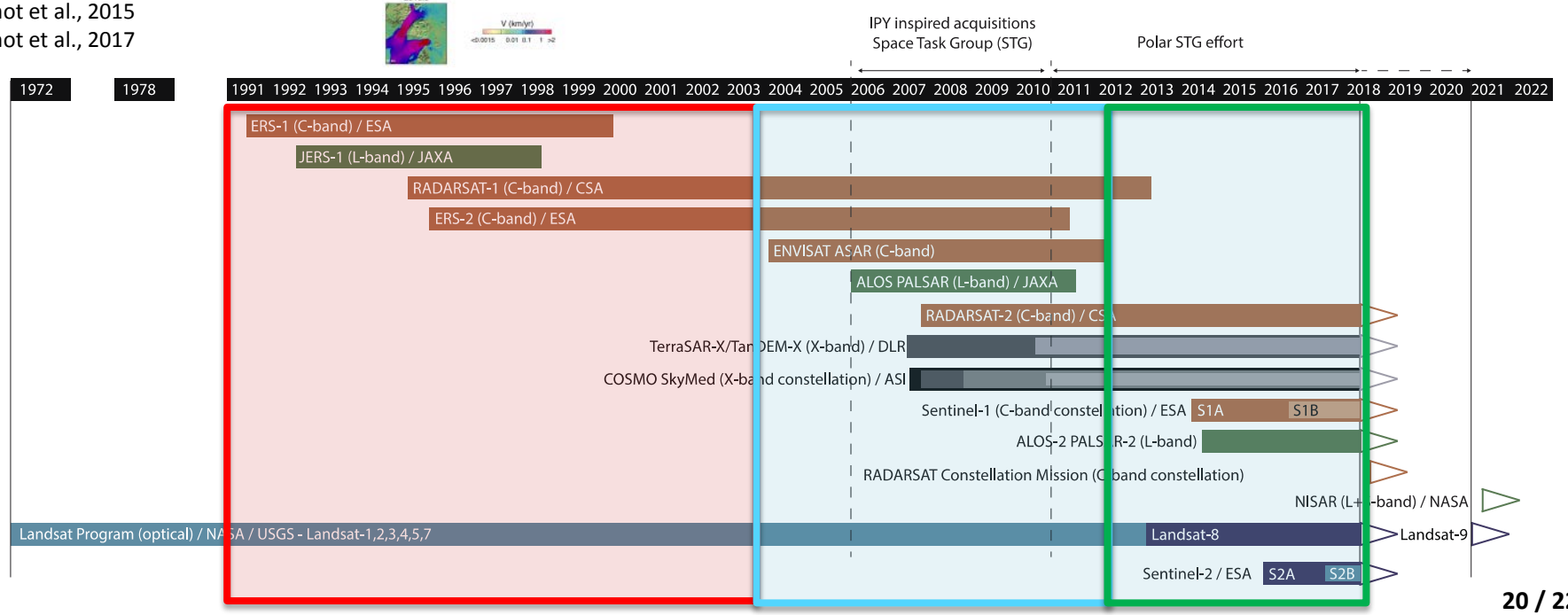


Example 3

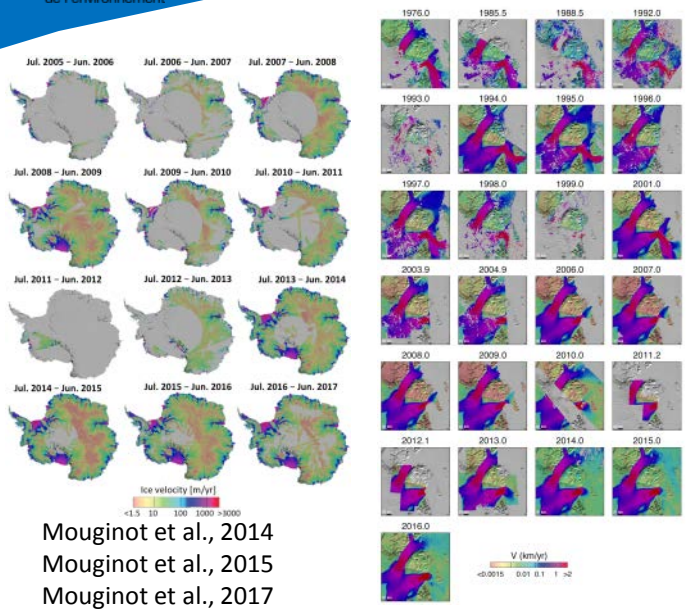


Mouginot et al., 2014
Mouginot et al., 2015
Mouginot et al., 2017

+ **Annual time series**
  + Long term evolution
  + Interaction with other component of the climate system (ocean/atmo.)
- **Published maps are and remain mosaicked, stacked**
  - Detailed temporal information is lost



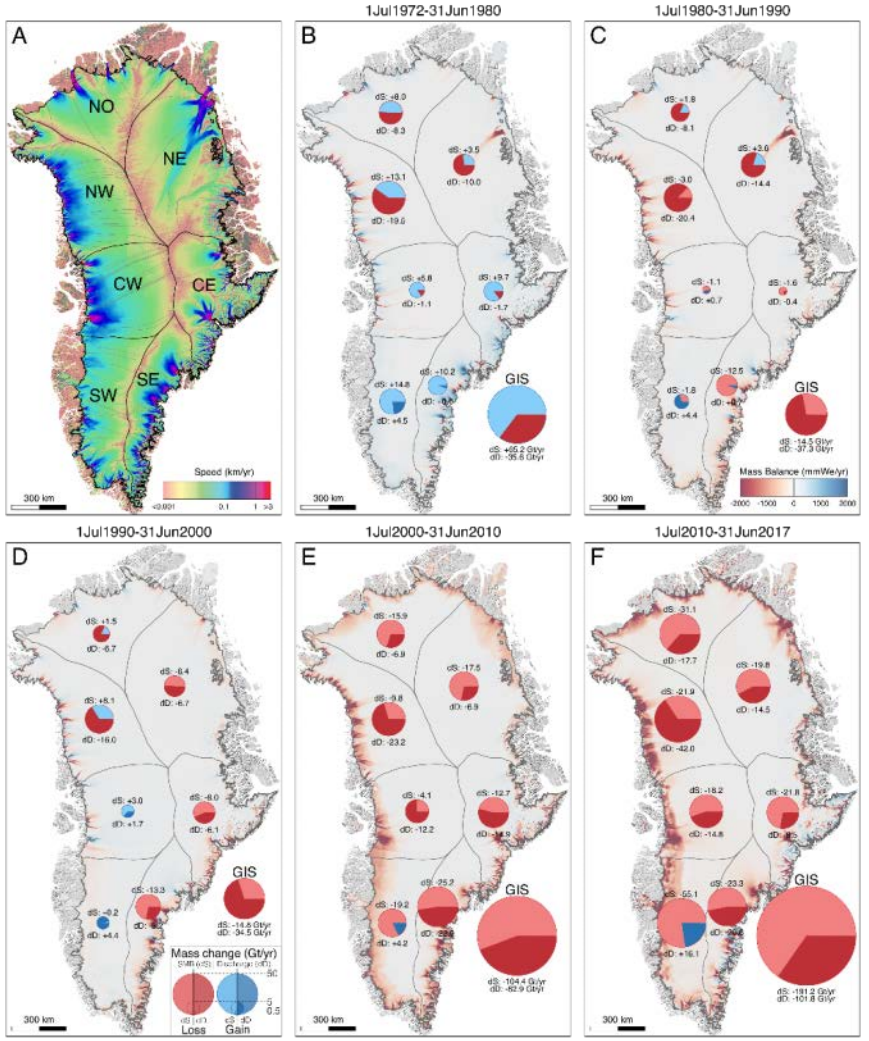
Example 3



Mouginot et al., 2014
Mouginot et al., 2015
Mouginot et al., 2017

From an almost steady state in the 1970s to a complete imbalance since the 2000s

45 years of detailed mass balance of the Greenland Ice Sheet using the component method: 1972 to 2017



Mouginot et al., 2019

Tank you

Questions?

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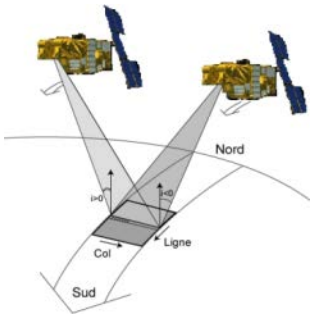
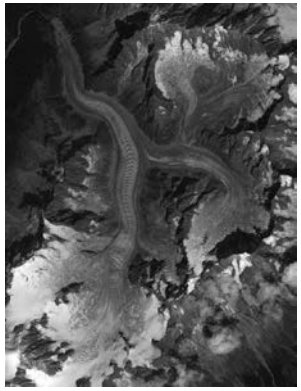
Supplementary material



Images satellites de résolution métrique Ou photo aériennes

2003

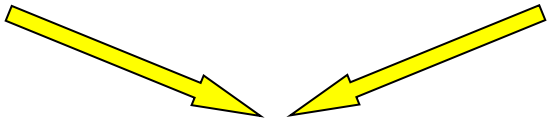
2012



Reconstruction du relief par effet stéréoscopique

MNT #1

MNT #2



MNT #2 - MNT #1
= MNT différentiel
⇨ Variations d'épaisseur = bilan moyen

Quelles évolutions ?

Observation

Mesure des vitesses d'écoulement par télédétection optique

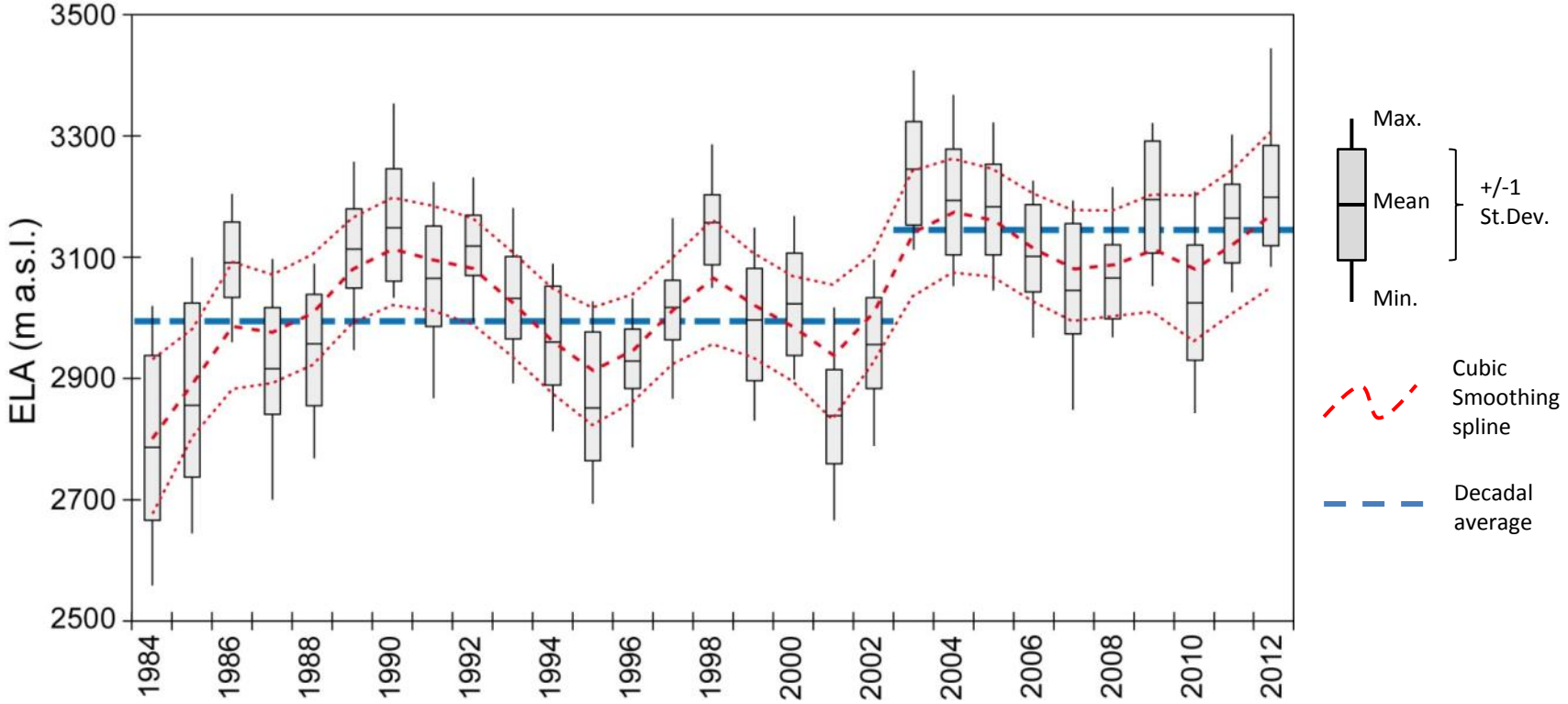
Satellite Venµs
Lancement début 2016

- Images pluri-spectral (12 bandes entre 420 et 910 nm)
- 5,3 m de résolution au nadir
- 1 images tous les deux jours pendant 30 mois

5 sites proposés : Alpes françaises, Himalaya, Nouvelle Zélande, Terre Adélie

Evolution de la ELA pour 30 glaciers des Alpes françaises (1984-2012)

=> Hausse moyenne de 6,4 m/an



Rabatel et al., Cryosphere., 2013b

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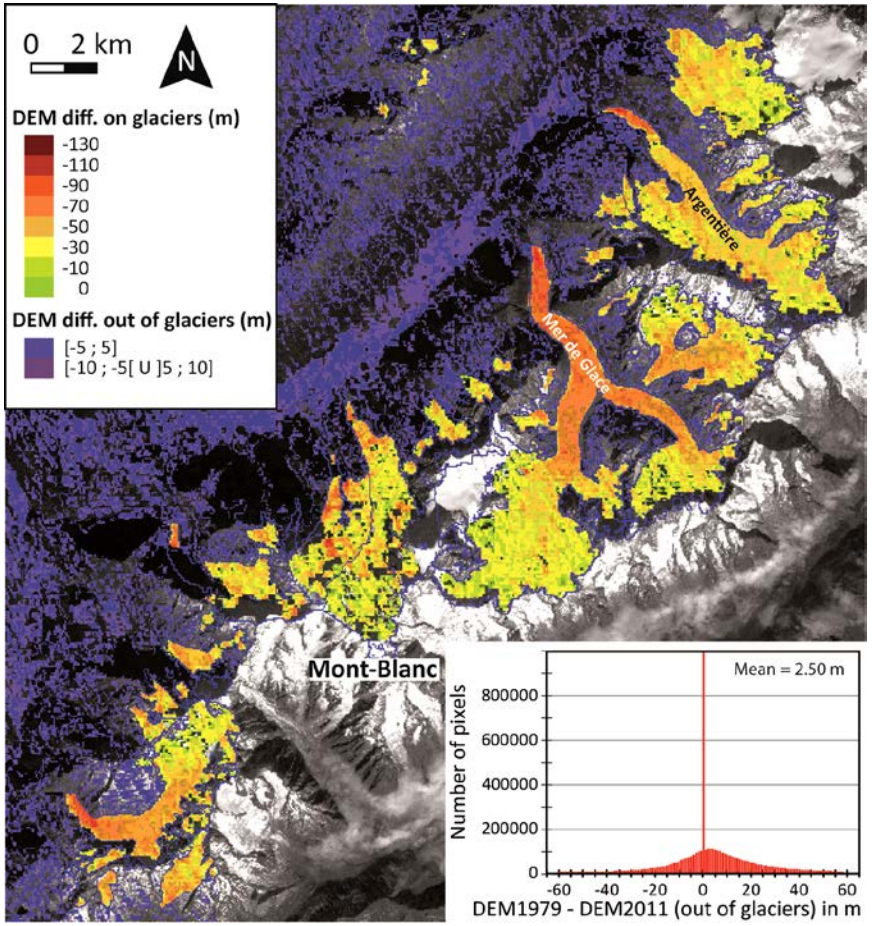
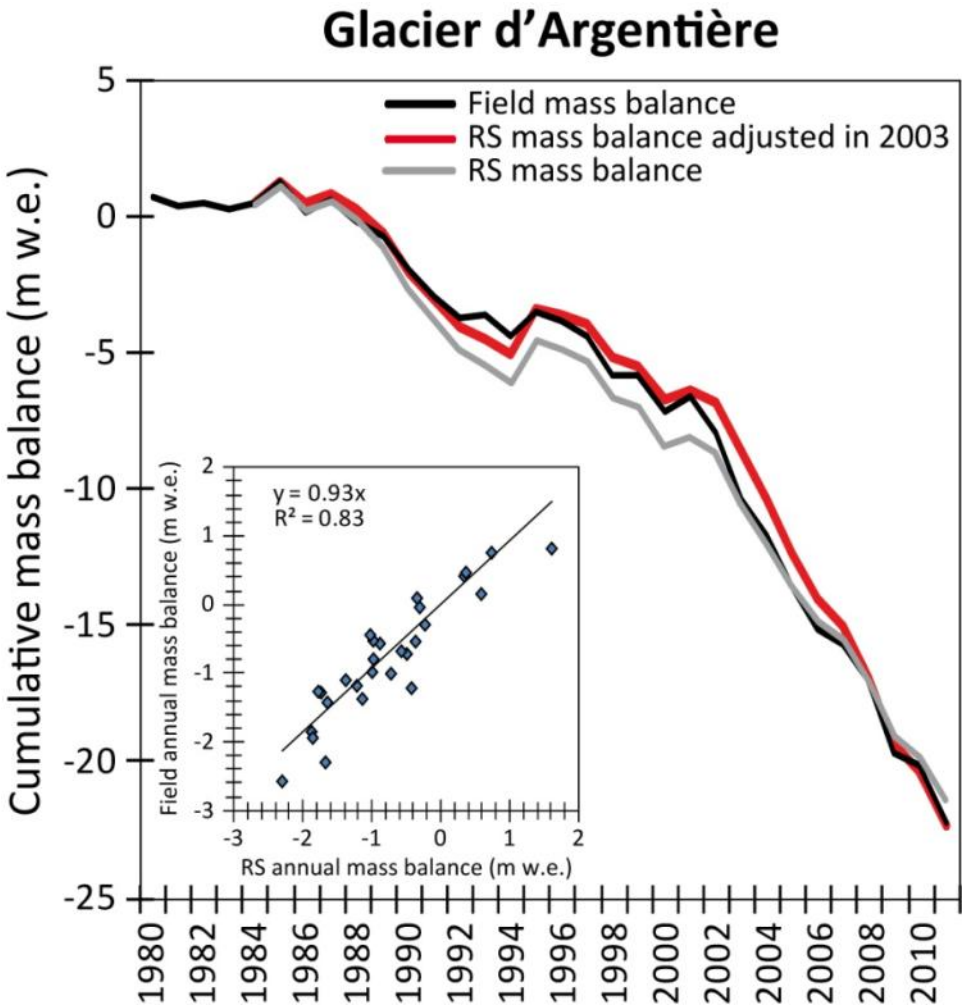
Evolution de l'altitude de la surface des glaciers du massif du Mont-Blanc pour l'ensemble de la période d'étude



Rabatel et al., in prep.

Bilans de masse annuels cumulés pour le Glacier d'Argentière entre 1980 et 2011, issus des mesures de terrain (courbe noire) et de la mesure de l'altitude de la ligne de neige par télédétection (courbes grise et rouge, cf. texte pour l'explication de la différence entre ces deux courbes). Le graphique inséré présente la comparaison des bilans annuels.

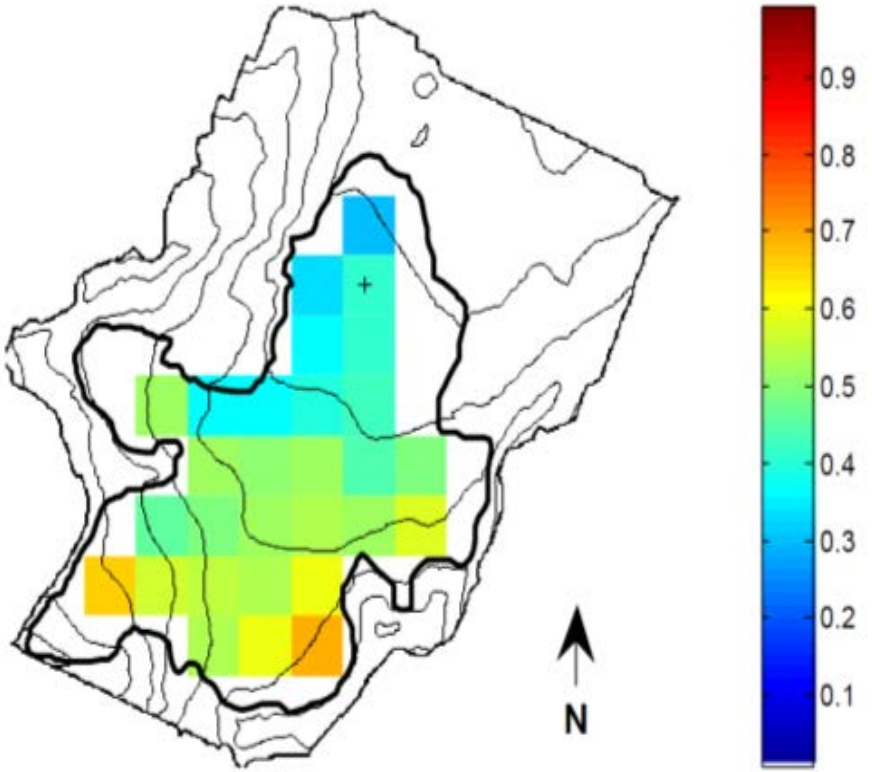
Figure issue de **Rabatel et al., in prep.**



Albedo et bilan de masse

Carte de l'albédo de surface du Glacier de Saint-Sorlin calculée à partir de l'image MODIS du 16 juillet 2007. La croix indique la position de la station météorologique située en zone d'ablation et utilisée pour valider les données.

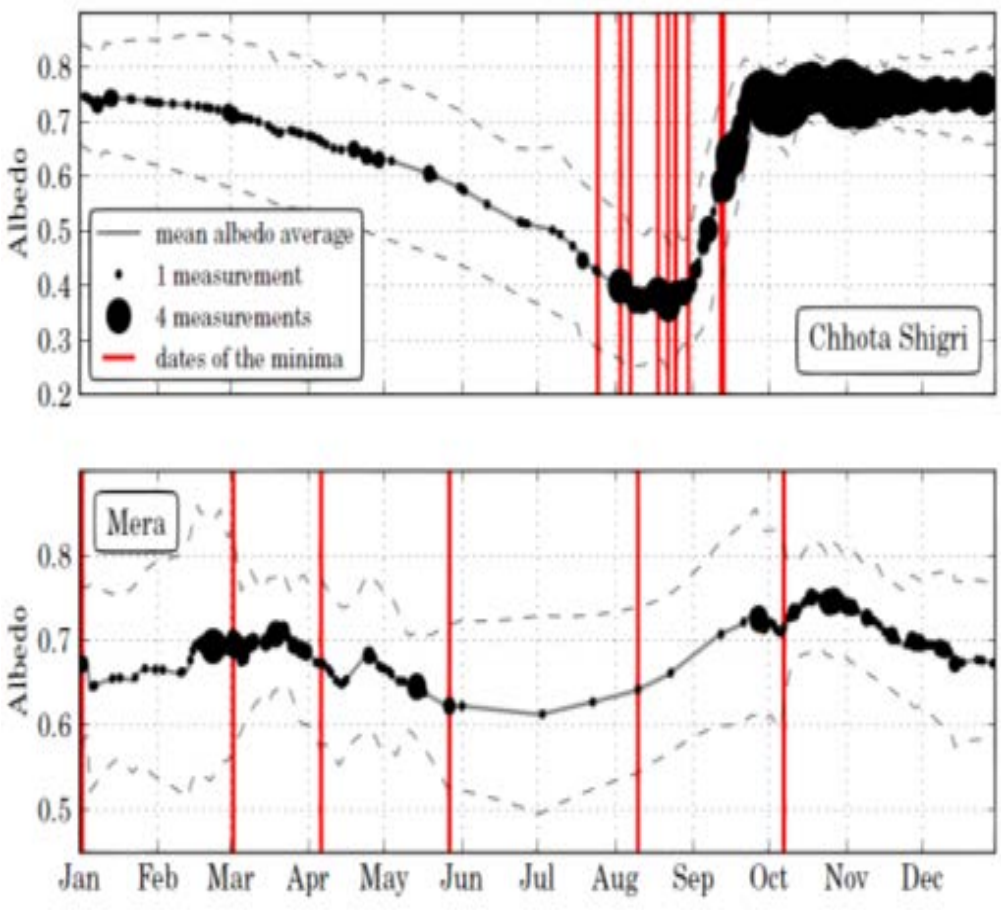
Figure issue de **Dumont et al., 2012.**



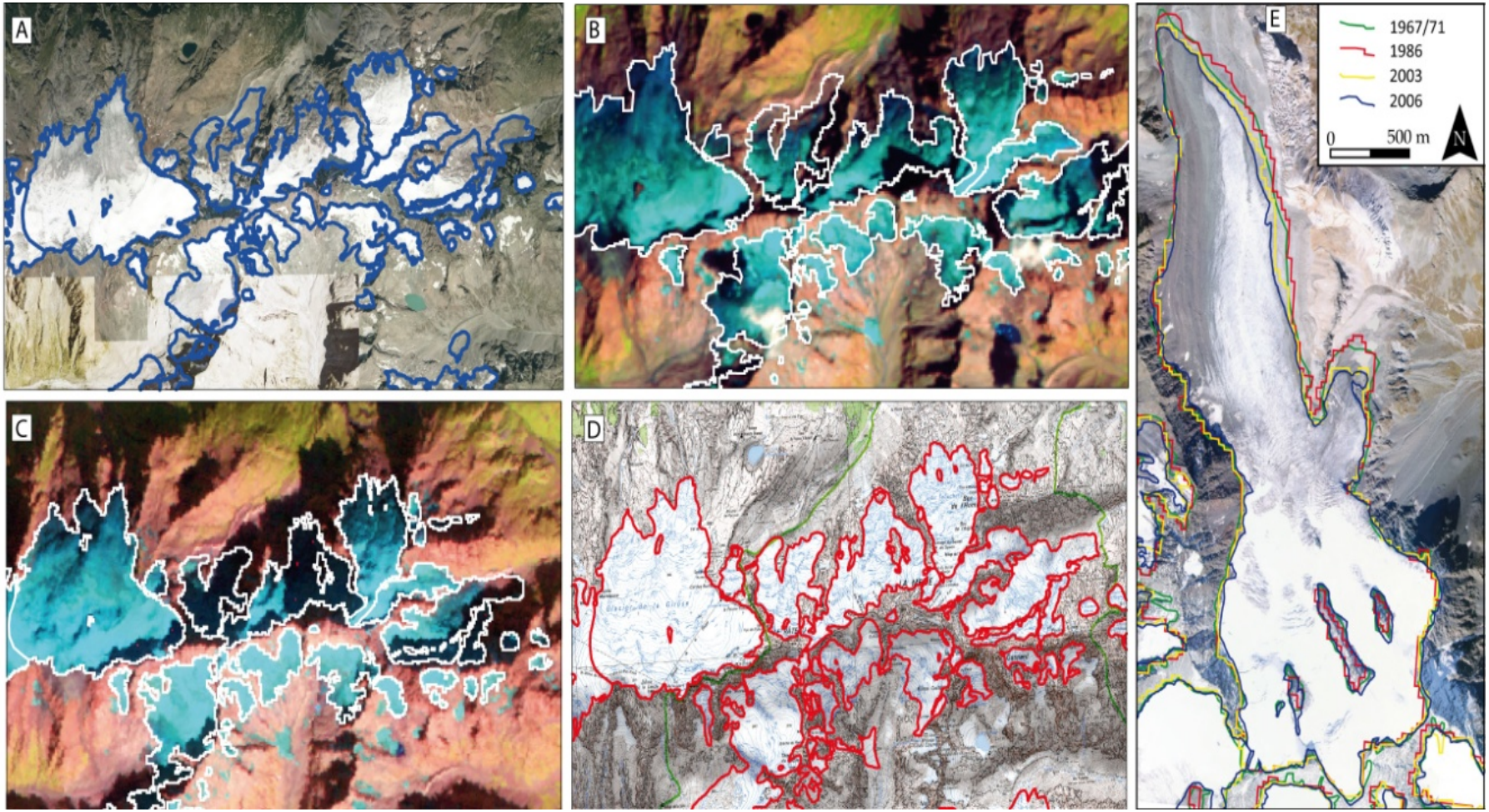
Albedo et bilan de masse

Variations saisonnières de l'albédo moyen pour les glaciers Chhota Shigri (haut) et Mera (bas) sur la période 2000-2013. La courbe grise représente la moyenne interannuelle de l'albédo moyen quotidien interpolée, avec une enveloppe à ±1 écart-type (pointillés gris). La taille des points est proportionnelle au nombre d'images de bonne qualité disponibles. Les barres verticales rouges indiquent les dates du minimum annuel pour chaque année.

Figure issue de **Brun et al., 2015.**



Inventaires glaciologiques



Champs de vitesse en surface

Champs de vitesses moyennes annuelles (année 2013/2014) pour le massif du Mont-Blanc, quantifiés à partir d'images Landsat 8 (bande panchromatique à 15 m) par corrélation croisée.

Figure extraite de **Jauvin [2014].**