Volume changes 2000 – 2011/2012 of glaciers in the Patagonia Icefields from TanDEM-X and SRTM data

Wael Abdel Jaber[1], Dana Floricioiu[1], Helmut Rott[2], Björn Sass[3]

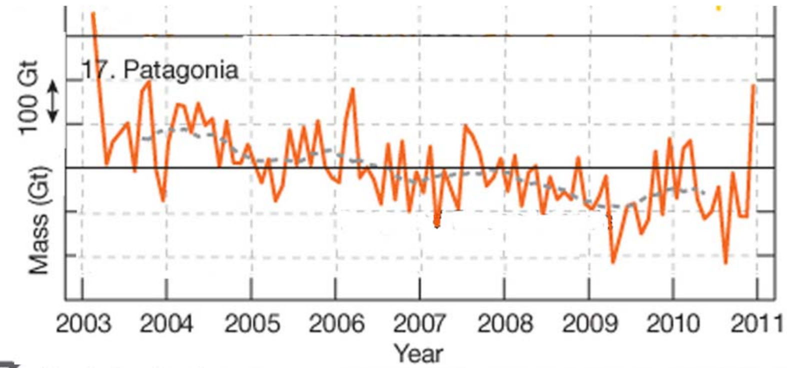
1) German Aerospace Center (DLR), Remote Sensing Technology Institute (IMF), Oberpfaffenhofen, Germany
2) Institute for Meteorology and Geophysics, University of Innsbruck, Austria
3) Friedrich-Alexander-Universität, Erlangen, Germany

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

TanDEM-X Science Team Meeting, Oberpfaffenhofen, Germany, 12 – 14 June 2013

The South Patagonia Icefield (SPI)

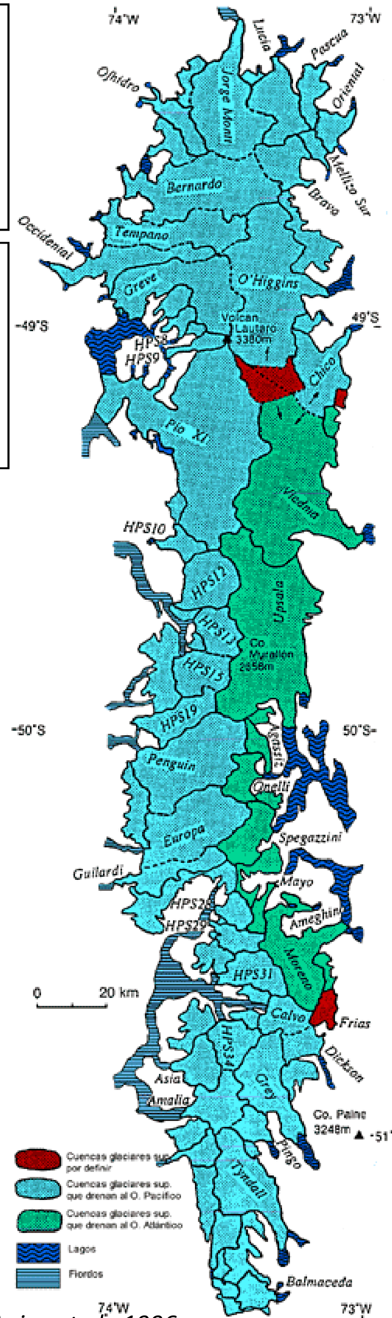
- SPI extension: **350 km** N-S. Mean width: **35 km**.
- First glacier inventory by Aniya et al. (1996):
  - 48 major outlet glaciers (see map)
  - 100+ small cirque and valley glaciers
- Most major glaciers calving into:
  - freshwater lakes
  - Pacific ocean fjords
- Most of major glaciers exhibit strong mass loss trends over the last decades, except Pio XI and Perito Moreno.
- Confirmed by low resolution mass trends obtained by GRACE gravity fields analysis [1].



[1] Jacob T. et al, „Recent contributions of glaciers and ice caps to sea level rise“, Nature, 2012

North Patagonia Icefield (NPI)
Lat: **73°35’ W**
Lon: **46°20’ to 47°40’ S**
Area**: 4,200 km²**

South Patagonia Icefield (SPI)
Lat: **73°30’ W**
Lon: **48°20’ to 51°30’ S**
Area: **13,000 km²**



Aniya et al., 1996

Source: www.glaciologia.cl

SRTM & TanDEM-X data

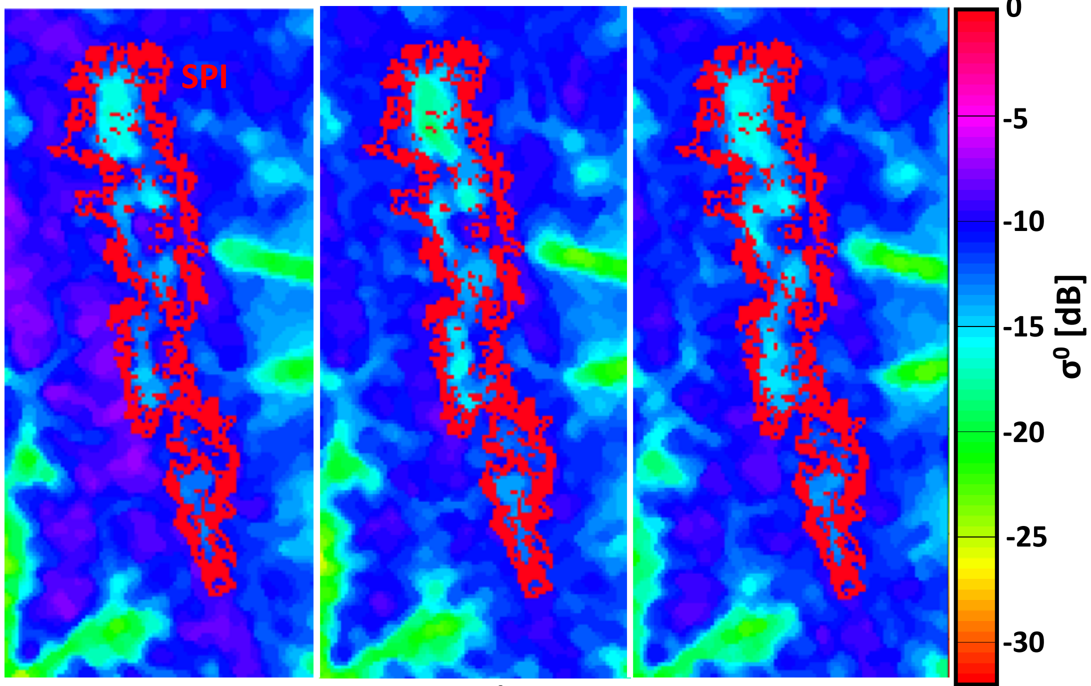
- Well suited **multitemporal elevation dataset** for mass balance estimation:
  - Both DEM from SAR bistatic interferometry
  - Both DEMs acquired in a relatively short time span
  - Temporal baseline: 11-12 years → allows detecting slower changes in elevation
- **SRTM**
  - Acquisition: **11 - 22 February 2000**
  - **C-band DEM:** USGS release 2.0 calibrated with ICESat altitude tie points (DFD) [1]
- **TanDEM-X**
  - **Integrated TanDEM-X Processor (ITP)**: CoSSC data → RawDEMs
  - **19 RawDEMs** (of which **4 with dual baseline phase unwrapping**) *(17 desc., 2 asc.)*
    - **2011**: **8** scenes in austral summer + **2** scenes in winter
    - **Early 2012**: **9** scenes in summer
- Issues:
  - Accurate coregistration of both DEMs
  - Possible biases in DEM difference due to different DEM spatial resolution
  - Radar signal penetration in ice/snow related to:
    - physical parameters of snow and ice (liquid water content, ice compactness, …)
    - system parameters (radar frequency, incidence angle)

[1] Felbier A., "Ausgleichung langwelliger Höhenfehler in SRTM mit Kugelflächenfunktionen auf Basis ausgewählter ICESat-Daten", TUM, 2009

Ice and snow surface conditions

During SRTM

QuikSCAT: Ku-band **backscattering (σ^0)** SIR products*:

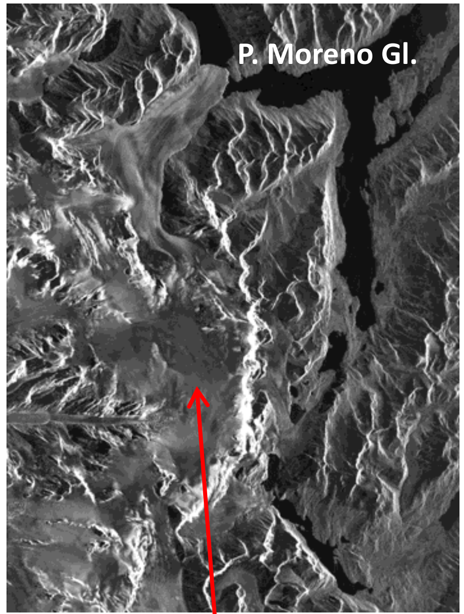


10-13 Feb. 2000 | 14-17 Feb. 2000 | 18-21 Feb. 2000

Feb. 2000 (summer): **$-10 < \sigma^0 < -20$ dB** → wet glacier surface

During TanDEM-X

Active channel of bistatic acquisition: X-band **backscattering (σ^0)**



17 Feb. 2011 (winter scene)

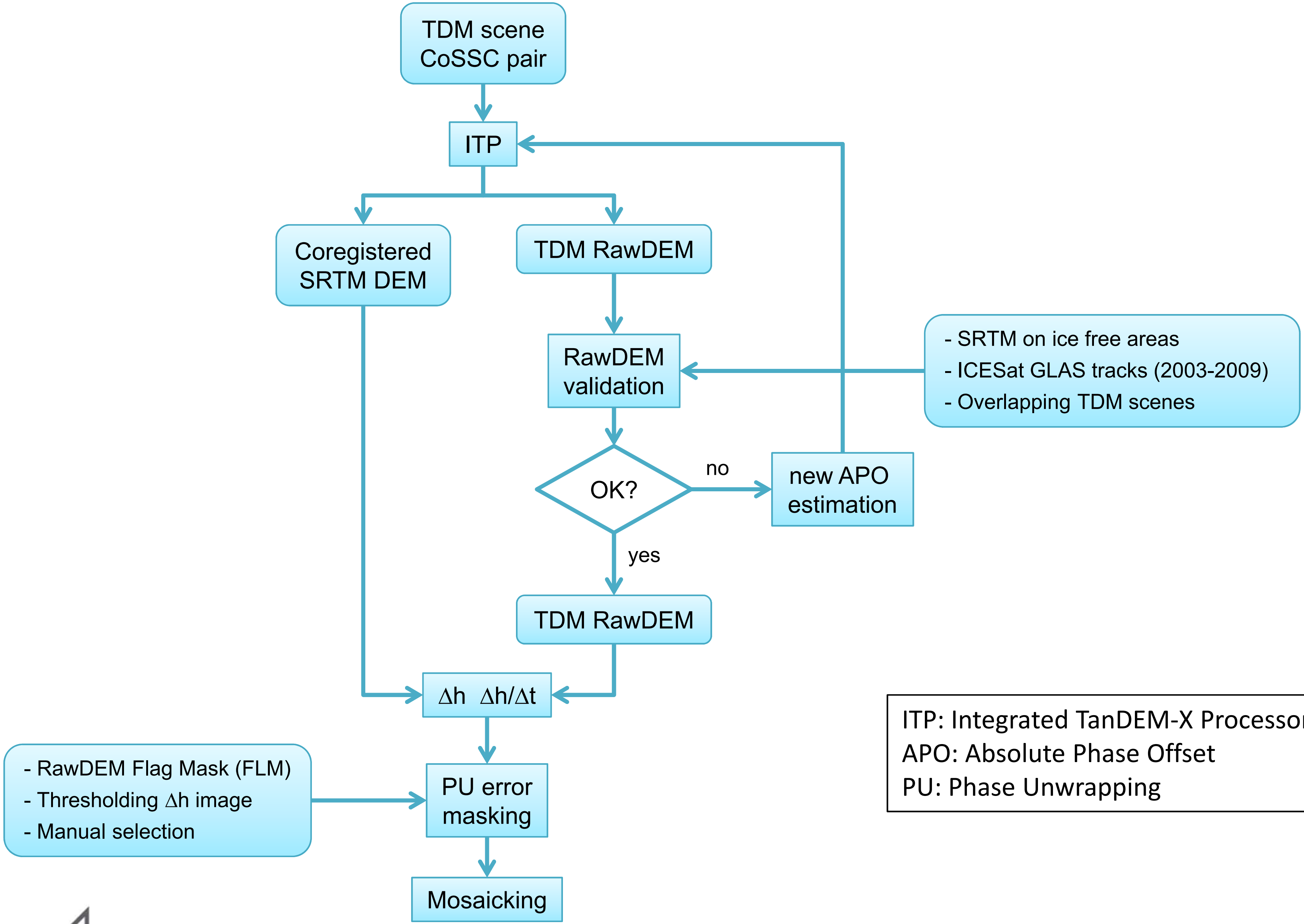
$\sigma^0 < -7$ dB on glacier plateau ($\theta_i = 39°$) → wet glacier surface

TDM acquisitions mostly in summer, only 2 acquisitions in winter

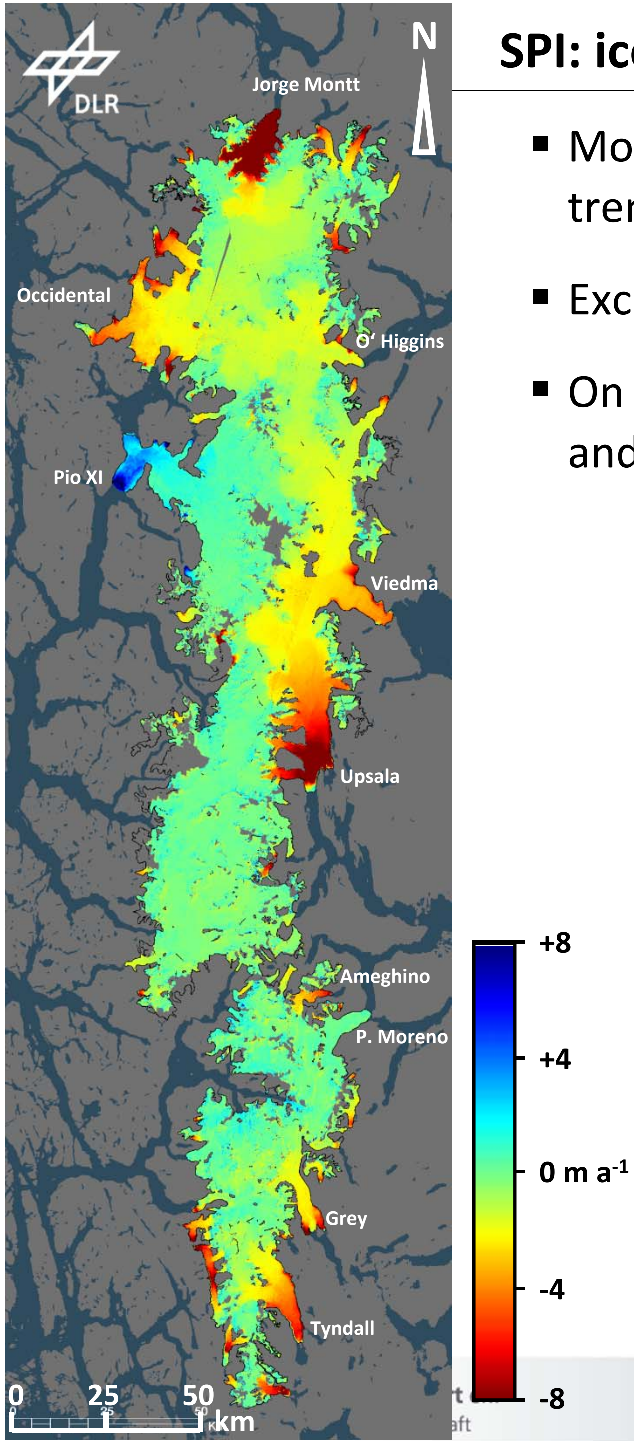
SRTM and TanDEM-X acquired with wet conditions on the firn area → penetration depth is negligible

** Courtesy Matthias Reif, IMGI, Univ. of Innsbruck*

Applied procedure for dh/dt derivation



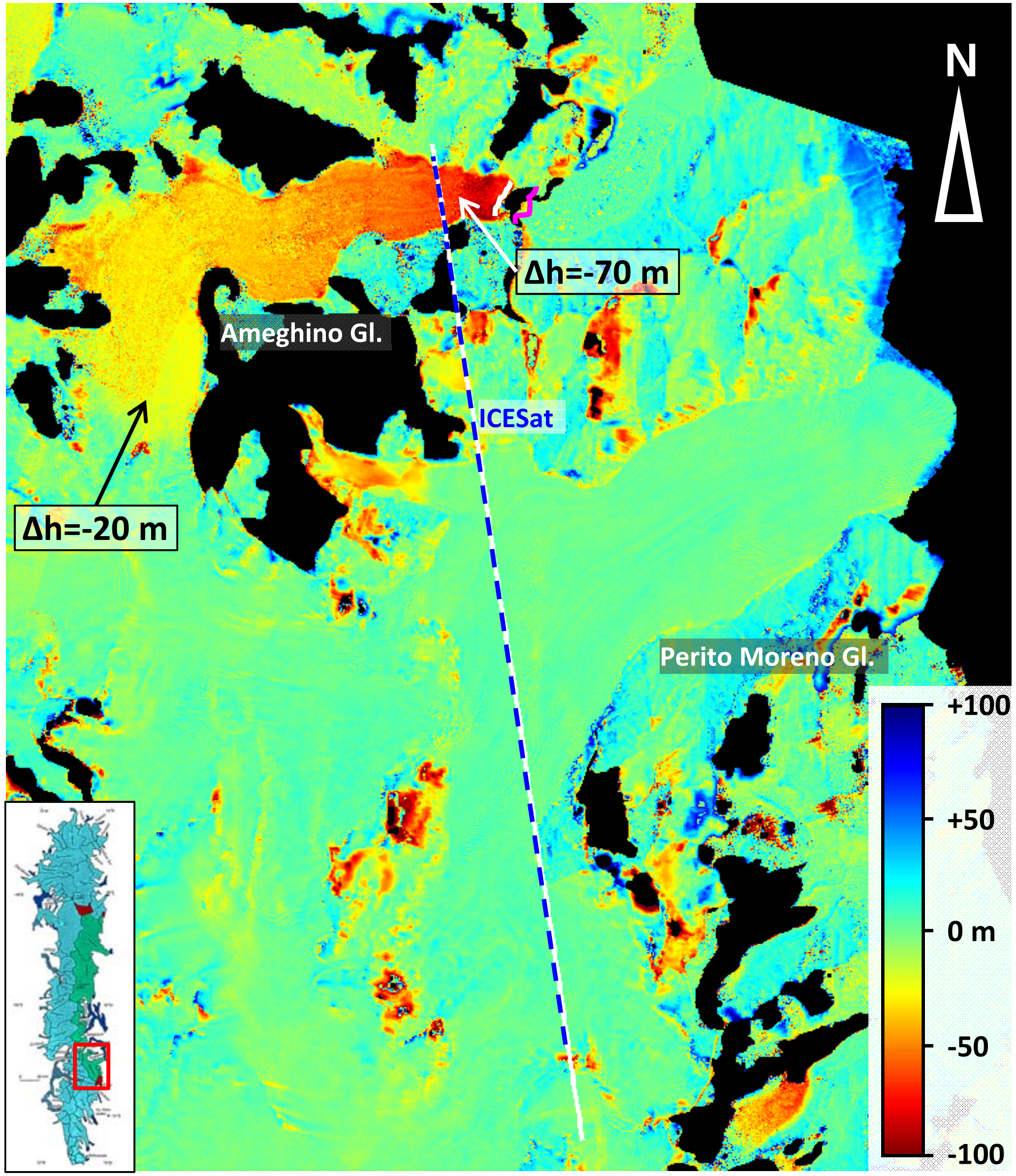
ITP: Integrated TanDEM-X Processor
APO: Absolute Phase Offset
PU: Phase Unwrapping



SPI: ice elevation change rate 2000 – 2011/2012

- Most glacier termini (0 – 1400m) display a significant thinning trend
- Exceptions: Pio XI and Perito Moreno
- On the plateau (1400 – 3600 m): thinning signal in the N-E part and equilibrium on West side and South sector

Perito Moreno and Ameghino: ice elevation change 2000 - 2011

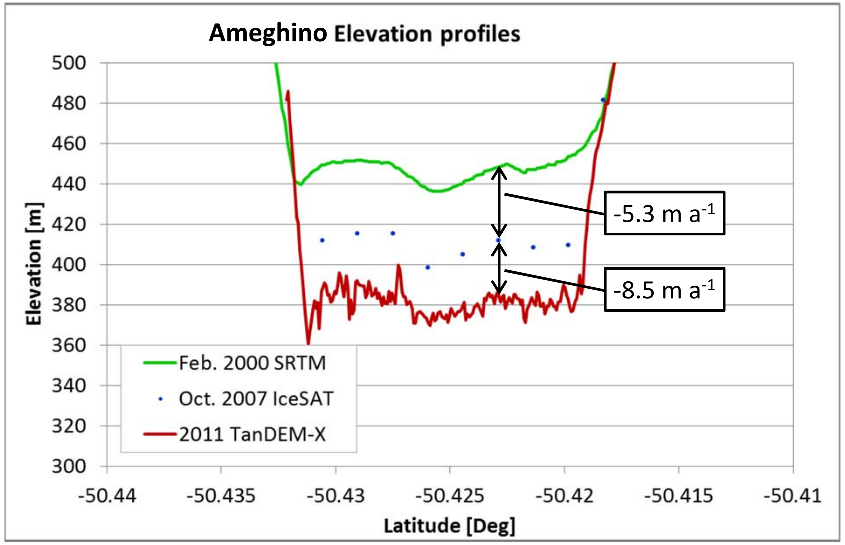


Perito Moreno *(area: 258 km²)*

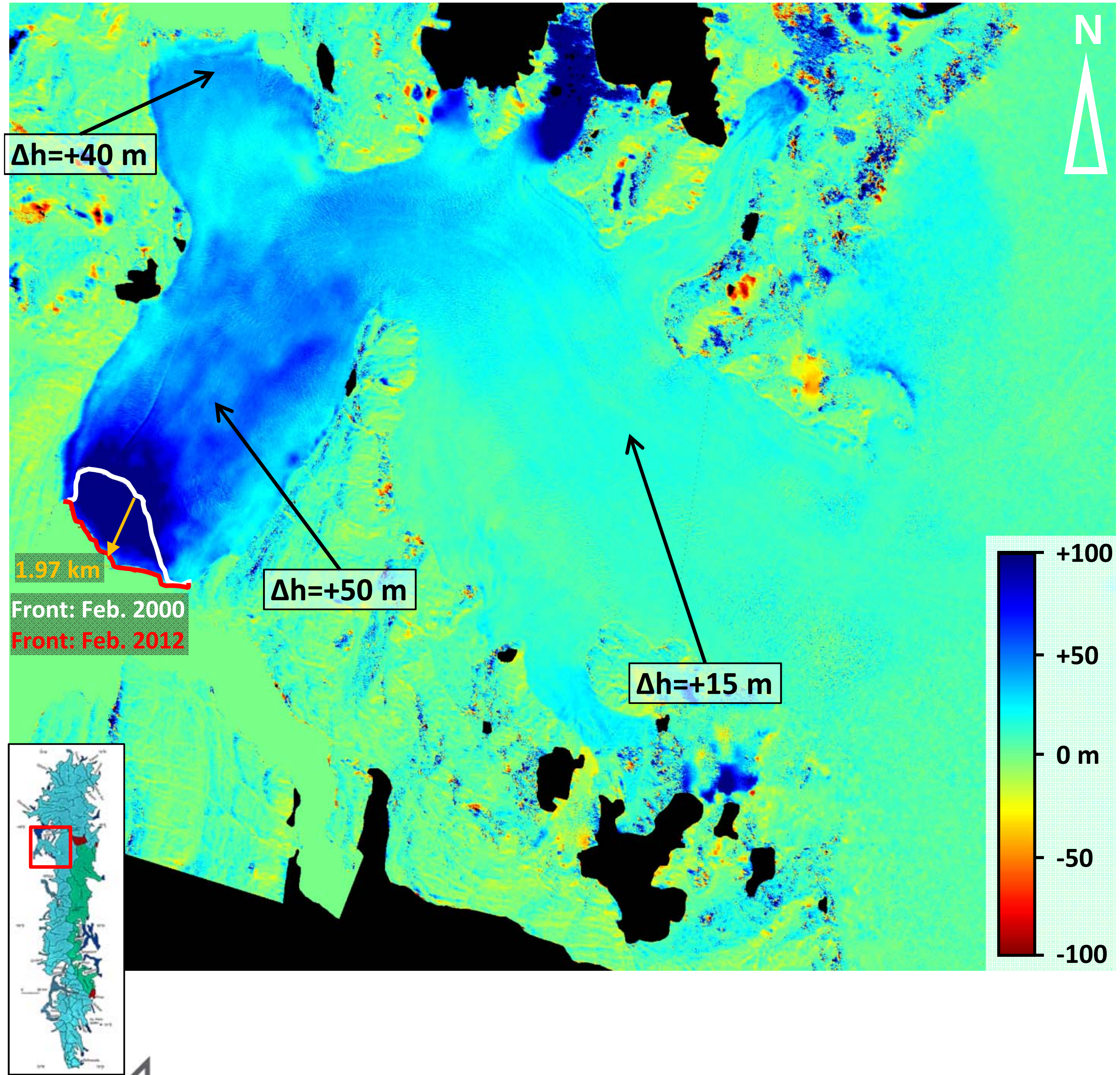
- front stable with periodical damming events
- no significant elevation changes

Ameghino *(area: 76 km²)*

- Front in retreat
  - **-0.8 km** (72.7 m a^{-1}) [2000-'11]
  - *-3.5 km (152 m a^{-1}) ['70-'93] : large proglacial lake*
- Significant surface lowering mostly below equilibrium line
  - **-6.4 m a^{-1}** [2000-'11] near current front
  - *-2.3 m a^{-1} ['49-'93] near '93 snout (Aniya et al., '96)*



Pio XI: ice elevation change 2000 - 2012



- Largest calving glacier of SPI
- Area: **1265 km²**. Length: **64 km**.
- Tidewater glacier

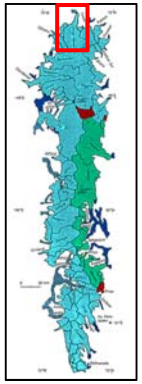
- Front advance: +**1.97 km** [2000 - 2012] (180 m a^{-1})

- Only main glacier with increased surface elevation trend
- **Δh > +50 m (+4.4 ma^{-1})** at 4.5 km from front
- Slight elevation increase on upper part: **Δh = +15 m (+1.25 ma^{-1})**

- *Average ice thickening on ablation area:* ***+2.2 ma^{-1}*** *['75-'95] (Rivera and Casassa, 1999)*

Jorge Montt Glacier: ice surface thinning and front retreat

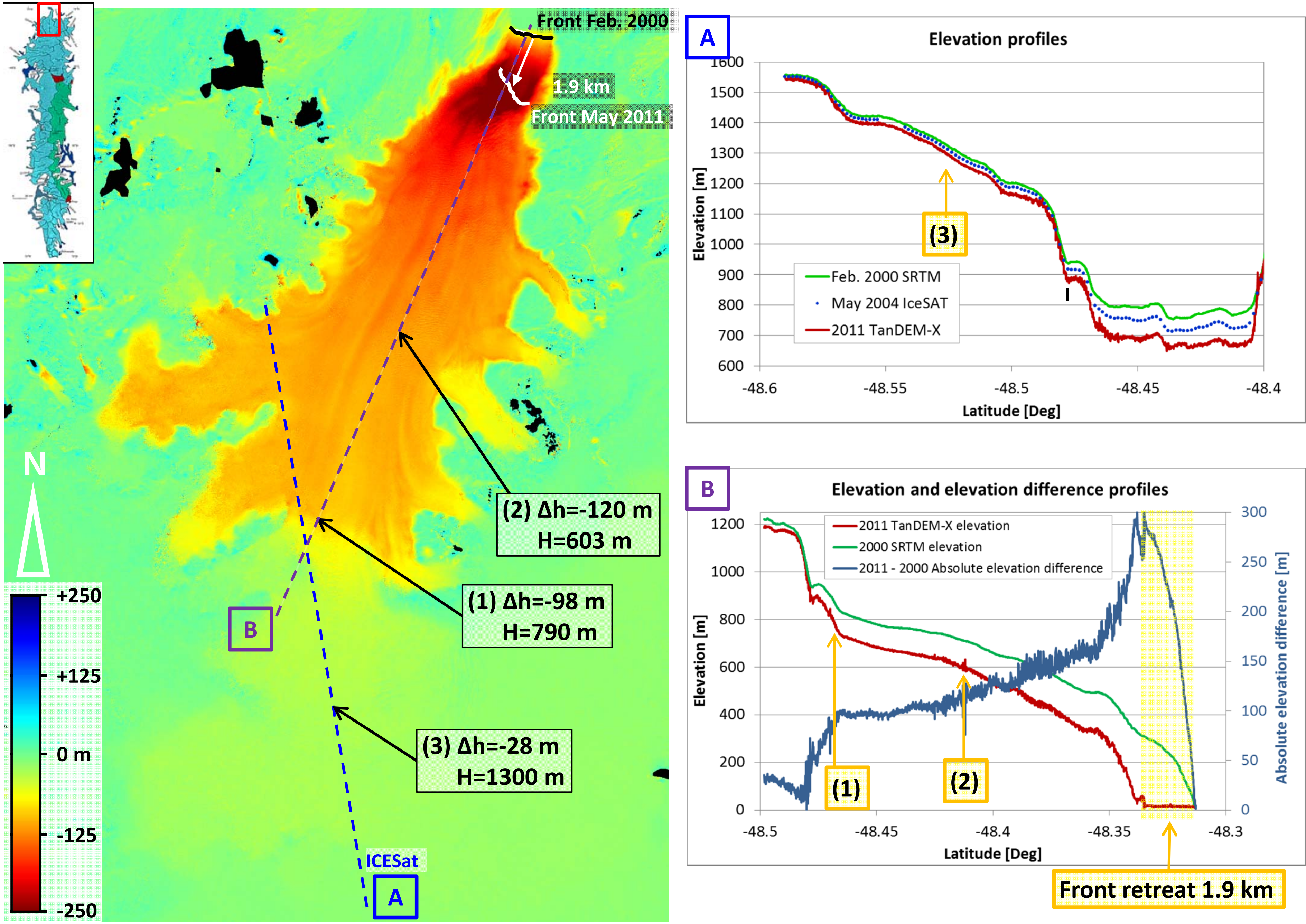
- Area: **500 km²**. Length: **41 km**.
- Ice thinning up to **18 ma^{-1}** concentrated **below 900 m a.s.l.** (near equilibrium line) where the glacier flows in a steep bed and temperatures are higher. Front retreat: **1.9 km** (**173 ma^{-1}**).
- *Thinning rate of **-3.3 ma^{-1}** (average on whole glacier) and **-18 ma^{-1}** at lower elevations [1975 – 2000]. Front retreat: **-8.5 km (340 ma^{-1})** (NASA, CECS)*
- *Front retreat >**800 ma^{-1}** [Feb. 2010 – Jan. 2011] (Rivera et al. [1])*



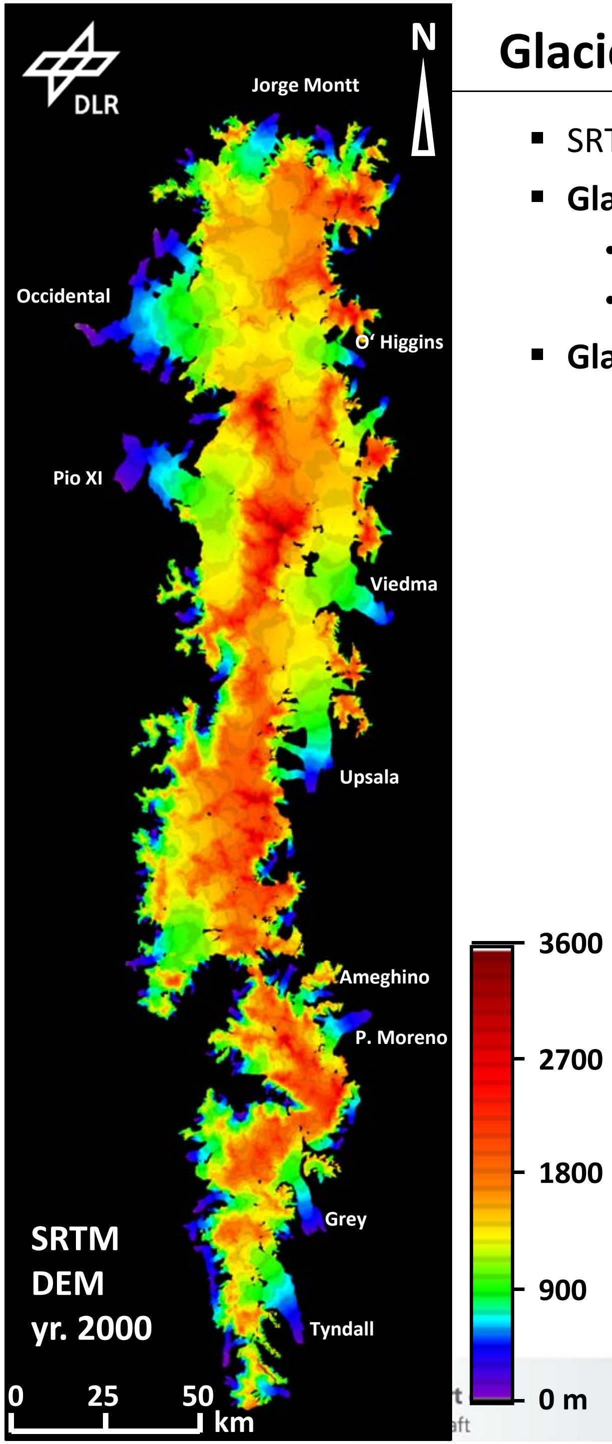
Centro de Estudios Cientificos (CECS), Chile

[1] Rivera, A., Koppes, M., Bravo, C., Aravena, J. C., "Little Ice Age advance and retreat of Glaciar Jorge Montt, Chilean Patagonia", Climate of the Past, 8, pp. 403-414, 2012.

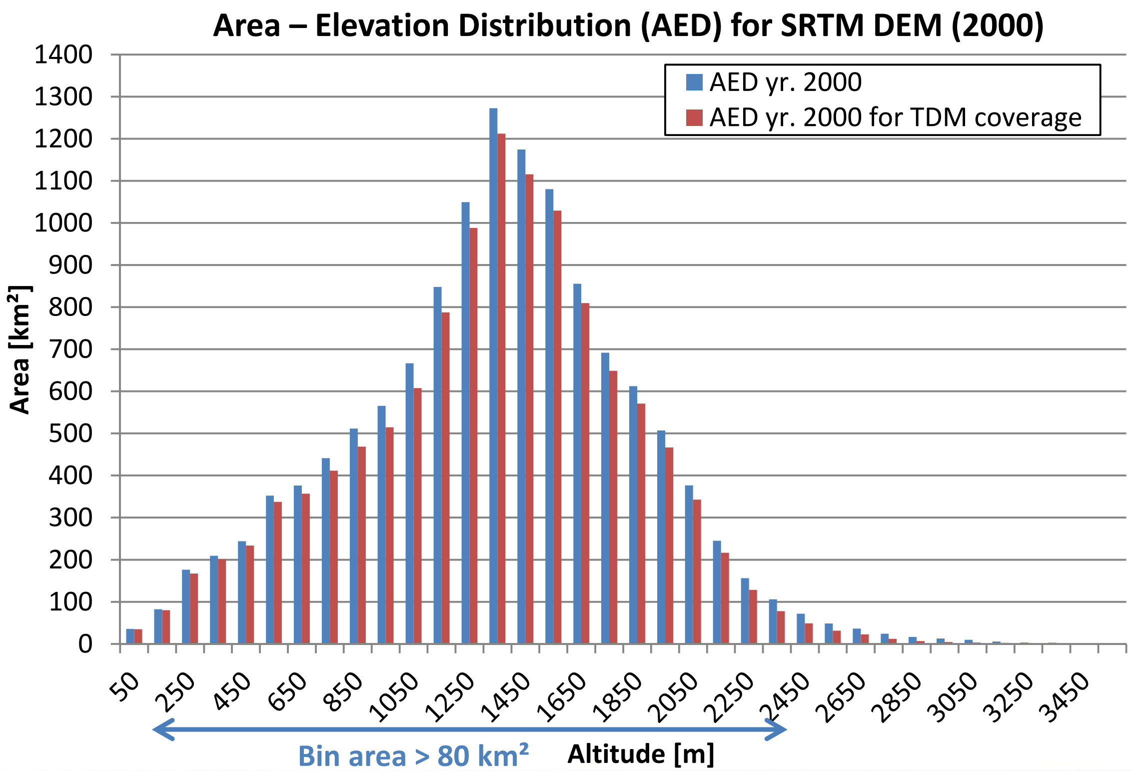
Jorge Montt: ice elevation change 2000 - 2011

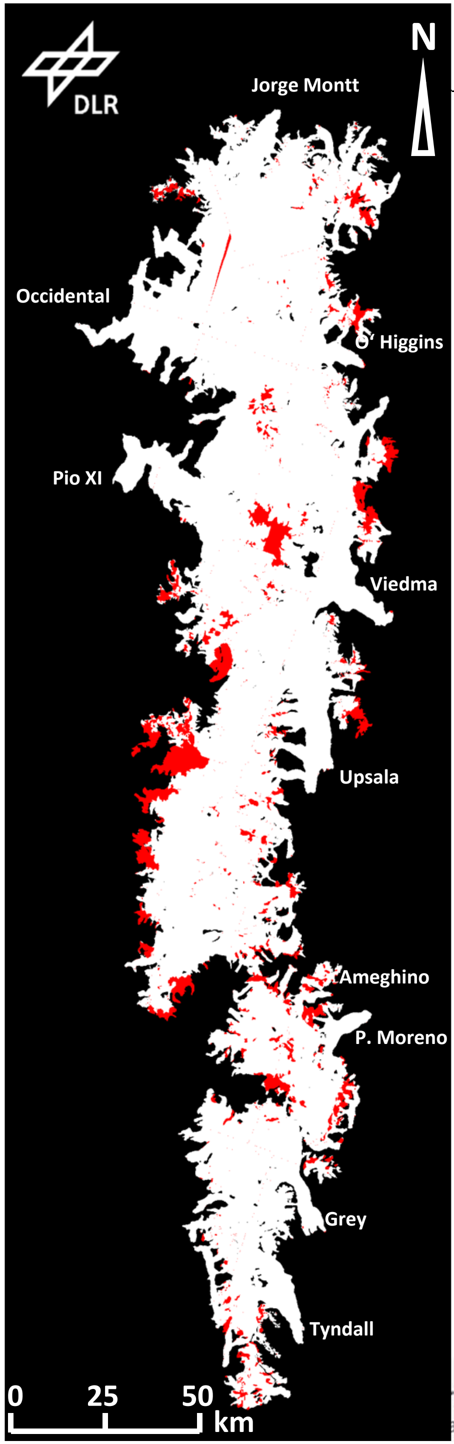


Glacier mask and Area Elevation Distribution



- SRTM DEM (yr. 2000) used as reference
- **Glacier mask:** improvement of Randolph Glacier Inventory (RGI) with:
  - LANDSAT 7 ETM (year: 2001-2003) → **NDSI = (b2-b5)/(b2+b5)**
  - SRTM DEM (glacier fronts)
- **Glacier area (yr. 2000)** → 12870 km^2





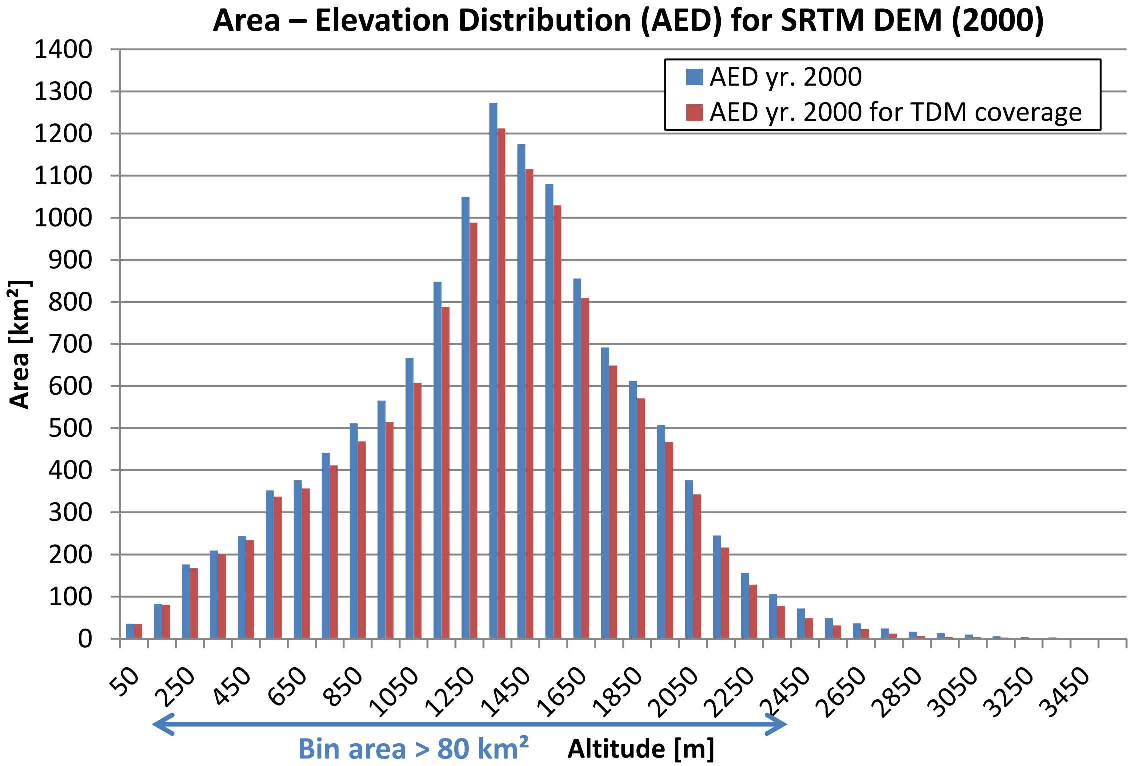
Glacier mask and Area Elevation Distribution

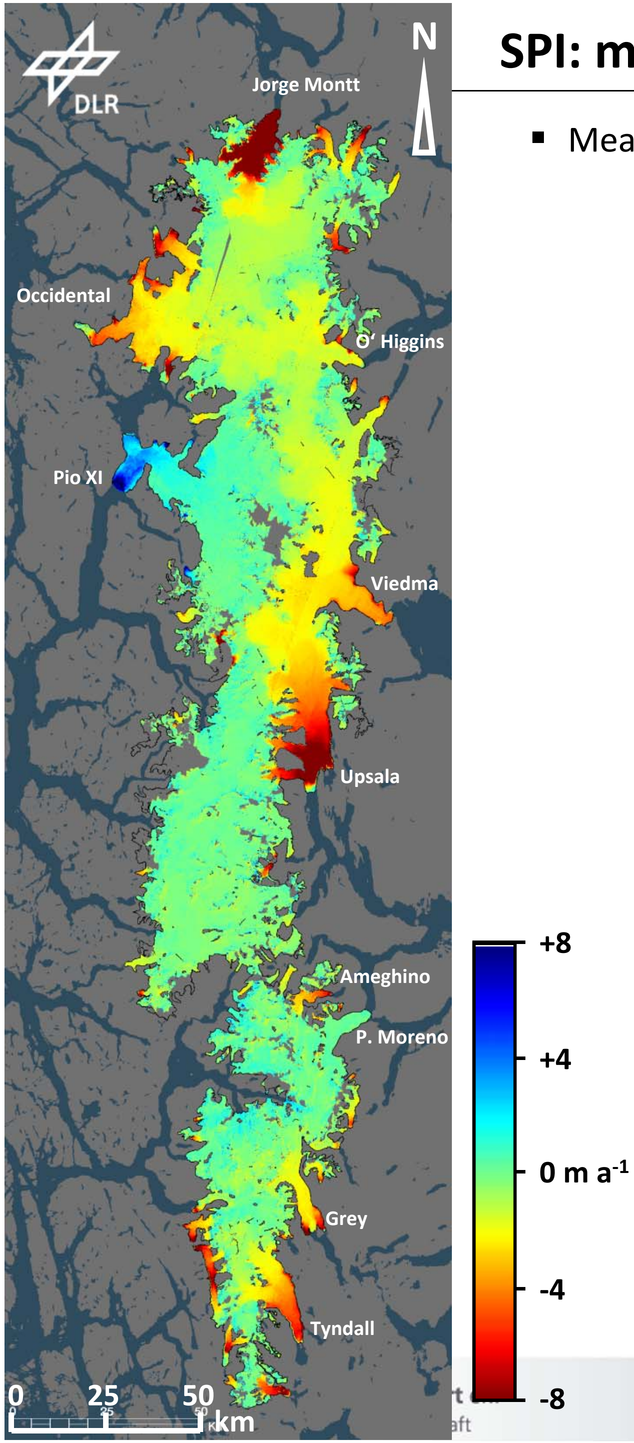
- SRTM DEM **(yr. 2000)** used as reference
- **Glacier mask**: improvement of Randolph Glacier Inventory (RGI) with:
  - LANDSAT 7 ETM (year: 2001-2003) → **NDSI = (b2-b5)/(b2+b5)**
  - SRTM DEM (glacier fronts)

Glacier area (yr. 2000) → 12870 km²

Glacier area covered with TDM data → 11940 km² (**92.8%**)

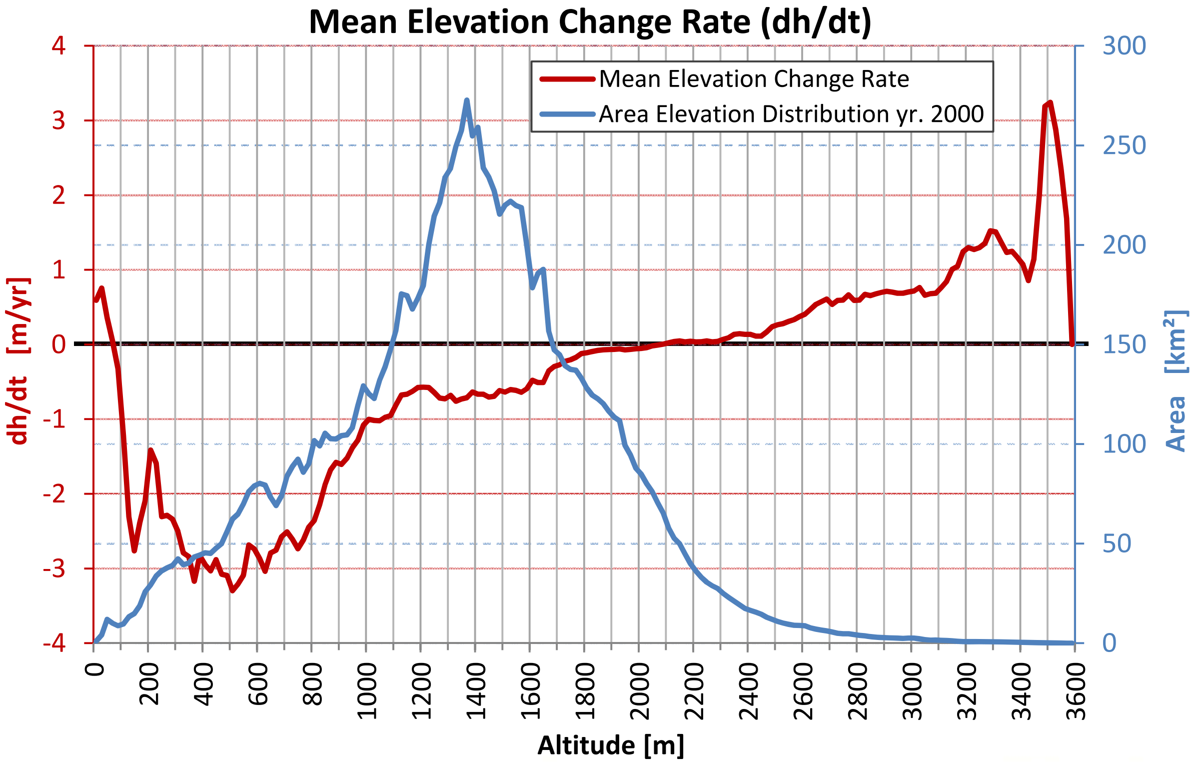
Glacier area with missing TDM data → 930 km² (**7.2%**)

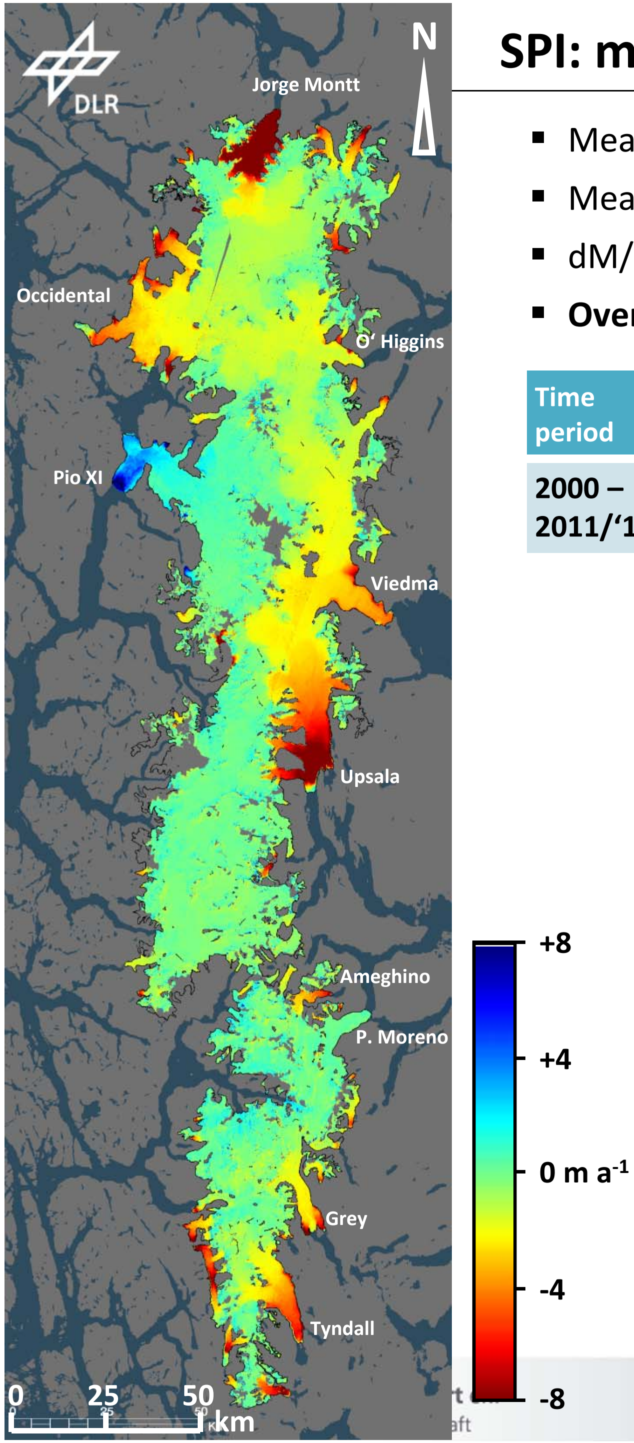




SPI: mass balance

- Mean dh/dt for each altitude bin (20 m) computed on bin area *covered by TDM*

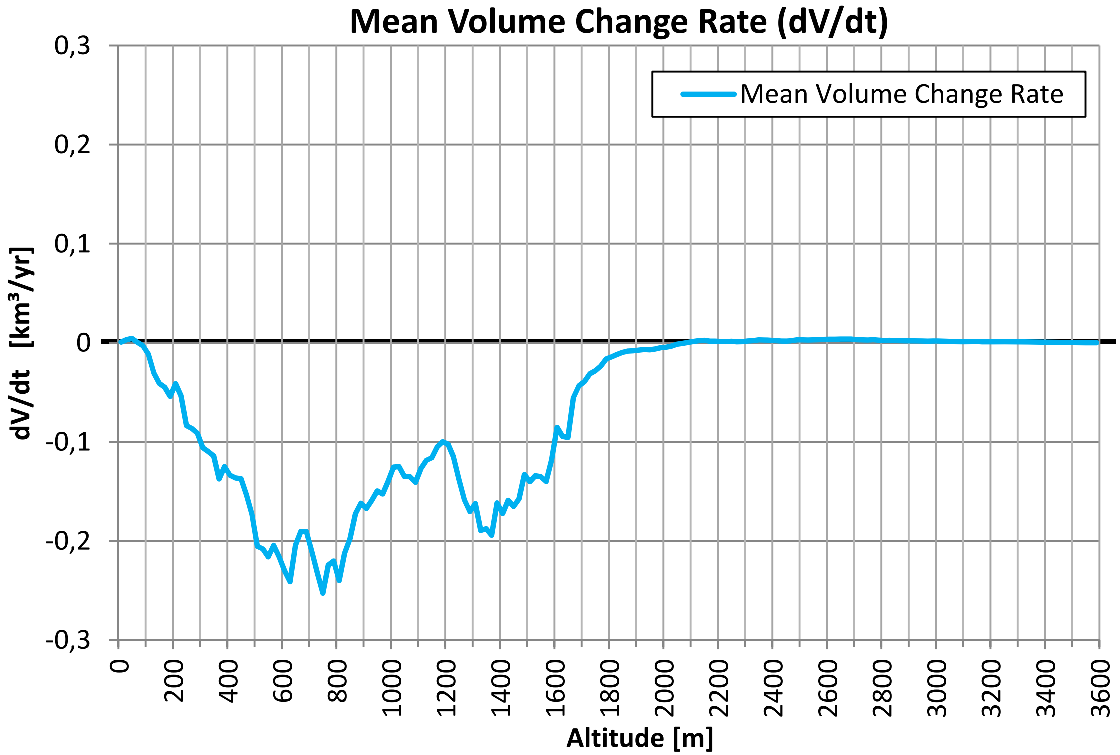


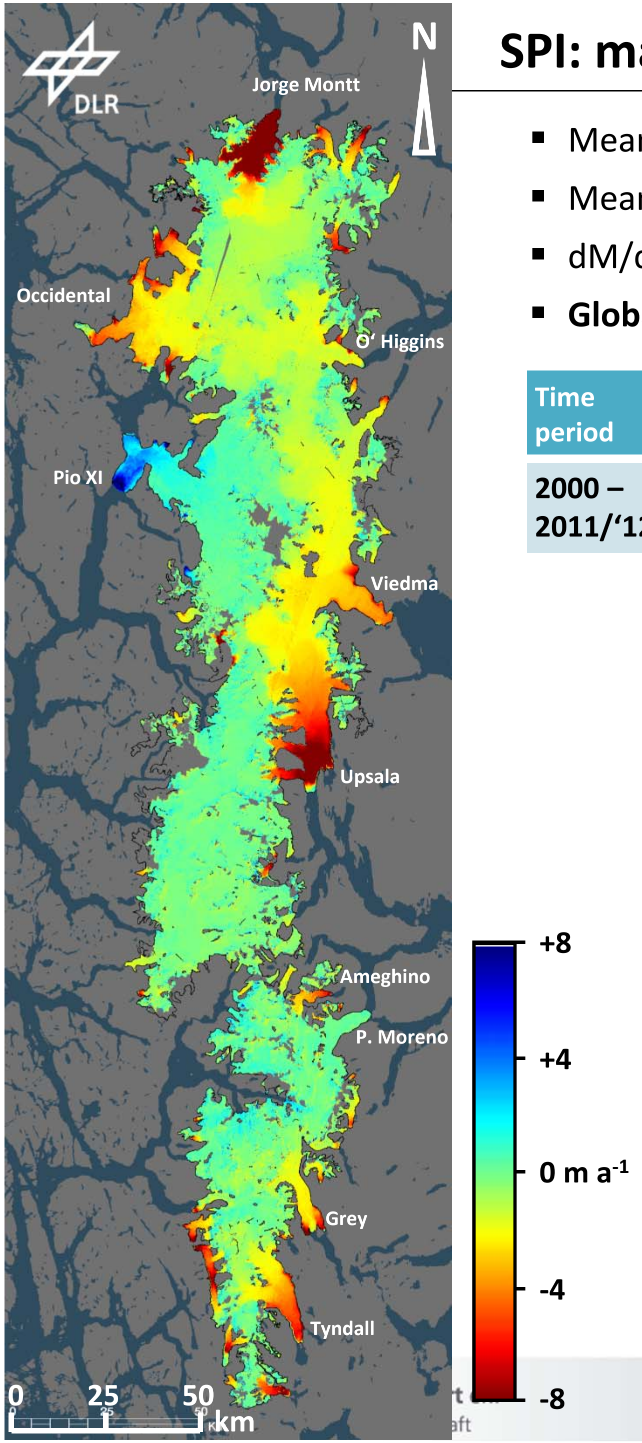


SPI: mass balance

- Mean dh/dt for each altitude bin (20 m) computed on bin area *covered by TDM*
- Mean dV/dt = (dh/dt) * (AED of yr 2000) → scaling data up to entire glacier surface
- dM/dt = (dV/dt) * ρ_{ice}. *Ice density* → ρ_{ice} *= 900 kg/m³*
- **Overall mass balance:**

Time period	SPI total area	Area covered by TDM	Mean dh/dt (area weighted)	Total dV/dt	Total dM/dt
2000 – 2011/'12	**12868.15 km²**	**11941.78 km²**	**-0.902 m/yr**	**-11.605 km³/yr**	**-10.444 Gt/yr**

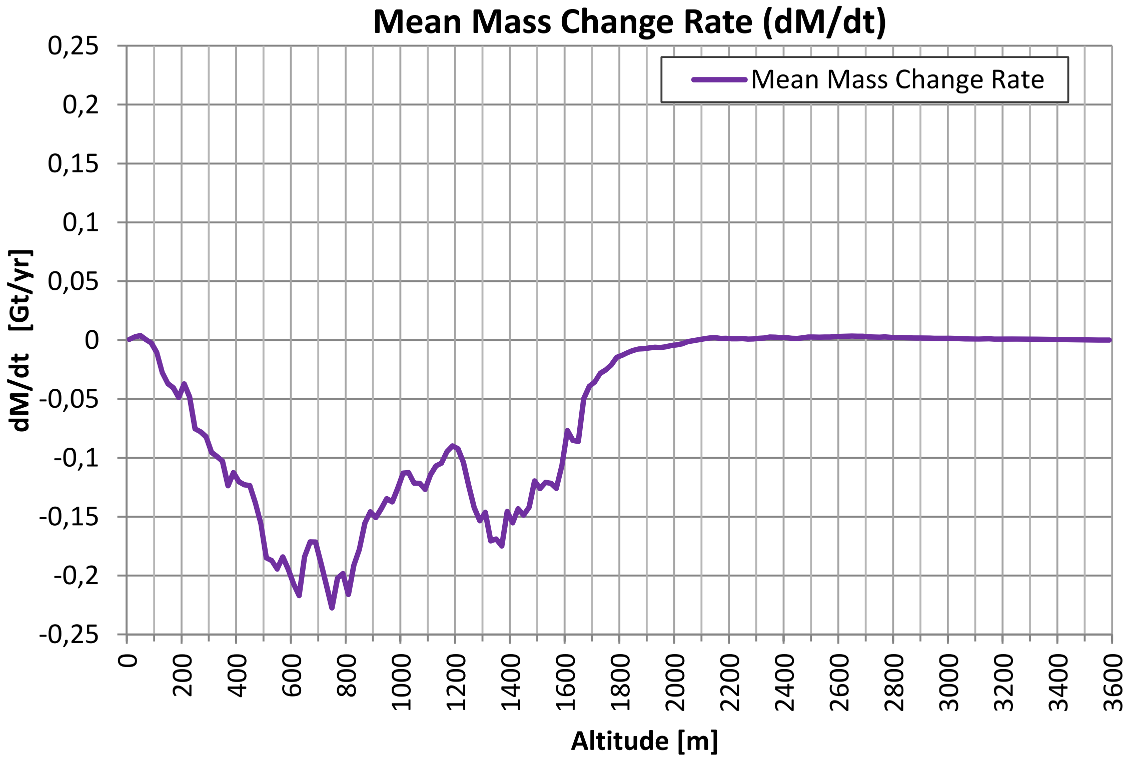




SPI: mass balance

- Mean dh/dt for each altitude bin (20 m) computed on bin area covered by TDM
- Mean dV/dt = (dh/dt) * (AED of yr 2000) → scaling data up to entire glacier surface
- dM/dt = (dV/dt) * ρ_{ice}. *Ice density* → *ρ_{ice}= 900 kg/m³*
- **Global mass balance:**

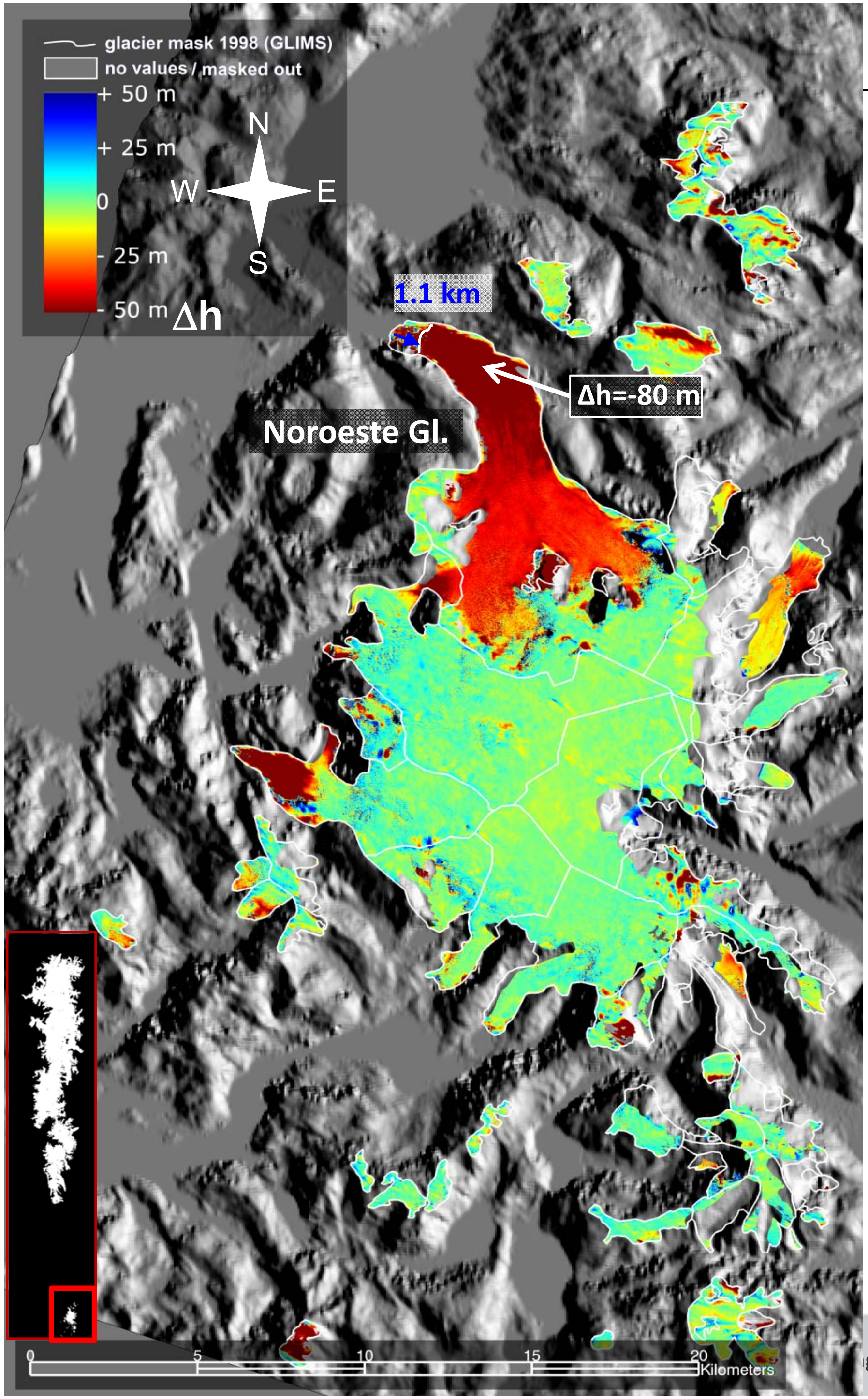
Time period	SPI total area	Area covered by TDM	Mean dh/dt (area weighted)	Total dV/dt	Total dM/dt
2000 – 2011/'12	**12868.15 km²**	**11941.78 km²**	**-0.902 m/yr**	**-11.605 km³/yr**	**-10.444 Gt/yr**

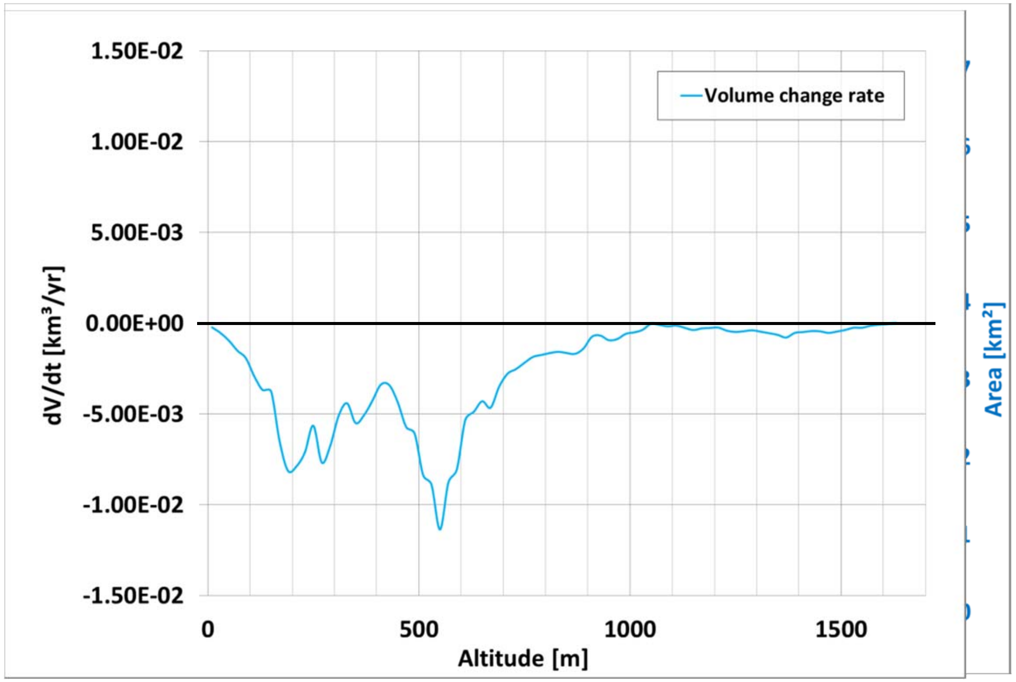


Gran Campo Nevado (53°S): ice elevation change

Analysis by: Björn Sass, FAU Erlangen

- **Area** GCN Icefield + adjacent glaciers [2007]: **252.6 km²**
  (Schneider et al, 2007)
- TanDEM-X: **2 descending** scenes, dual baseline processing
- Temporal baseline: Feb. 2000 – Feb. 2012
- **Front retreat** of Noroeste Glacier: **-1.1 km** (-91.6 ma^{-1})
- **Δh = -80 m (6.7 ma^{-1})** near main calving front of Noroeste Glacier (100 m a.s.l.)



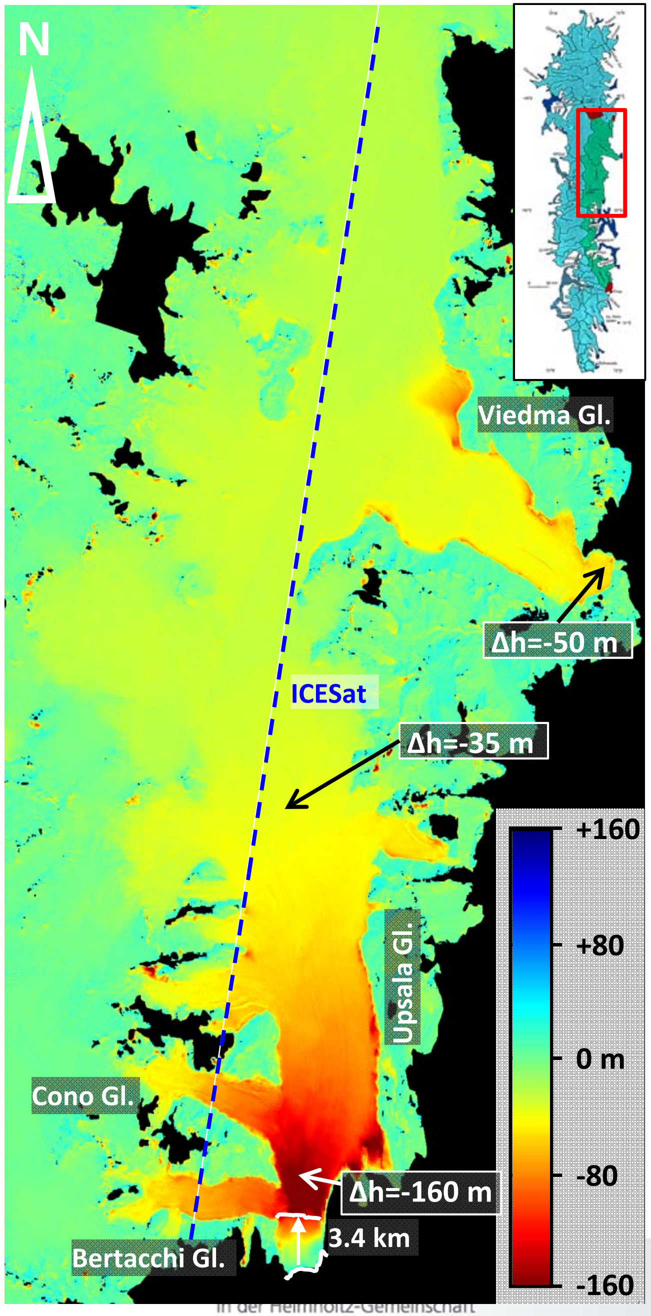


Conclusions

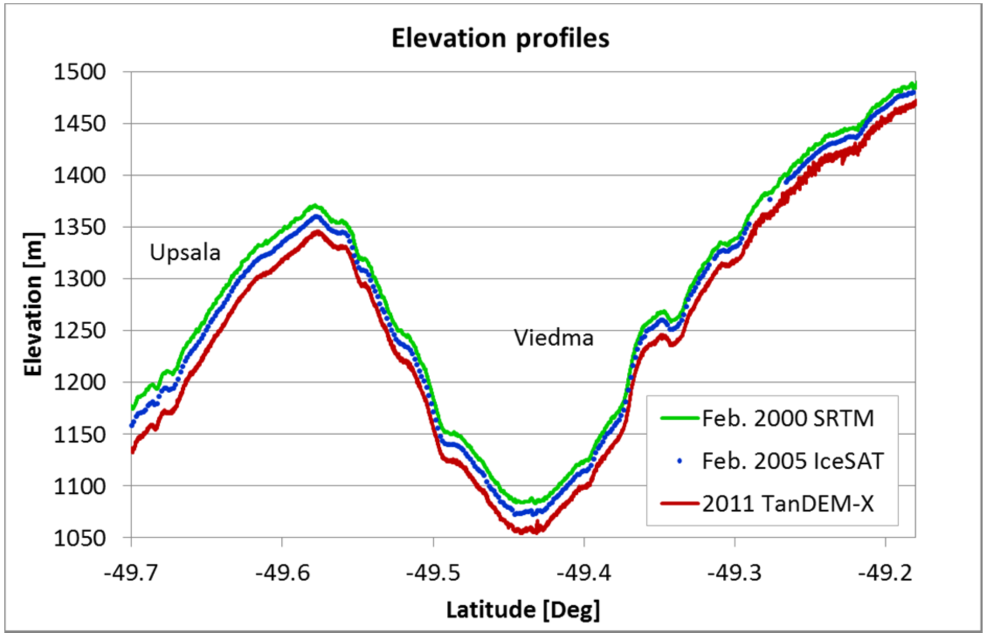
- TanDEM-X and SRTM data were used to derive **temporal trends of ice elevation change** in the SPI and GCN for the period 2000 – 2011/’12.
- An overall mass balance was derived, necessary for estimating the contribution of the Patagonia Icefields to sea level rise.
- Contrasting behavior is observed on different glaciers with respect to changes in ice elevation and front position. This emphasizes the importance of spatially detailed repeated observations in order to understand the complexity of glacier response to climate change.
- The method will be applied to the remaining Patagonian icefields (NPI, Cordillera Darwin).
- Near future work:
  - Error budget estimation for the DEM difference
  - Estimation of ice mass loss due to frontal retreat, including subsurface ice loss

Thank you for your attention!

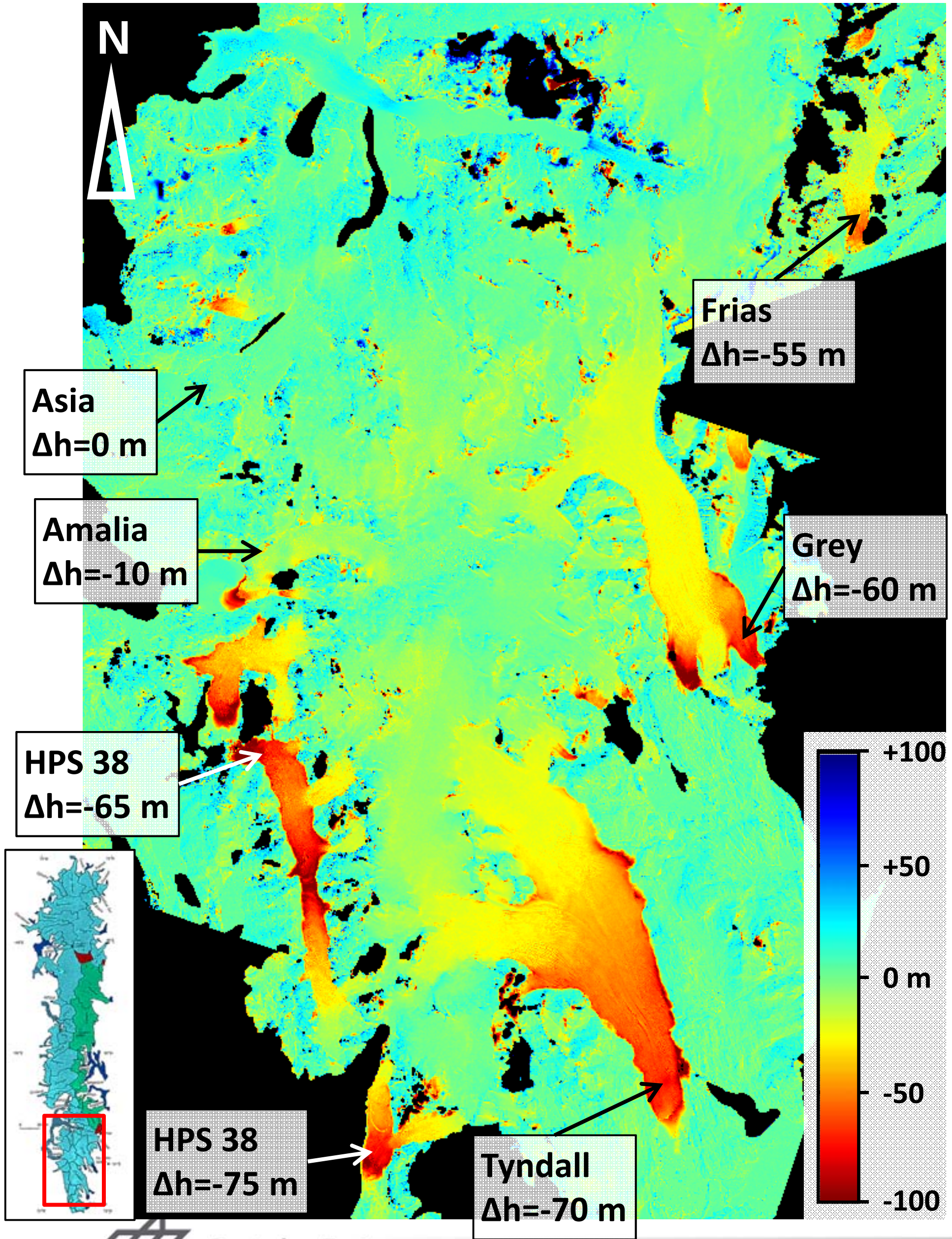
Upsala: ice elevation change 2011 - 2000



- Front retreat: -**3.4 km** [Feb. 2000 – May 2011] **(0.3 m a^{-1})**
- **Δh > -160 m (14.5 m a^{-1})** near main calving front
- **Δh ~ -110 m (10 m a^{-1})** on tributaries Bertacchi and Cono
- **Δh = -30** to **-40 m (10 m a^{-1})** near equilibrium line (1200 m a.s.l)
- Dynamic thinning due to acceleration and large calving events.
- Field survey: **-9.5** to **-14 m a^{-1}** [‘91 - ‘93] *(Naruse et al., 1997)*



Grey, Tyndall, Asia, Amalia: ice elevation changes

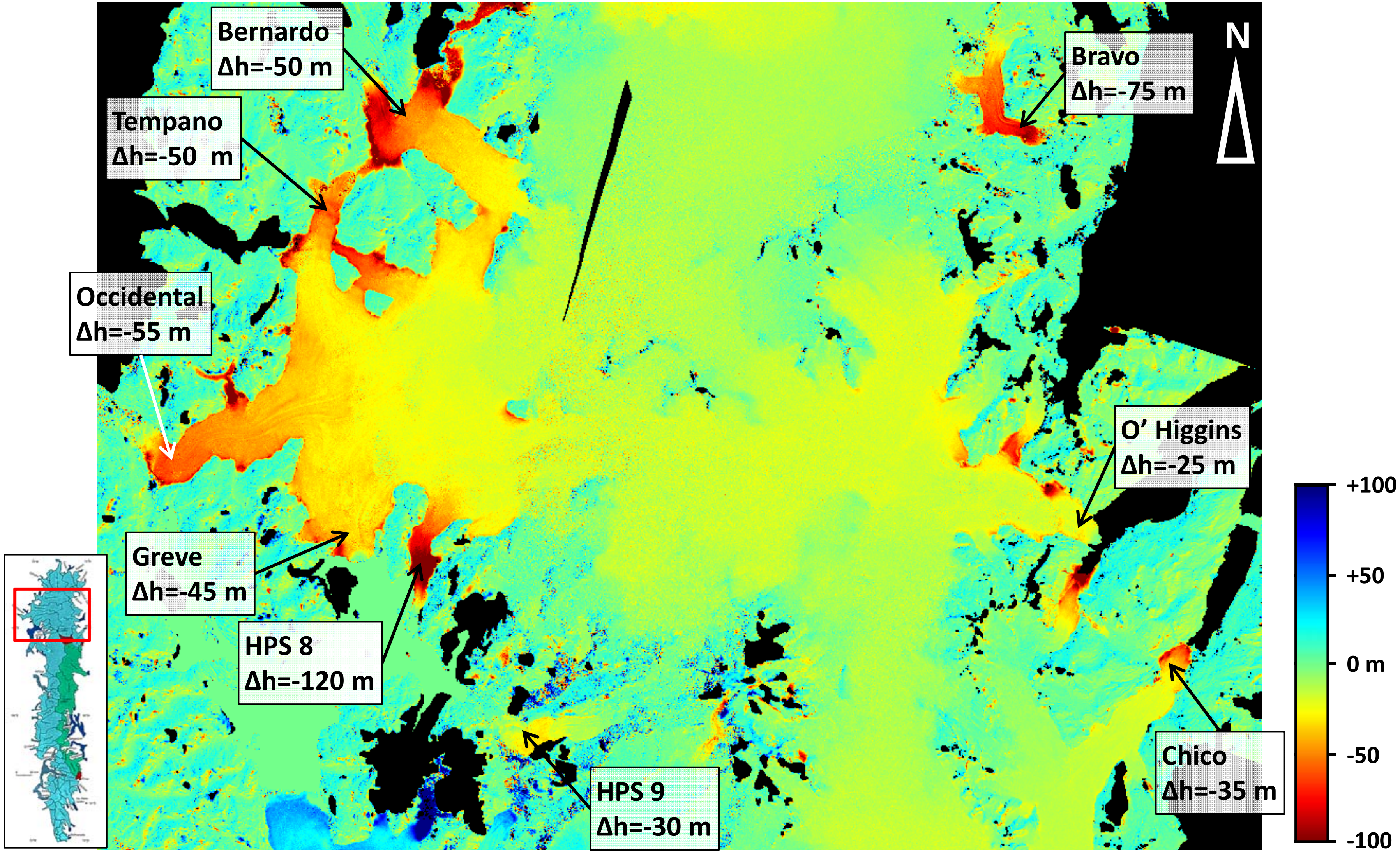


- **Tyndall Gl.**:
  - **-6.3 ma^{-1}** on terminus [2000-'11]
  - **-4.9 ma^{-1}** average ['93-'99] *(Raymond et al. 2000)*

- **Grey Gl.:**
  - **-5.4 ma^{-1}** on east terminus
  - **-3.6 ma^{-1}** on main terminus
  - **-6.5 ma^{-1}** on west terminus

Grey Glacier, front.

O’ Higgins, Bernardo, Occidental: ice elevation changes



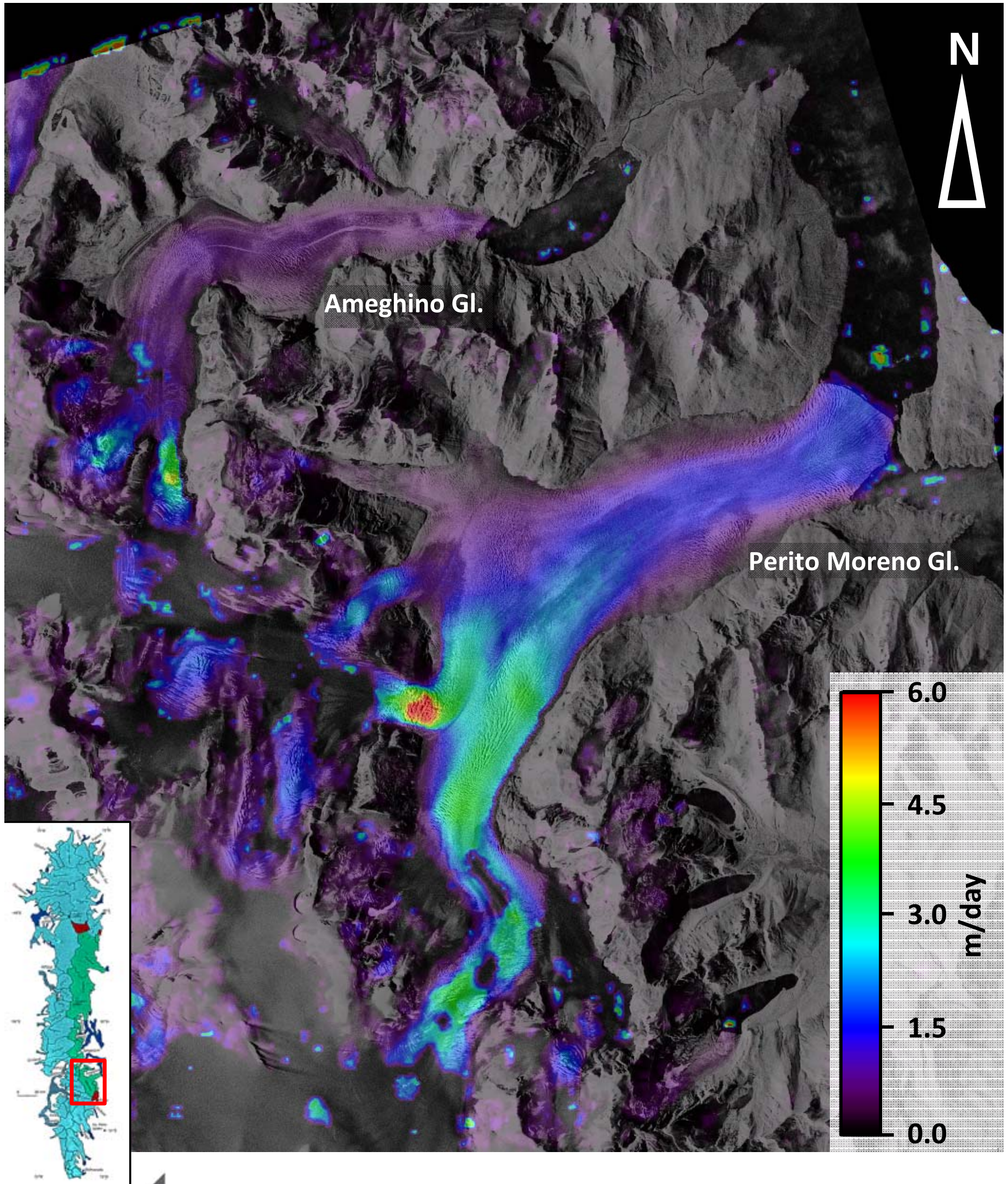
- **O’ Higgins: -2.5 ma^{-1}** on terminus [2000-’12]
- Glacier with strong historical retreat trend: **14.6 km** during the period **1896 - 1995** *(Casassa et al. , 1997)*

SPI ice elevation and volume change 2000 – 2011/2012

Total SPI area [km^2]	Area covered by TanDEM-X [km^2]	Time period	Volume change rate [km^3 yr^{-1}]	Mass change rate [Gt yr^{-1}]
12826.39	11354.67	2000 - 2011/12	**-11.83**	**-10.65**

Author	Data source	Area covered	Time period	Volume change rate [km^3 yr^{-1}]	Mass change rate [Gt yr^{-1}]
Jacob et al, 2012	GRACE	SPI and NPI	Jan. 2003 - Dec. 2010		-23 ± 9
Ivins et al, 2011	GRACE	SPI and NPI	Jan. 2003 – Mar. 2009		-26 ± 6
Rignot et al, 2003	DEM diff. (cartography & SRTM)	SPI	1975 - 2000 1995 - 2000	-13.0 ± 0.8 -38.7 ± 4.4	
Willis et al, GRL, 2012	DEM diff (ASTER & SRTM)	SPI NPI	2000 – 2012 2000 – 2011	**-22.2±1.3** -4.9±0.3	**-20.0 ± 1.17** -4.4 ± 0.27

Perito Moreno and Ameghino: ice velocities



- Area: Perito Moreno: 258 km², Ameghino: 76 km².

← Ice velocity map

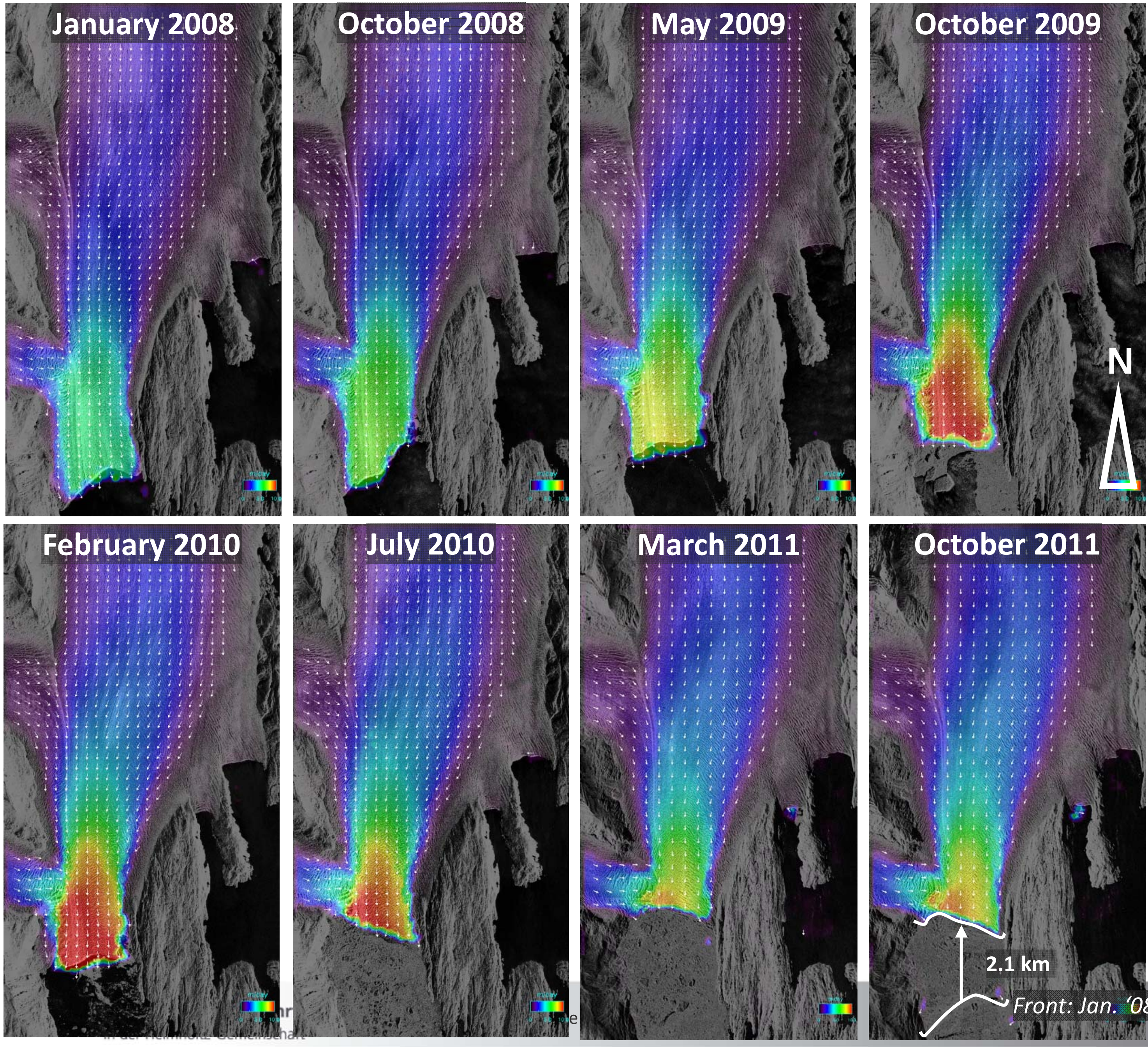
  - 3 May 2011 / 14 May 2011 (11 days)

- P. Moreno and Ameghino:
  - light seasonal variability
  - constant annual mean velocity (2008-2012)
  - agreement with GPS and InSAR [1]

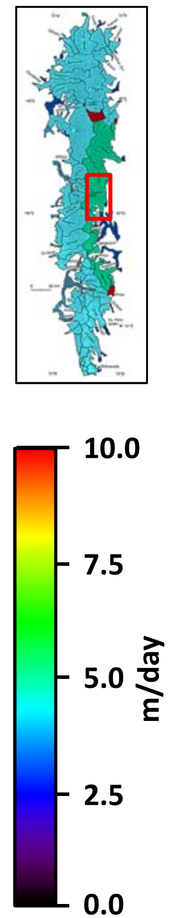
Photo: H. Steinberg

[1] Stuefer, M., H. Rott, and P. Skvarca, "Glacier Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events," Journal of Glaciology, 53 (180), pp. 3-16, 2007.

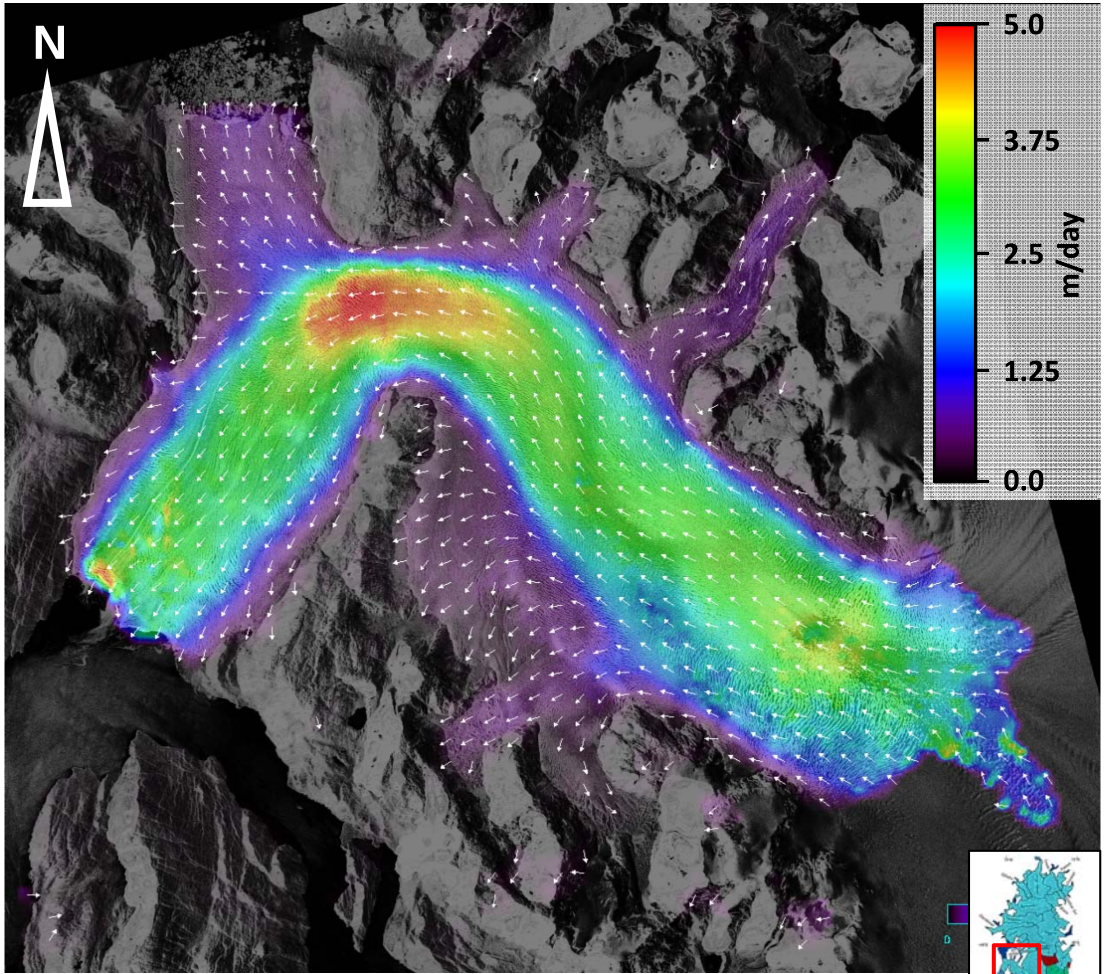
Upsala Glacier: ice velocities

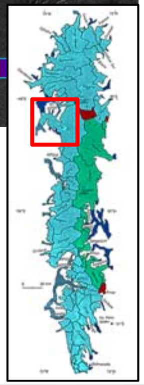


Upsala Glacier area: 902 km²



Pio XI: ice velocity





- Largest calving glacier of SPI
- Area: **1265 km²**. Length: **64 km**.
- Tidewater glacier

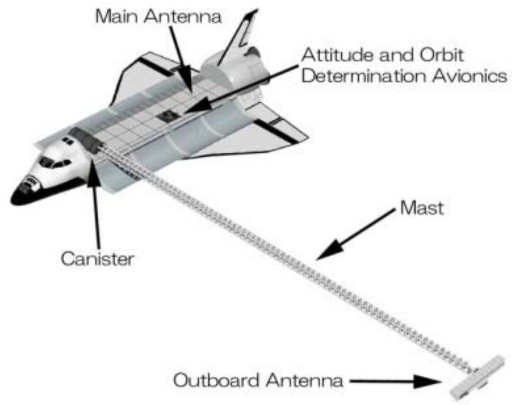
← Ice velocity map

- 3 May 2011 / 14 May 2011
- Velocities from **1** to **5 md^{-1}** at the bend.


Photo: Ralf Rosenau, TU Dresden

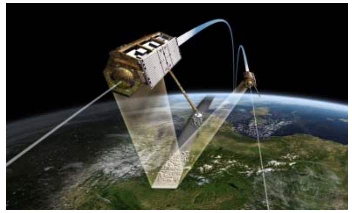
Shuttle Radar Topography Mission (SRTM)

- NASA/DLR mission: semi-global DEM by means of single pass interferometry
- Acquisition: **11 - 22 February 2000**
- Coverage: **56°S to 60°N**
- Bistatic interferometric system:
  - **C-band:** full coverage
  - **X-band:** partial coverage (gaps)
- **C-band DEM** spatial posting: **3 arcsec (90 m)**
- Nominal vertical accuracy (90% linear point-to-point error):
  - Relative: 10 m / Absolute: 16 m
- Nominal horizontal accuracy (90% circular error):
  - Relative: 15 m / Absolute: 20 m
- DEM available at DFD is calibrated with ICESat altitude tie points → increased accuracy



- **ICESat** (*Ice, Cloud, and land Elevation Satellite*) → NASA mission 2003 - 2009
  - Geoscience Laser Altimeter System (GLAS) **space borne LIDAR altimeter**
  - Footprint: **65 m** of diameter. Sampling distance: **170 m**.

TanDEM-X and ITP



- Objective: global DEM by means of single pass interferometry
- Bistatic interferometric system in **X-band**
- Launch: **June 2010**
- Nominal relative vertical accuracy (90% linear point-to-point error): **2 m** (less than 20% slopes), **4 m** (more than 20% slopes)
- Nominal relative horizontal accuracy (90% circular error): **4 m**
- Integrated TanDEM-X Processor (ITP) used to generate RawDEMs from CoSSC data
- RawDEM mean asbolute vertical error globally **below 3 m**
- **19 RawDEMs** processed with ITP (acquired: **2011 and early 2012)**
    - **4 RawDEMs →** dual baseline phase unwrapping

TanDEM-X DEM:
O' Higgins Glacier (SPI)