Fresh Water fluxes from Iceberg

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Fresh water fluxes from icebergs

- Ice shelves and iceberg calving = ~equal paths of freshwater flux (**FWF**) between the Antarctic ice cap and the Southern Ocean.
- For Greenland ice cap, figures are quite similar even if surface melting plays a more significant role.
- ***Basal and surface melt waters*** distribute over the upper few 100’s m of coastal water.
- ***Icebergs*** drift and melt *farther* away from land.

- Northern hemisphere icebergs in general <10km^2 i.e. “small” icebergs
- Southern ocean: large icebergs (> 100km^2) transport ice far away from Antarctic coast into ocean interior.
  - **Fragmentation**: diffusive process generating plumes of small icebergs melting more efficiently than large ones.

- ***OGCM*** *with iceberg module show*
  - *Basal ice-shelf and iceberg melting have different effects on circulation*
  - *Icebergs induce significant changes in modeled ocean circulation and sea-ice conditions around Antarctica or in the northern Atlantic.*
  - Ice transport of away from coast by icebergs and associated FWF cause these changes.
- Important role plaid by icebergs and their FWF in the climate system.
- ***No direct reliable estimate of iceberg FWF for validation or forcing of models.***

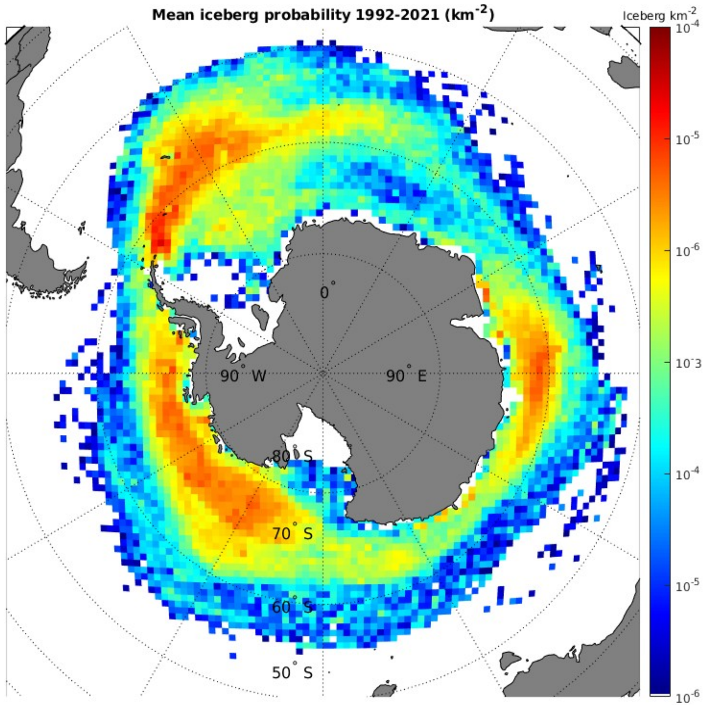
Small icebergs data base : ALTIBERG

- Since 2008 **ALTIBERG** project : small iceberg (<10km²) database (North and South hemispheres)
  - detection method by analysis of altimeter waveforms.
- Hypotheses: ice σ_0=Cst and freeboard=28m, used to compute area from backscatter and range.

- Individual icebergs: time, location, σ_0, area, distance to nadir
- ***14*** altimeters: *ERS1, ERS2, TOPEX/Poseidon, ENVISAT, JASON1, JASON2, CRYOSAT, ALTIKA, HY2A, JASON3, Sentinel3 A and B, HY2B and GEOSAT*.

- **G**ridded products :
  - 1992-2021: *monthly* mean iceberg probability, (100km polar and 1°x2°lat/lon grids), mean iceberg area and mean volume of ice
  - **2010-2021:** *biweekly* mean iceberg probability, (50km polar), mean iceberg area and mean volume of ice

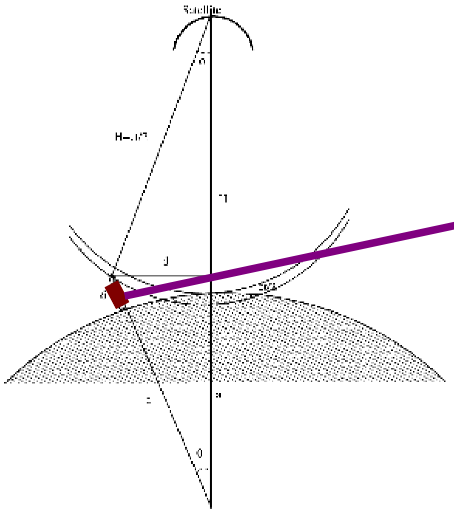
Mean Prob 1992-2021

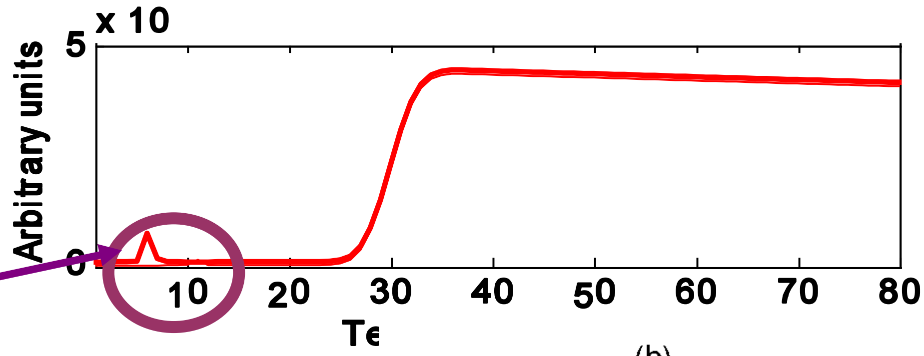


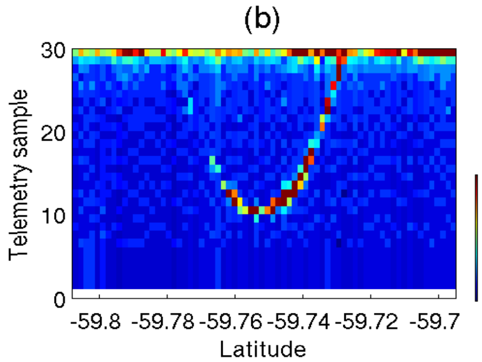
Icebergs detection from Pulse Limited (LRM) data

- Targets emerging from the sea : detectable signature in the noise part of Altimeter WF [*Tournadre et al , 2008, 2012*].
- In the waveform space the signature is a parabola determined by the orbital parameters. Detection algorithm: detection of parabola in the WF ***thermal noise part*** (TNP).
- Works only in open water

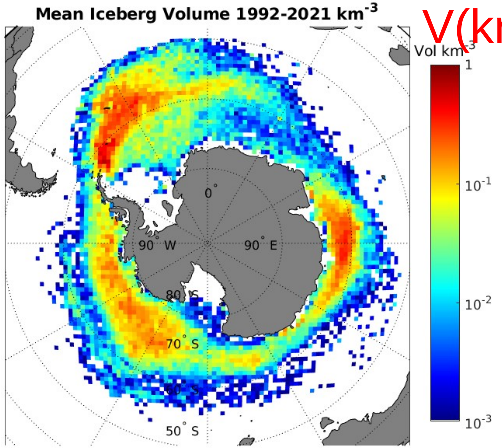
Peak of   before mean sea level



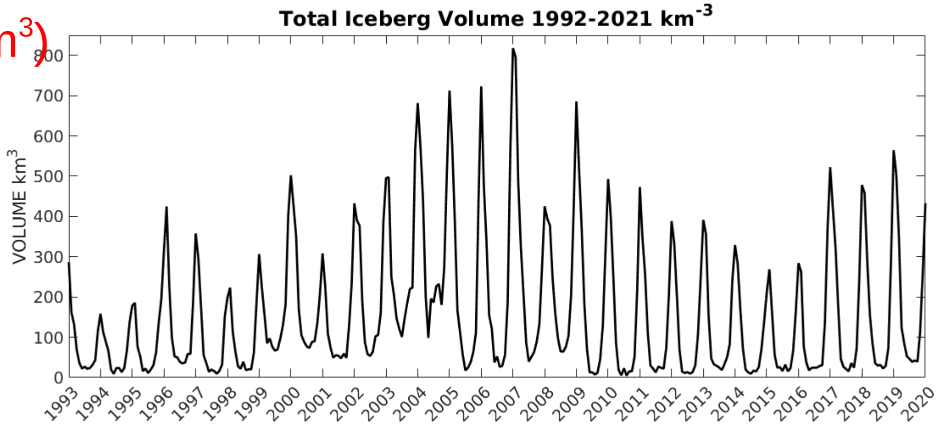




30 years of Ice volume 1992-2021

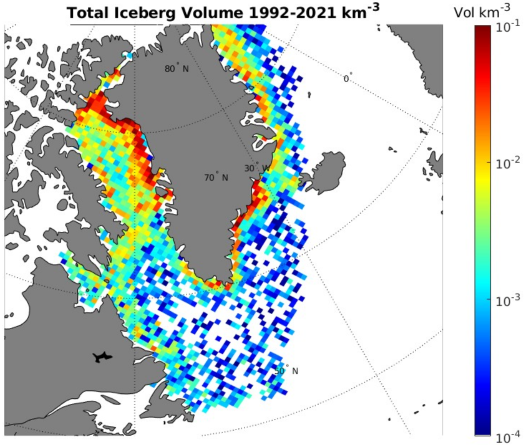


V(km^3)

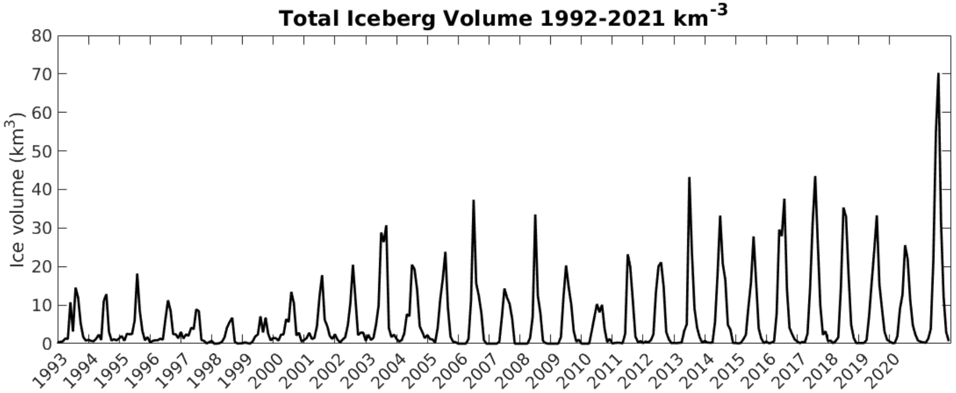


Strong interannual variability related to the calving of giant icebergs (e.g. C19, A68 ...)

V(km^3)



Significant increase of ice volume around Greenland ~2-3%/year



Iceberg drifting and melting model

For each detected iceberg a drifting and melting model is applied to estimate its trajectory, melting and the associated FWF.

Classical motion and thermodynamics equations for iceberg (*see Biggs et al 1997, Gladstone et al 2001*)

Equation of motion

$$M\frac{d\vec{V}_i}{dt} = -Mf\,\vec{k}\wedge\vec{V}_i + \vec{F}_w + \vec{F}_a + \vec{F}_s + \vec{F}_r + \vec{F}_p$$

where
$\vec{V_i}$ iceberg horizontal velocity,
M its mass, f the Coriolis parameter,
t the time, $\vec{k}$ the vertical unit vector,
$\vec{F_p}$ water pressure gradient force exerted by the water on the iceberg,
$\vec{F_w}$ drag exerted on the submarine part of the iceberg by the surrounding water
$\vec{F_a}$ atmospheric drag on the iceberg's above-water extent,
F_s drag exerted by any sea-ice field through which the iceberg moves
$\vec{F_r}$ is the wave radiation force

Where the drags are defined by

$$\vec{F}_j = \frac{1}{2}\rho_j C_j A_j |\vec{V}_j - \vec{V}_i|(\vec{V}_j - \vec{V}_i)$$

where
j : air (a), water (w) or sea-ice (s),
ρ and C density and the drag coefficient of the medium,
A effective cross-section area in the current flow
$\vec{V_j}$ velocity of the considered medium.

F_a, F_s, F_r are small compared to water force and are neglected (*Bigg et al 1997*)

$$M\frac{d\vec{V}_i}{dt} = -Mf\,\vec{k}\wedge\vec{V}_i + \vec{F}_w$$

Iceberg drifting and melting model

- Acceleration term neglected based on the expectation << other terms in the momentum balance
- Coriolis force also neglected

$$\vec{F}_w = Mf\,\vec{k} \wedge \vec{V}_i$$
$$\frac{1}{2}\rho_w C_w A_w |\vec{V}_w - \vec{V}_i| (\vec{V}_w - \vec{V}_i) = Mf\,\vec{k} \wedge \vec{V}_i$$
$$\vec{V}_i \approx \vec{V}_w$$

- In a first order approximation **the iceberg is assumed to drift at the current speed.**

$$\boxed{V_i = V_w}$$

- Same results by *Wagner et al (2017)*, using an Analytical Model of Iceberg Drift , and by *Bouhier et al (2018)* using analysis of large icebergs drift.

Iceberg thermodynamics : evolution of volume

Evolution of iceberg volume given by

$$\rho_i \frac{d(HWT)}{dt} = \rho_i(-LWM_b - H(L+W)(M_e+M_v))$$

L length, W width, H thickness, ρ_i ice density, M_b basal melting, M_v side erosion, M_e wave erosion

Basal Melting: Thermal turbulent exchange of Hellmer and Olbers (1989)

$$M_b = \rho_w C_{pw} \gamma_T \rho_i \frac{T_b - T_w}{L_H - C_{pi} \Delta T}$$

M_b met rate (in m/s^{-1}), $L_H = 3.34.10^5$ J.kg^{-1} fusion latent heat,
$C_{pw} = 4180$ J.kg^{-1}.K^{-1} $C_{pi} = 2000$ J.kg^{-1}.K^{-1} heat capacity of seawater and ice
$T_b = -0.057 S_w + 0.0939 - 7.64 \cdot 10^{-2} P_w$ freezing temperature at the base of the iceberg
S_w and P_w salinity (in PSU) and pressure (in MPa),
$\Delta T = T_i - T_b$ temperature gradient within the ice at the iceberg base

$$\gamma_T = \frac{u^*}{2.12 \log(u^* l \nu^{-1}) + 12.5 Pr^{2/3} - 9}$$

where $P_r = 13.1$ molecular Prandtl number of sea water,
$l = 1$ m mixing length scale, $\nu = 1.83 \cdot 10^{-6}$ water viscosity
u^* friction velocity. $C_D = 0.0015$ $u \simeq V_w - V_i$, by $u^{*2} = C_D u^2$.

Impossible to estimate γ_T at each time step : use 2 values corresponding to the lower and larger values from *Bouhier et al (2018) by analysis of the basal melting of large icebergs, also in agreement with values from Jansen et al (2007)*

$$\gamma_T = 5 \cdot 10^{-5} m.s^{-1}$$

$$\gamma_T = 2.9 \cdot 10^{-4} m.s^{-1}$$

- ***Side melting and Wave erosion***
  - S_s significant wave height,
  - T_w water temp.
  - A_i sea ice coverag***e***
- ***Iceberg roll over empirical stability criterion***
  - *D Draft*
- ***Constants and parameters used***

$$M_v = 7.62 \cdot 10^{-3} T_w + 1.29 \cdot 10^{-3} T_w^2$$
$$M_e = \frac{1}{12} S_s \left(1 + \cos\left(\pi A_i^3\right)\right)\left(T_w + 2\right)$$

$$L < \sqrt{0.92 D^2 + 58.32 D}$$
$$D = \rho_i / \rho_w H \approx 0.9 H$$

Iceberg interior temperature $T = -4^oC$
Drag coefficient $C_d = 0.0015$
Sea water heat capacity $C_{pw} = 4180\,\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$;
Ice heat capacity $C_{pi} = 2000\,\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
Sea water viscosity $v = 1.83 \cdot 10^{-6} m^2 \cdot s^{-1}$ at 0^0C
Prandtl number $Pr = 13.1$
Sea water density $\rho_w = 1025\,\mathrm{kg \cdot m^{-3}}$
Iceberg ice density $\rho_i = 917\,\mathrm{kg \cdot m^{-3}}$
Ice fusion latent heat $L_h = 3.34 \cdot 10^5\,\mathrm{J \cdot kg^{-1}}$
Sea water freezing temperature $T_b =$

Forcing parameters

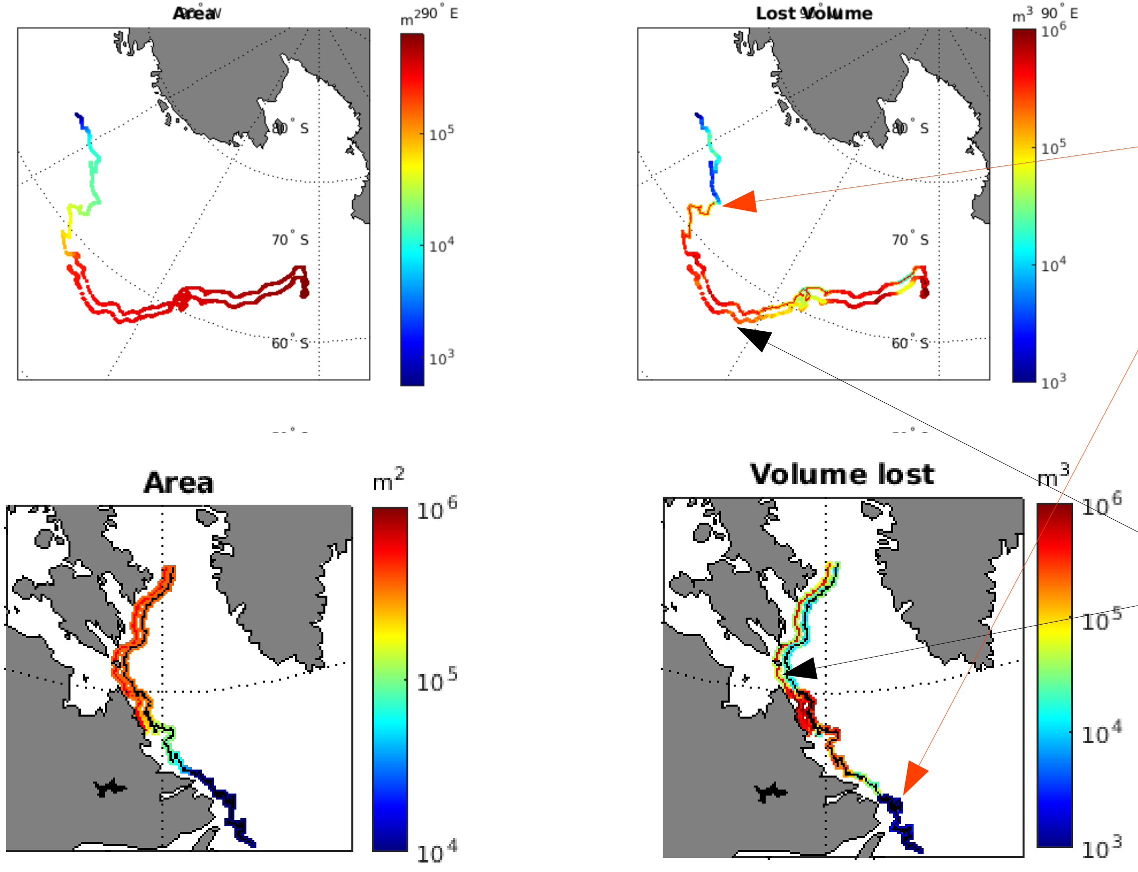
The model depends on *surface current speed, SST, sea state and γ_T*

Use of *satellite* and *model* Current and SST data for Greenland,

Satellite only for the Southern Ocean

Forcing parameters						
zone	Antarctic		Greenland			
γ_T	5.10^{-5}	$2.9\ 10^{-4}$	$5\ 10^{-5}$	$2.9\ 10^{-4}$	$5\ 10^{-5}$	$2.9\ 10^{-4}$
Current speed	AVISO DUACS	AVISO DUACS	AVISO DUACS	AVISO DUACS	TOPAZ model	TOPAZ model
SST	ODYSEA	ODYSEA	ODYSEA	ODYSEA	TOPAZ	TOPAZ
Sea State	WW3	WW3	WW3	WW3	WW3	WW3

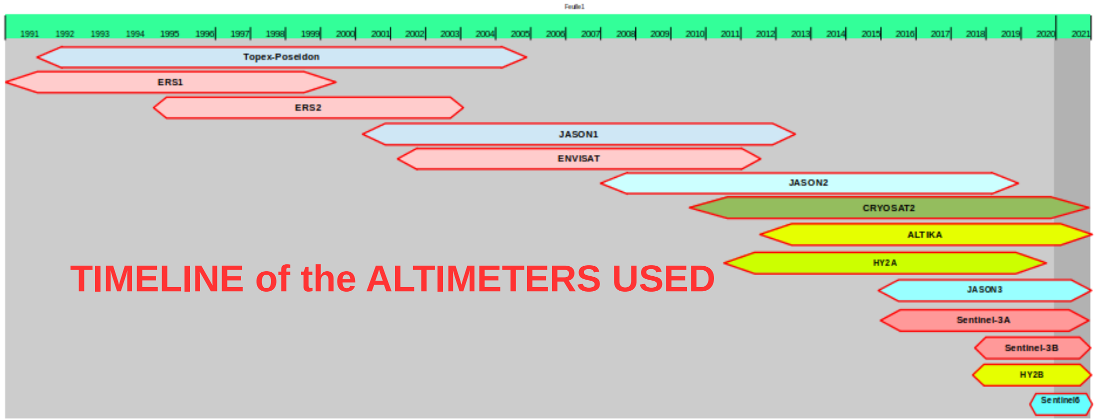
Example of trajectories



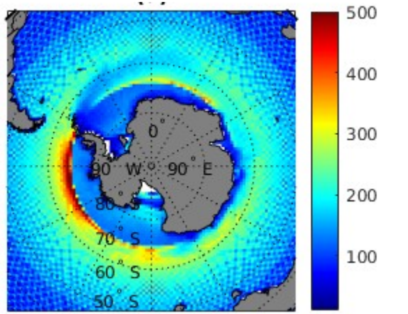
$\gamma_T = 5 \cdot 10^{-5} m.s^{-1}$

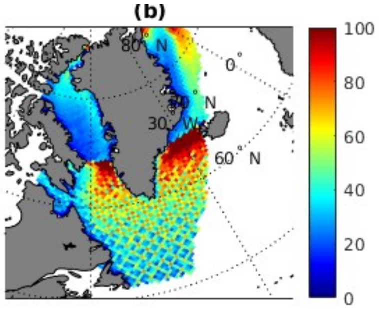
$\gamma_T = 2.9 \cdot 10^{-4} m.s^{-1}$

Taking into account the number of altimeters

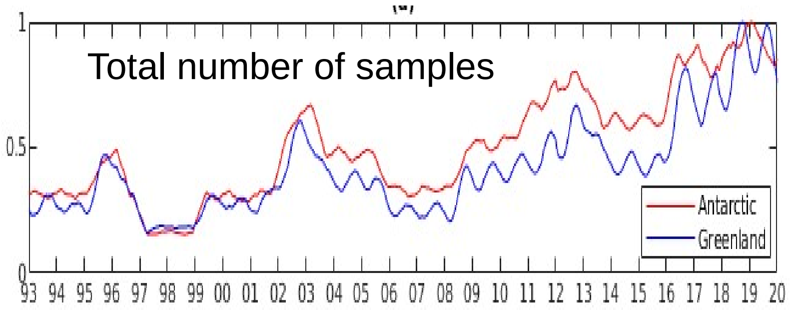


- Number of operating altimeters from 2 in the 90's to 7 at present:
- Difference of orbit inclination :66° for Jason series 98° for ERS, Envisat
- **A coefficient depending** on monthly altimeters sampling coverage applied to each iceberg
- **Daily FWF estimated on a regular polar grid using the iceberg volume loss.**
- **FWF converted to mm/day**





Mean number of altimeter samples

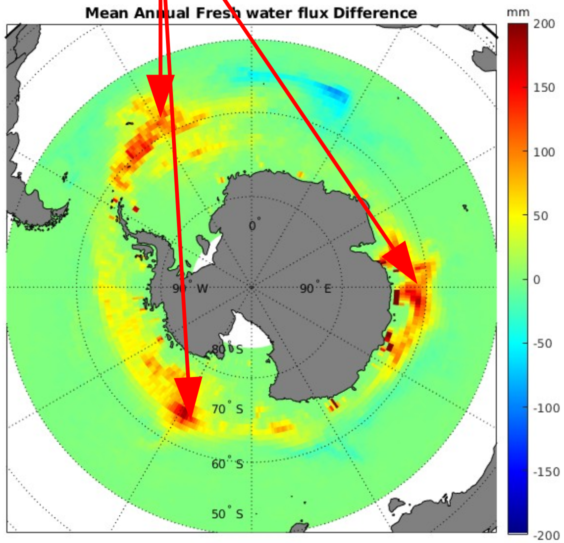


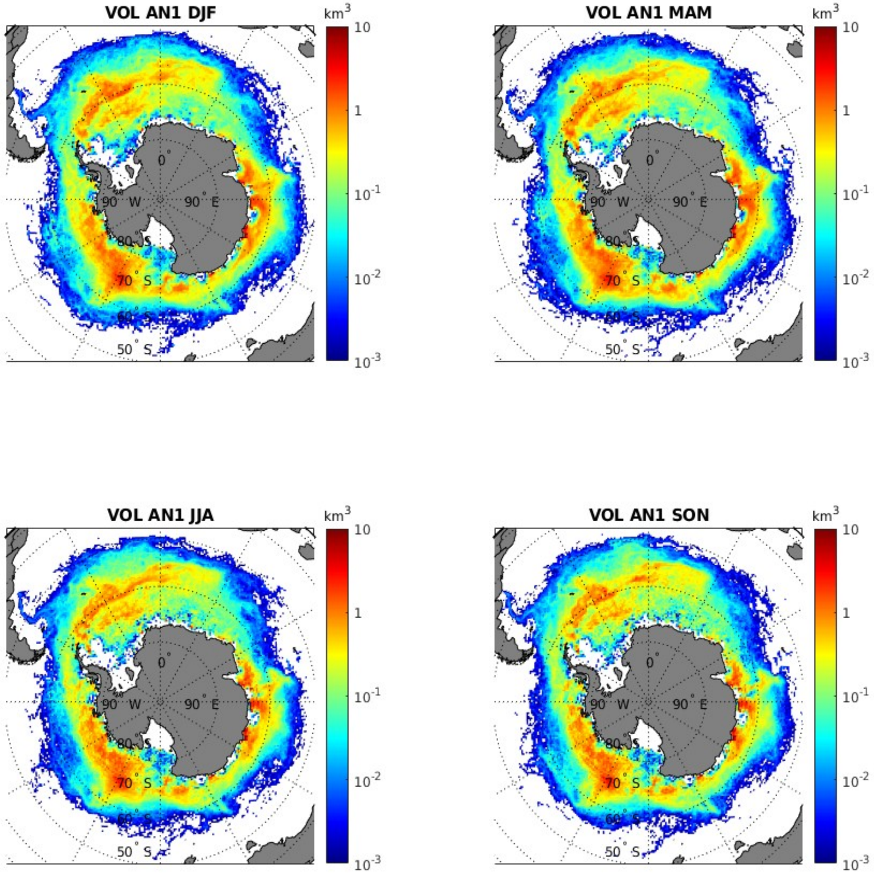
Trajectories of individual icebergs 2002-2003

Daily FWF 2002-2003

Seasonal FWF in the Southern Ocean runs AN1 & AN2

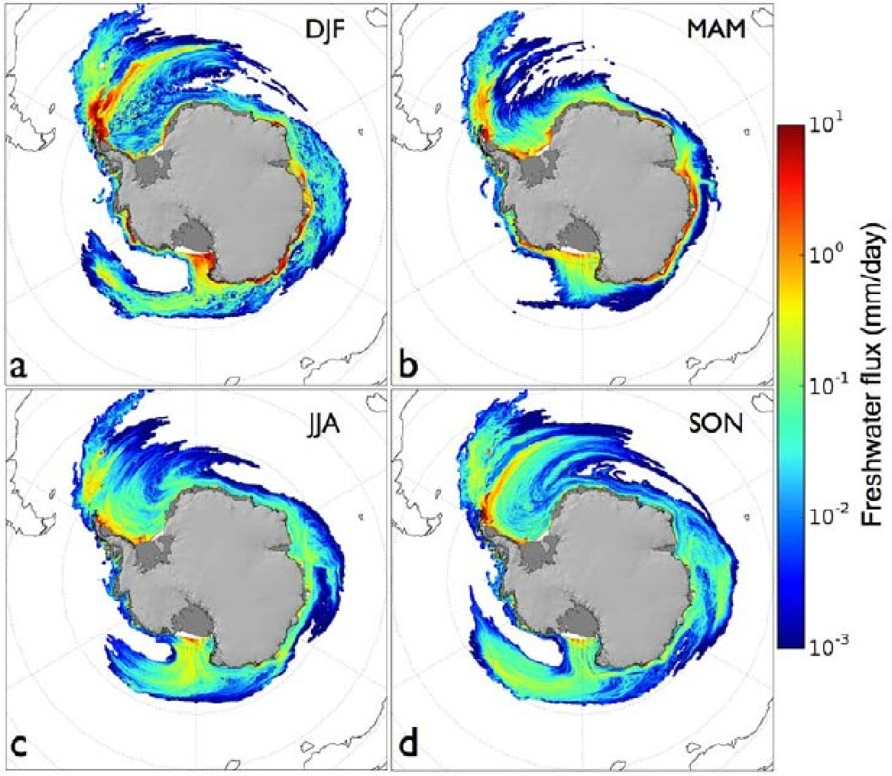
- AN1: γ_T=5 10^{-5}
  - side and wave erosion dominant over basal melting
- AN2: γ_T= 2.9 10^{-4}
  - Basal melting dominant





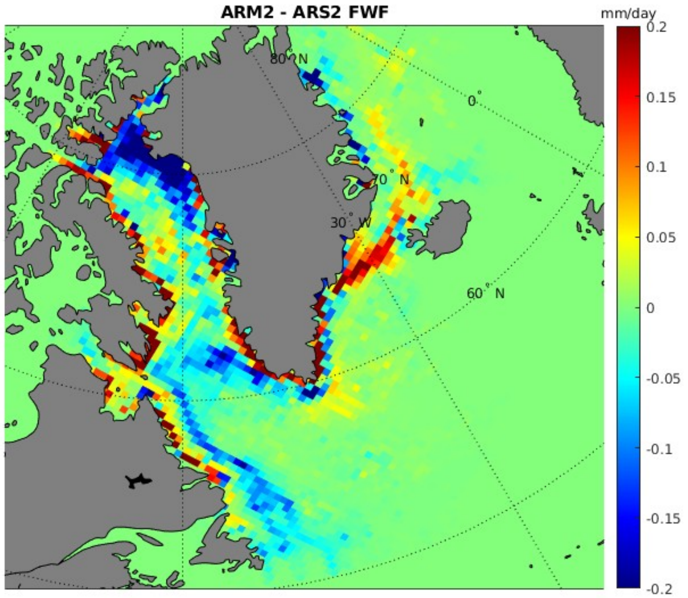
Same order of magnitude of FWF compared to OGCM output (here Merino et al 2016)

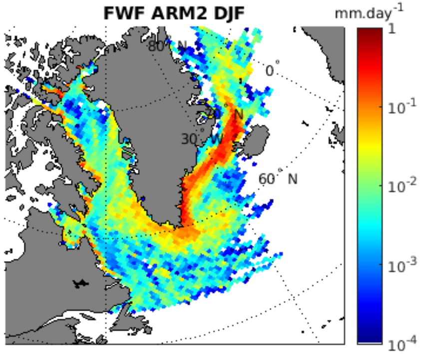
- Very different patterns
- OGCM have problem to transport ice far away from the continent because they don’t include large icebergs breaking that transport the major part of the volume of ice

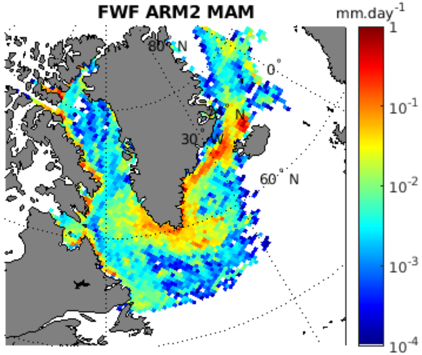


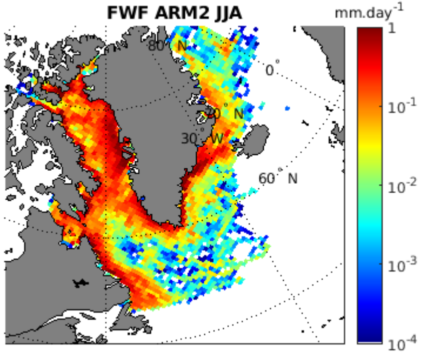
Seasonal FWF around Greenland

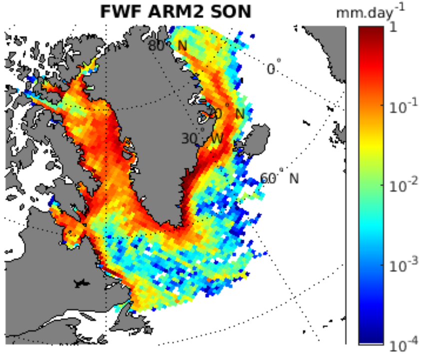
- ARS2: γ_T=2.9 10^{-4} Satellite data
  - Larger FW in North Baffin Sea
- ARM2: γ_T= 2.9 10^{-4} model data
  - Larger FW along Labarador ans East Greenland



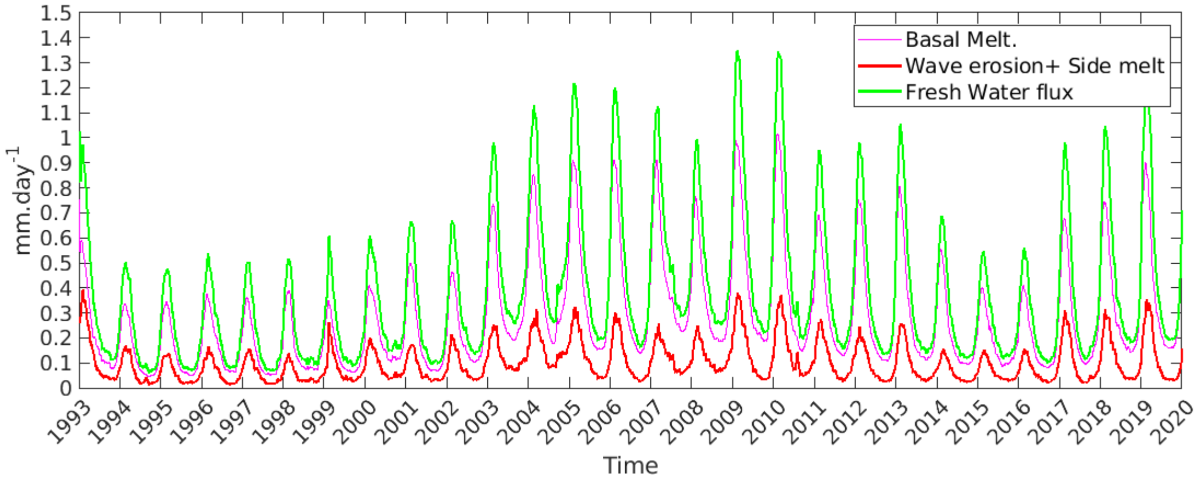






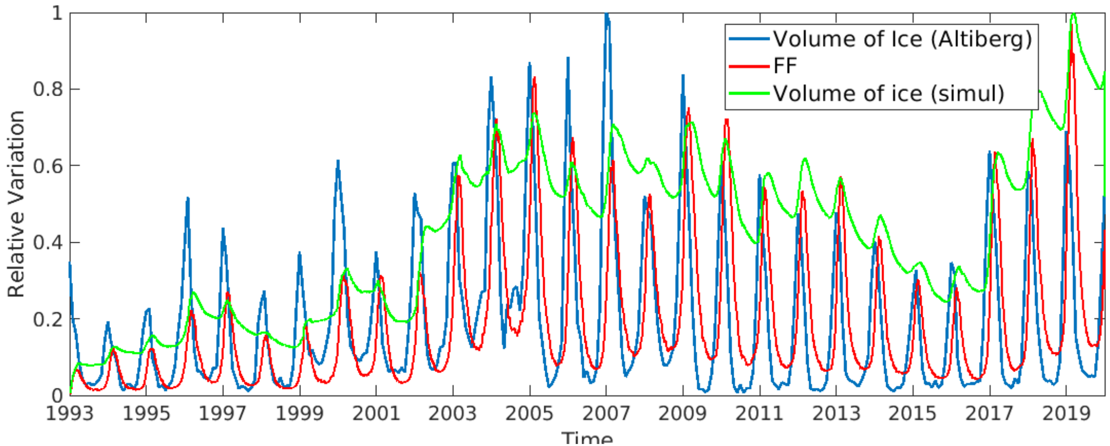


Total Fresh Water Flux 1993-2020 Southern Hemisphere

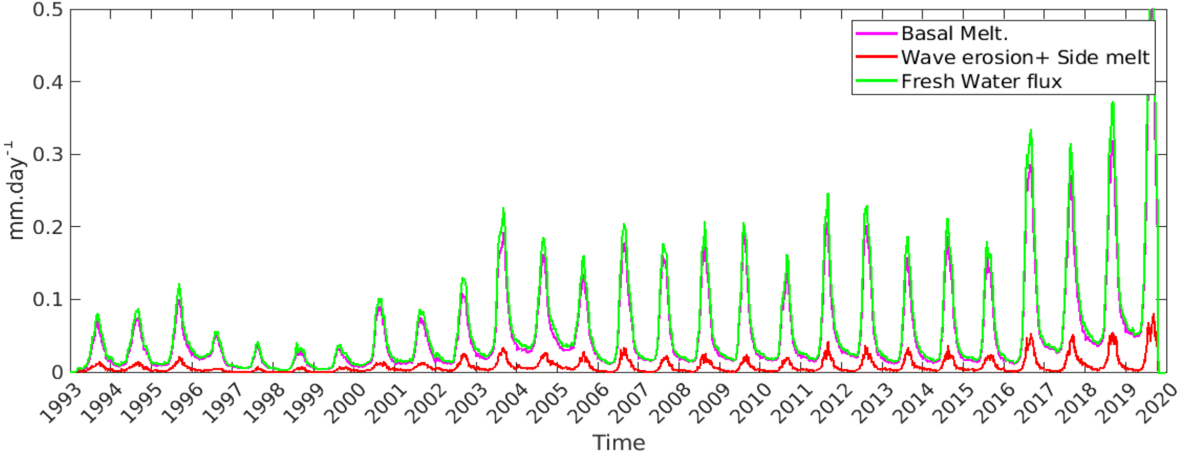


- Mean FWF in the Southern Ocean run AN2,
- Basal Melting (dominant)
- Wave erosion and Side melting (~20%)

- Comparison of FWF variation, Volume of ice an volume of ice in open sea from ALTIBERG
- Good agreement of the relative variation of the 3 parameters

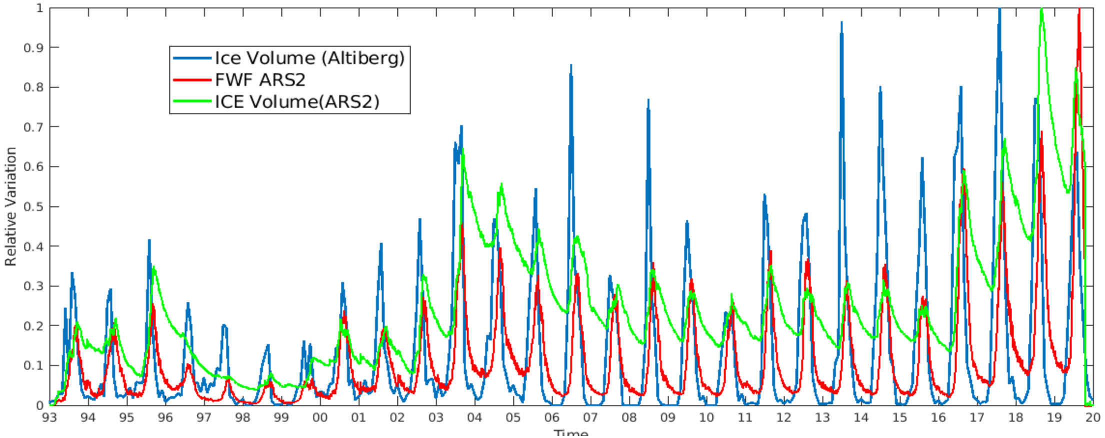


Total Fresh Water Flux 1993-2020 Northern Hemisphere



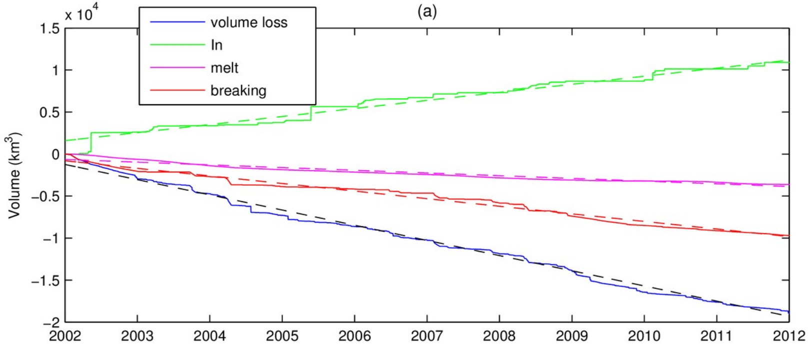
- Mean FWF around Greenland run ARS2,
- Basal Melting (dominant)
- Wave erosion and Side melting (~10%)
- Significant increase

- Comparison of FWF variation, Volume of ice an volume of ice in open sea from ALTIBERG
- Relative variations of the 3 parameters more complex
- Further analysis of the 4 runs to be conducted



Summary

- Icebergs are an important component of the climate system and more and more ocean circulation model include iceberg module
- Altimeters are very powerful tools to detect, analyze small icebergs and to create iceberg climatology of probability of presence and volume of ice
- Up to now no direct estimate of fresh water fluxes from icebergs
- Tournadre et al 2015 fresh water flux from large icebergs through basal melting.
- FWF same order of magnitude as Precipitation in the Southern Ocean
- Very different geographical patterns compared to OGCM with icebergs module, further away from the coasts
- Analysis of the uncertainties by comparison of the different runs.




Merci
Thank You