ESA Cryosphere Training Course – Day 4, Thursday 15 September 2016

Input-Output Method - Ice Sheet Mass Balance

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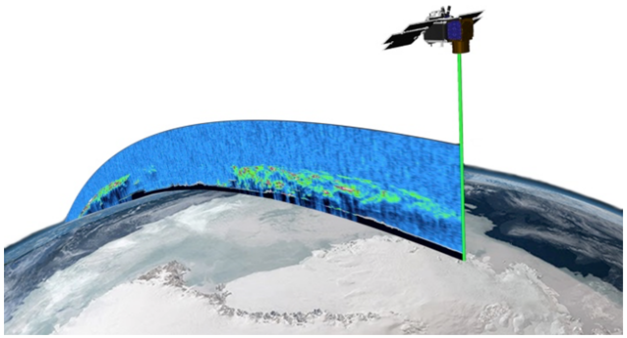
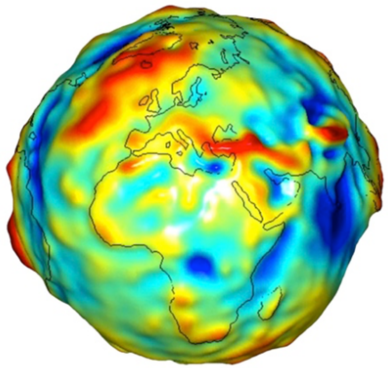
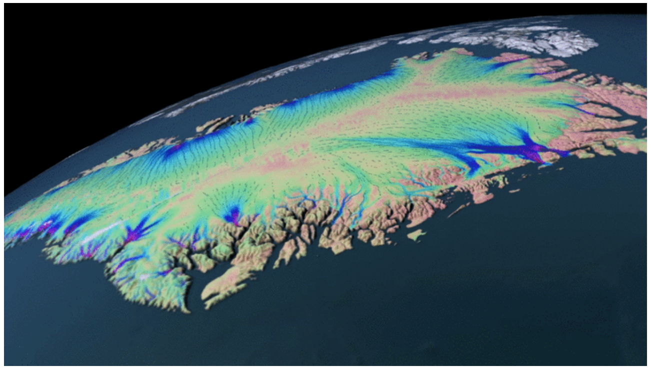
Ice Sheet Mass Balance

- 3 Methods
  - Altimetry - **Volume changes**
  - Gravimetry - **Mass changes**
  - Input-Output - **Dynamic changes**





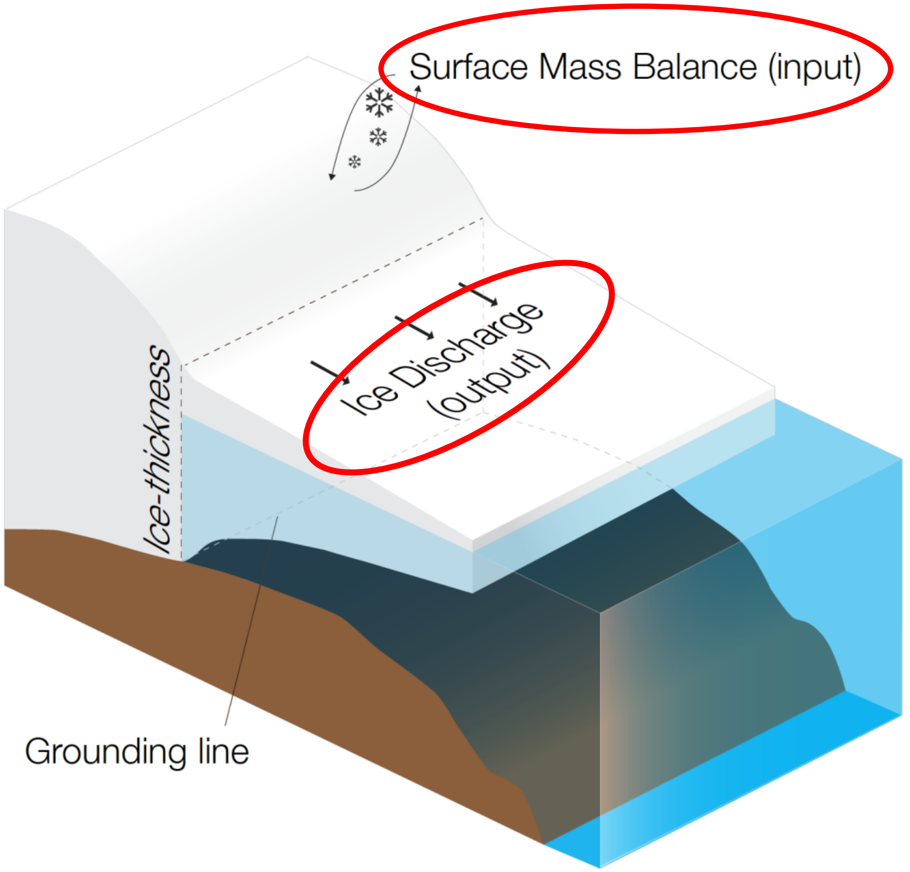
- 3 **independent** techniques globally converging toward the same result :
  - Example : the ice sheet mass balance inter-comparison exercise (IMBIE)



Want to learn more, visit: http://imbie.org/

Input and Output Fluxes

- **Input** (SMB)= Surface Mass Balance Reanalysis from climate models coupled with snow model
  - Snowfall, rainfall, snowdrift, snowmelt, percolation, refreezing



- **Output** (D) = Ice discharged into the ocean (or lakes).
  - *Output is zero for Land Terminating glaciers*

MB = SMB – D (Gt/yr)

Mass balance – partitioning

- Mass changes : Dynamic or SMB driven ?
  - Antarctic Peninsula, West Antarctica : *Dynamic*
  - East Antarctica : *SMB* (close to balance), largest uncertainties.
  - Greenland : *mixtures of dynamic and SMB*, loss is about equal between the 2 processes.
  - Ice caps or mountain glaciers are usually controlled by *SMB*
- Only method that look directly at the **partitioning** between dynamic and SMB

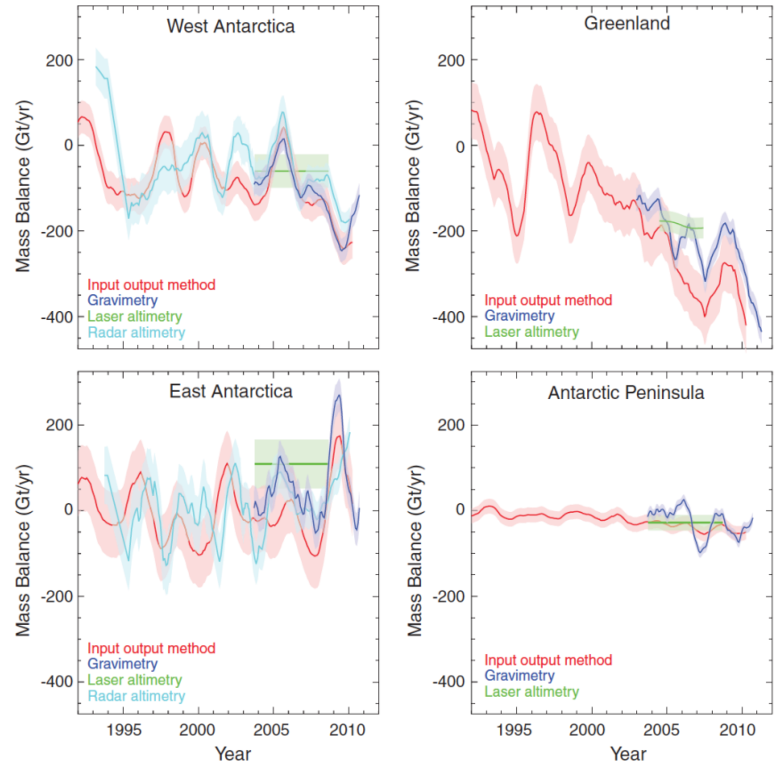
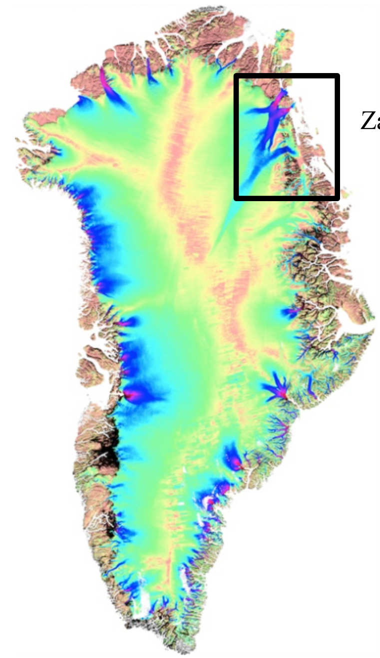


Fig. 4. Rate of mass change of the four main ice-sheet regions, as derived from the four techniques of satellite RA (cyan), IOM (red), LA (green), and gravimetry (blue), with uncertainty ranges (light shading). Rates of mass balance derived from ICESat LA data were computed as constant and time-varying trends in Antarctica and Greenland, respectively. The gravimetry and RA mass trends were computed after applying a 13-month moving average to the relative mass time series. Where temporal variations are resolved, there is often consistency in the interannual variability as determined by the independent data sets.

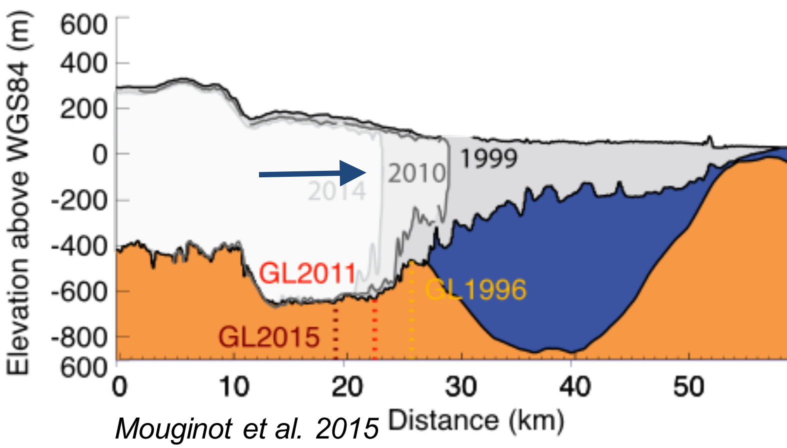
Shepherd et al. 2012

Cooking Ingredients



- **Input** ➪ Surface Mass Balance
  - ① **Drainage basins**
- **Output** ➪ Where is the boundary between the ocean and the ice sheet - define ?
  - ② **Gate locations**
- **Output** ➪ How much ice is passing through this boundary
  - ③ **Ice thickness** and ④ **ice velocity.**

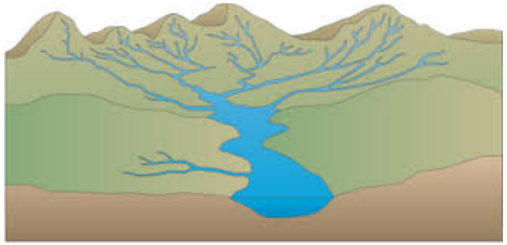
Each part will be illustrated with the example of Zachariae Isstrom, Northeast Greenland.



Evolution of Zachariae Isstrom section along flow between 1996 and 2015

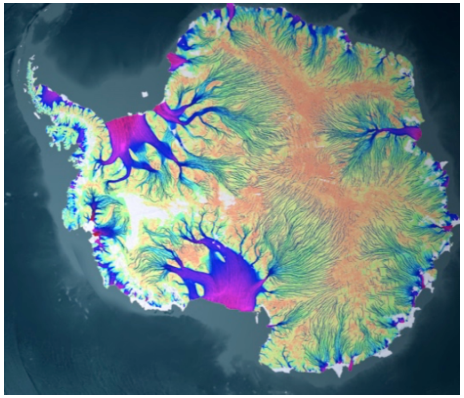
① Define the drainage basins (Input)

- We want know the catchment basin associated with each glacier. The SMB is then integrated over each individual basin = our **input fluxes**

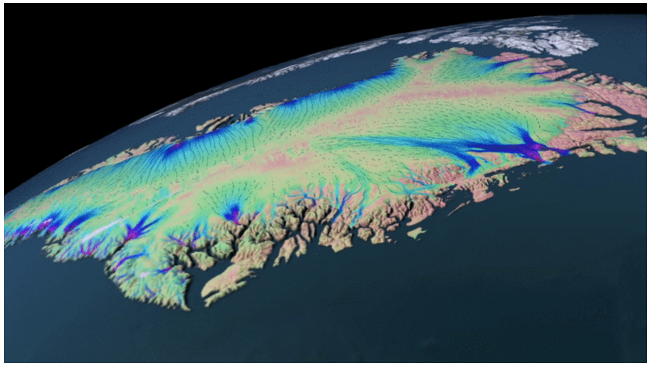


Similar to catchment basin of river

- Every glacier (even adjacent) evolves in its own way, so the more basins you draw the better it is.



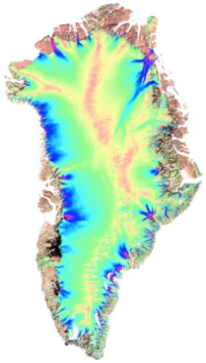
- However for comparing with the other methods, these basins can be merged into larger regions.

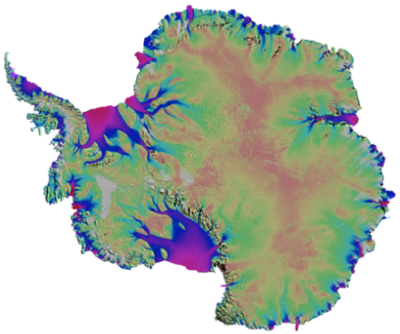


- Error on SMB are typically around **10%**

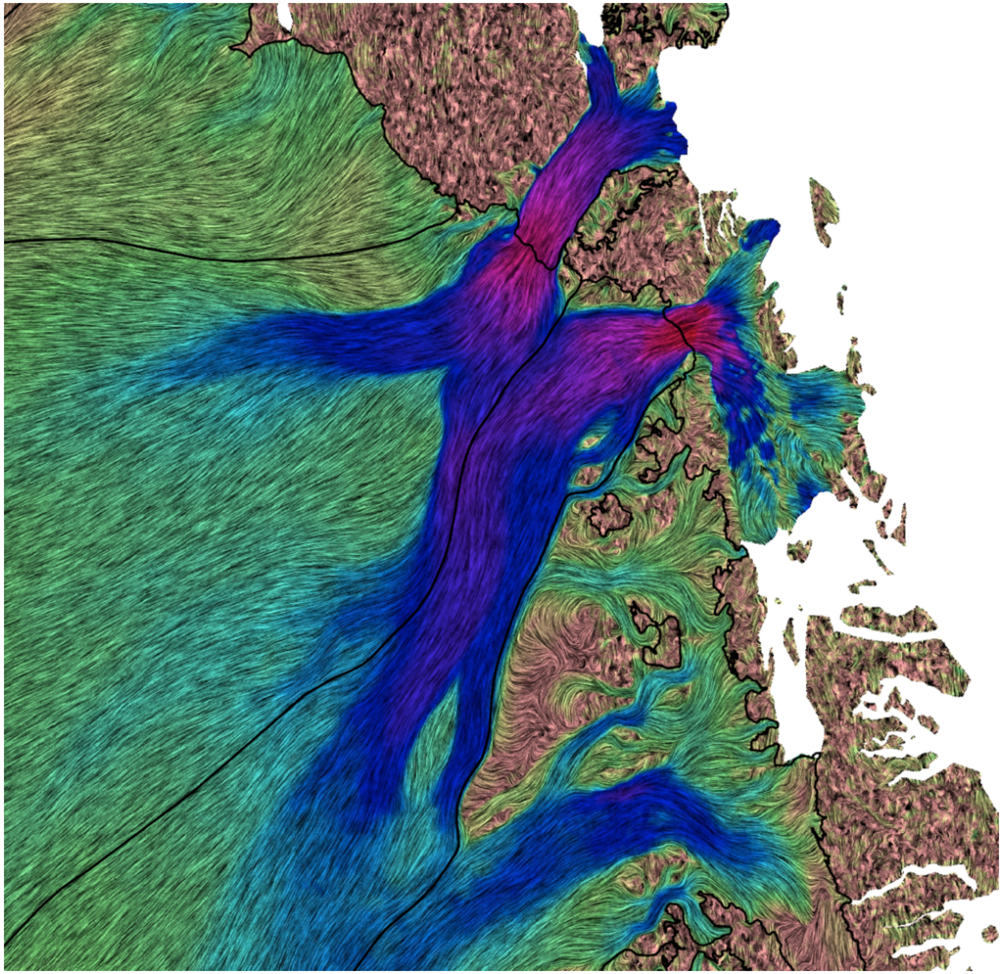
① Define the drainage basins (Input)

- For each glacier, where the ice is coming from ?
- Surface velocity field
  - Define the ice flow





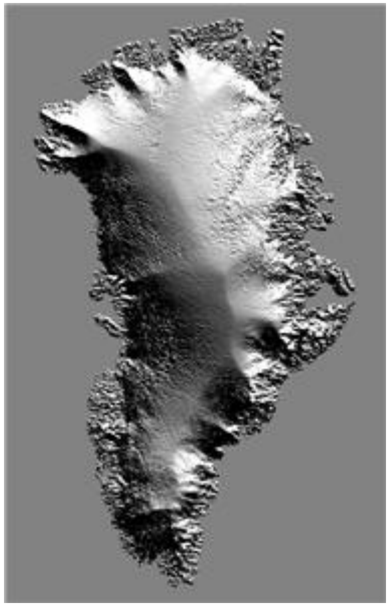
- However precision (5-10 m/yr) is not enough to describe accurately the flow close to the ice divides.



Line integral convolution of surface ice velocity of the northeast ice stream, Greenland

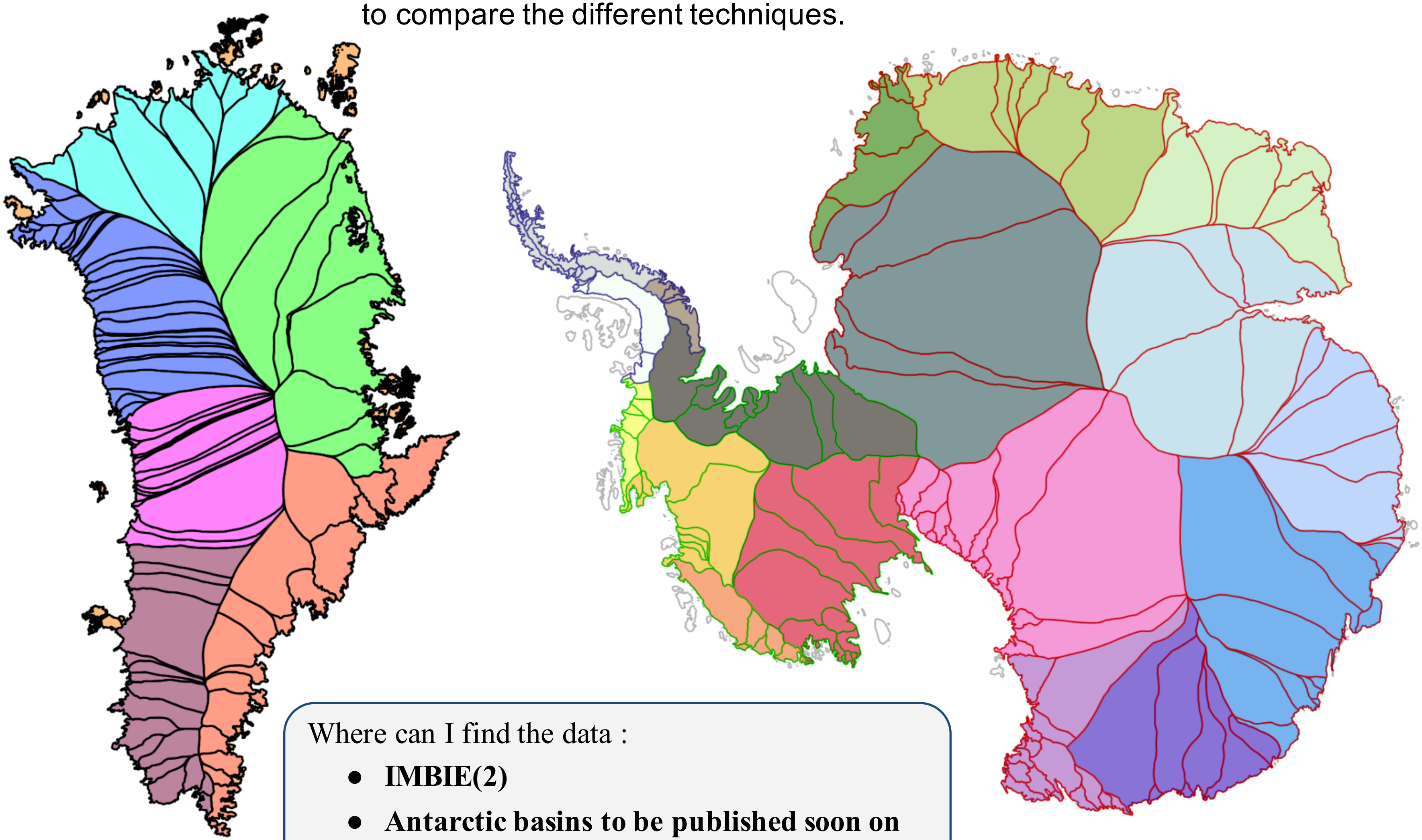
① Define the drainage basins (Input)

- Using DEM assuming that flow is parallel to the local surface slopes.
- DEM need to be smoothed to remove short-wavelength undulations (typically 5 to 20 ice thickness)
- In our case we use the ice velocity in fast flow regions and DEM slopes for slower regions.



① Define the drainage basins (Input)

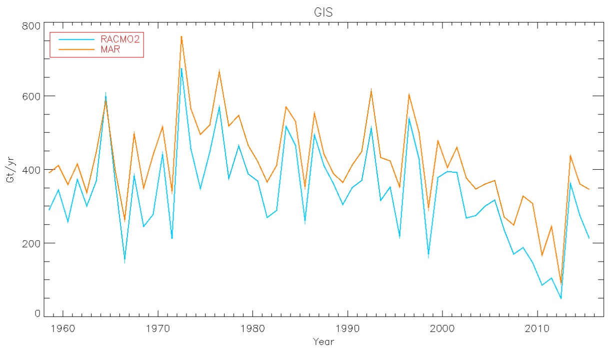
Color defined the larger basin used in IMBIE2 to compare the different techniques.

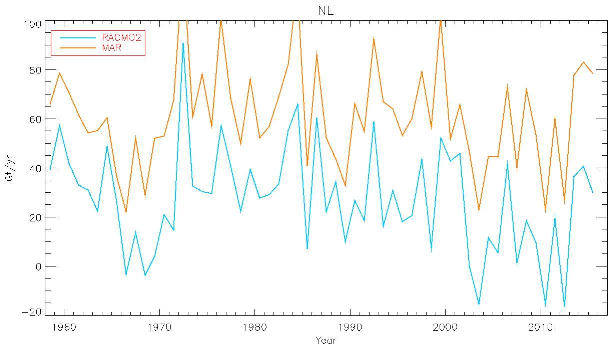


Where can I find the data :

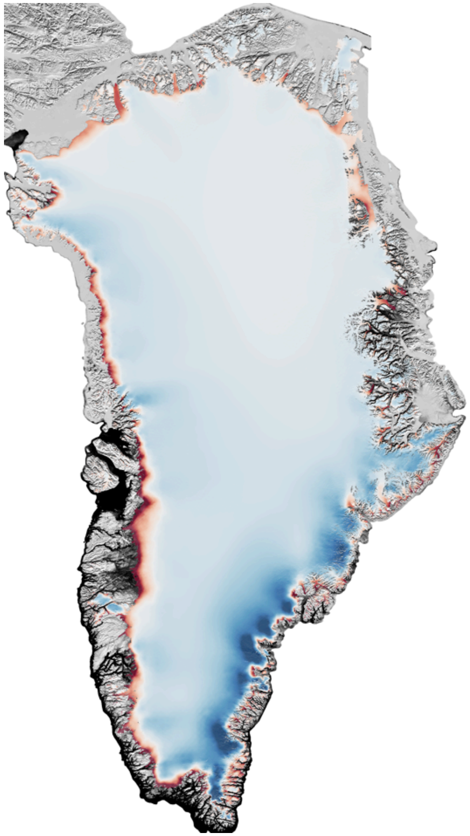
- **IMBIE(2)**
- **Antarctic basins to be published soon on NSIDC**

① Integrate SMB over the basins

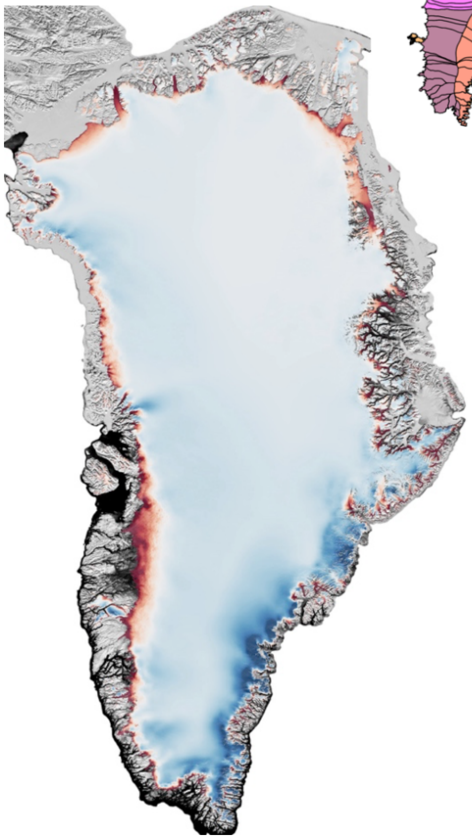


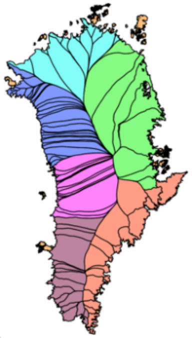


MARv3.5.2_20km@5km



RACMO2.3@1km





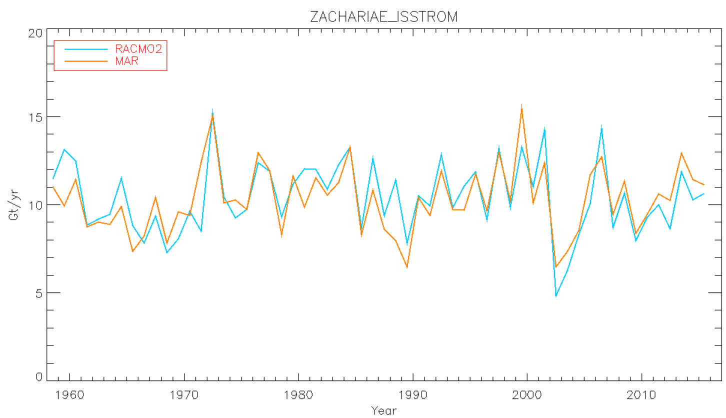
Where can I find the data :

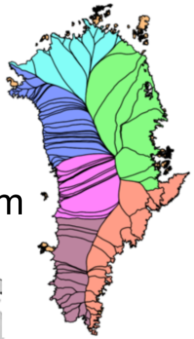
- **RACMO2 :** https://www.projects.science.uu.nl/iceclimate/models/racmo.php
- **MAR (greenland only):** ftp://ftp.climato.be/fettweis/MARv3.5/Greenland/, http://www.cryocity.org/mar-explorer.html

① Integrate SMB over the basins

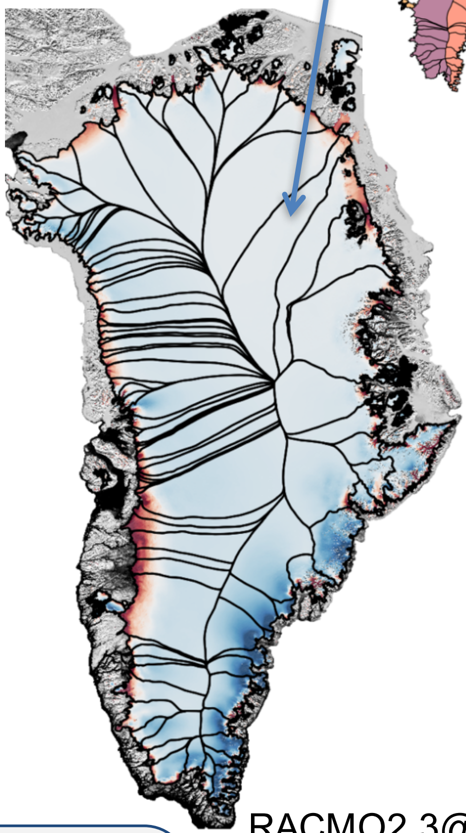
- Annual integration for each glacier of the SMB
- Mean SMB before the 90's

Example of Zachariæ Isstrøm





Zachariæ Isstrøm



RACMO2.3@1km

Where can I find the data :

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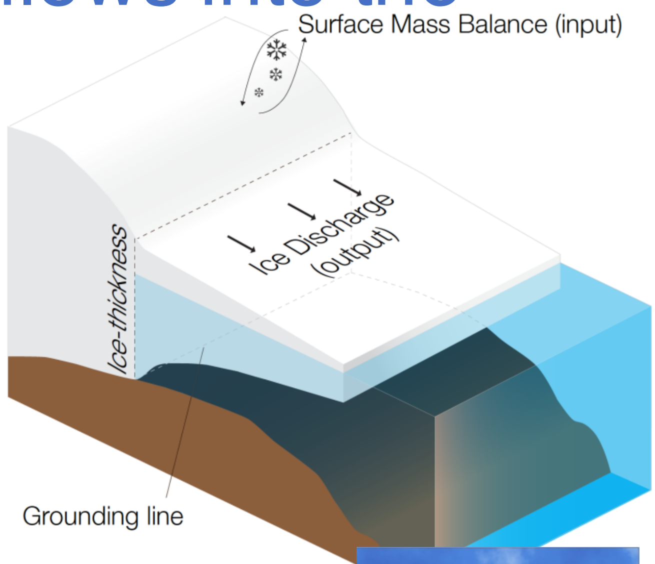
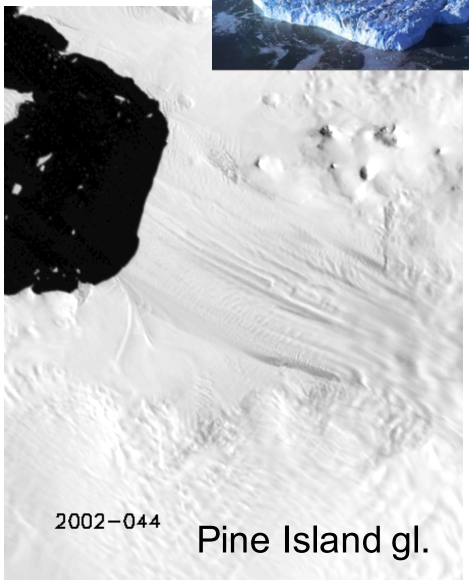
② Gates - Where does the ice flows into the ocean ?



- The limit between floating ice and grounded ice is called the **grounding line (GL)**. Ice discharge must be measured here.
  - For glaciers with no floating section (Greenland), the GL is obvious : the ice front.

- Best way to find the GL, DInSAR to measure the tidal displacement of the floating ice.

Tidewater gl.



Pine Island gl.

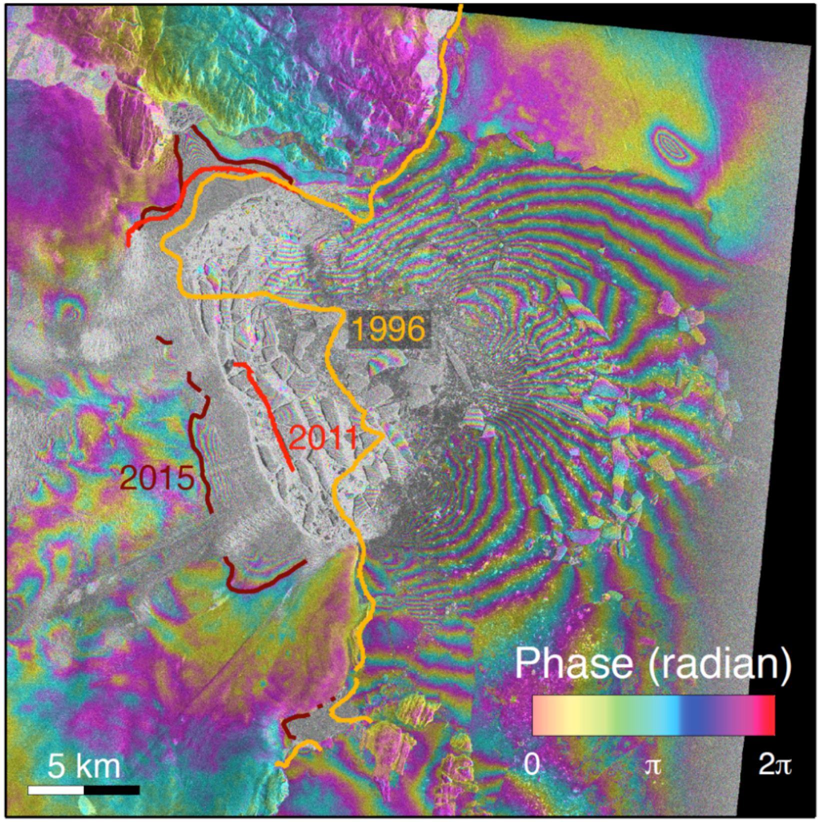
Where can I find the data :

- **NSIDC-0498. :** MEaSUREs Antarctic Grounding Line from Differential Satellite Radar Interferometry
- **NSIDC :** MEaSUREs Antarctic Boundaries for IPY from Satellite Radar
- Measure it directly with ERS-1&-2/ESA, Sentinel-1a&b/ESA

② Gates evolution

- Grounding line is moving and so should your gates.
  - Account for ice above floatation loss during GL retreat

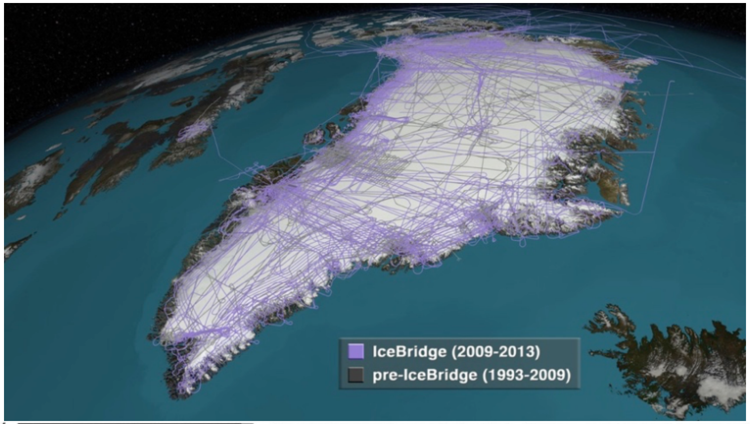
- Zachariae's example :
  - 7 km retreat at its center compared to 1996

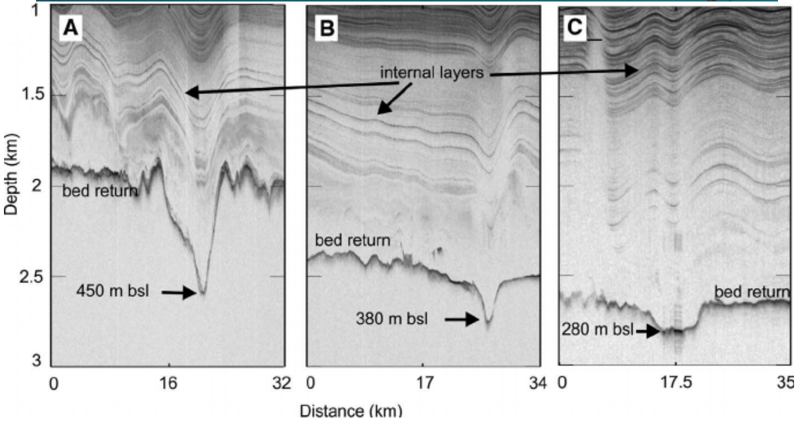


COSMO SkyMed differential interferogram

③ Ice thickness - “direct” measurements

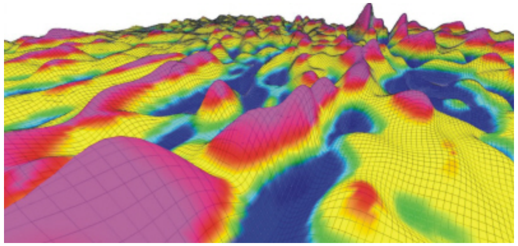
- Ground penetrating radar
  - Measures ice thickness along lines with a precision of about 10-30 meters
  - Limited by surface clutter and absorption in the ice (wet).





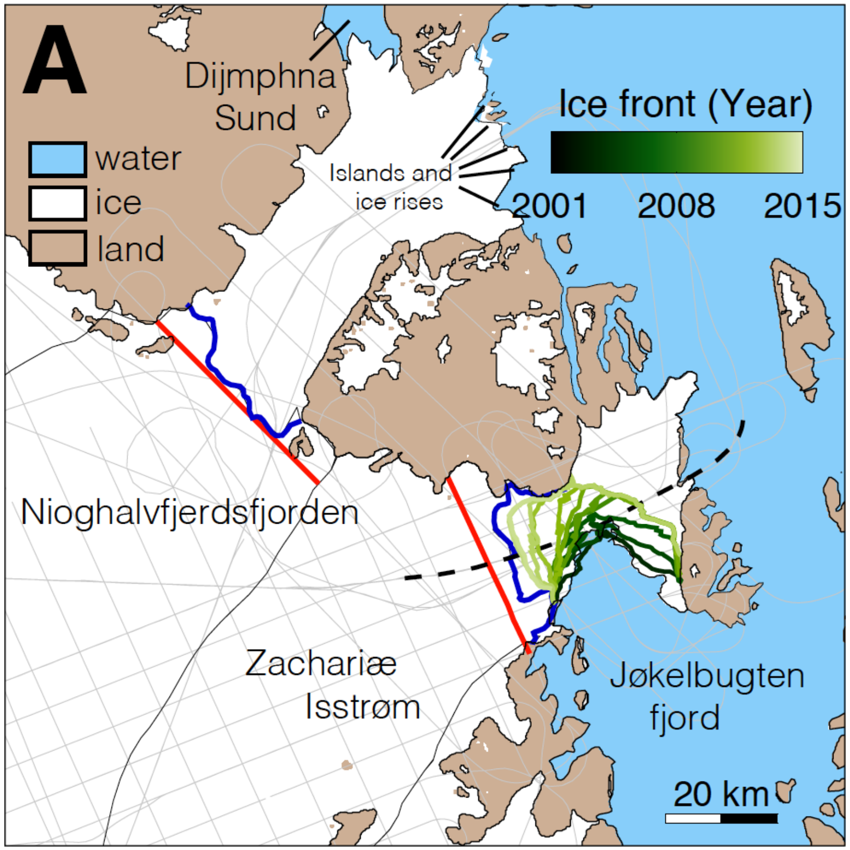
- *Airborne Gravimeters*
  - *Can measure ice thickness from the inversion of gravity anomalies*
  - *Low resolution*

Where can I find the data :
- **NASA/Operation IceBridge** : https://nsidc.org/data/icebridge
- **CReSIS data** : https://data.cresis.ku.edu/



②+③ What can I do if there are no thickness measurements at the grounding line ?

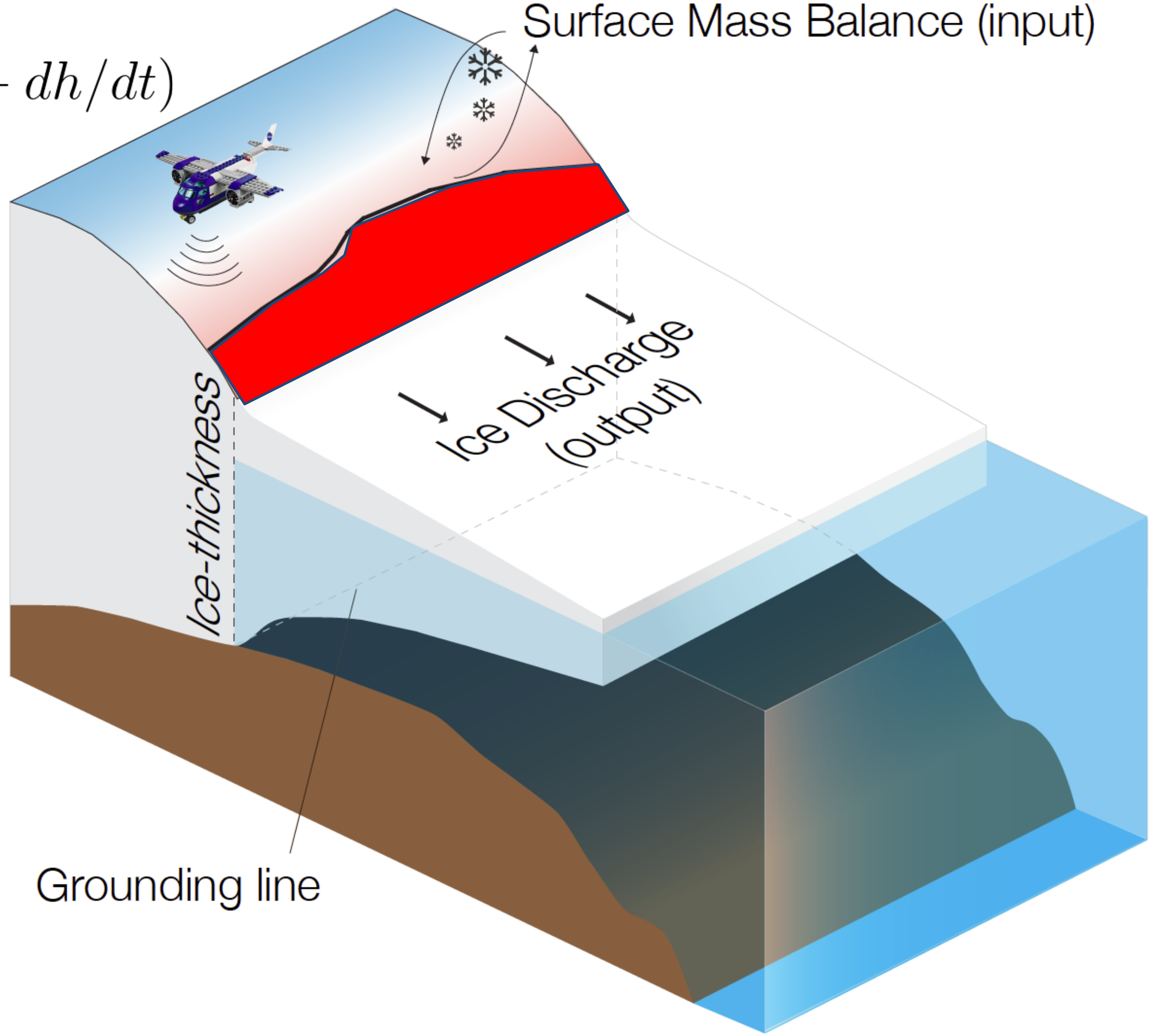
- Flight tracks can be found 5, 10 km upstream the grounding line.
- But we have to correct for what happen to the ice between the gate and the grounding line



②+③ Define your gates

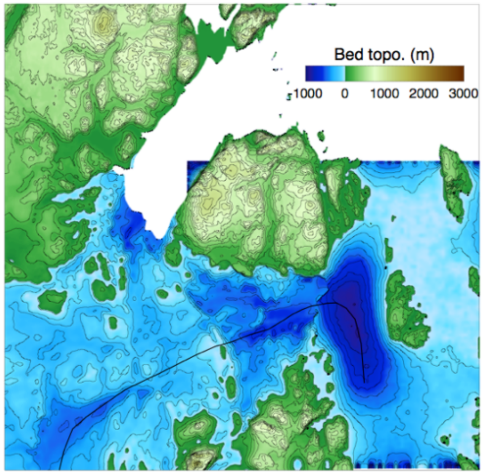
$$\phi_{gl} = \phi_{gate} - (\text{SMB} + dh/dt)$$

dh/dt=0 if glacier is in steady state

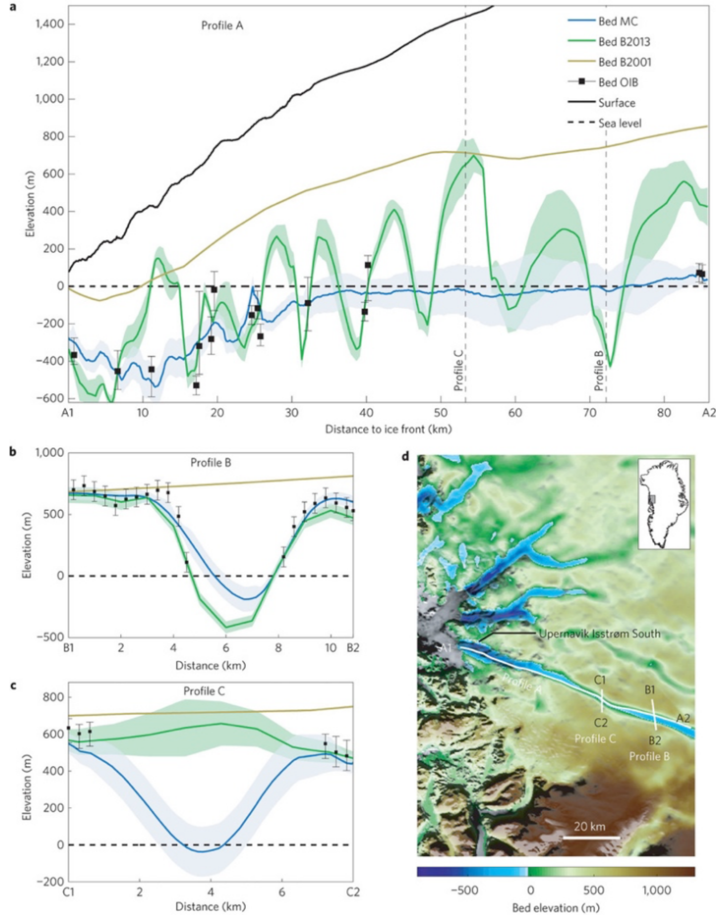


②+③ Define your gates - 2nd option

- Using interpolated dataset :
  - Kriging
  - Mass conservation bed :



Morlighem et al. 2014



Where can I find the data :

- **Kriging** : https://www.bas.ac.uk/project/bedmap-2/,
- **Mass conversation** : http://sites.uci.edu/morlighem/dataproducts/bedmachine-greenland/, http://nsidc.org/data/docs/daac/icebridge/idbmg4/index.html

③ Ice thickness - no/few measurements

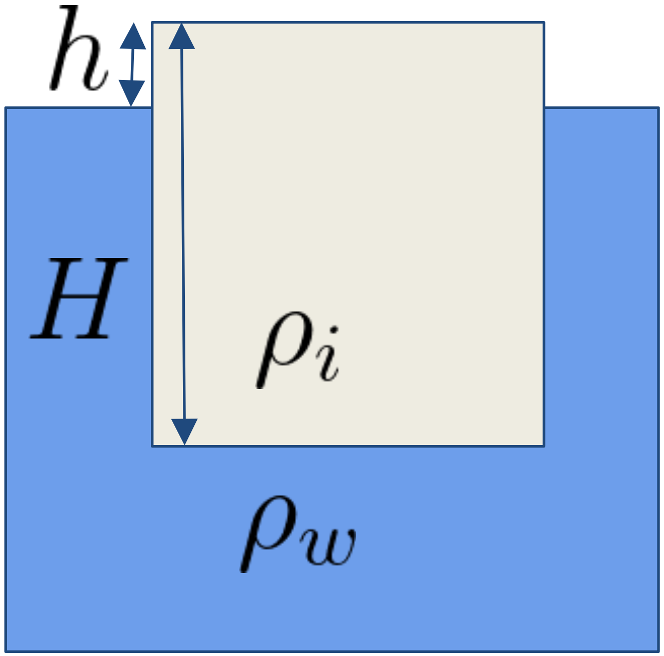
Assuming that ice is close to hydrostatic equilibrium at the grounding line, ice thickness can be inferred from surface elevation :

$$H = \frac{\rho_w h}{\rho_w - \rho_i}$$

$$h = elevation$$

$$\rho_w = seawaterdensity$$

$$\rho_i = icedensity$$



Of course you should take into account firn. Firn layer has a much lower density than ice (if not taken into account, you will overestimate your ice thickness)

③ Ice thickness - no/few measurements (center line)

Ice thickness along center line only. Assuming a shape for the glacier trough, typically U-shape.

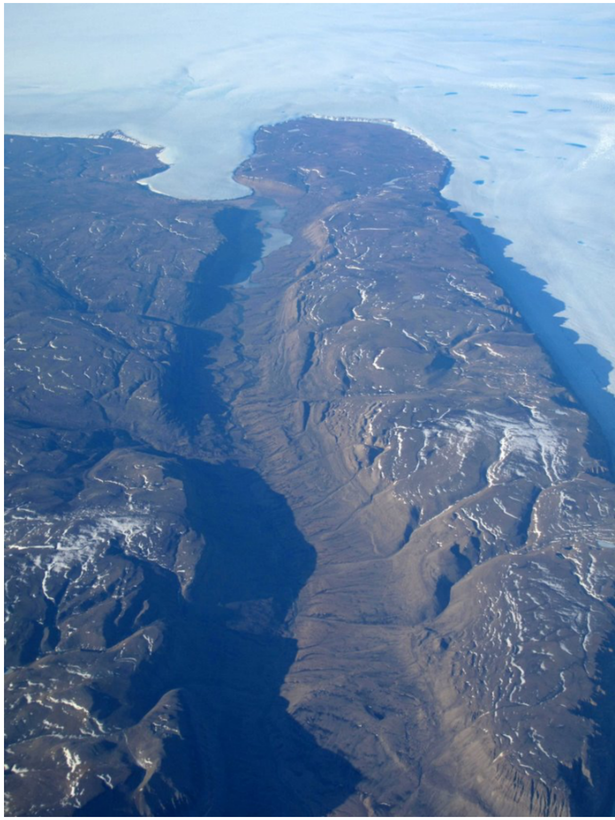
Example with a parabolic interpolation :

$$H(x) = H_c + (H_m - H_c)\frac{(x - x_c)^2}{x_c^2}$$

$$H_c = \text{Ice thi. @ center line}$$

$$x_c = x \text{ center line}$$

$$H_m = \text{Ice thi. @ margin} = 0, 10, 100 \text{ m}$$



③ Ice thickness changes - correction

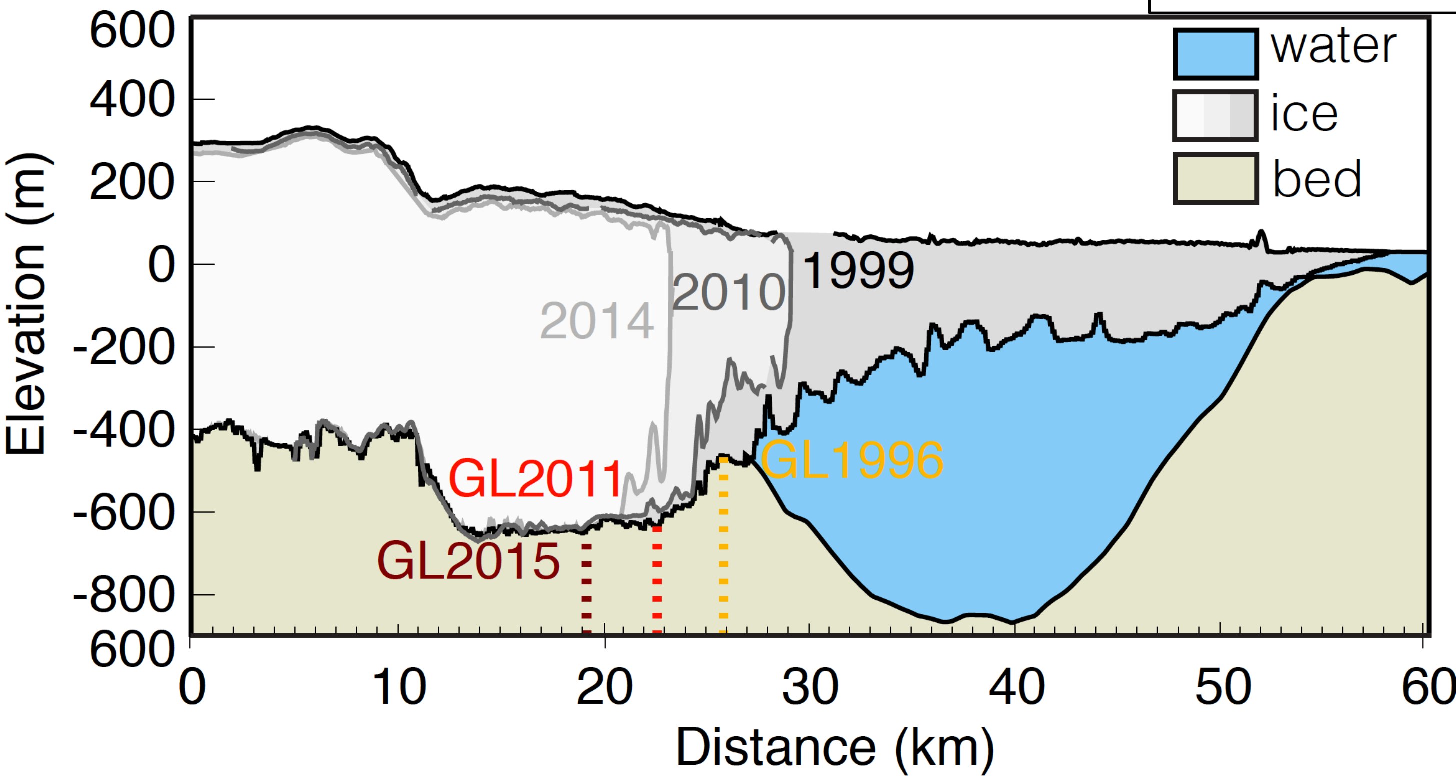
- With glacier acceleration and enhanced melting, glaciers are experiencing **thinning** :
  - Best would be to measure frequently (annually) ice thickness along our gates.
  - For most glaciers with relatively small dynamic changes, it translates into less 1-2% decrease in ice thickness.
  - For glacier with substantial dynamic changes (the ones that matter), we have to apply ice thickness correction :
    - If you have **high resolution dh/dt** mapping, keep bed elevation constant, adjust surface elevation using altimetry measurements
    - If you only have few points, estimate the percentage of ice thickness change at a location and apply to the entire gate.
      - Ice thinning is mostly dynamic, your estimate should be made in a fast flow area.

③ Ice thickness changes - Zachariæ Isstrøm

Surface elevation change
1999-2010 : 27±1 m, or 2.5±0.1 m/yr
2010-2014 : 21±1 m, or 5.1±0.3 m/yr

Ice thickness change @GL :
1999-2010 : 179±43 m
2010-2014 : 121±50 m

Bottom melting :
1999-2010 : 13.8±4.1 m/yr
2010-2014 : 25±12 m/yr



③ Ice thickness changes - correction

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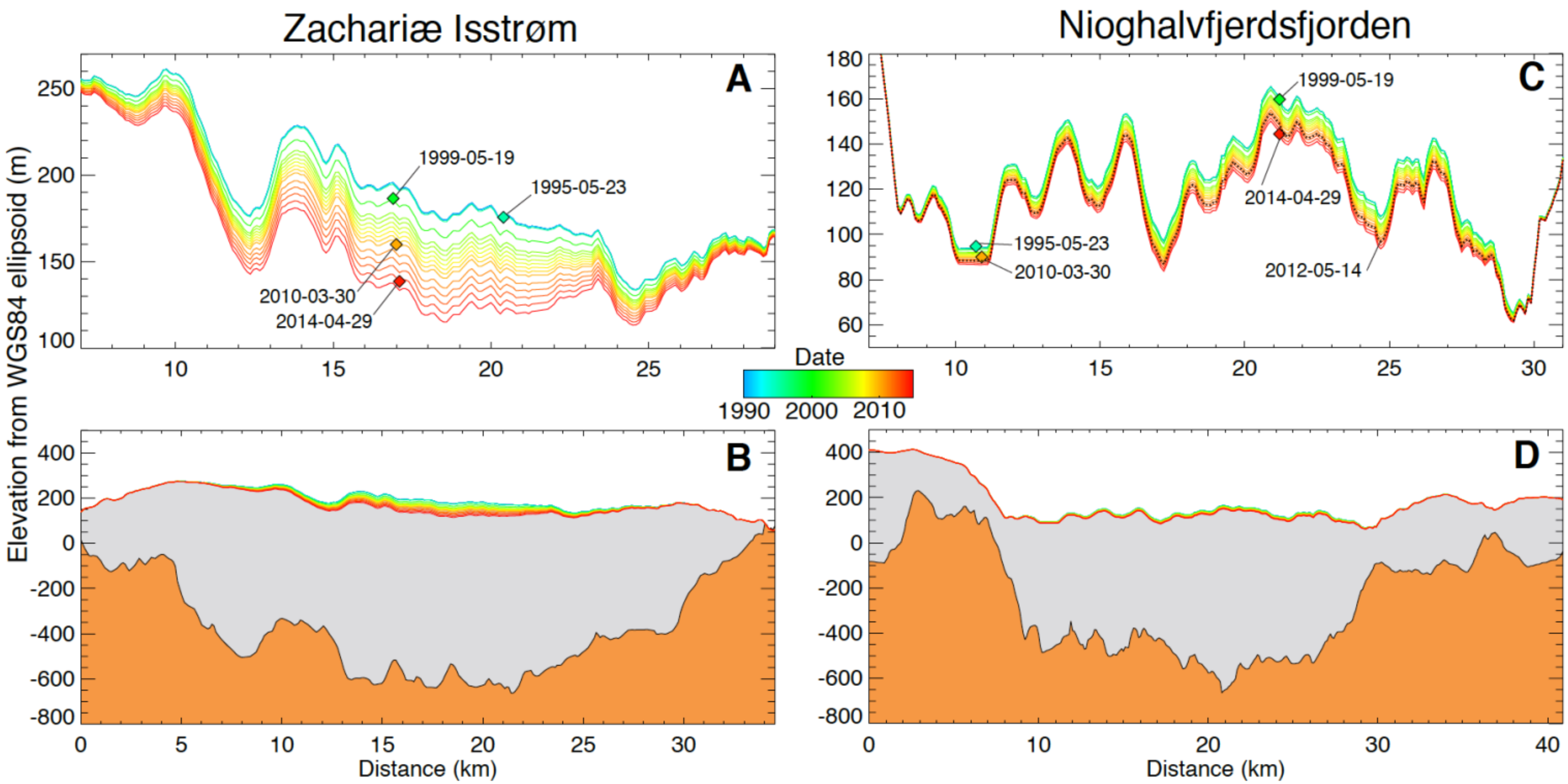
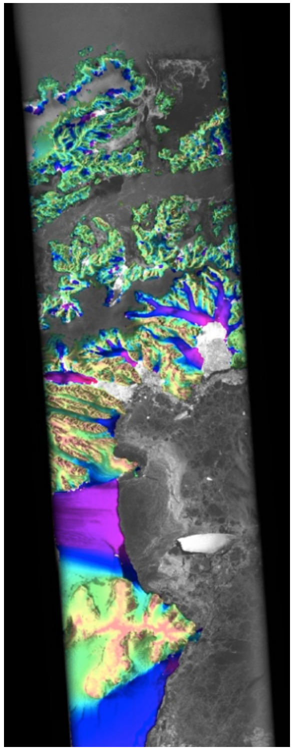
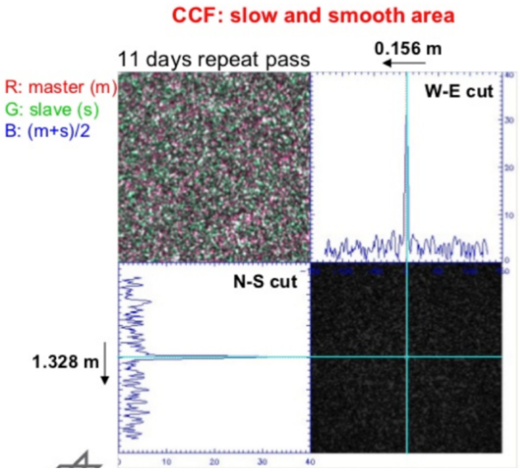


④ Ice velocity - measurements

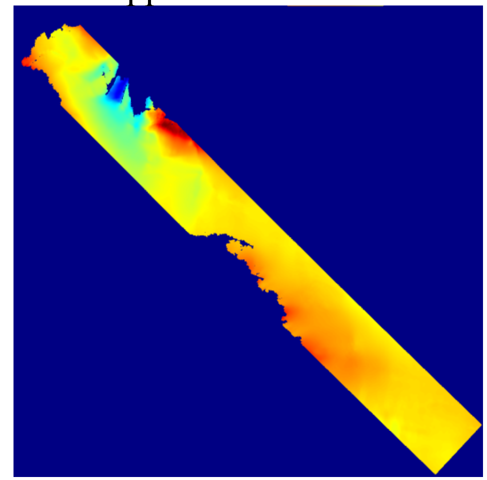


- Geographic Positioning System (GPS)
  - High temporal resolution, high precision, single point...
- Remote sensing with optical instruments or synthetic aperture radars (SAR)
  - Weekly to yearly, high spatial res. over large areas
  - Velocity is estimated from sequential images :
    - **Image cross-correlation**

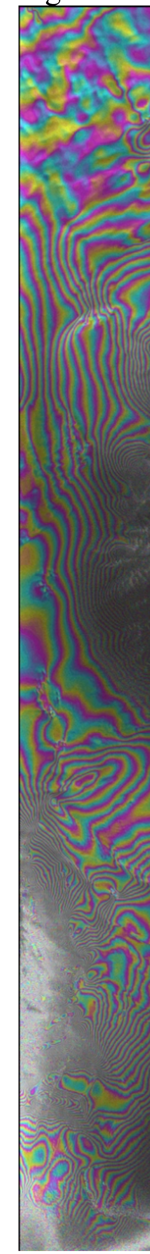


④ Ice velocity - measurements

Unwrapped



Interferogram



- Geographic Positioning System (GPS)
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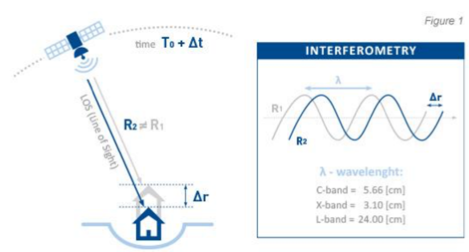
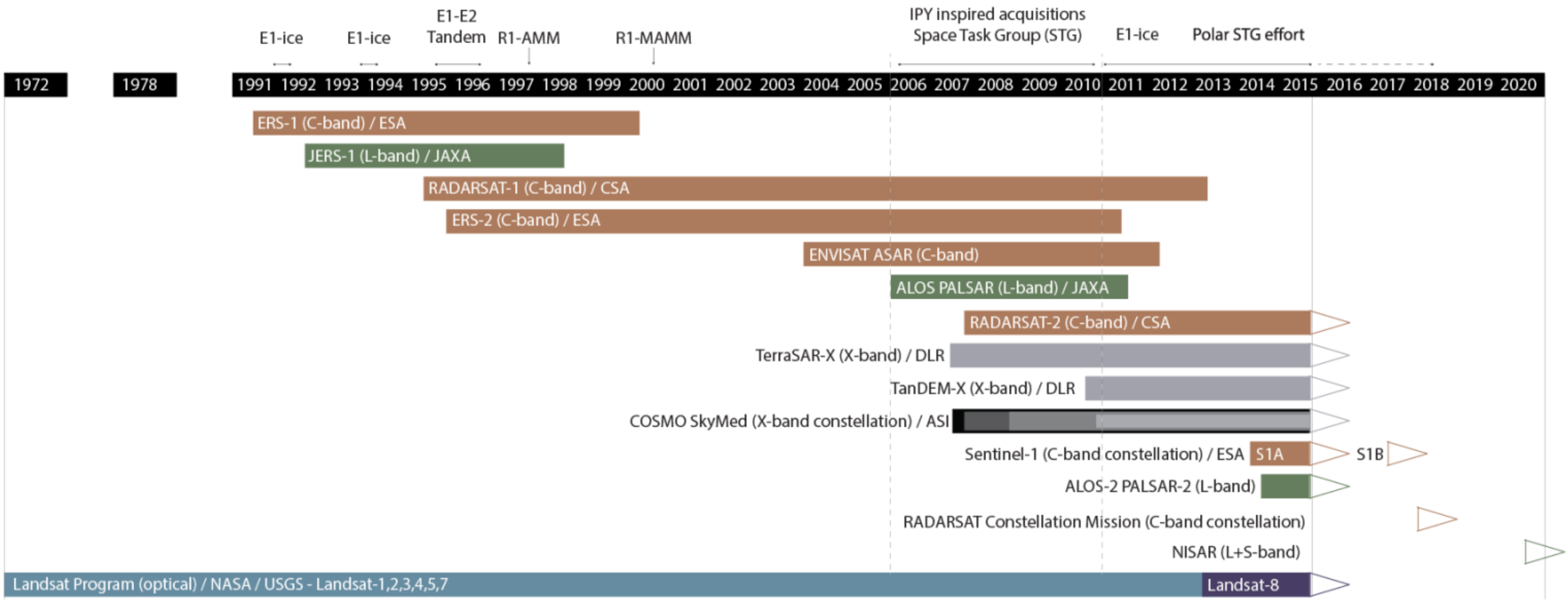
    - Image cross-correlation
    - **Interferometry**



④ Ice velocity - sensors



Where can I "easily" find some raw data :

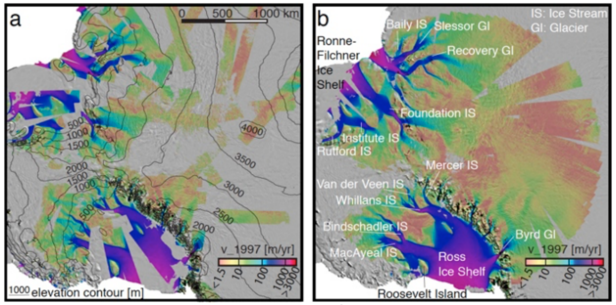
- **Landsat/NASA :** **http://earthexplorer.usgs.gov/**
- **ERS, ENVISAT, Sentinel-1a/ESA :** **https://earth.esa.int/web/guest/data-access**, **https://scihub.copernicus.eu/**

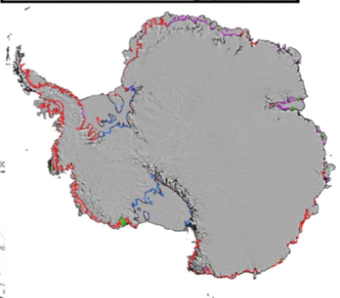
④ Ice velocity

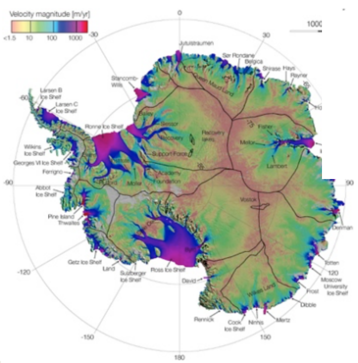
Ice velocity products exists.

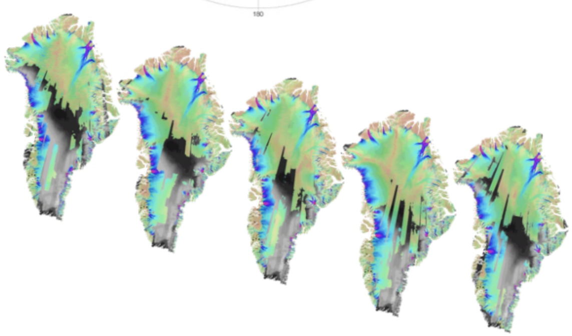
Where can I find processed velocity data :

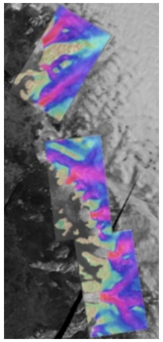
- **NSIDC :** http://nsidc.org/data/measures/data_summaries.html
- **CPOM : http://www.cpom.ucl.ac.uk/csopr/iv/**
- **ENVEO : http://cryoportal.enveo.at/**
- **ESA CCI :http://www.esa-icesheets-greenland-cci.org/**





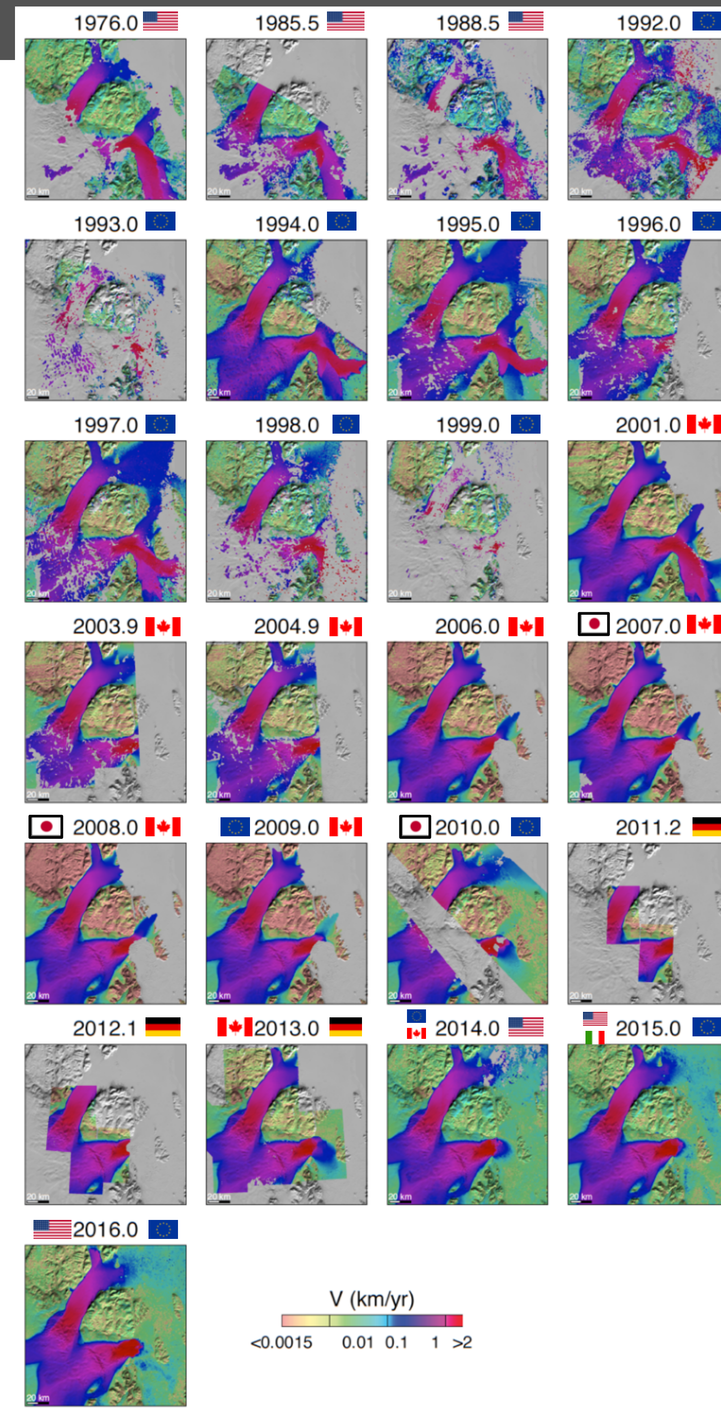




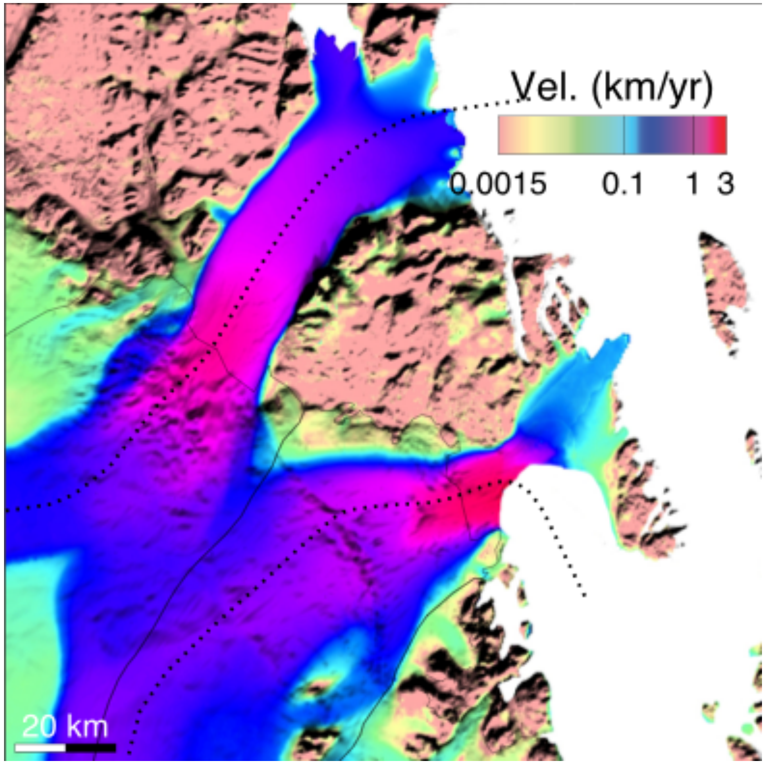


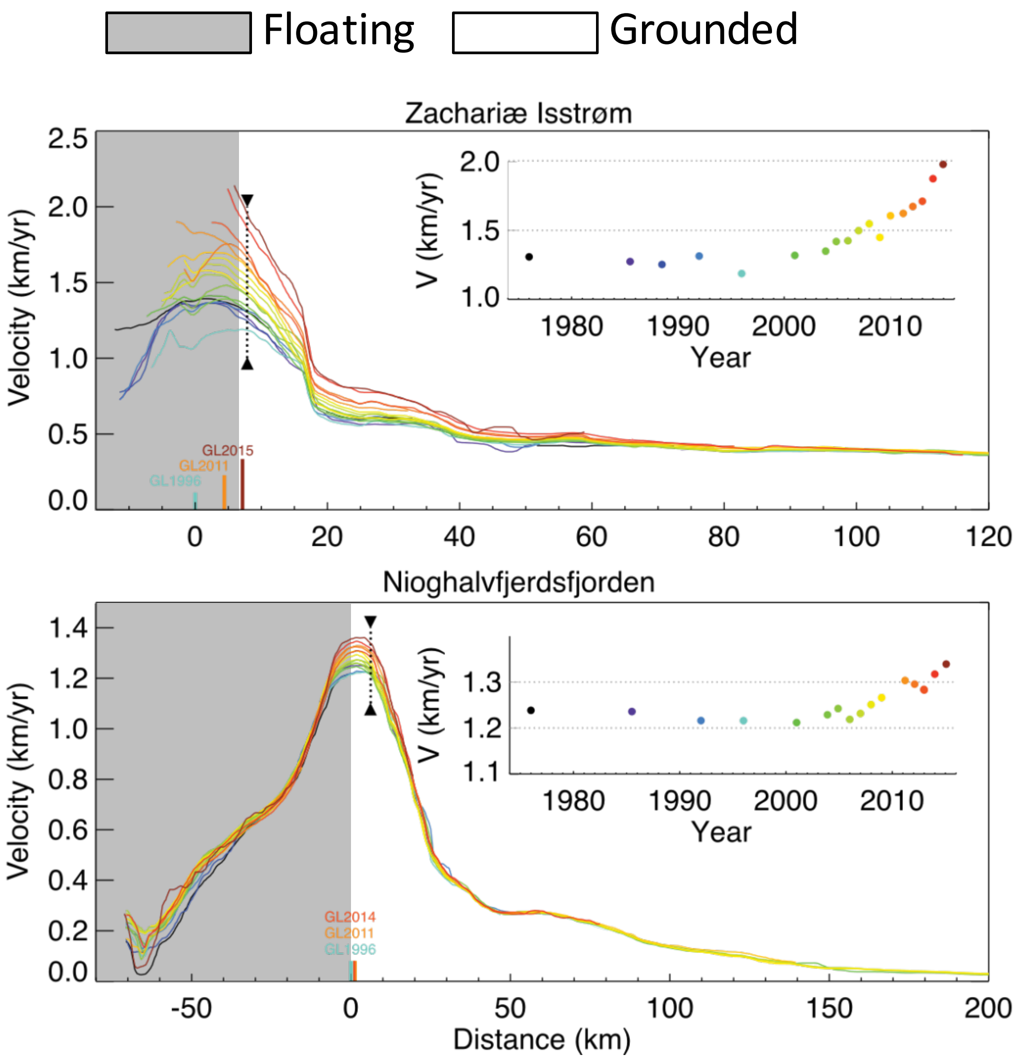
④ Ice velocity - Zachariae

- Landsat
- ERS
- RADARSAT
- ALOS/PALSAR
- ENVISAT/ASAR
- RADARSAT-2
- TerraSAR-X
- TanDEM-X
- COSMO-SkyMeD
- Sentinel-1a



④ Ice velocity - Zachariae



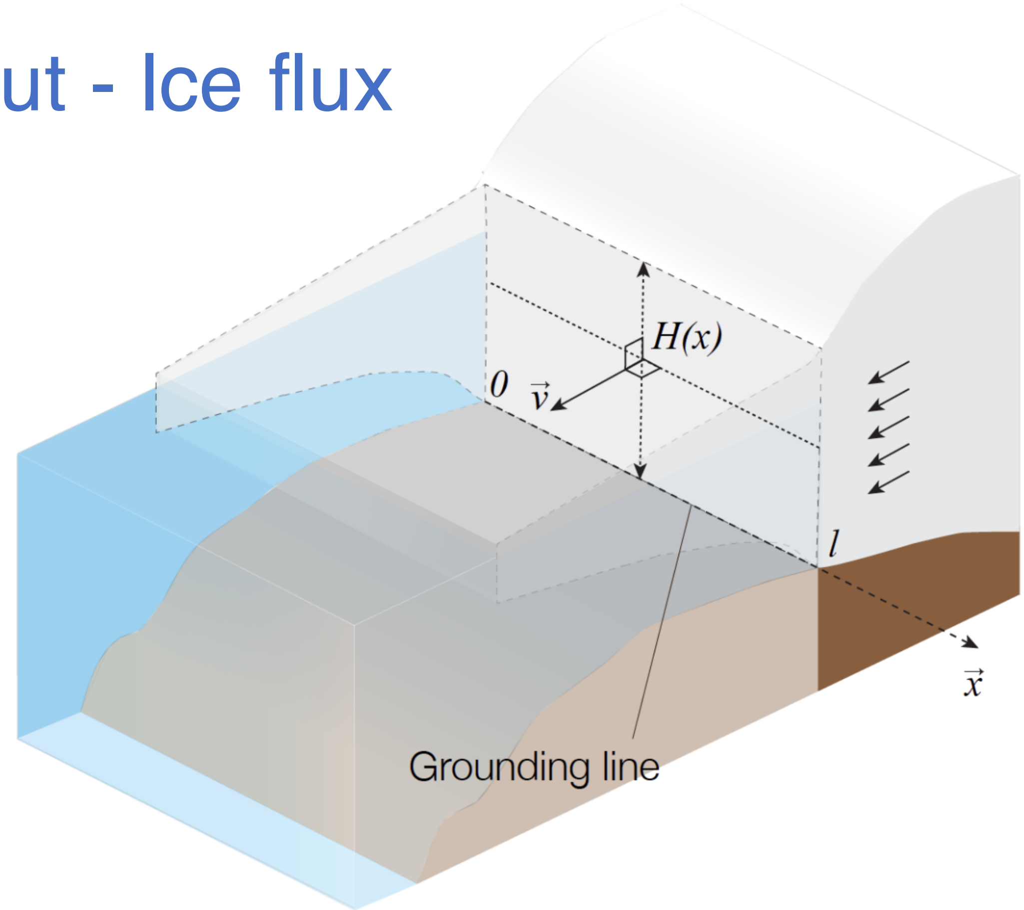


Zachariæ Isstrøm
55% increase since 2000
half of it after 2012

Nioghalvfjerdsfjorden
8 % since 2000

①+②+③+④ Output - Ice flux

- Assumptions :
  - Ice density is uniform
  - Ice flow is vertically uniform



$$\phi = \iint \vec{F}.dA$$

$$\phi = \rho_{ice} \int_{x=0}^{x=l} H(x)\vec{v}(x).d\vec{x}$$

$$\rho_{ice} = 917.2 = \text{ice density } [\text{kg.m}^{-3}]$$

$$H(x) = \text{ice thickness } [\text{m}]$$

$$\vec{v}(x) = \text{depth-averaged ice velocity } [\text{m.yr}^{-1}]$$

$$\phi = \text{ice flux } [\text{kg.yr}^{-1}][10^{-12}.\text{Gt.yr}^{-1}]$$

362 Gt ~ 1 mm SLR equivalent
1 Gt/day ~ 1mm/yr

Error Analysis

If you consider the error are independent then

$$F = \rho_{ice} \sum_{x=0}^{x=l} v_x H_x s_x$$

$$dF = \sqrt{\left(\frac{\partial F}{\partial v}\right)^2 + \left(\frac{\partial F}{\partial H}\right)^2}$$

Assume no error on ice density

$$\frac{\partial F}{\partial v} = \rho_{ice} \sum_{x=0}^{x=l} dv_x H_x s_x$$

$$\frac{\partial F}{\partial H} = \rho_{ice} \sum_{x=0}^{x=l} v_x dH_x s_x$$

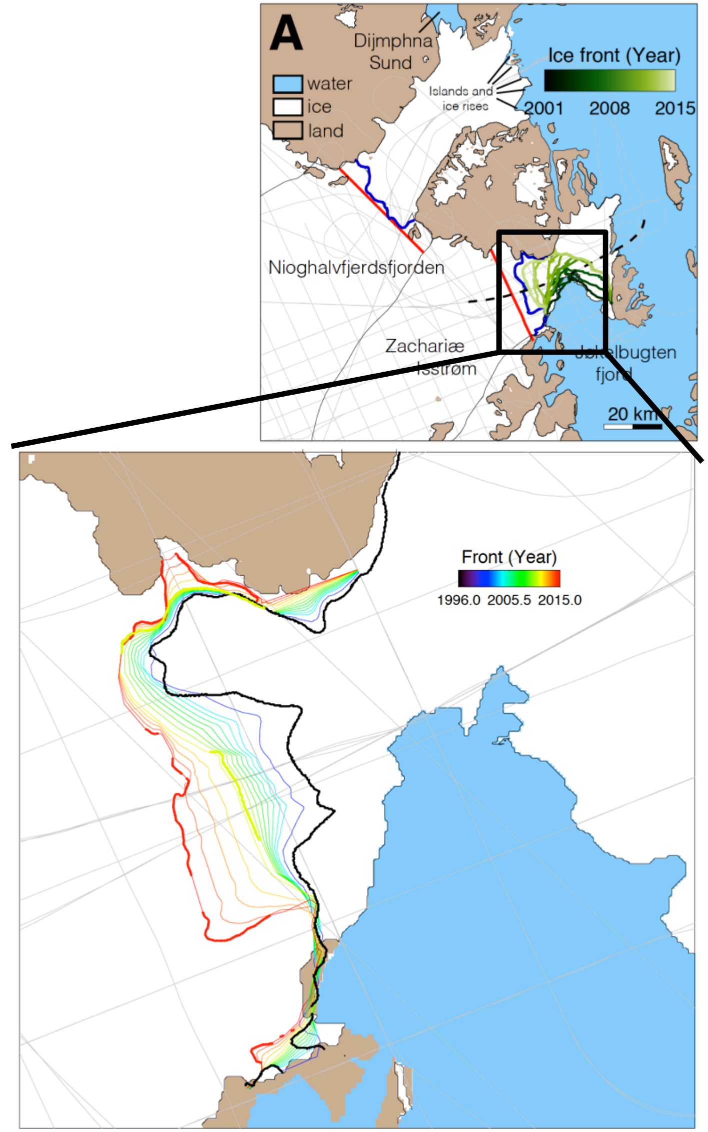
Error are generally around 5-10% of your ice discharge

Time series of ice discharge - 4 approaches

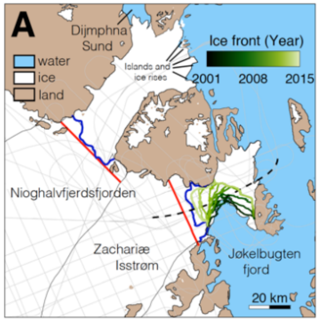
@GL (blue line)

- ② Time series of grounding line location
- ③ Time series of ice thickness
- ④ Time series of ice velocity

- As your grounding is retreating, ice above floatation is also contributing to the ice mass loss. (Correction is small)



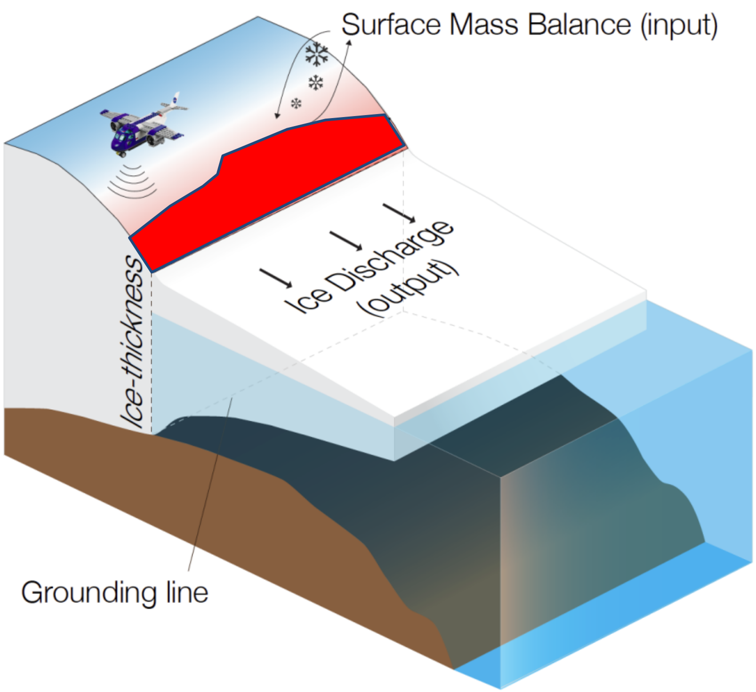
Time series of ice discharge - 4 approaches



@flight line

- ② Time series of grounding line location
- ③ Time series of ice thickness
- ④ Time series of ice velocity

- Fixed flux gates above the GL
- SMB+dhdt correction between flight line and GL



Time series of ice discharge - 4 approaches

Scaling

- Reference ice discharge on a flight line
  - SMB correction between flight line and grounding line
  - Better to take a year where glacier was stable (dhdt=0)
- Around the grounding line :
  - % of ice velocity change
  - % of ice thickness change from dh/dt
- α_v is measured on a small region close to the grounding line from the ratio v/v_{ref}
- $d\alpha_v$ is the standard deviation v/v_{ref}

Change in % (pointing to α_v and α_H)

$$F = F_{ref} + (\alpha_v + \alpha_H)F_{ref}$$

$$dF = \sqrt{\left(\frac{\partial F}{\partial F_{ref}}\right)^2 + \left(\frac{\partial F}{\partial \alpha_v}\right)^2 + \left(\frac{\partial F}{\partial \alpha_H}\right)^2}$$

$$\frac{\partial F}{\partial F_{ref}} = dF_{ref} + (\alpha_v + \alpha_H)dF_{ref}$$

$$\frac{\partial F}{\partial \alpha_v} = d\alpha_v F_{ref}$$

$$\frac{\partial F}{\partial \alpha_H} = d\alpha_H F_{ref}$$

Time series of ice discharge - 4 approaches

Scaling but no thickness measurements

- Reference ice discharge is your mean SMB
- % of ice velocity change
- Assume than ice thickness is small, generally an order of magnitude smaller than speed.

- Difficult to evaluate the errors :
  - Error on SMB.
  - Glacier might to be in balance for the year we have chosen
  - No thickness correction
  - But better than nothing !

Table flux

CReSiS flight line + SMB correction

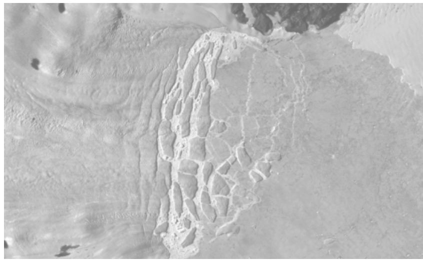
Mass conservation bed + gate at the grounding line

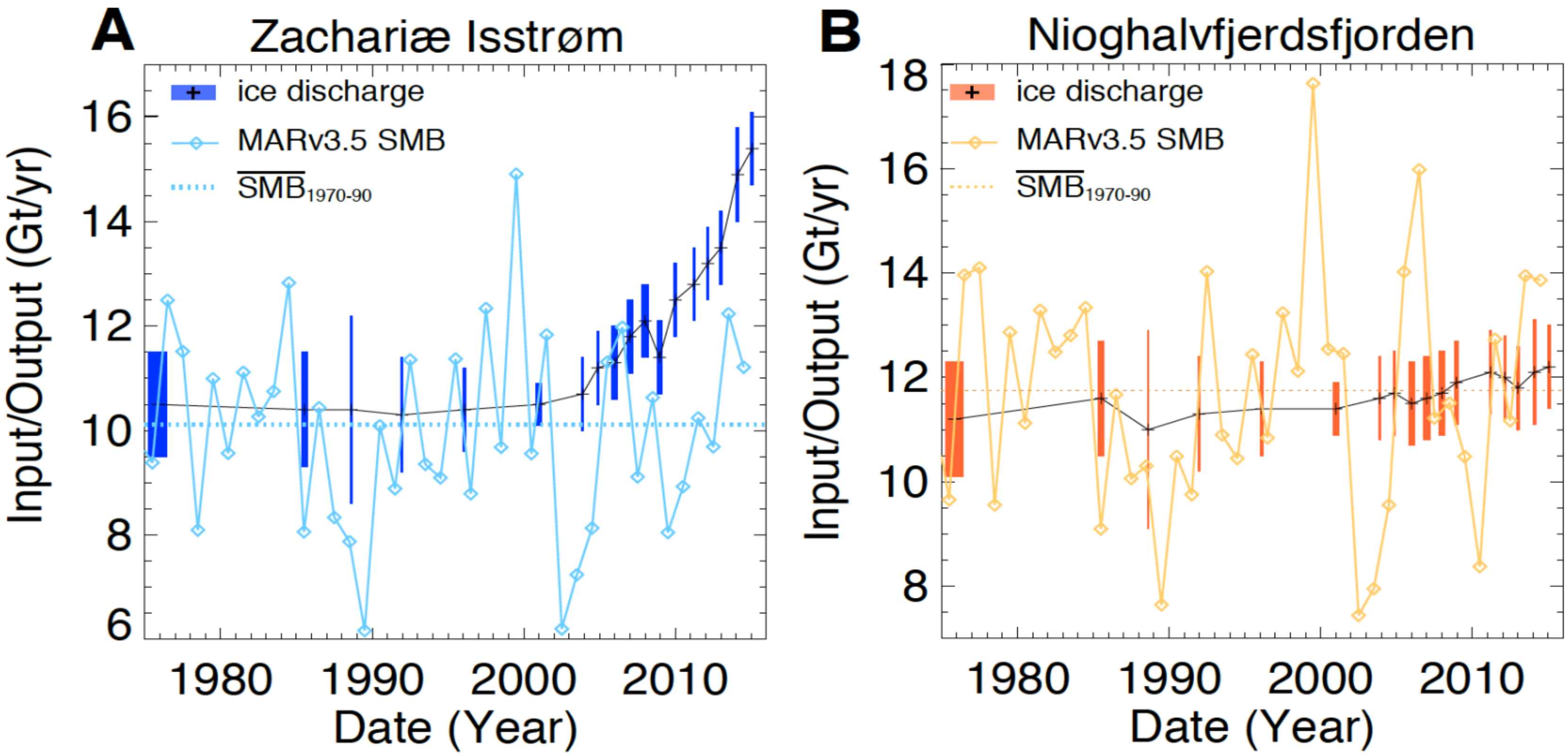
Scaling from ref flux

			Zachariæ Isstrøm						
		err in speed (m/yr)	Flux on CRESIS line (Gt/yr)	Corr SMB gate-GL2014 (Gt/yr)	Final (Gt/yr)	Flux @GL2014 (Gt/yr)	Scaled Flux (Gt/yr)	Ice vel. scale factor (%)	Ice thi. scale factor (%)
1975.3	**1976.4**	20	10.6 ± 1.1	-0.2 ± 0.1	**10.4 ± 1.2**	**10.1 ± 1.6**	**10.5 ± 1.0**	-0.7 ± 4.2	0.5 ± 0.9
1985.3	**1985.7**	25	10.4 ± 0.8	-0.2 ± 0.1	**10.2 ± 0.8**	**9.8 ± 1.2**	**10.4 ± 1.1**	-1.6 ± 5.0	0.5 ± 0.9
1988.6	**1988.7**	70	10.0 ± 0.8	-0.2 ± 0.1	**9.8 ± 0.9**	**9.8 ± 1.7**	**10.4 ± 1.8**	-1.6 ± 12.5	0.5 ± 0.9
1991.9	**1992.0**	25	10.5 ± 0.5	-0.2 ± 0.1	**10.3 ± 0.5**	**9.8 ± 1.5**	**10.3 ± 1.1**	-2.3 ± 5.0	0.5 ± 0.9
1996.0	**1996.2**	8	9.9 ± 0.6	-0.2 ± 0.1	**9.7 ± 0.7**	**9.3 ± 1.2**	**10.4 ± 0.8**	-1.6 ± 2.2	0.5 ± 0.9
2000.8	**2001.2**	5	10.7 ± 0.4	-0.2 ± 0.1	**10.5 ± 0.4**	**9.9 ± 0.9**	**10.5 ± 0.4**	0.0 ± 0.0	0.0 ± 0.9
2003.8	**2004.0**	5	10.8 ± 0.4	-0.2 ± 0.1	**10.6 ± 0.4**	**10.5 ± 1.0**	**10.7 ± 0.7**	2.9 ± 1.7	-0.9 ± 0.9
2004.8	**2005.0**	5	11.5 ± 0.4	-0.2 ± 0.1	**11.3 ± 0.5**	**11.1 ± 1.0**	**11.2 ± 0.7**	7.6 ± 1.7	-1.2 ± 0.9
2005.8	**2006.2**	2	11.4 ± 0.4	-0.2 ± 0.1	**11.2 ± 0.4**	**10.6 ± 1.0**	**11.3 ± 0.7**	8.9 ± 1.2	-1.6 ± 0.9
2006.8	**2007.2**	2	11.8 ± 0.4	-0.2 ± 0.1	**11.7 ± 0.4**	**11.1 ± 1.0**	**11.8 ± 0.7**	13.6 ± 1.2	-1.9 ± 0.9
2007.8	**2008.2**	2	12.2 ± 0.4	-0.2 ± 0.1	**12.1 ± 0.4**	**11.5 ± 1.1**	**12.1 ± 0.7**	17.3 ± 1.2	-2.2 ± 0.9
2008.8	**2009.1**	5	11.5 ± 0.4	-0.2 ± 0.1	**11.3 ± 0.5**	**10.7 ± 1.1**	**11.4 ± 0.7**	10.4 ± 1.7	-2.5 ± 0.9
2009.9	**2010.1**	5				**12.2 ± 1.5**	**12.5 ± 0.7**	21.9 ± 1.7	-2.8 ± 0.9
2011.2	**2011.3**	7	12.7 ± 0.4	-0.2 ± 0.1	**12.5 ± 0.5**	**12.2 ± 1.2**	**12.8 ± 0.7**	24.3 ± 2.0	-3.1 ± 0.9
2012.1	**2012.2**	7	13.4 ± 0.5	-0.1 ± 0.1	**13.2 ± 0.6**	**12.8 ± 1.3**	**13.2 ± 0.7**	29.0 ± 2.0	-3.5 ± 0.9
2012.9	**2013.1**	5	12.9 ± 0.5	-0.1 ± 0.1	**12.8 ± 0.5**	**12.7 ± 1.2**	**13.5 ± 0.7**	32.4 ± 1.7	-4.0 ± 0.9
2014.0	**2014.2**	15	14.8 ± 0.7	-0.1 ± 0.1	**14.6 ± 0.7**	**14.4 ± 1.5**	**14.9 ± 0.9**	46.0 ± 3.3	-4.5 ± 0.9
2015.0	**2015.2**	5	14.9 ± 0.5	-0.1 ± 0.1	**14.8 ± 0.6**	**14.6 ± 1.4**	**15.4 ± 0.7**	51.7 ± 1.7	-4.9 ± 0.9

Mass balance

Calving front of Zachariæ during 2014 summer





MB = D-SMB

Flux calculation

- You can mix the different approaches but remember :
  - Ice discharge has to be evaluated **at the grounding line**, proper correction have to be made if you are computing your flux above the GL.
  - Change in **speed is the main control** on the ice discharge.
  - Change in ice thickness is an order of magnitude smaller but not always negligible.
  - I usually expect **mean SMB (input) and ice discharge (output)** to be close before 2000.

Conclusion for the IOM

- Only methods that looks at the **dynamic history** of the glaciers, most relevant for modelers in order to capture the ice physics and run forward prediction.
  - Although other methods can be used to calculate mass balance, unless co-temporanious ice velocity speedup is also observed, it is difficult to conclude with certainty that a region is dynamically unbalanced.
- How the ice dynamic will **change in near future** is one of the main concern/uncertainties for SLR prediction.
- Each methods as its weaknesses :
  - Need a lot of different inputs with each associated errors : SMB, thickness, velocity and GL. Some of them are difficult to get.
- Looks at large input/output fluxes and sometimes small changes in mass balance.

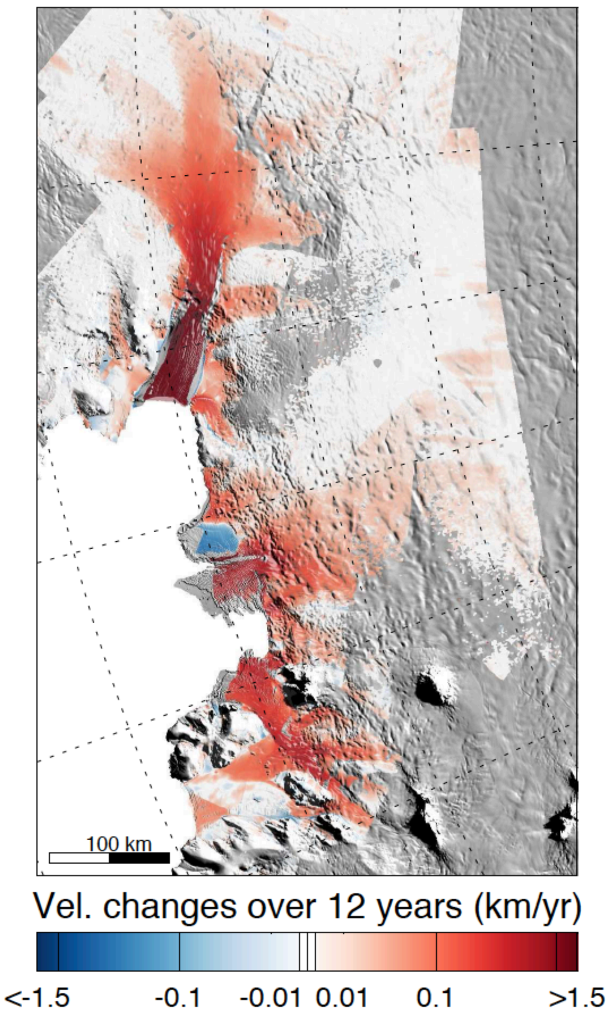
Perspectives

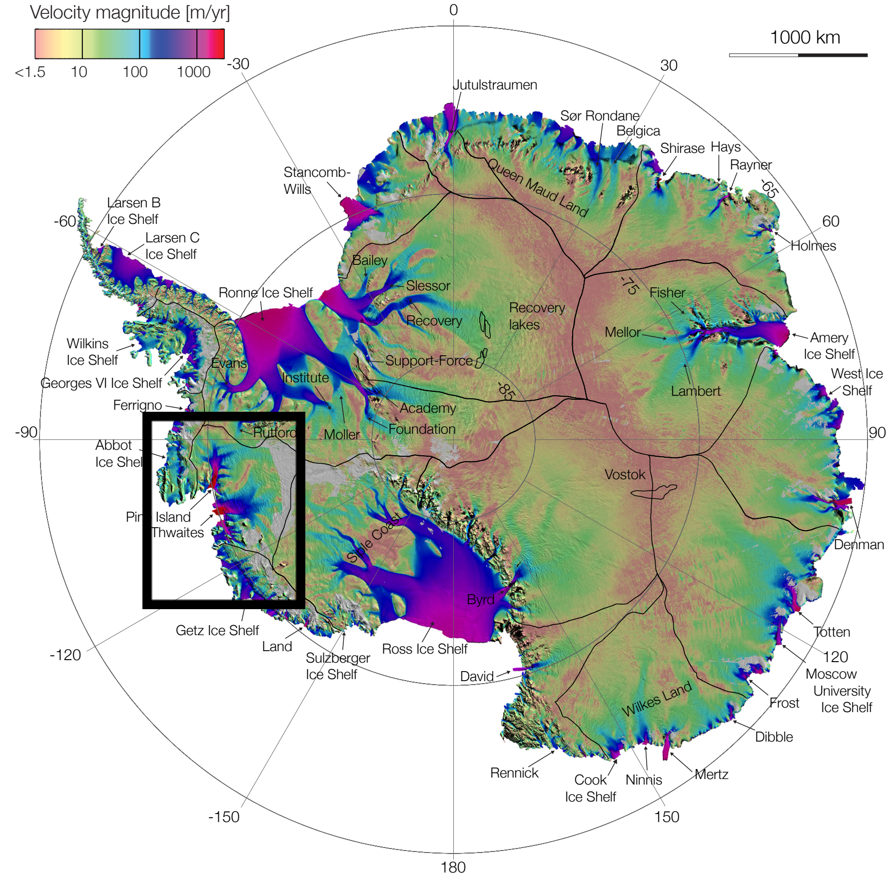
- Continuous mapping from satellite sensors.
  - Extend in past with images released from spy satellites or old aerial photographies
- Ice thickness measurements are still the weak link for measuring ice discharge.
  - Especially in south, southeast parts of Greenland and in East Antarctica or Antarctic Peninsula.
- With 20-30 years of remote sensing data, we still have a snapshot of ice dynamic of the ice sheet:
  - What will be the major source of ice loss, dynamic or SMB ?

Additional Slides – the examples of Amundsen Sea Embayment, West Antarctica

Amundsen Sea Sector

Y2008 - Y1996

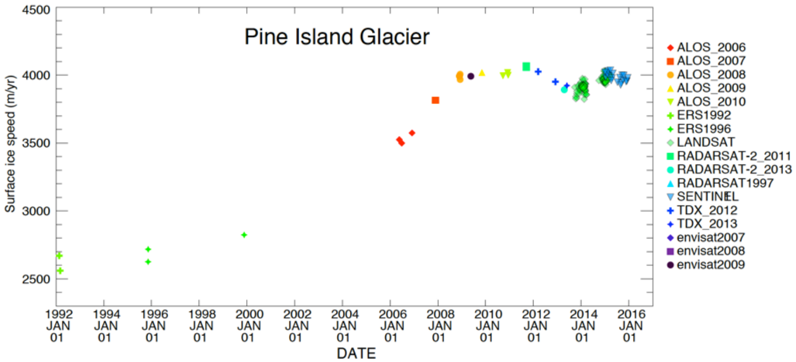


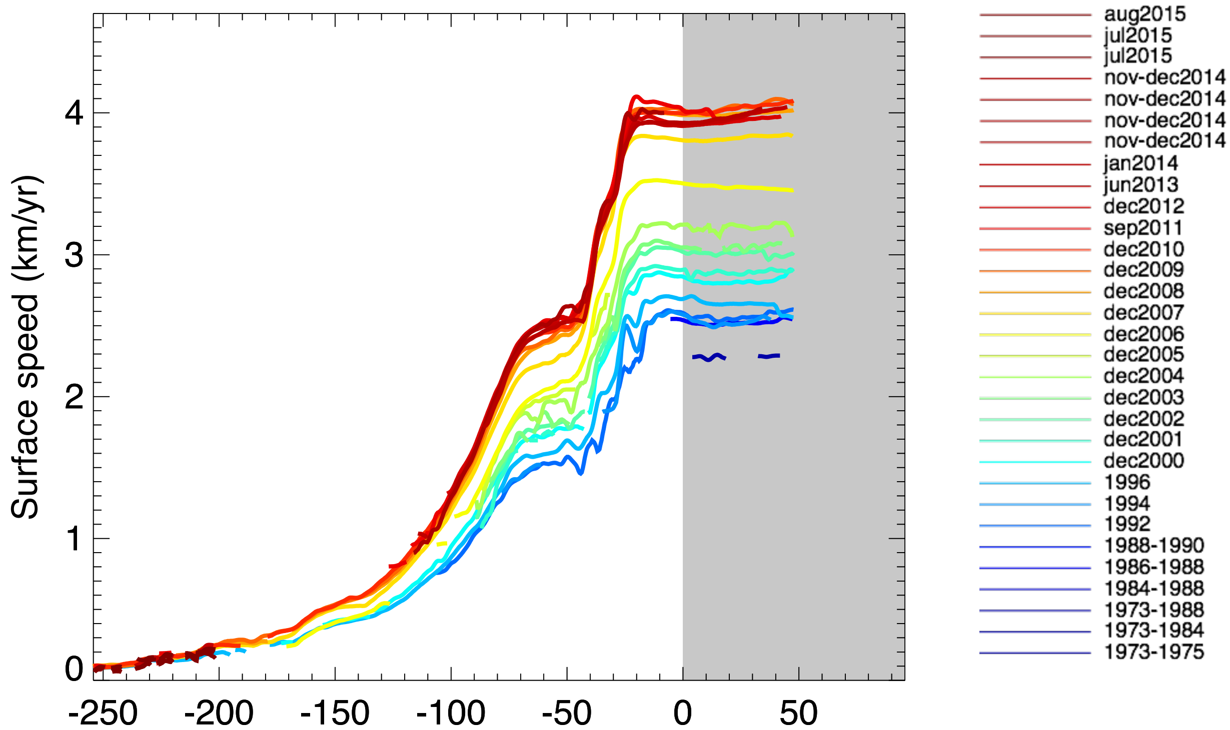


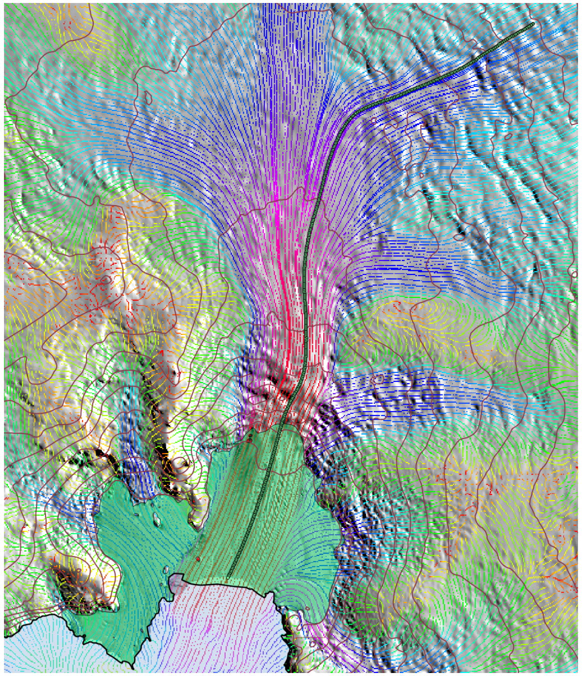
- Drain by 6 main glaciers
  - equivalent than 2/3 of Greenland flux

Amundsen Sea Sector – Pine Island

- Ice-shelf flow speed increased by 1.7 km/yr or 75% between 1973 and 2015, but no further acceleration since 2008-2009

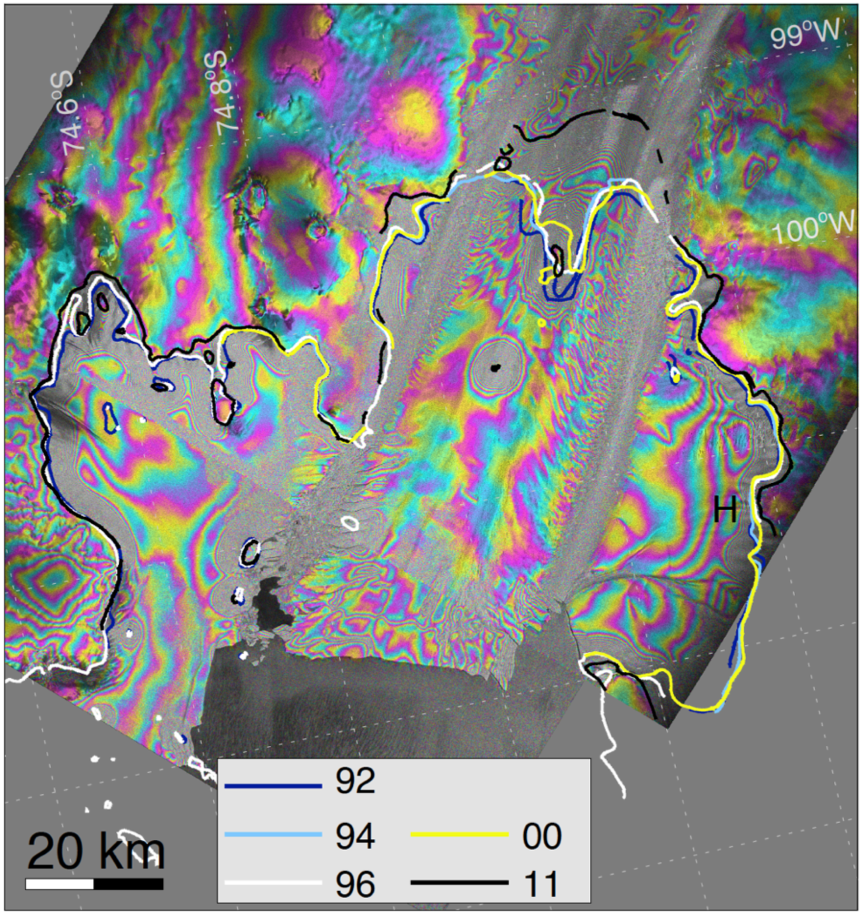






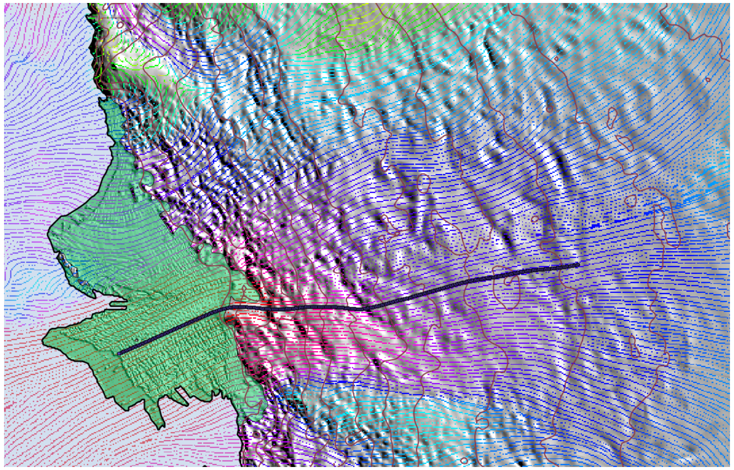
Amundsen Sea Sector - Pine Island

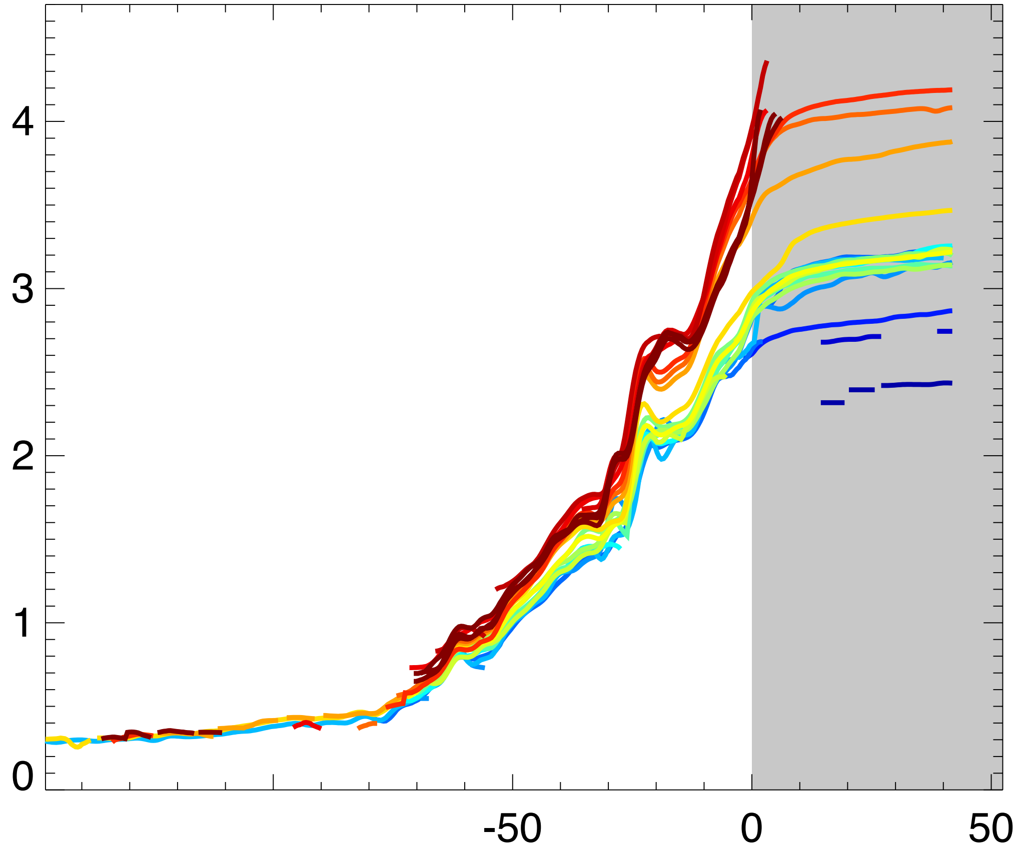
- Grounding line is now localized at the inland end of the ice plain.



Rignot et al. 2014

Amundsen Sea Sector - Thwaites

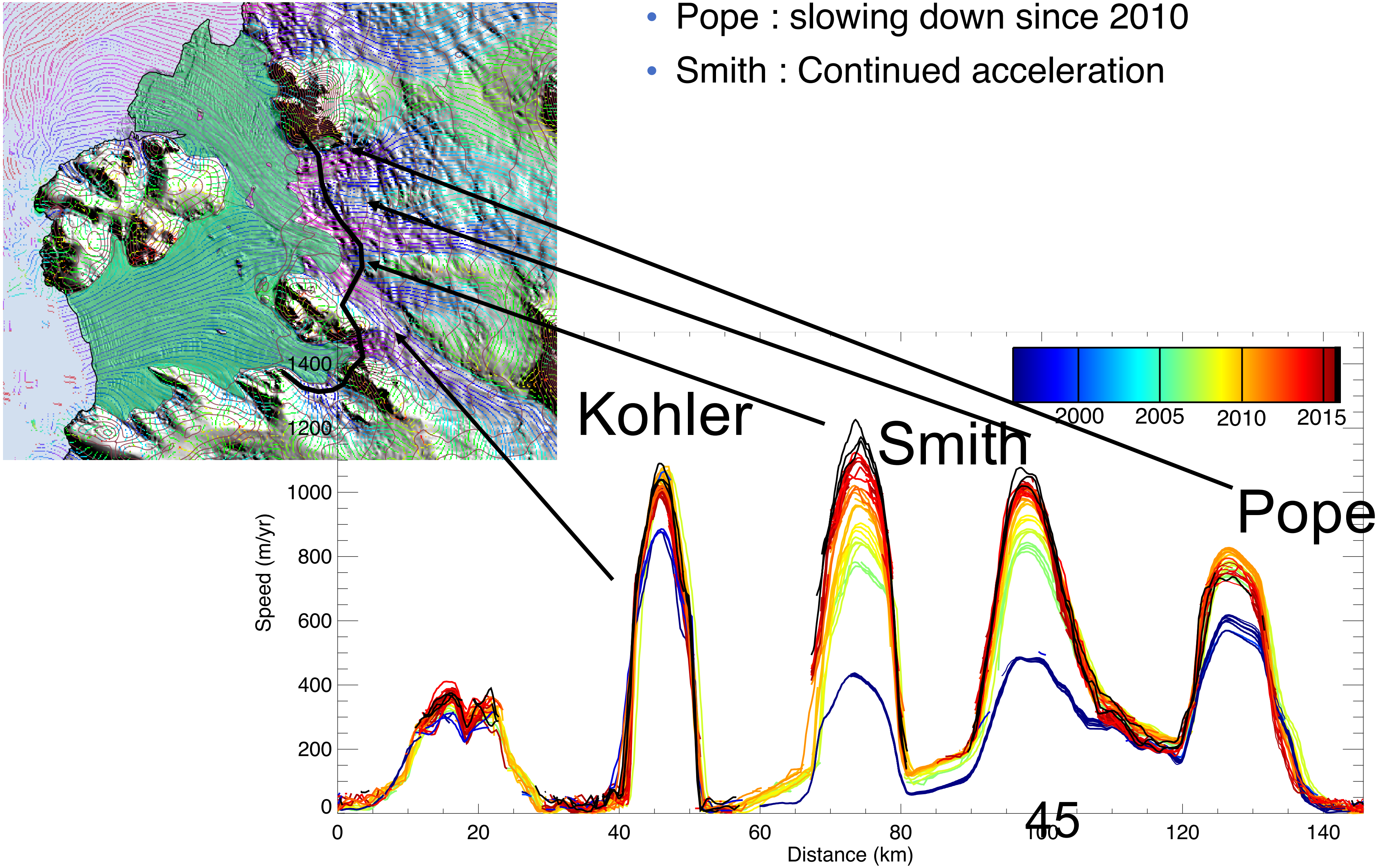




- 3 phases :
  - 1973-1996 acceleration by 33%,
  - 1996-2006 stable,
  - 2006-2013 acceleration by 33%

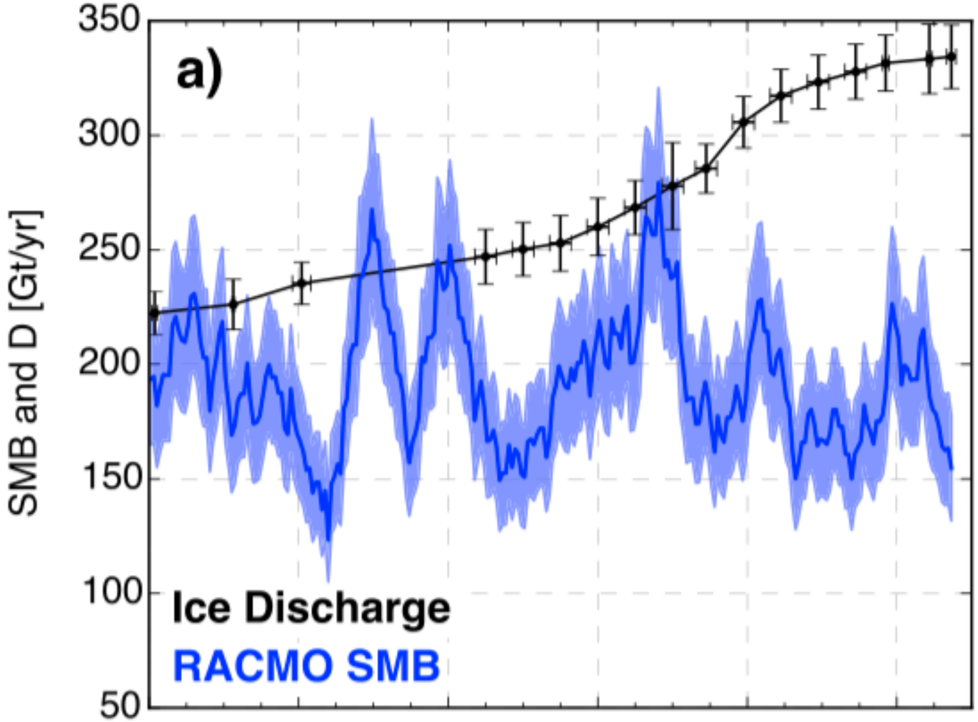
Amundsen Sea Sector – Crosson & Dotson Ice Shelves

- Pope : slowing down since 2010
- Smith : Continued acceleration



Amundsen Sea Sector

- The total ice discharge has **increased** by 77% since 1973. • The grounding lines of all glaciers has **retreated** by tens of kilometers.
  - SLR = 4.5 ± 0.1 mm for 1992–2013 periods



Mouginot et al. 2014

Sutterley et al. 2014