

living planet symposium | BONN 23–27 May 2022

TAKING THE PULSE
OF OUR PLANET FROM SPACE



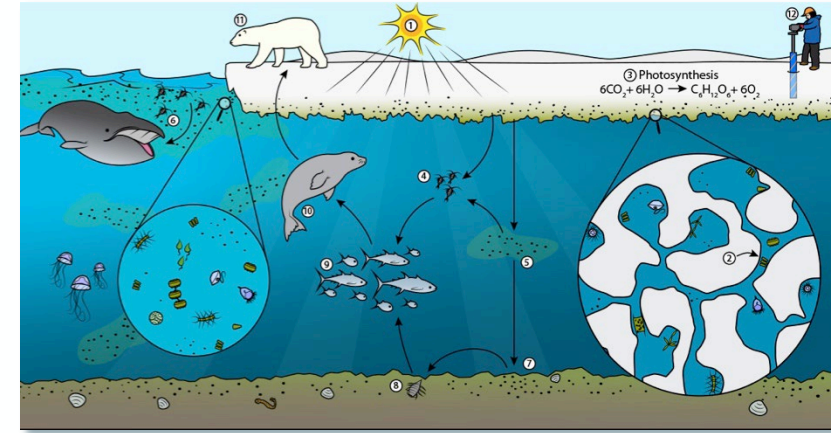
Evaluation of a snow depth product using Ka/Ku dual-frequency altimetry

S.Fleury, F.Garnier, M.Bocquet, A.Carret, F.Rémy
LEGOS/OMP/CNRS

2022/05/23

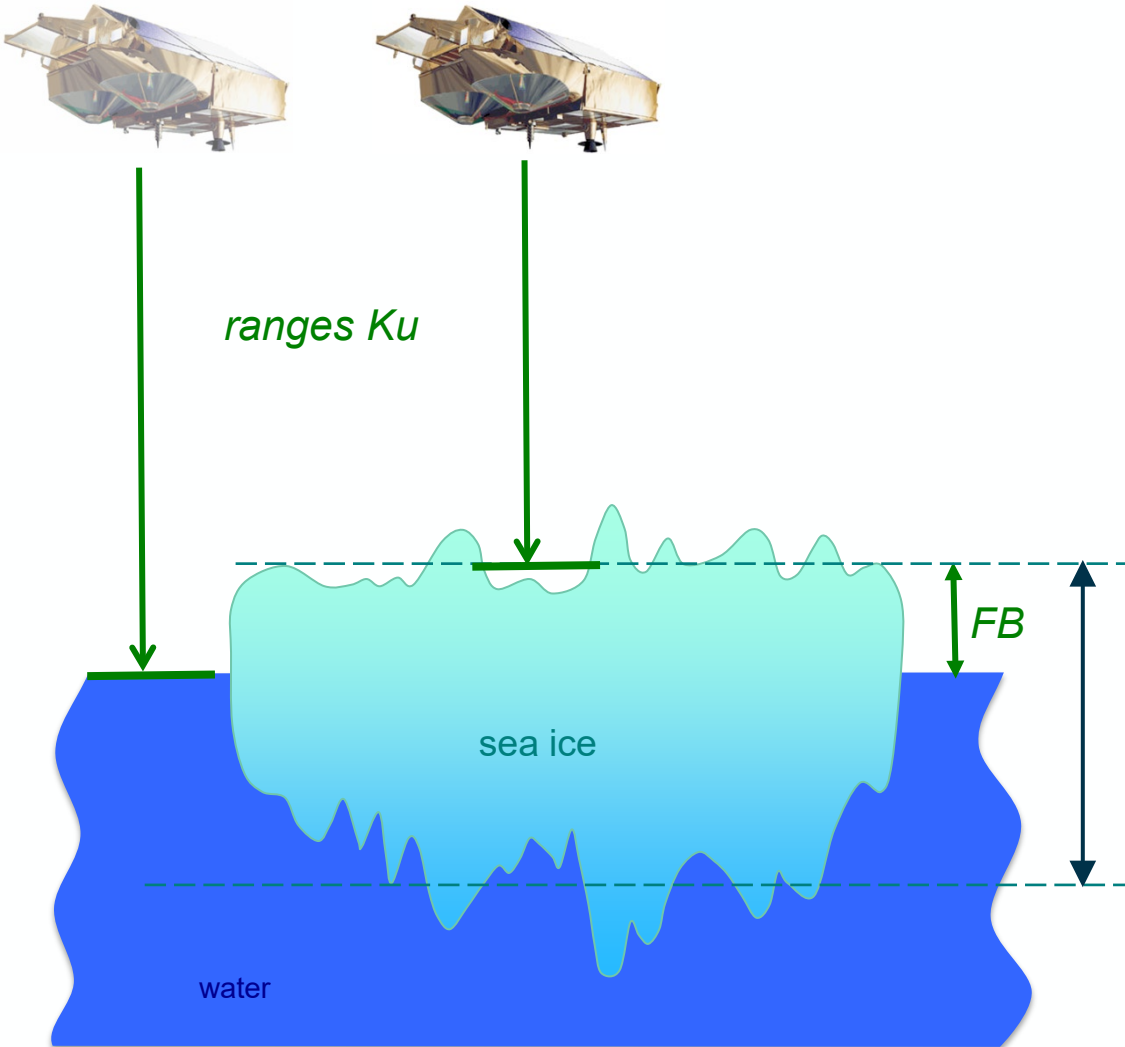
Importance of Snow over Sea ice

- snow acts as a thermal insulator
=> it slows down the growth of the sea ice
- snow acts as an UV reflector
=> it increases the ice albedo
- snow acts as a light filter
=> it limits planktonic development under the ice
- snow acts as a gas filter
=> it limits ocean/atmosphere gas exchanges
- snow increases ice friction
=> it limits ice breakers progression



1 Key Knowledge Gap [IPCC Special Report of the Ocean and Cryosphere (SROC)]
“Snow depth on sea ice is essentially unmeasured,
limiting mass balance estimates and ice thickness retrievals”

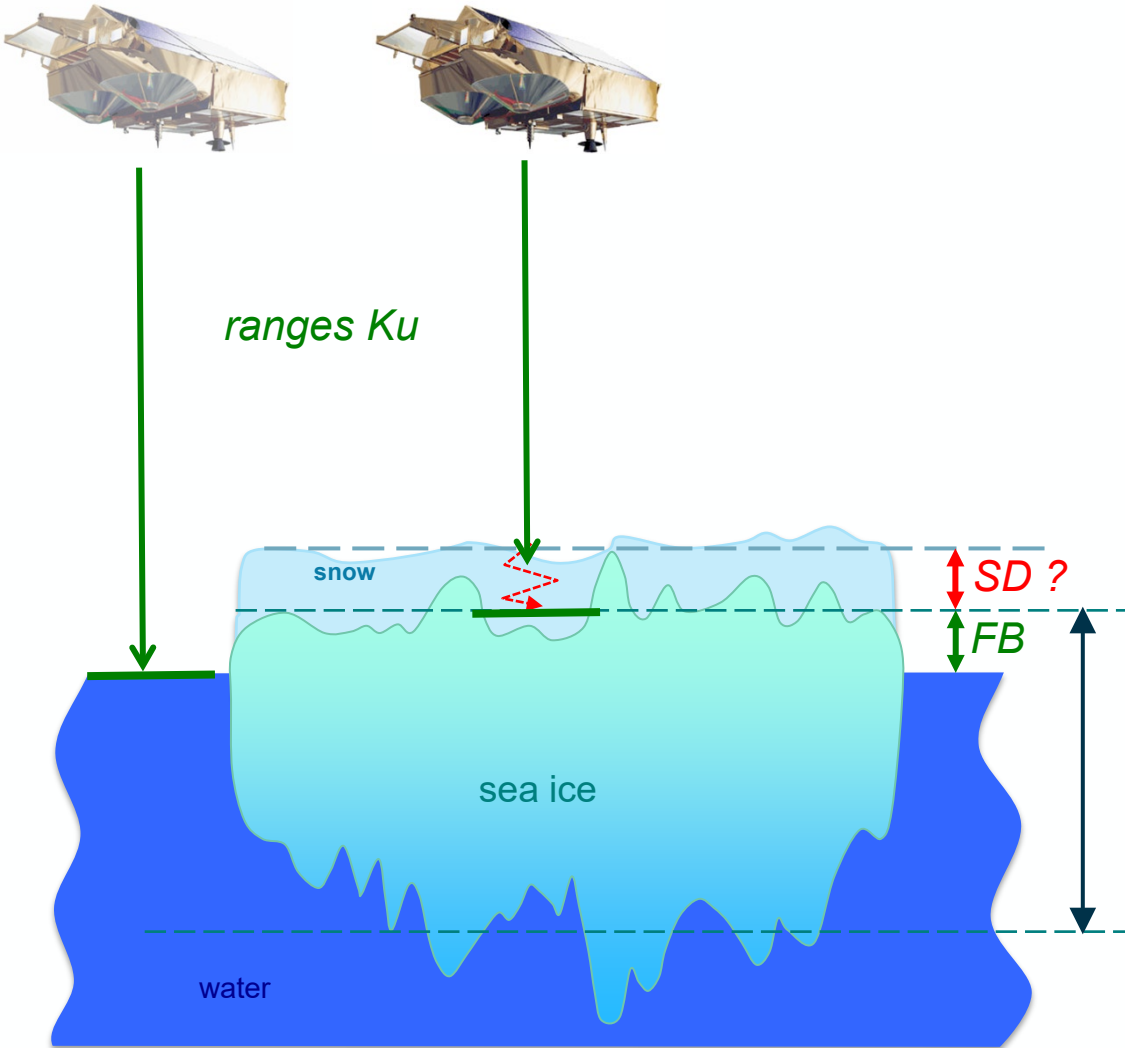
Sea Ice Thickness by Altimetry: Effect of snow load



$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB$$

hydrostatic equilibrium equation

Sea Ice Thickness by Altimetry: Effect of snow load



Snow Layer involves:

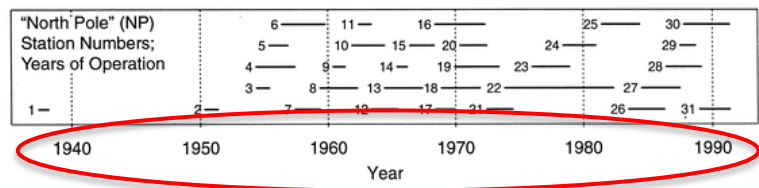
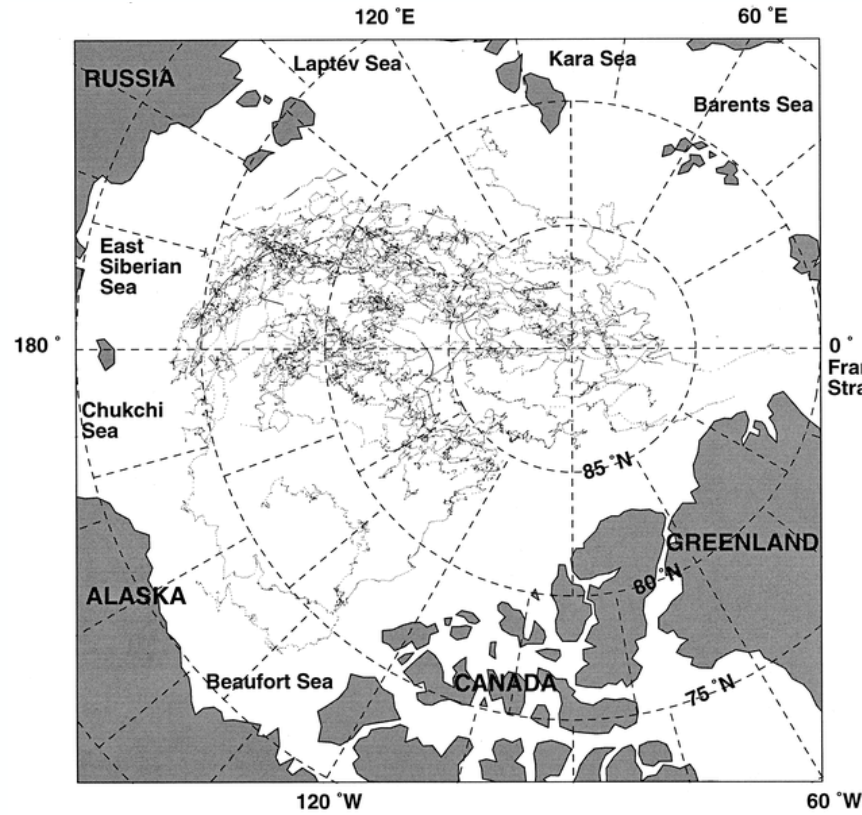
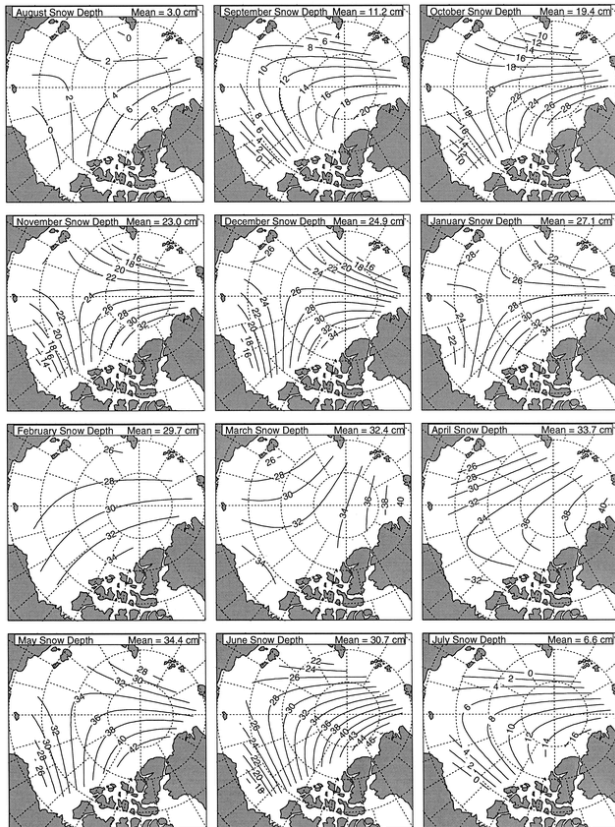
Ku speed reduction + snow load

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB + \frac{(1 - c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

hydrostatic equilibrium equation

How to Estimate Snow Depth over Sea Ice ?

Until recently, only the **Warren 1999** climatology



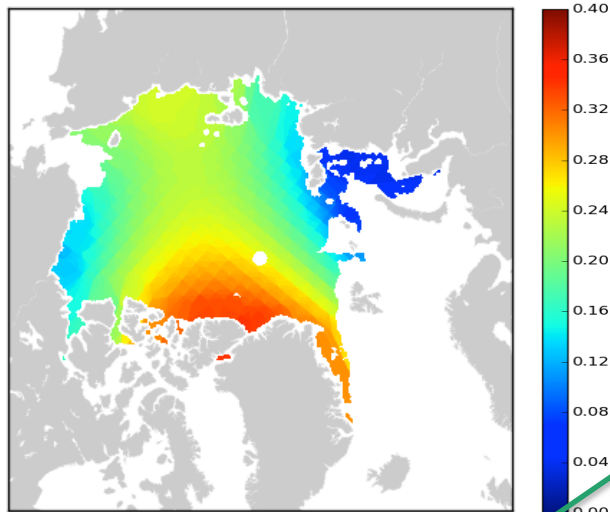
[Warren et al (1999). Snow Depth on Arctic Sea Ice Journal of Climate, 12(6), 1814-1829.]



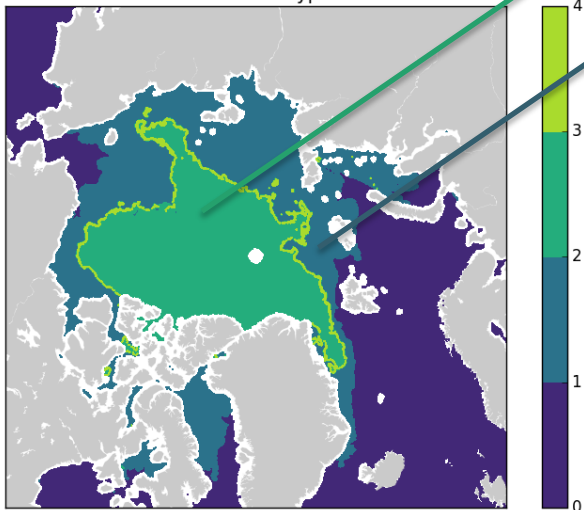
Data from 1940-1990 measurements !

Modified Warren Climatology to Account for CC

April
Warren SD
Climatology



OSISAF Ice type

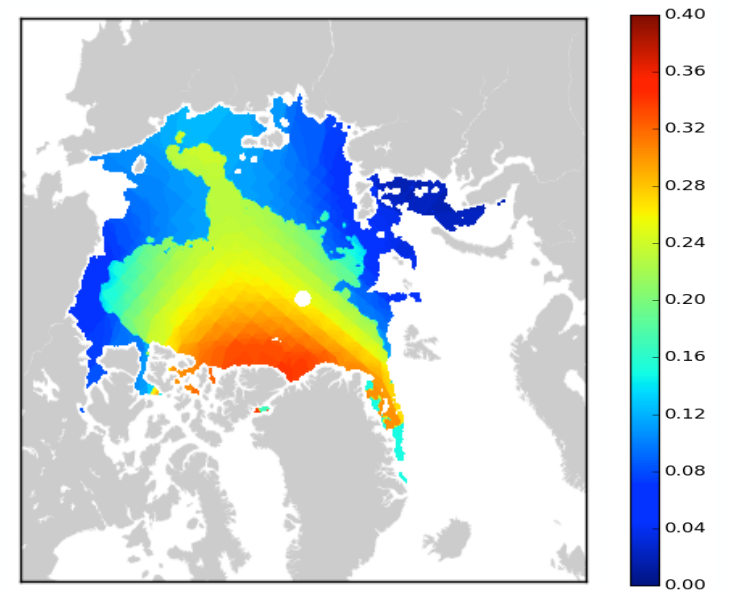


April 2013
OSISAF ice-type

For MYI: $SD = SD_{\text{warren}}$

For FYI: $SD = SD_{\text{warren}} / 2.$

April 2013
Modified Warren



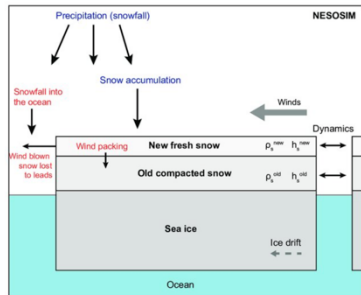
[N.Kurtz et al]

How to Estimate Snow Depth over Sea Ice ?

Models of Snow Accumulation

Using:

- Re-analyses models (MERRA2, ERA5, ...) for snow precipitations and wind
- Sea Ice Drift



Main Available Snow Depth Products

| | | |
|--------------|-----------------------|-------|
| PIOMAS | 1980-now | NH |
| GIOMAS | 1980-now | NH+SH |
| NESOSIM | 2002-2011 2012-now | NH |
| SnowModel-LG | 1980-2018 | NH |

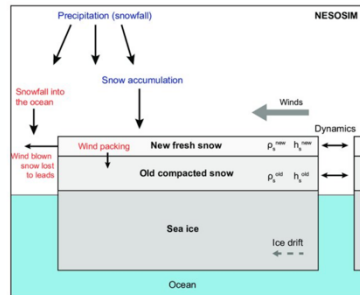
..., etc.

How to Estimate Snow Depth over Sea Ice ?

Models of Snow Accumulation

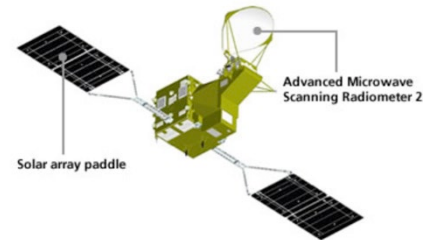
Using:

- Re-analyses forecasts (MERRA2, ERA5, ...) for snow precipitations and wind
- Sea Ice Drift



Multi-frequency Passive Radiometers

AMSR-E (2002-2011) and
AMSR-2 (2012-now)



$$GR(37/19) = \frac{Tb_{37} - Tb_{19} - k_1(1 - C)}{Tb_{37} + Tb_{19} - k_2(1 - C)}$$

Main Available Snow Depth Products

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..., etc.

| | | |
|-----------------------|-----------------------|---------------------|
| [Meier et al 2018] | 2002-2011 2012-now | FYI only NH + SH |
| [Rostosky et al 2018] | 2002-2011 2012-now | NH |

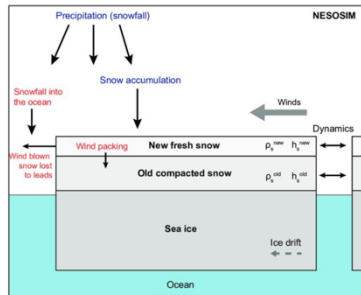
- + [Winstrup 2019]
- + [Braakmann-Folgmann et al 2019]

How to Estimate Snow Depth over Sea Ice ?

Models of Snow Accumulation

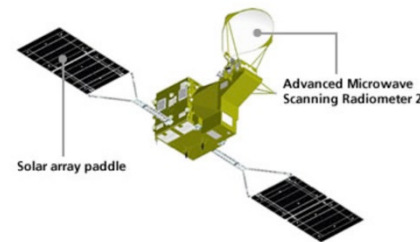
Using:

- Re-analyses forecasts (MERRA2, ERA5, ...) for snow precipitations and wind
- Sea Ice Drift



Multi-frequency Passive Radiometers

AMSR-E (2002-2011) and AMSR-2 (2012-now)



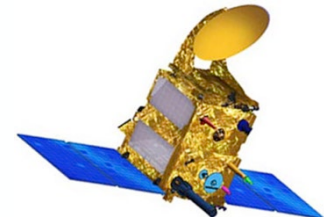
$$GR(37/19) = \frac{Tb_{37} - Tb_{19} - k_1(1 - C)}{Tb_{37} + Tb_{19} - k_2(1 - C)}$$

Bi-frequency Altimeters

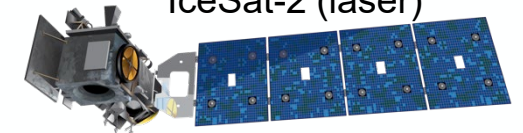
CryoSat-2 (Ku)



Saral (Ka)



IceSat-2 (laser)



Main Available Snow Depth Products

| | | |
|--------------|-----------------------|-------|
| PIOMAS | 1980-now | NH |
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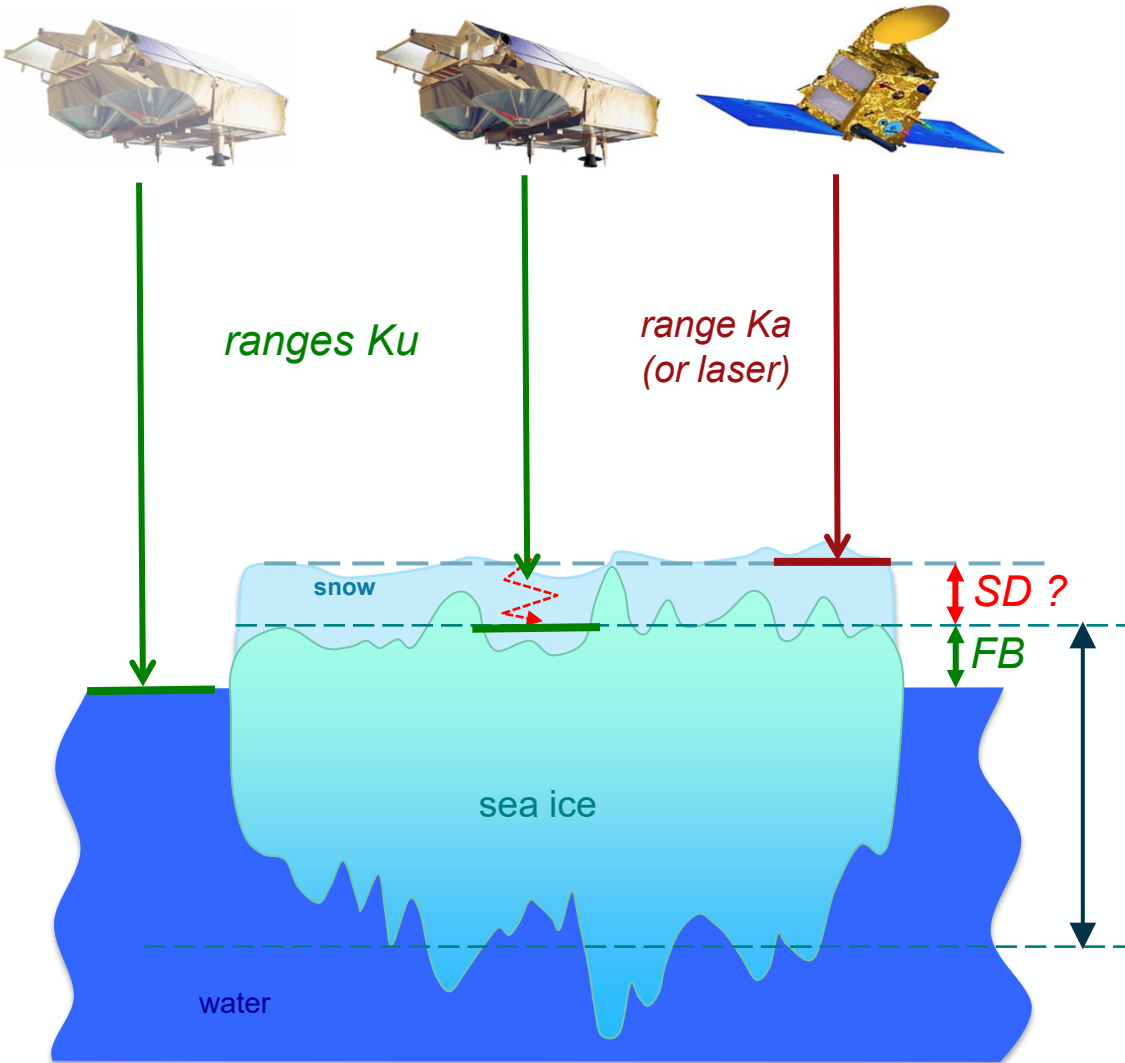
..., etc.

| | | |
|-----------------------|-----------------------|---------------------|
| [Meier et al 2018] | 2002-2011 2012-now | FYI only NH + SH |
| [Rostosky et al 2018] | 2002-2011 2012-now | NH |

- + [Winstrup 2019]
- + [Braakmann-Folgmann et al 2019]

| | | | |
|---------------|--|---------------|---------------|
| ASD Ka/Ku | [Guerreiro et al 2016] [Garnier et al 2021] | 2013- now | 82°NH + SH |
| DuST Ka/Ku | [Lawrence et al 2018] | 2013- now | 82°NH |
| Ku/laser | [Kwok 2020] | 2018- 2019 | NH |

How to retrieve Snow Depth with Altimetry?

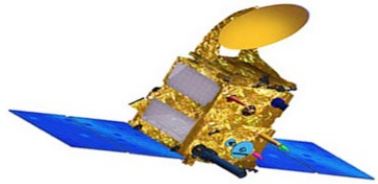


$$SD \approx range_Ku - range_Ka$$

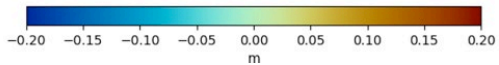
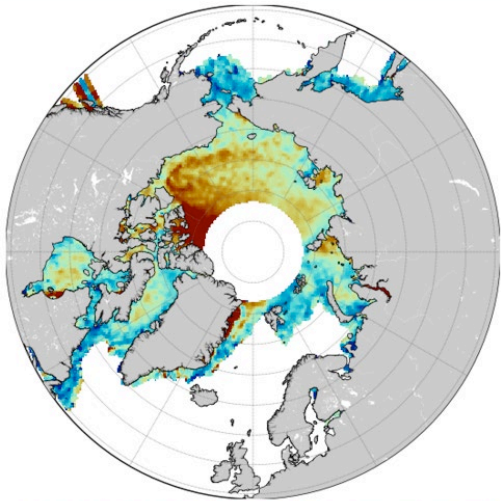
[Guerreiro et al. 2016]

$$SIT = \frac{\rho_w}{\rho_w - \rho_i} FB + \frac{(1 - c_s/c)\rho_w + \rho_s}{\rho_w - \rho_i} SD$$

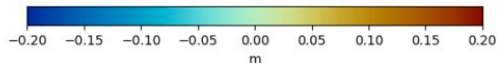
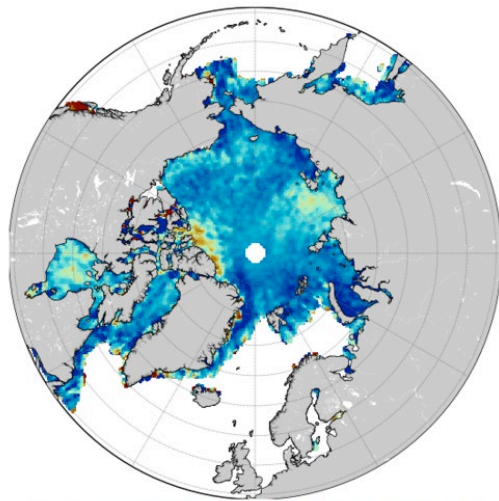
hydrostatic equilibrium equation



Saral (LRM Ka)



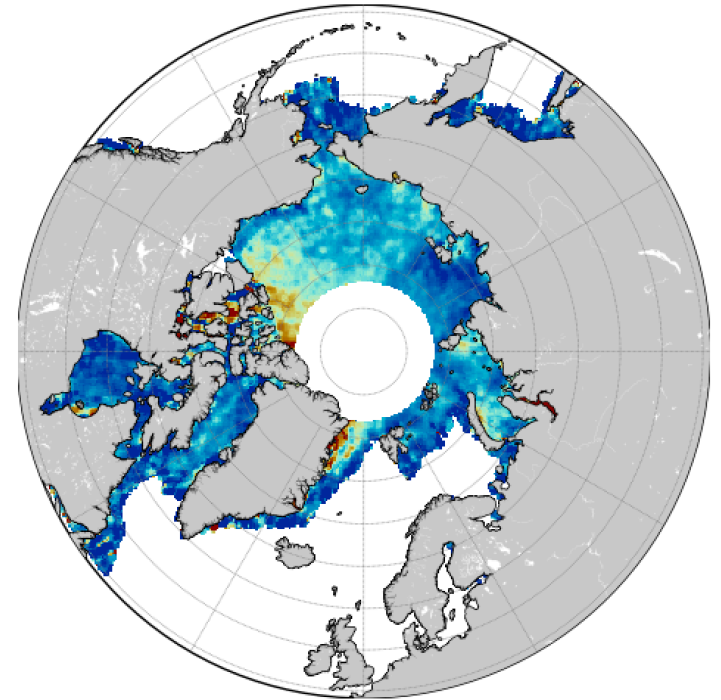
CryoSat-2 (pLRM Ku)



-

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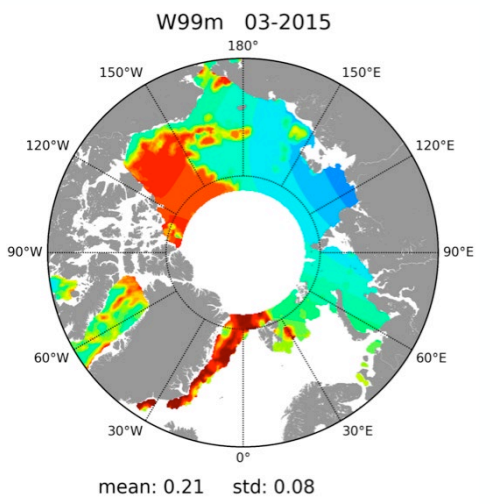
Snow Depth



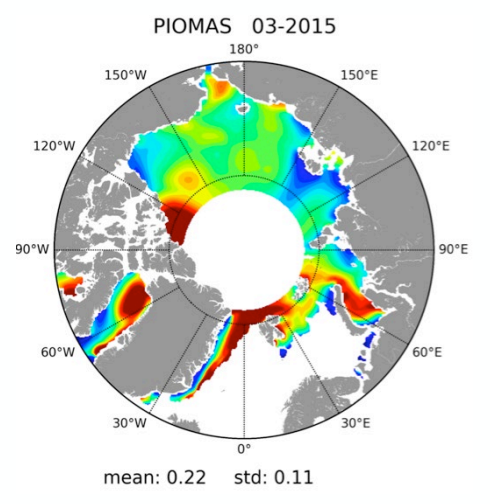
[Garnier et al. in The Cryosphere 2021] 11

Products comparison

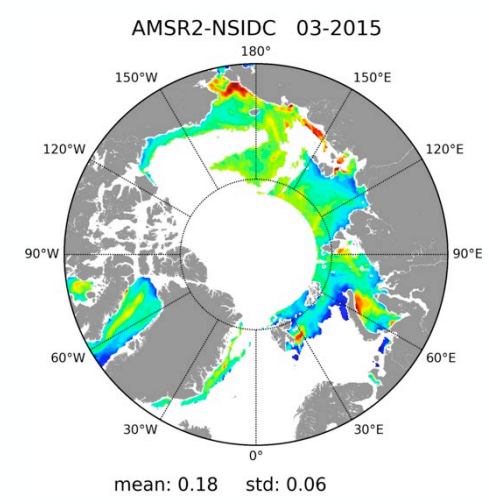
Modified W99



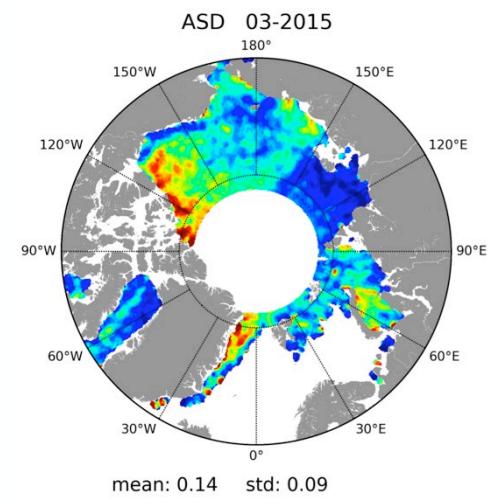
Models



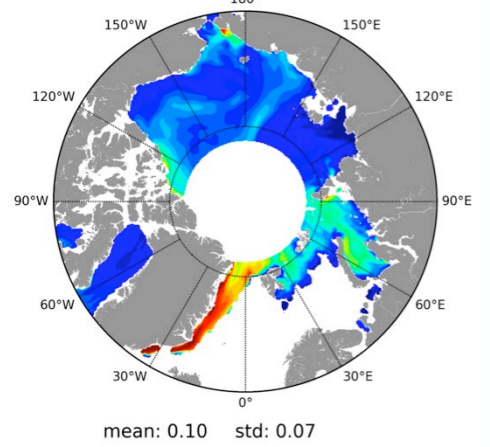
Passive Radiometers



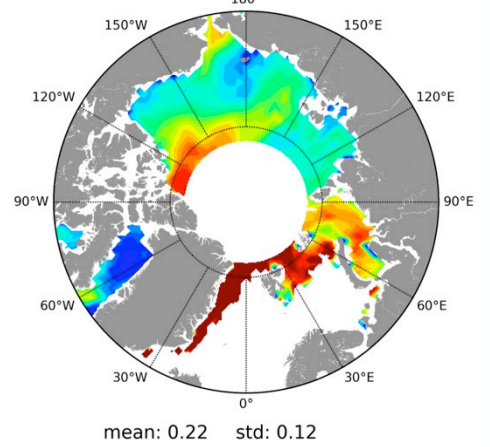
Altimetry



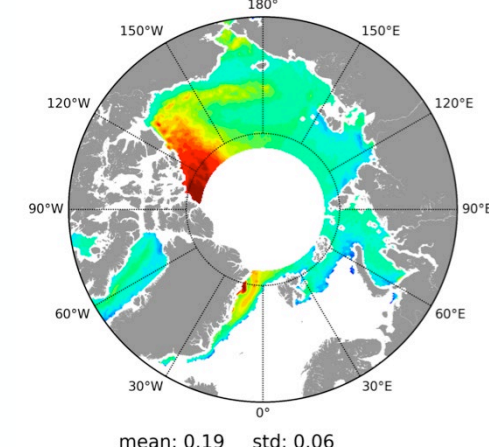
MERCATOR 03-2015



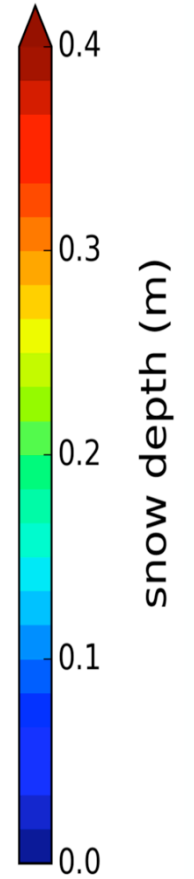
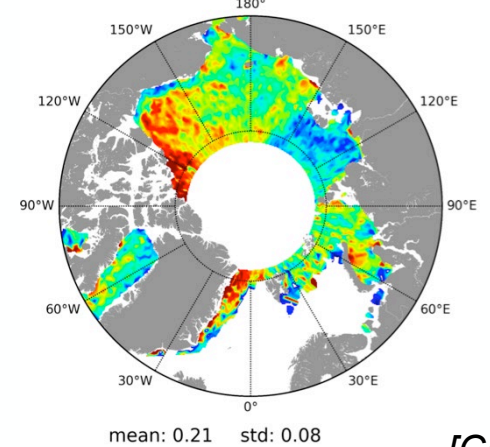
NESOSIM 03-2015



AMSR2B 03-2015

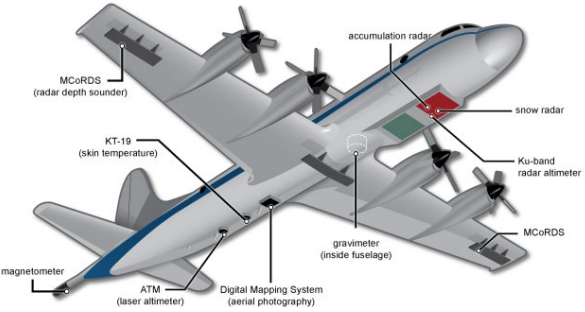


DuST 03-2015

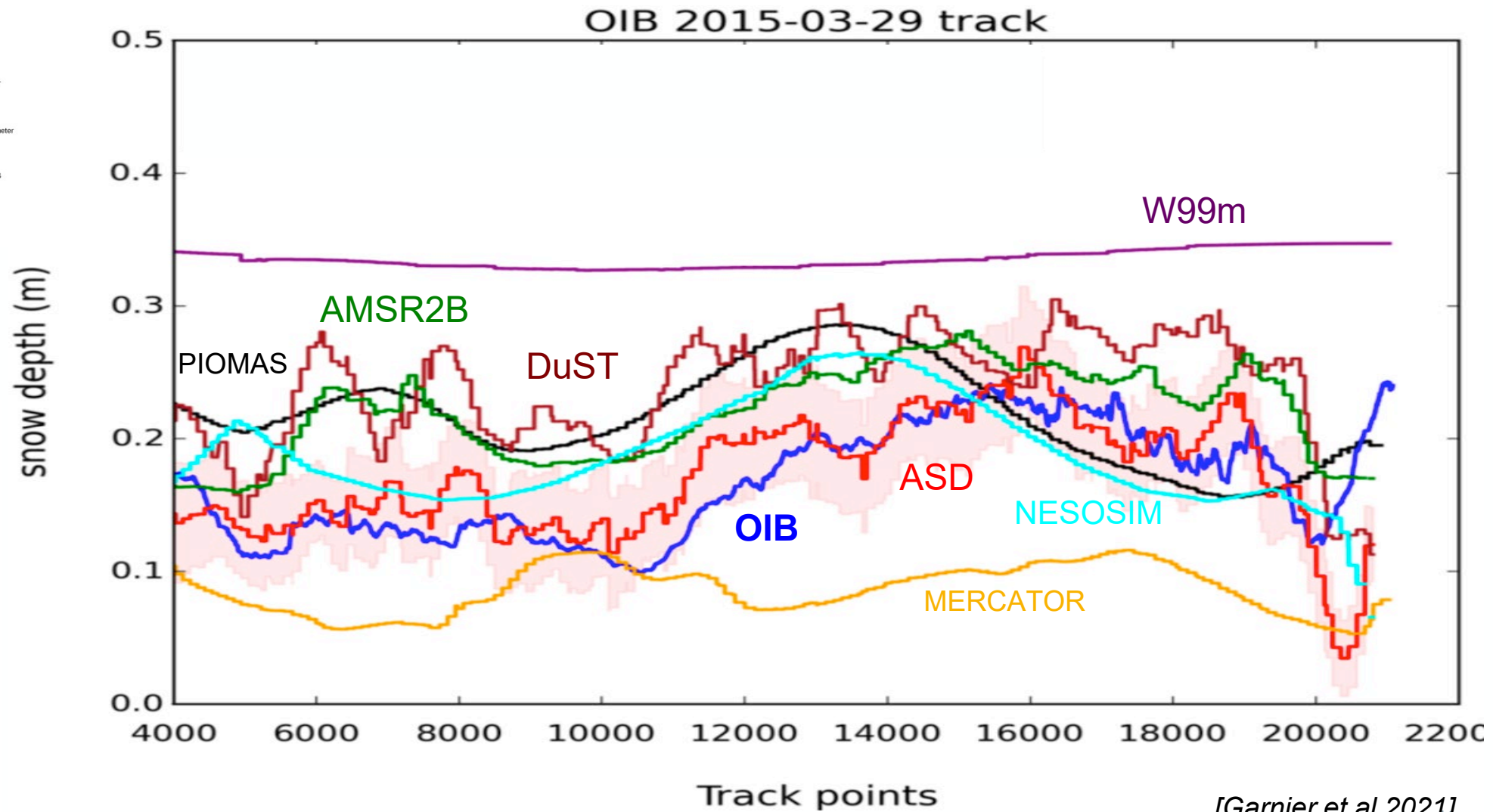
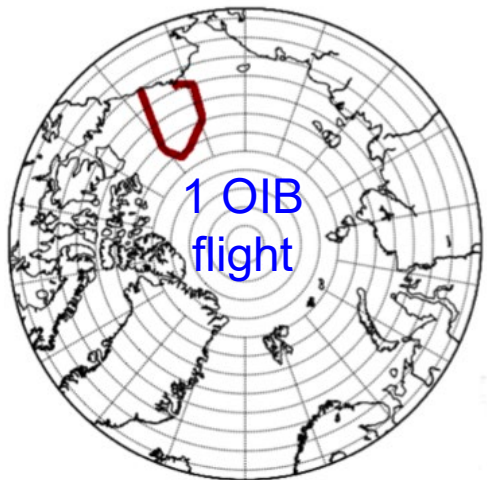


[Garnier et al 2021]

Comparison against OIB airborne Snow Radar



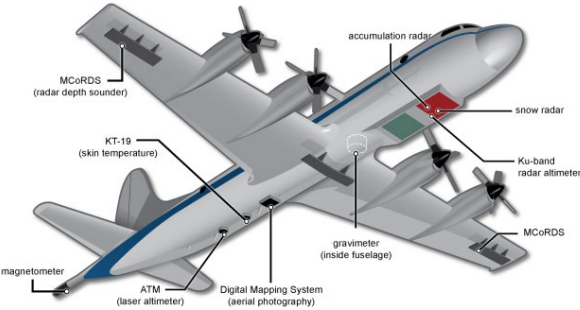
airborne snow radar from OIB



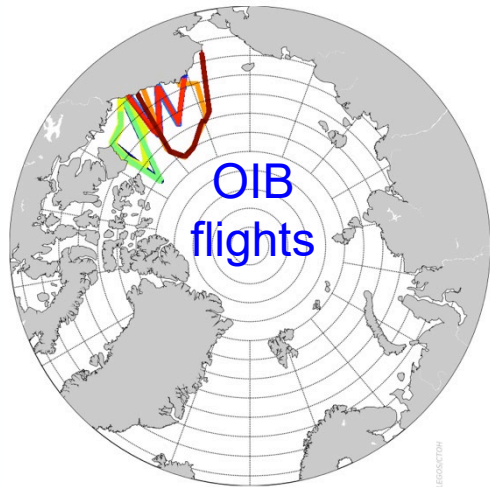
[Garnier et al 2021]



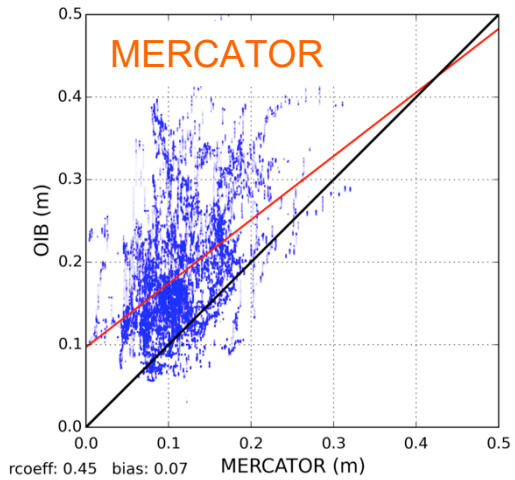
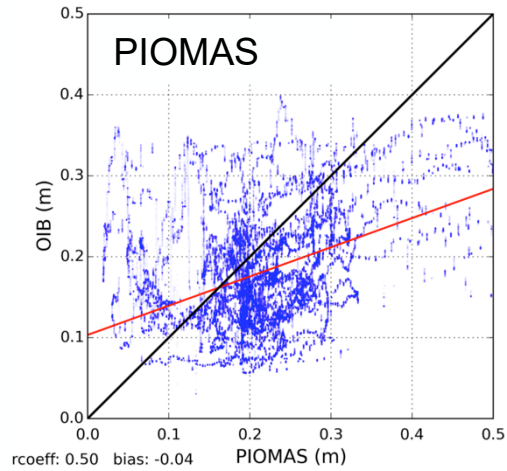
Comparison against OIB Snow Radar



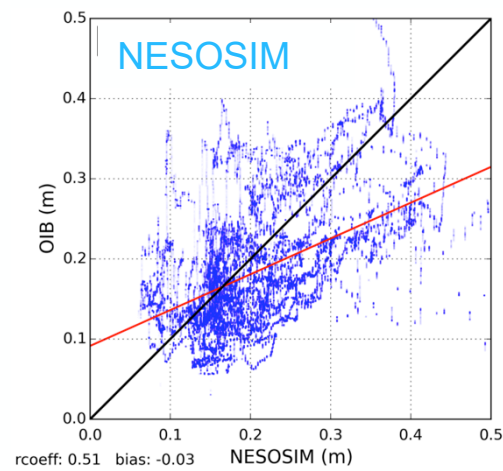
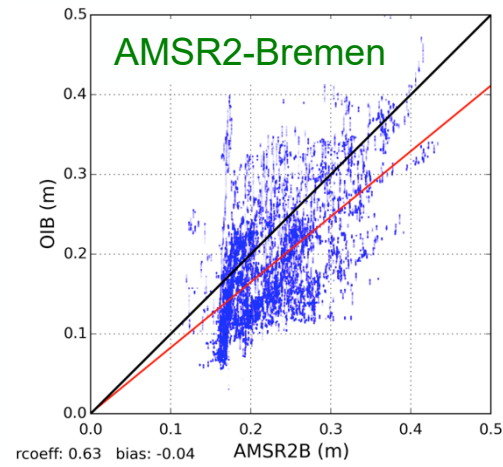
airborne
snow radar
from OIB



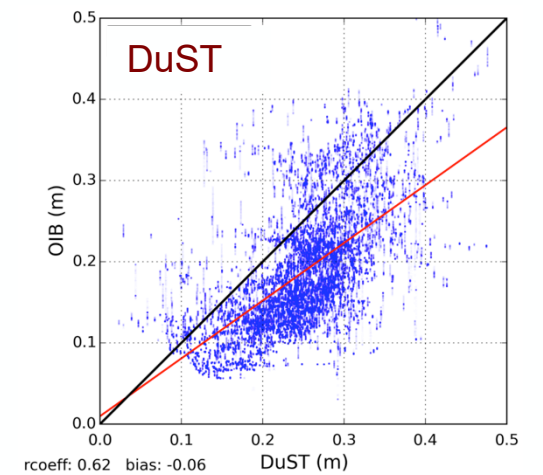
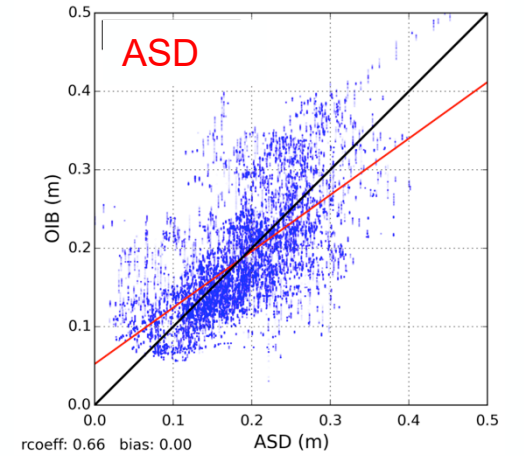
Models



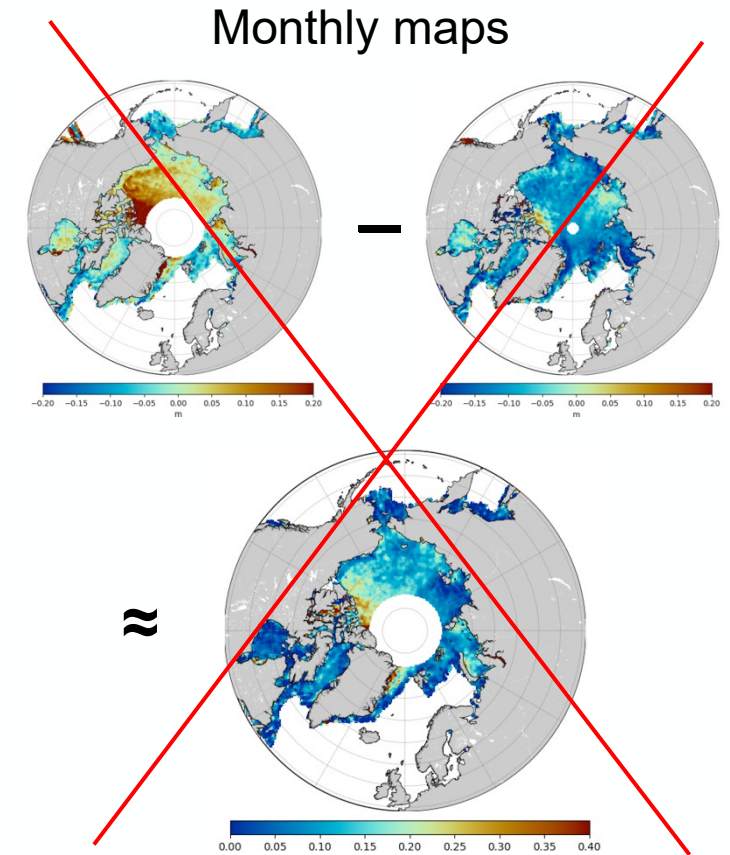
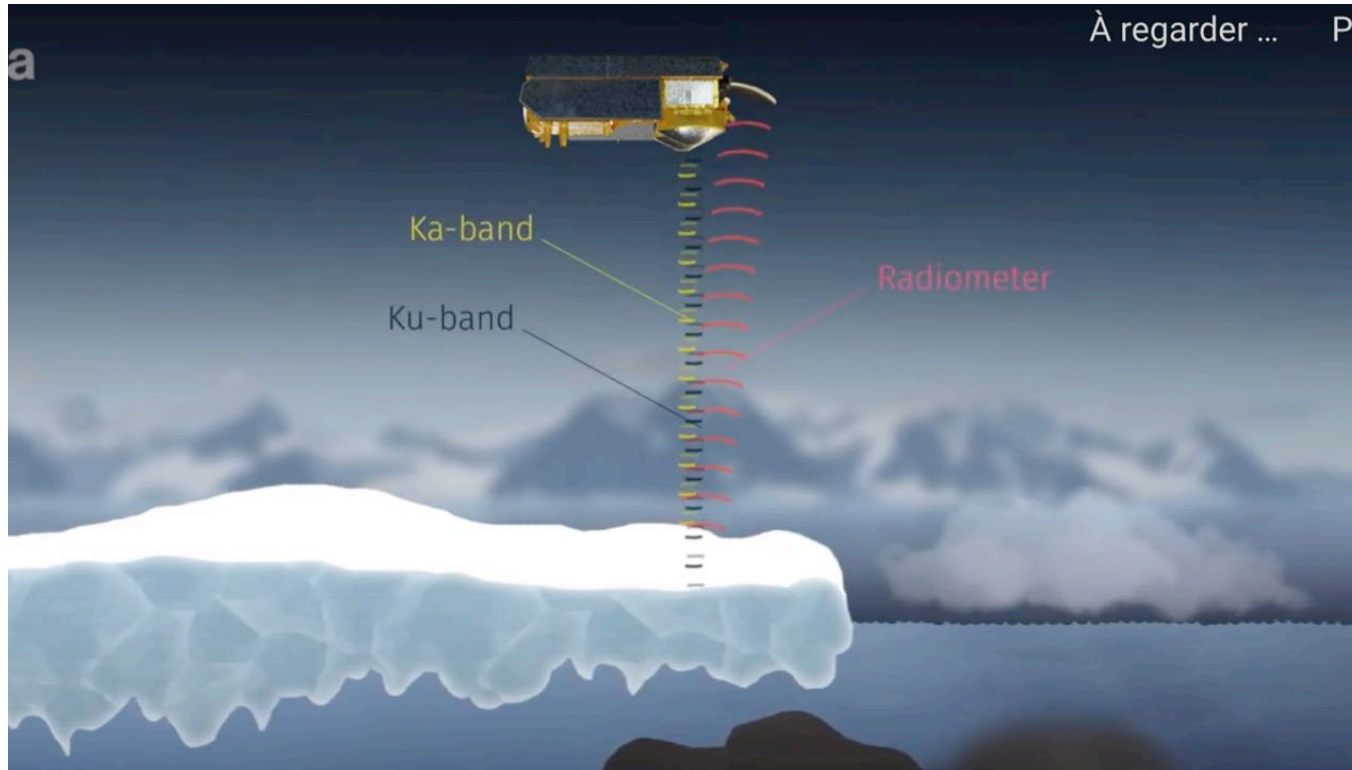
Passive Radiometers



Altimetry

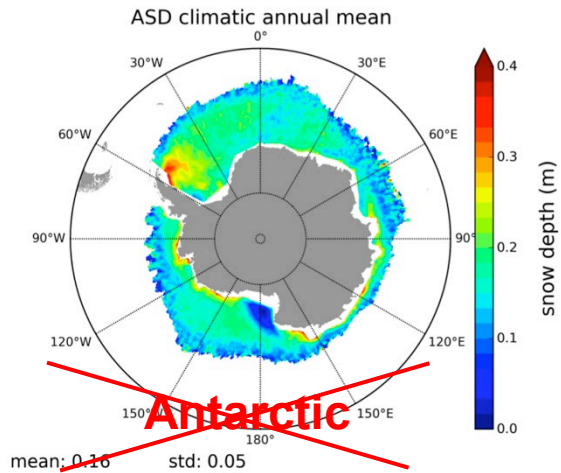
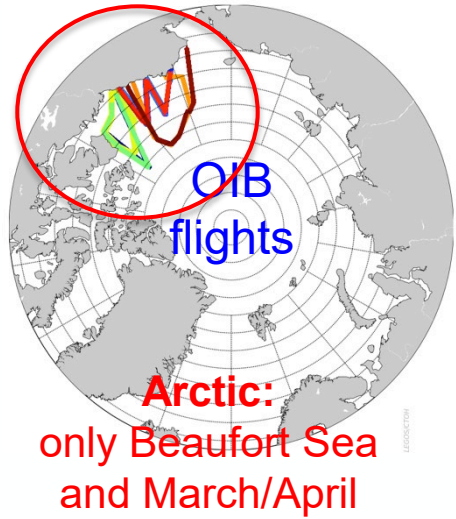


First Ka/Ku satellite altimeter ... for 2027

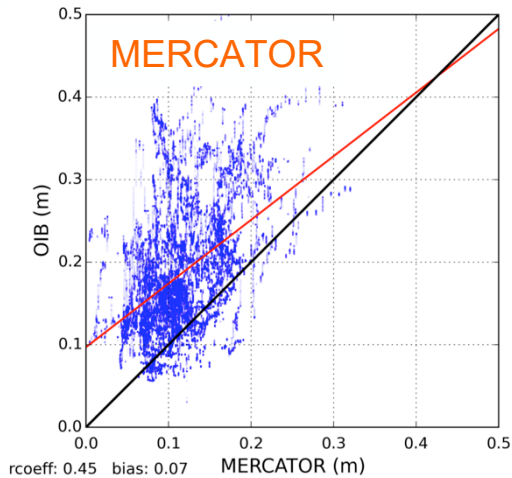
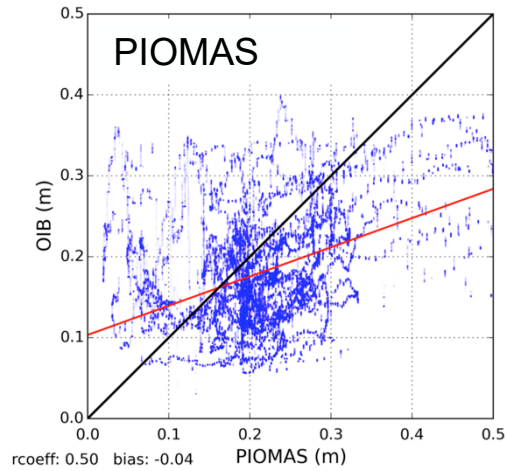


Simultaneous sea ice thickness and snow depth measurements !

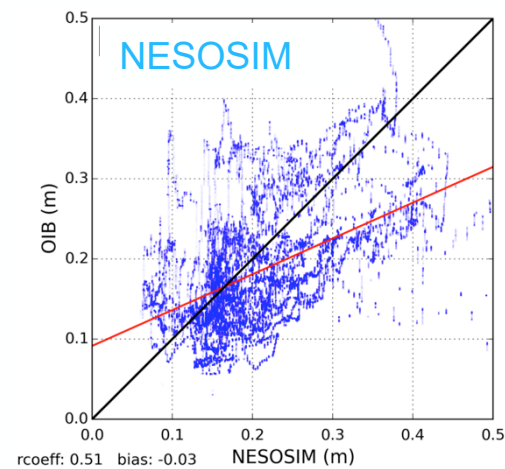
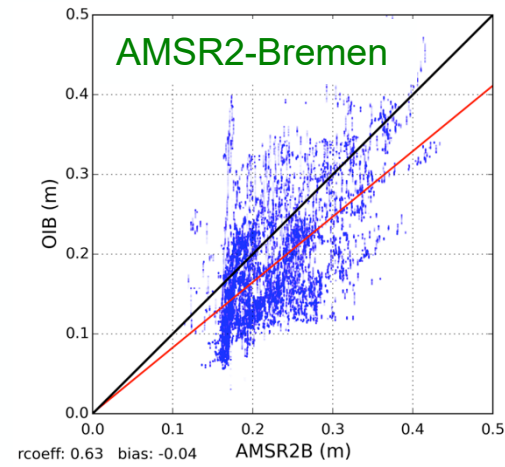
Comparison against OIB Snow Radar



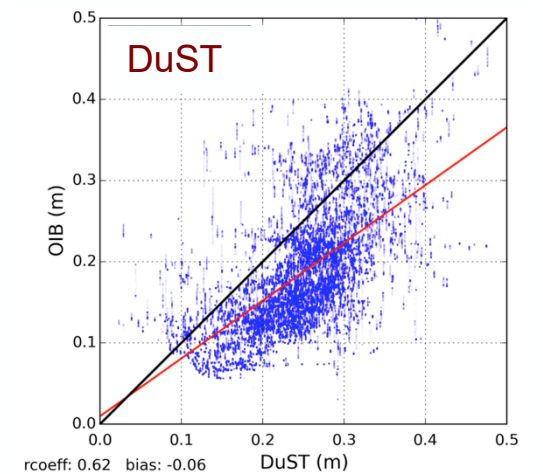
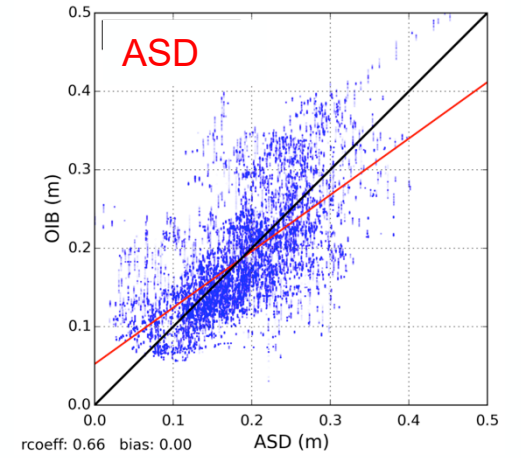
Models



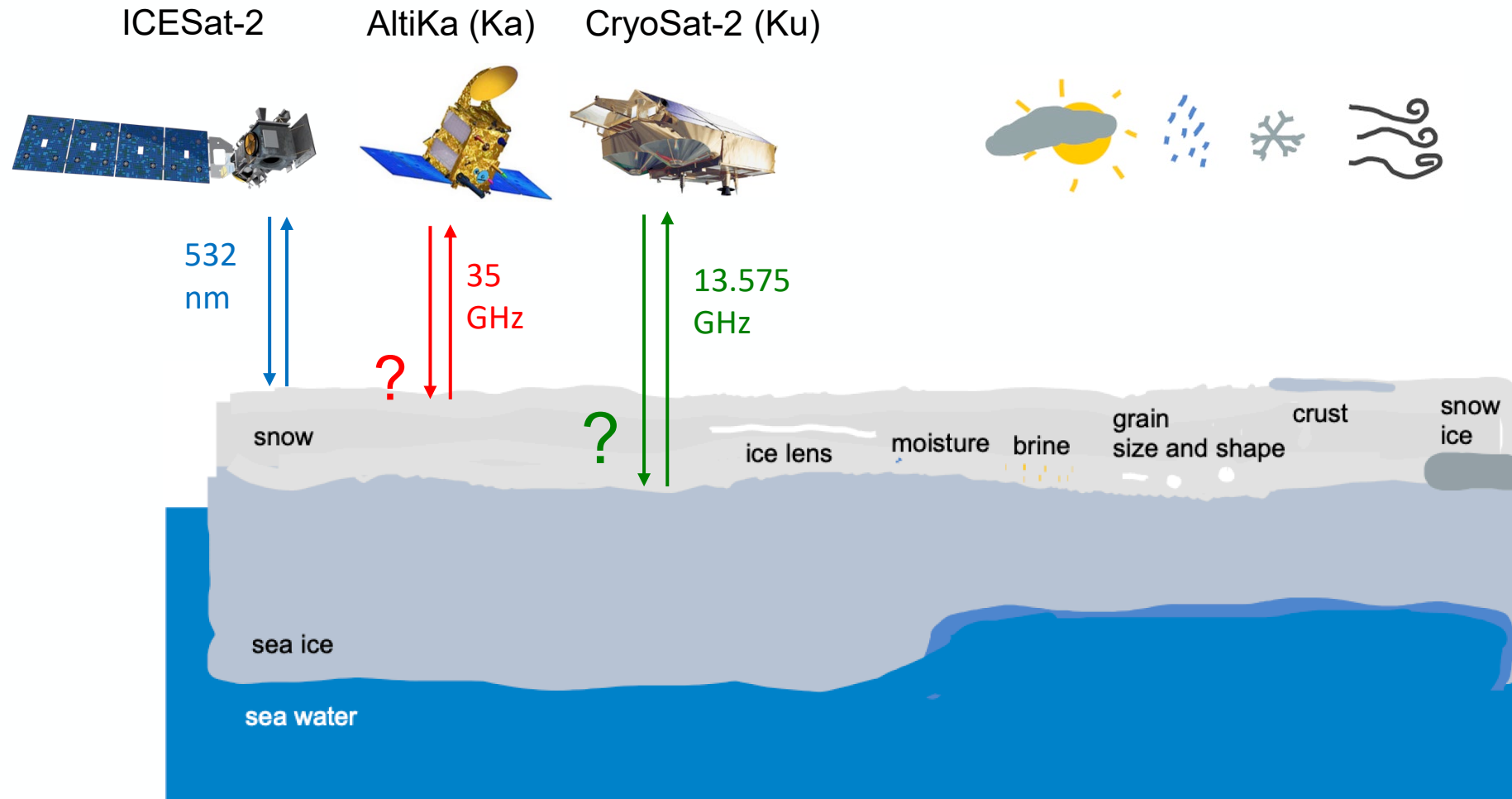
Passive Radiometers



Altimetry



Penetration depends on Snow Type !



V.Nandan, J.Stroeve, J.Yackel, ..., MOSAIC, etc.

FYI Snow Penetration correction

[Nandan et al, GRJ 2017] *Effect of Snow Salinity on CryoSat-2 Arctic First-Year Sea Ice Freeboard Measurements*

BGEP mooring (principle schema)

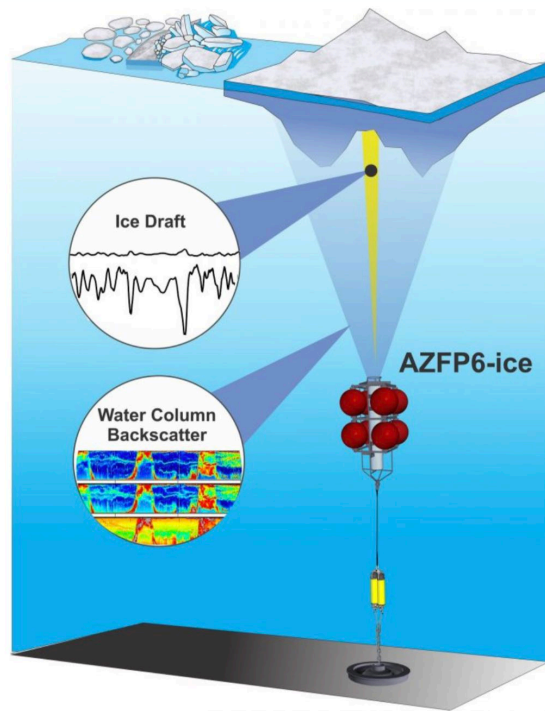
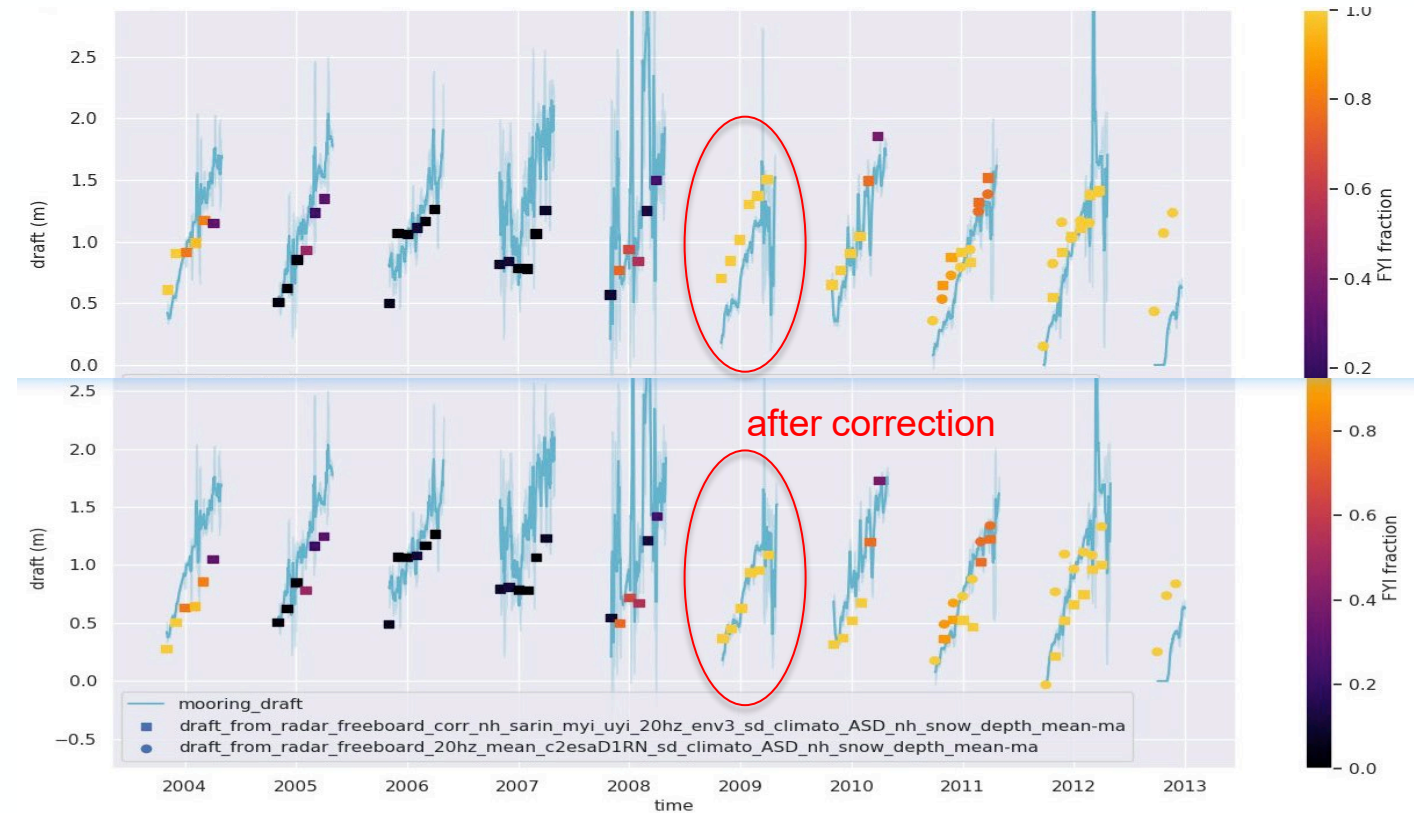


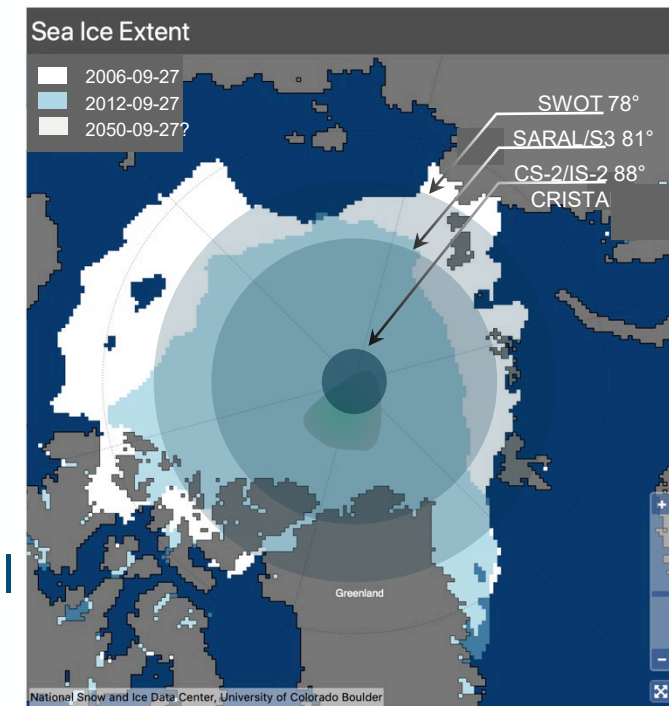
illustration of the principle from hydro-international.com

Penetration correction law in FYI snow layer:

$$\Delta_S = 1.4022229 + 0.9114689H_S - 0.0437265H_S^2 + 0.00061H_S^3$$

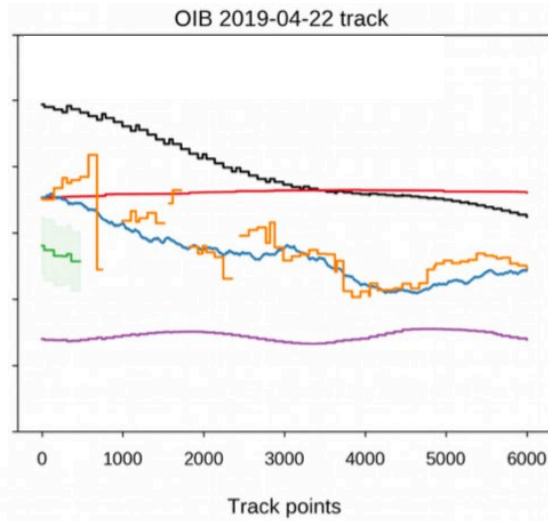
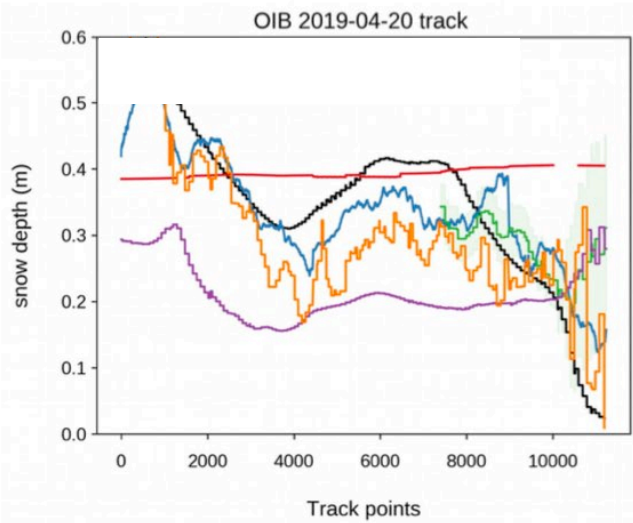


- Ka/Ku approach works well ... in Spring over West Arctic basin
- Miss of validation data East of Arctic and whole Antarctic
- Operation Ice Bridge has ended -> no more systematic snow depth data (AWI?, see A.Jutila presentation)
=> **Need for a (Copernicus?) airborne and/or drone-borne snow radar for Cal/Val**
- Need more studies to determine the conditions of Ku penetration into snow
- Need more studies to evaluate if Ka penetrates or not the snow
=> IceSat2 is a good opportunity
- **Importance not having delay for the launch of CRISTAL**
=> try a relay with the already 12 years old CryoSat-2 -> 2027?
=> no relay means no more sea ice thickness monitoring in summer at all
(there will be not more autumn sea ice below 81.5°N from ~2025)

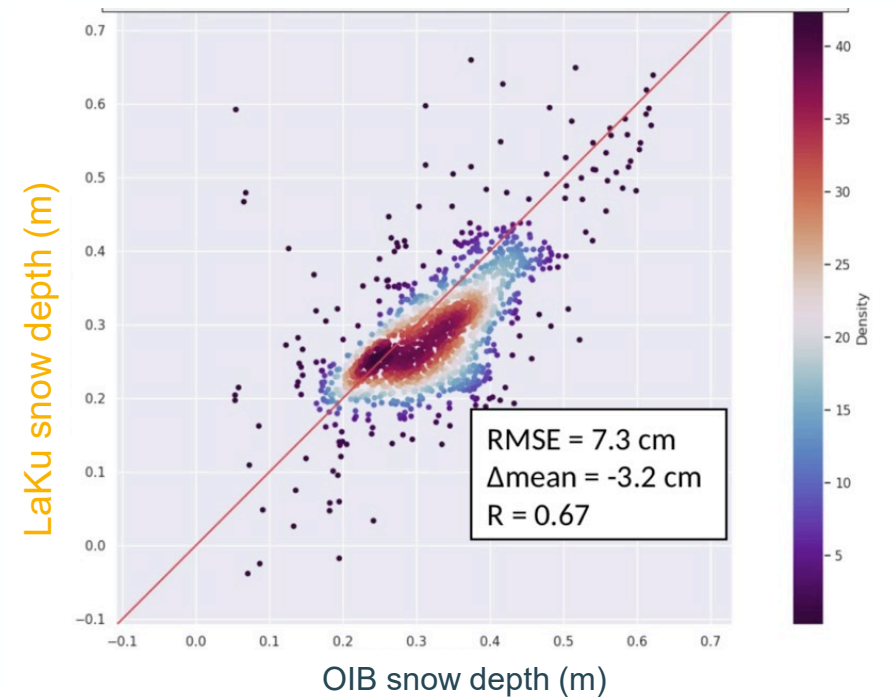
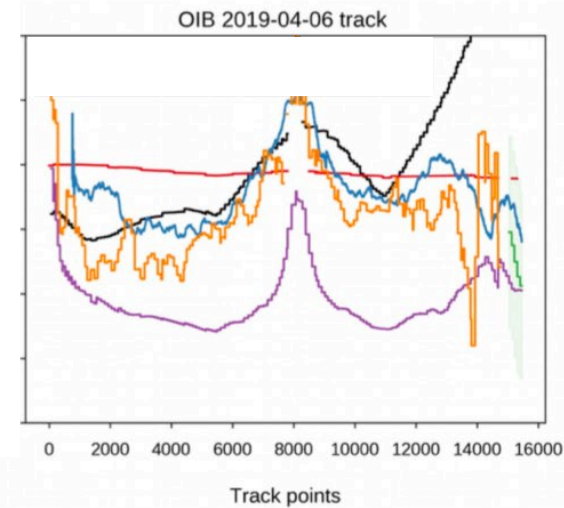
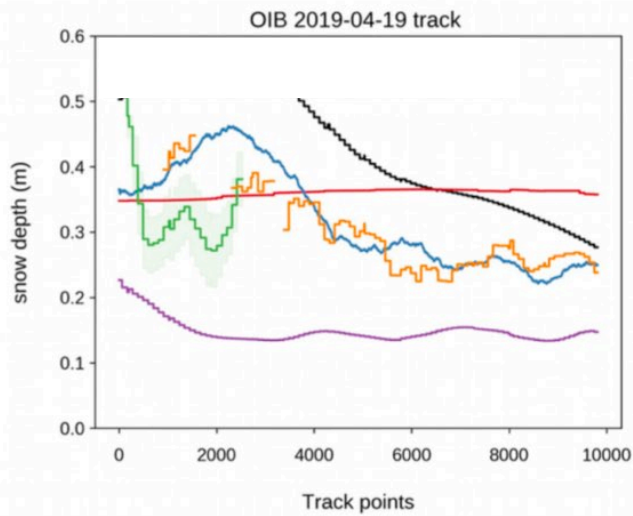


Annexes

Snow laser/Ku versus Ka/Ku

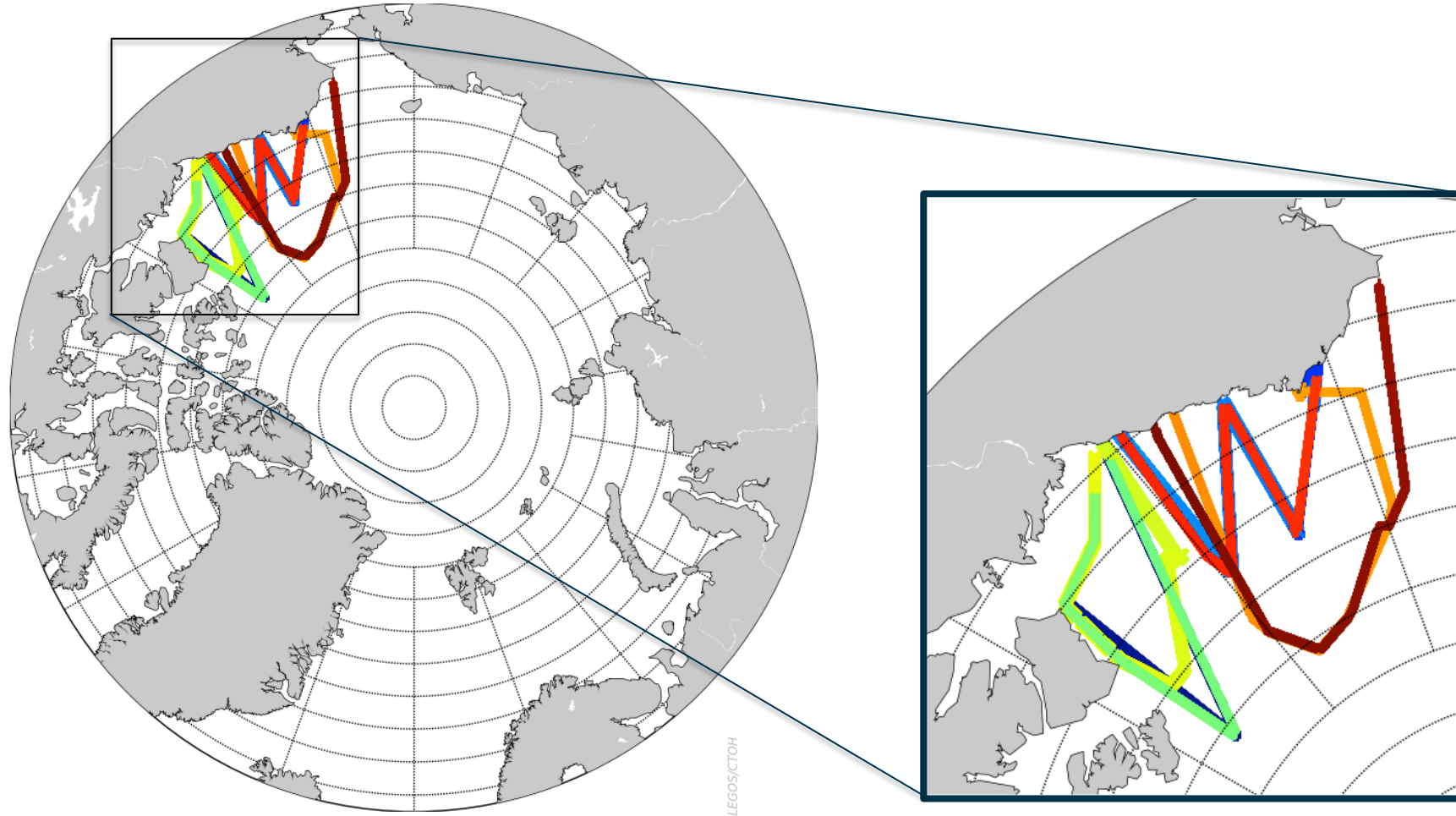


PIOMAS
 W99mod
 LaKu
 OIB
 ASD
 MERCATOR

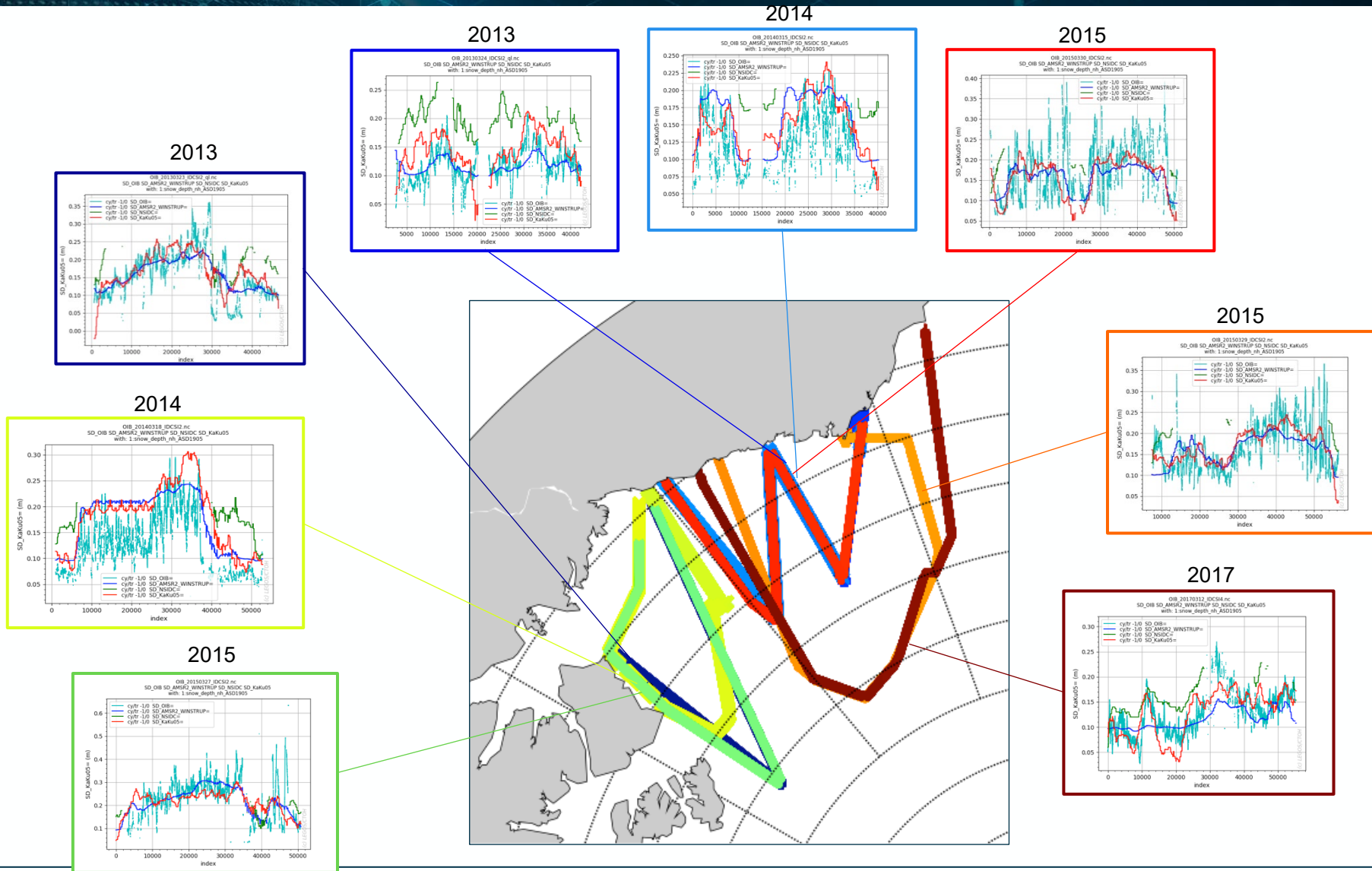


See Alice Carret presentation

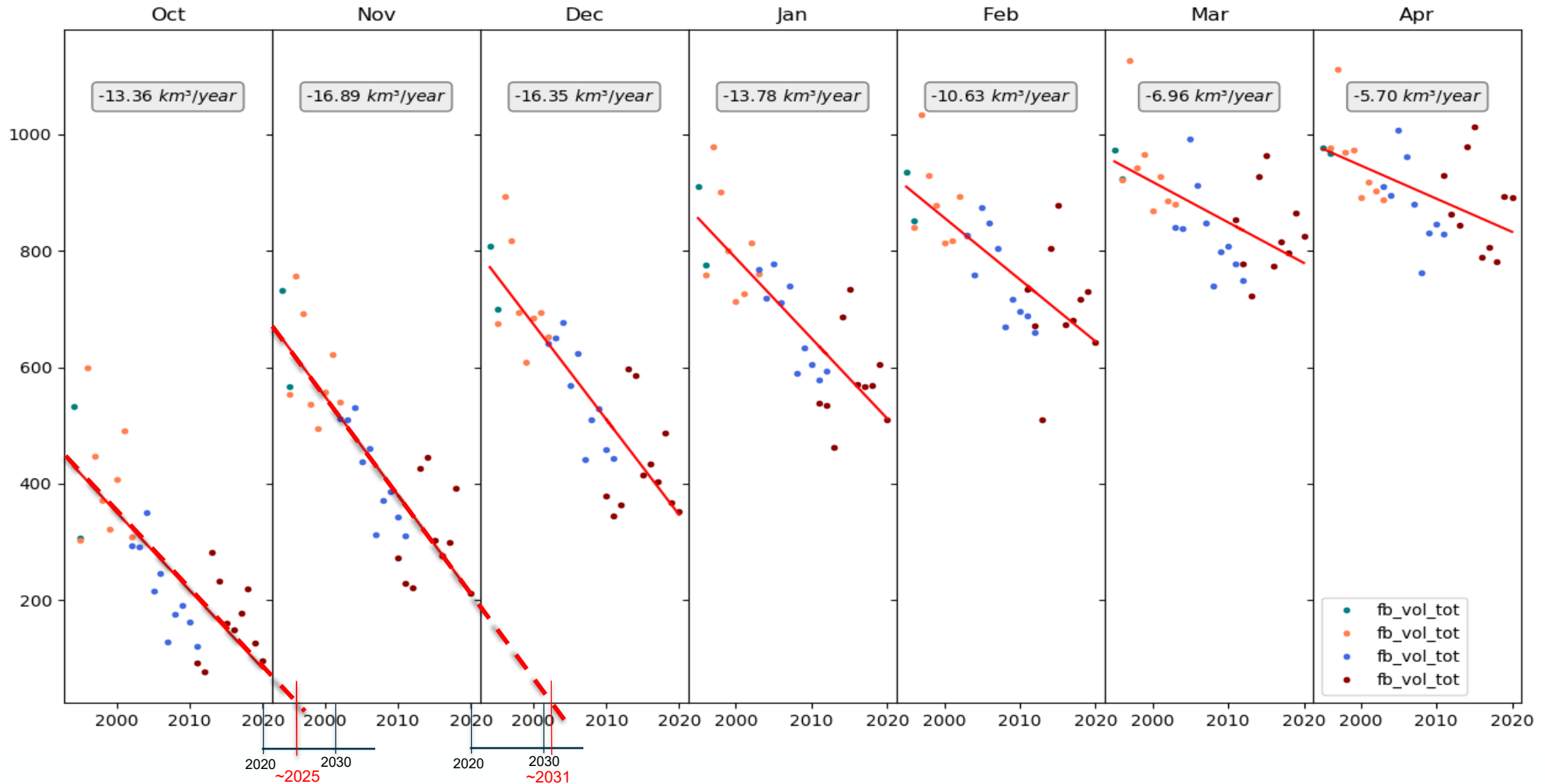
Ka/Ku Snow Depth Validation with OIB



Ka/Ku Snow Depth Validation with OIB



Results over Arctic



How to retrieve Snow Depth ?

