Monitoring South-West Greenland's ice sheet melt with ambient seismic noise

Aurélien Mordret

Postdoc associate,
Department of EAPS

In collaboration with Dylan Mikesell [1,2], Christopher Harig [3], Brad Lipovsky [4] & German Prieto [1]

[1] MIT, [2] Boise State U., [3] Princeton U., [4] Harvard U.

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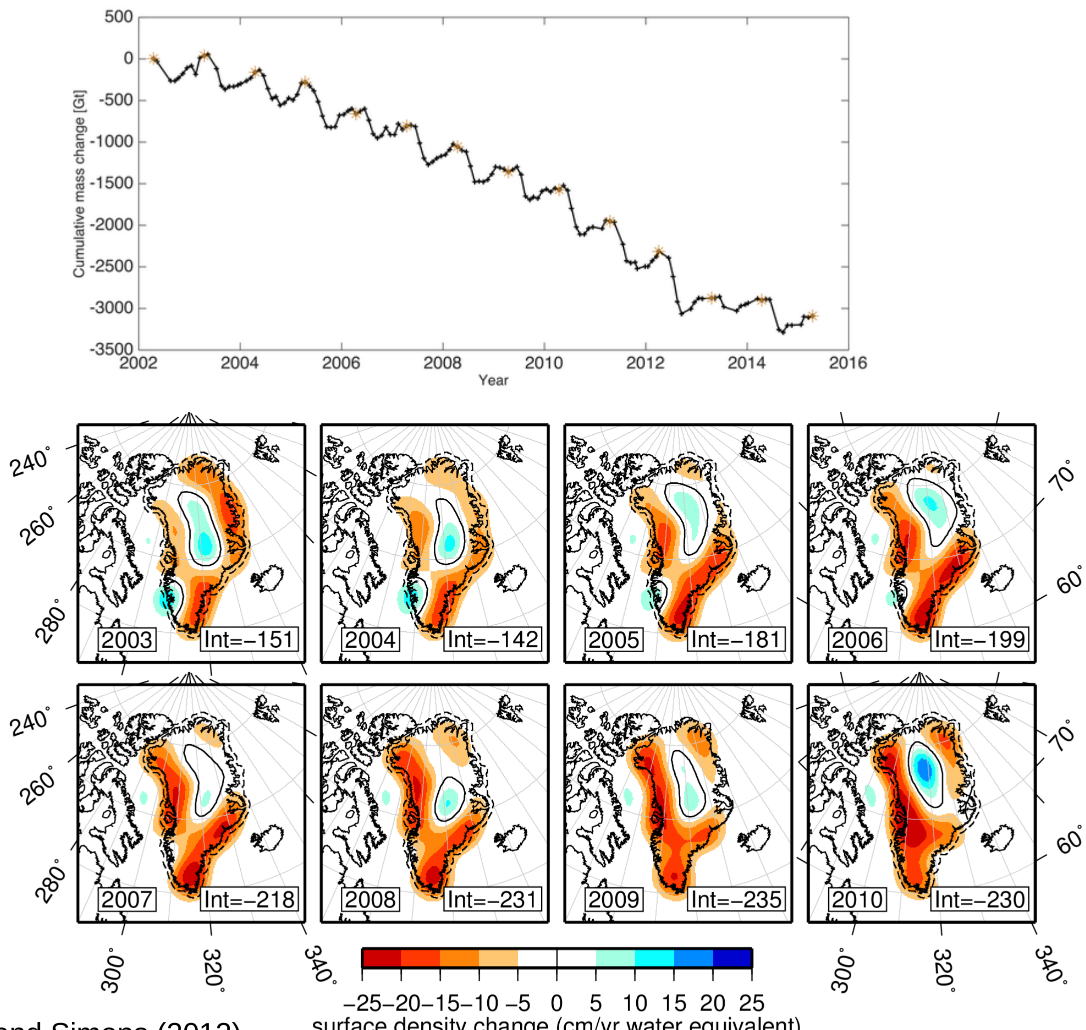
Outlines

1) What is happening in Greenland? And why does it matter?
2) Why use seismic waves to monitor ice sheets?
3) Passive seismic monitoring in Greenland
4) Forward modeling and interpretation
5) Conclusion and perspectives

What is happening in Greenland?



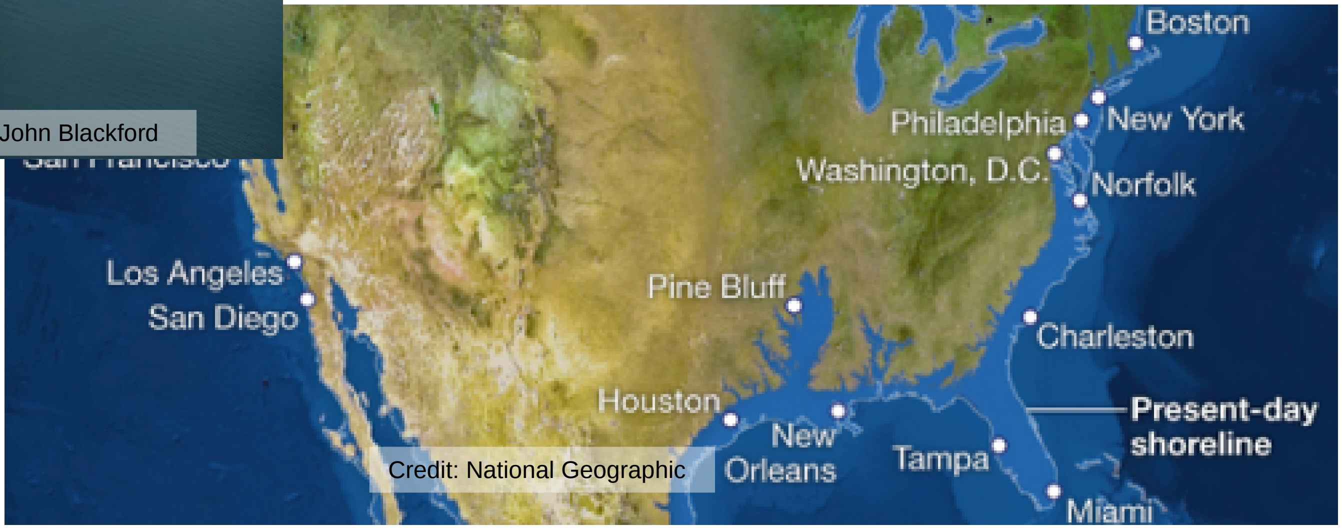
Harig and Simons (2012)

- Ice mass loss as seen from GRACE data
- Global accelerating trend
- Spatio-temporal pattern with stronger losses in coastal areas
- Temporal variability controlled by oceanic and atmospheric circulations

Why does it matter?

60-80 m elevation if all ice from Greenland and Antarctica melted


Original photograph by Cameron Davidson; photo illustration by John Blackford



Credit: National Geographic

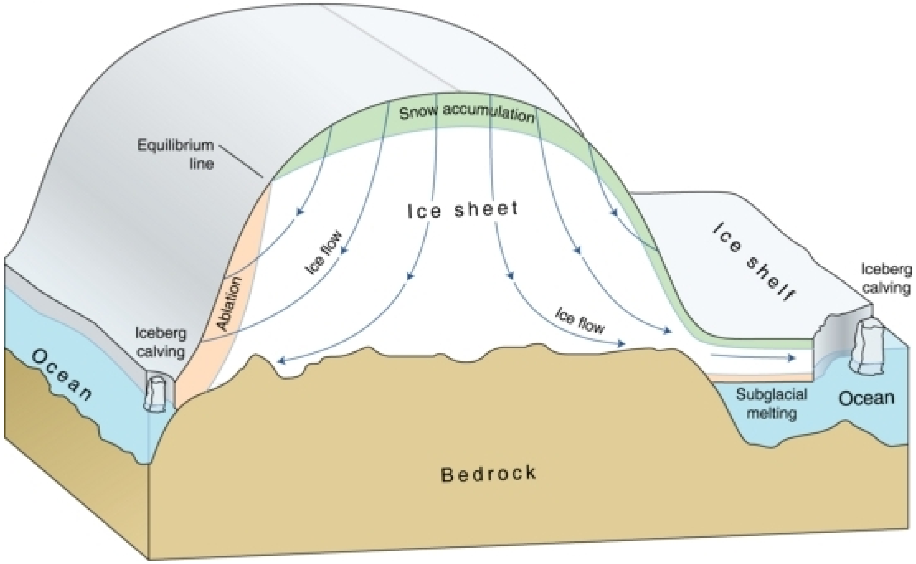
What should we monitor?

The key parameter to measure is the quantity of ice that melted into the ocean:

M = Snow accumulation – Ablation – Calving

With

Ablation = Runoff - Refreeze



- Estimation of each of these parameters is difficult
- Large uncertainties
- Can depend on many other parameters (snow compaction rate, snow/ice density profile, portion of refreeze...)

- M directly measured by gravimetry and/or GPS
- So, why bother with seismic data?

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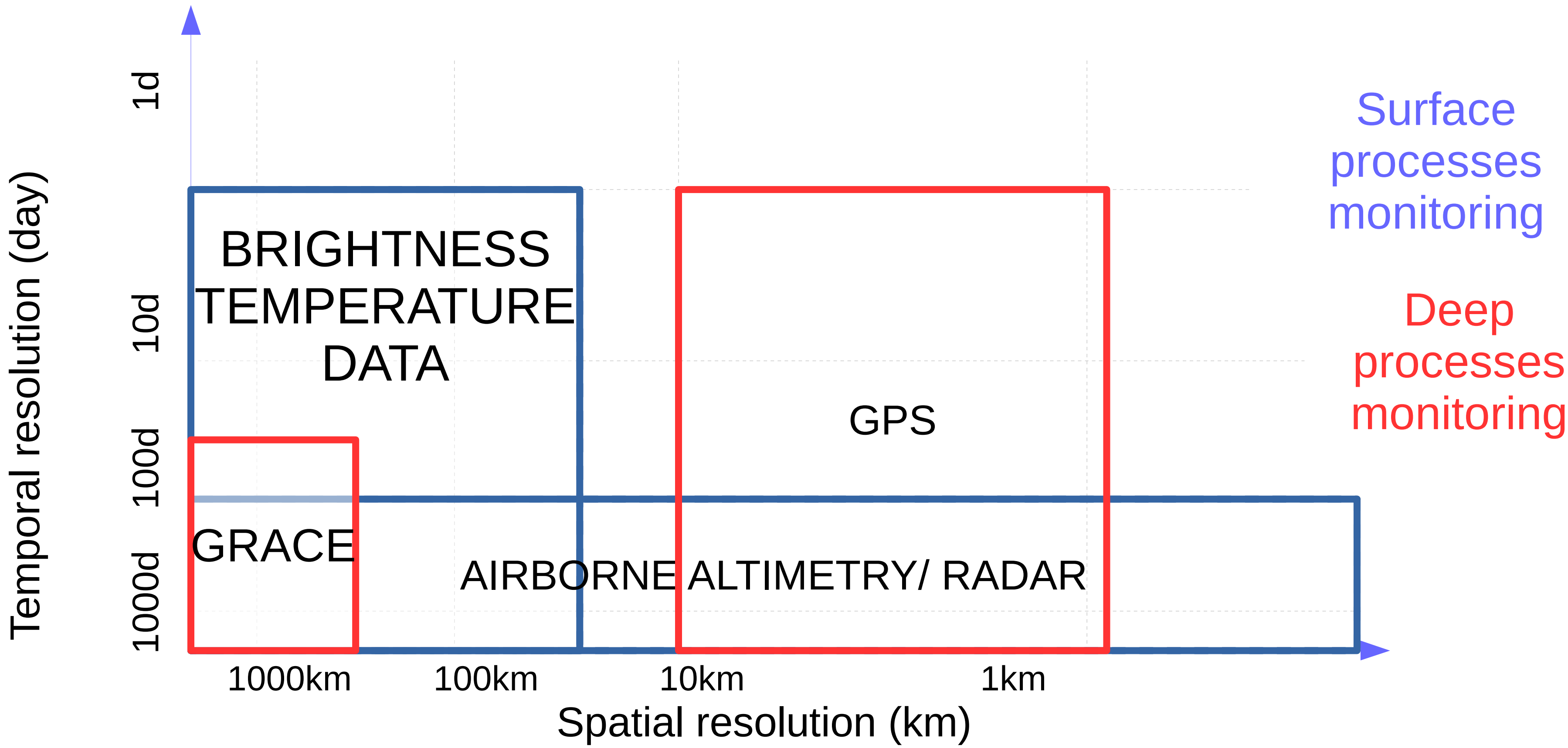
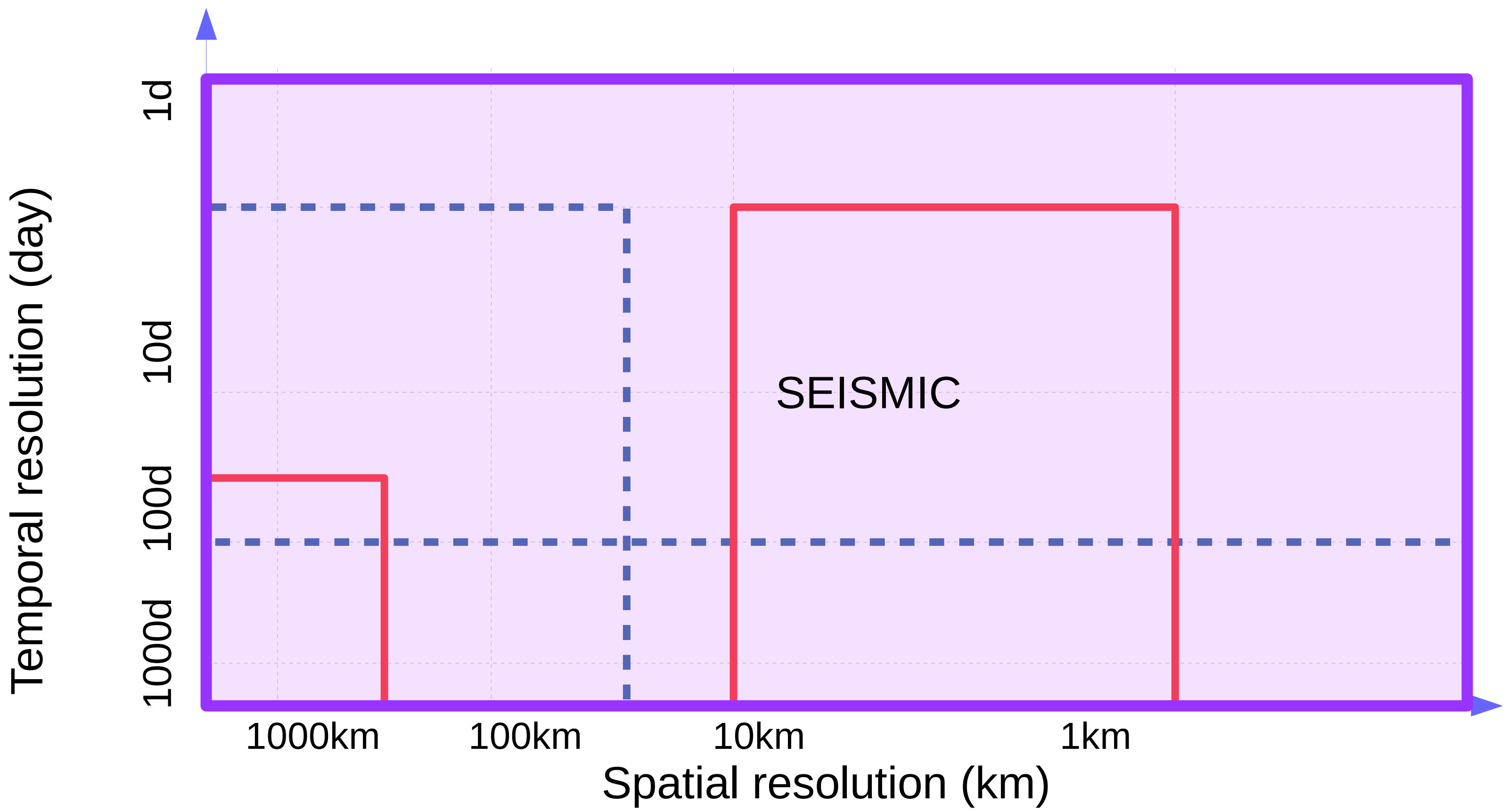
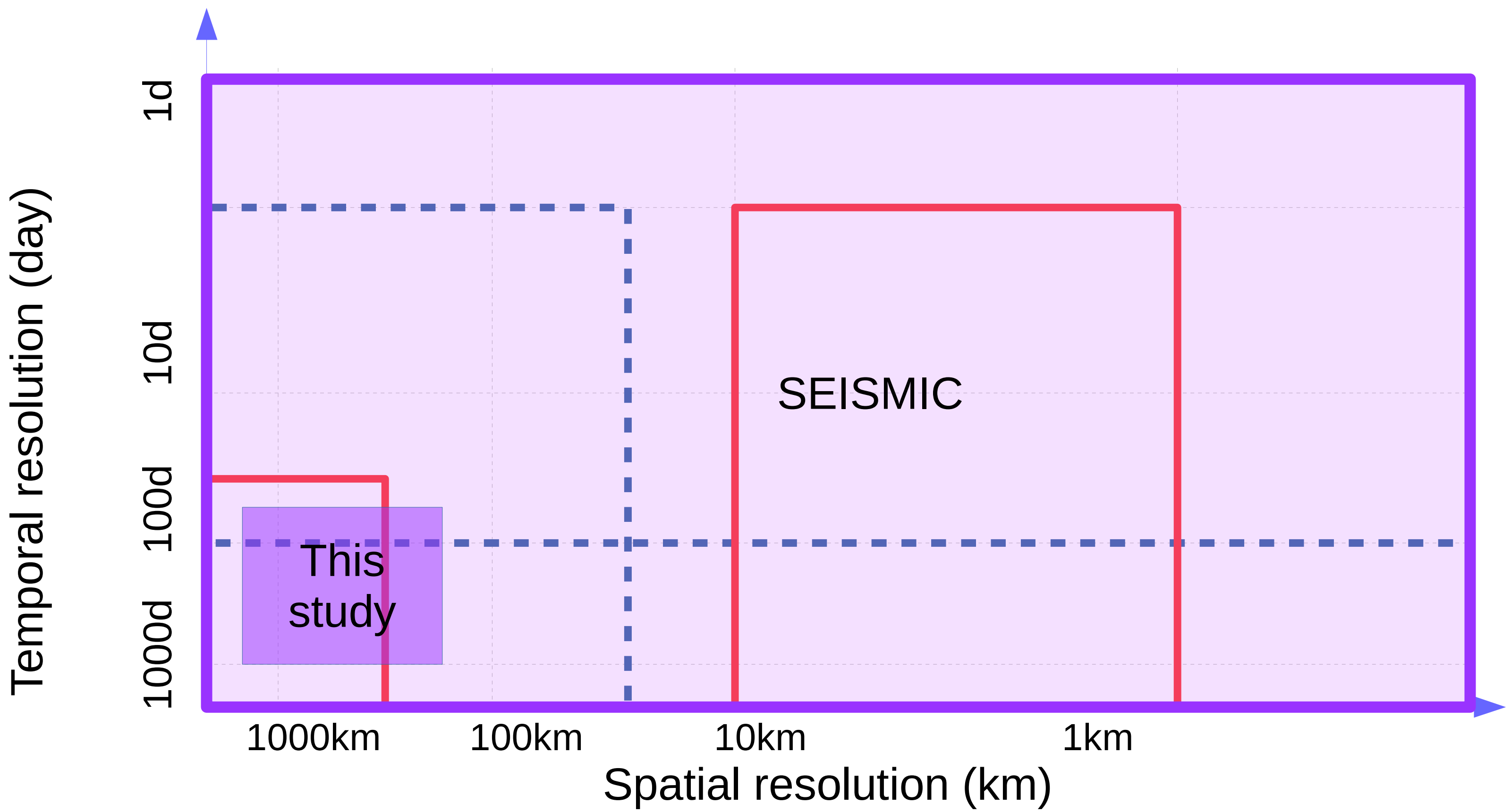
Why use seismic waves to monitor ice sheets?



Why use seismic waves to monitor ice sheets? : An other string to the bow

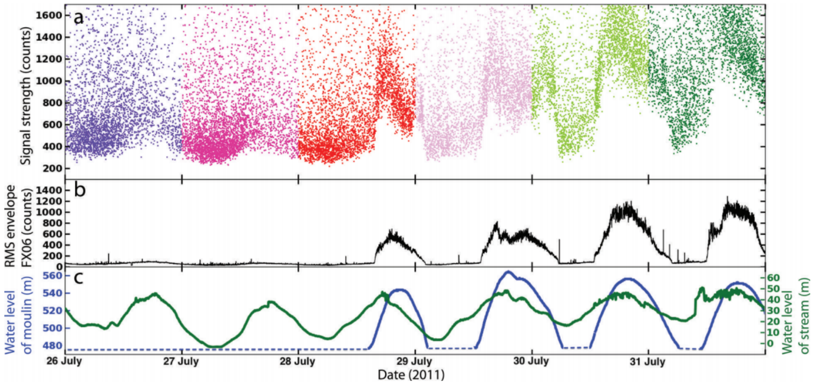


Why use seismic waves to monitor ice sheets? : An other string to the bow

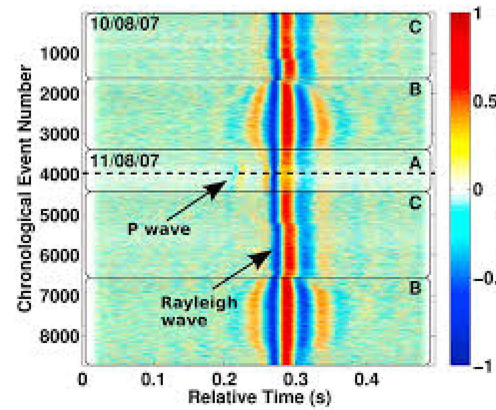


Why use seismic waves to monitor ice sheets? : An other string to the bow

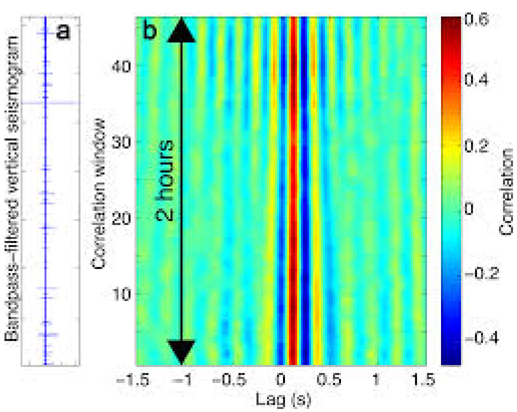
Examples of seismic monitoring studies in ice-sheet and glacier context:



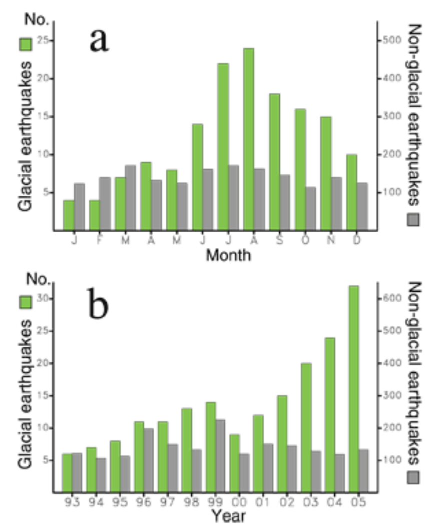
Roosli et al. (2014): Icequakes & moulin water level correspondence



Mikesell et al. (2012): Repetitive icequakes at Bench Glacier, Alaska (USA).



Walter et al. (2015): Moulin tremor cross-correlation



Ekstrom et al. (2006): Seasonal and long-term recurrence of icequakes in Greenland

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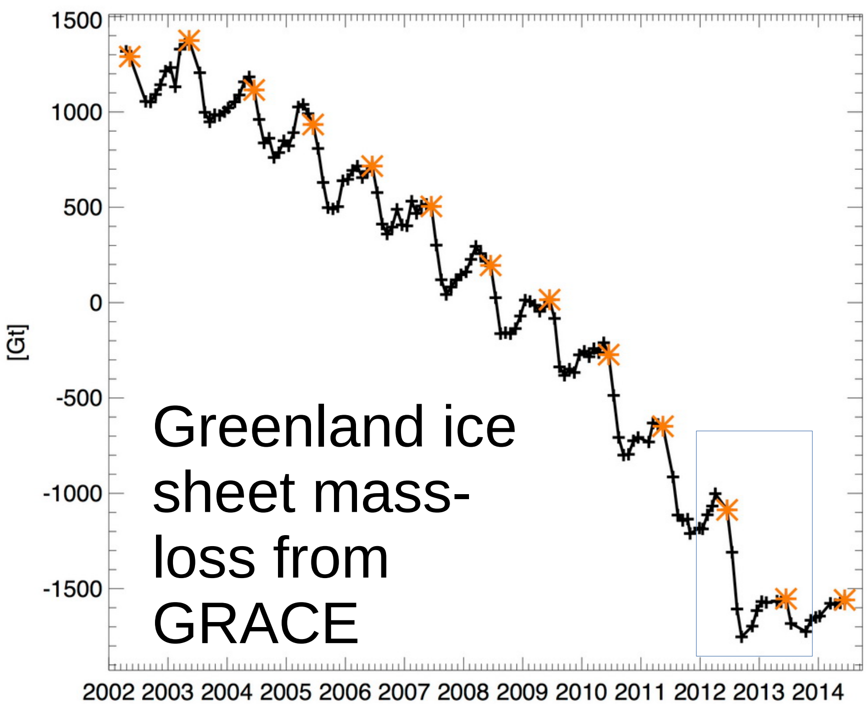
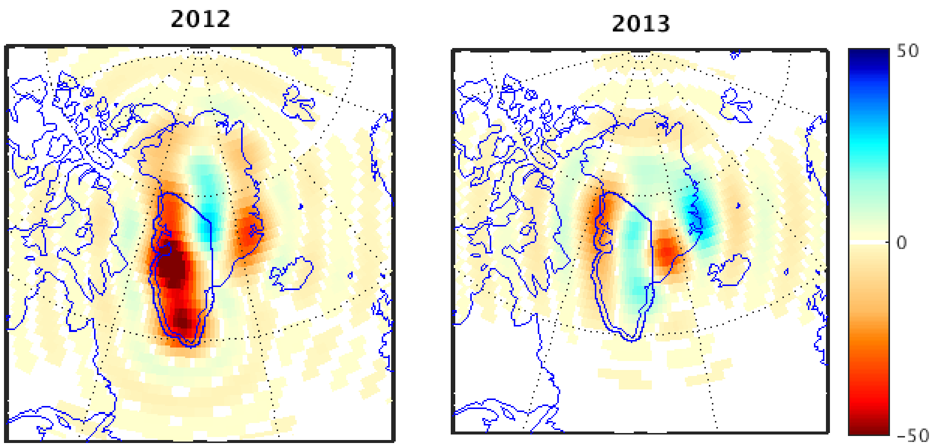
Ice mass changes from GRACE in 2012-2013



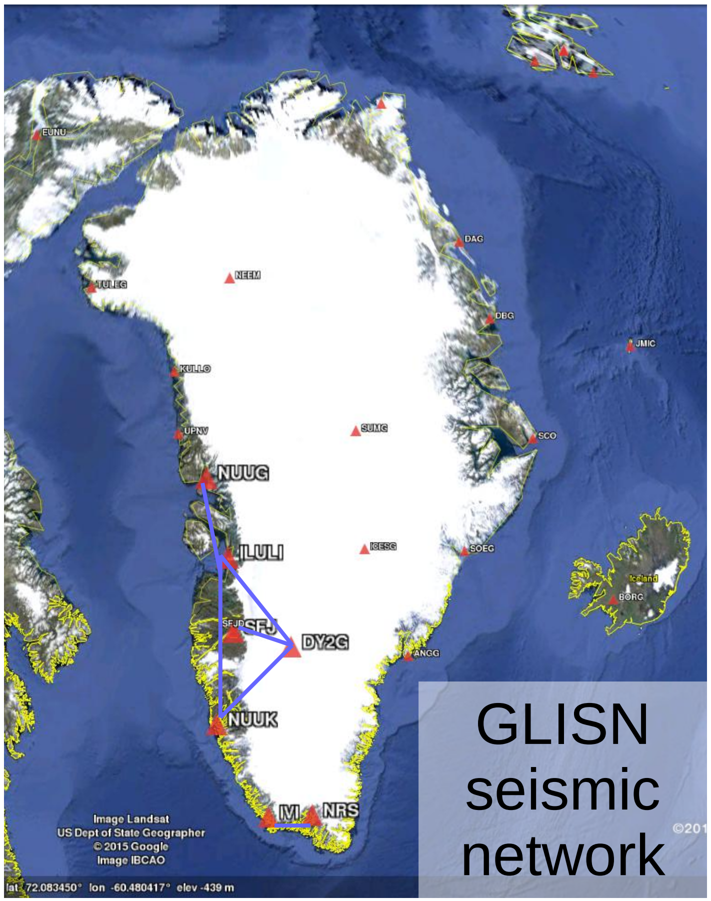
Modified after Tedesco et al. (2015)

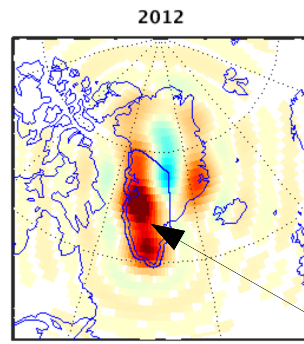


Christopher Harig pers. com. (2015)

2012-2013 = Extreme years for ice-melting in South-West Greenland

Dv/v in 2012-2013 (0.1-0.3 Hz)





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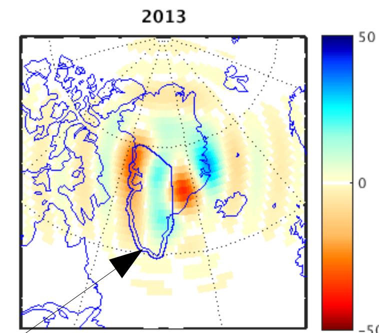
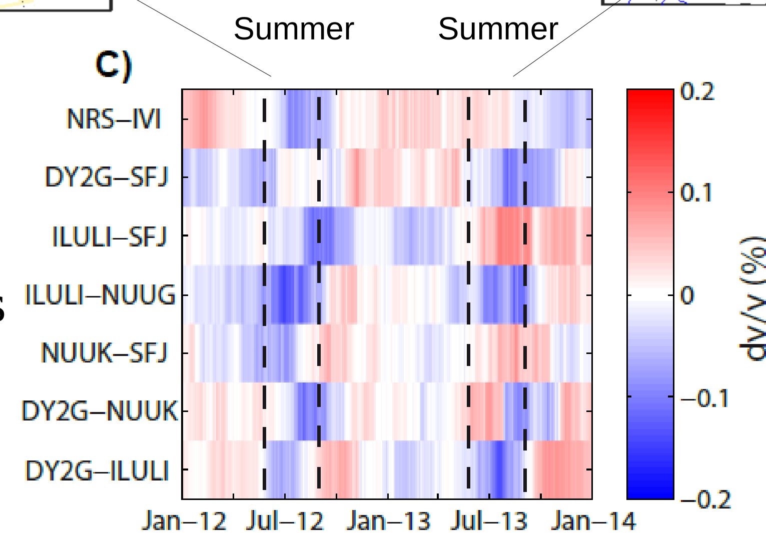
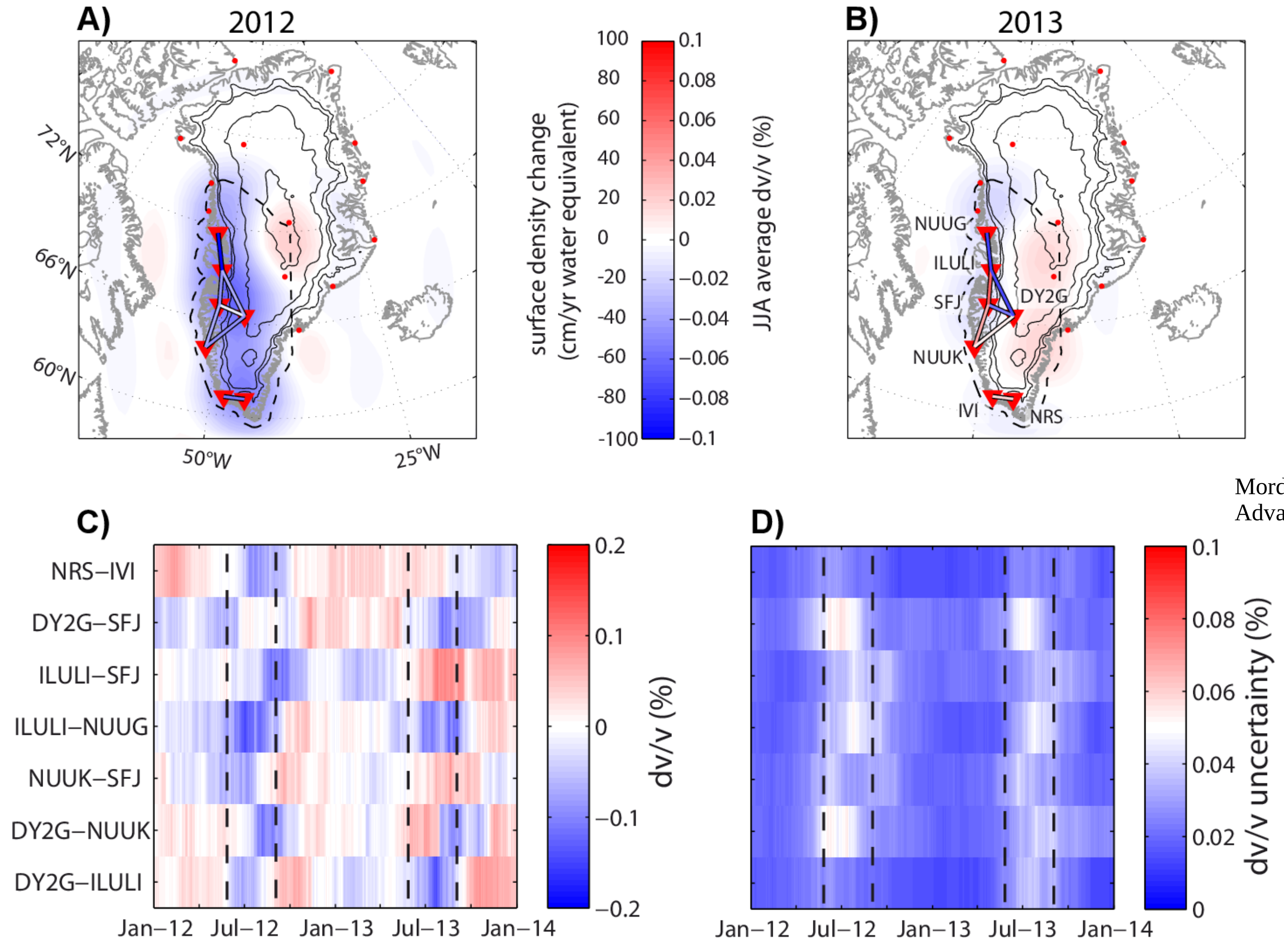


Velocity variations



Mordret et al. (2016, Science Advances)

Dv/v in 2012-2013



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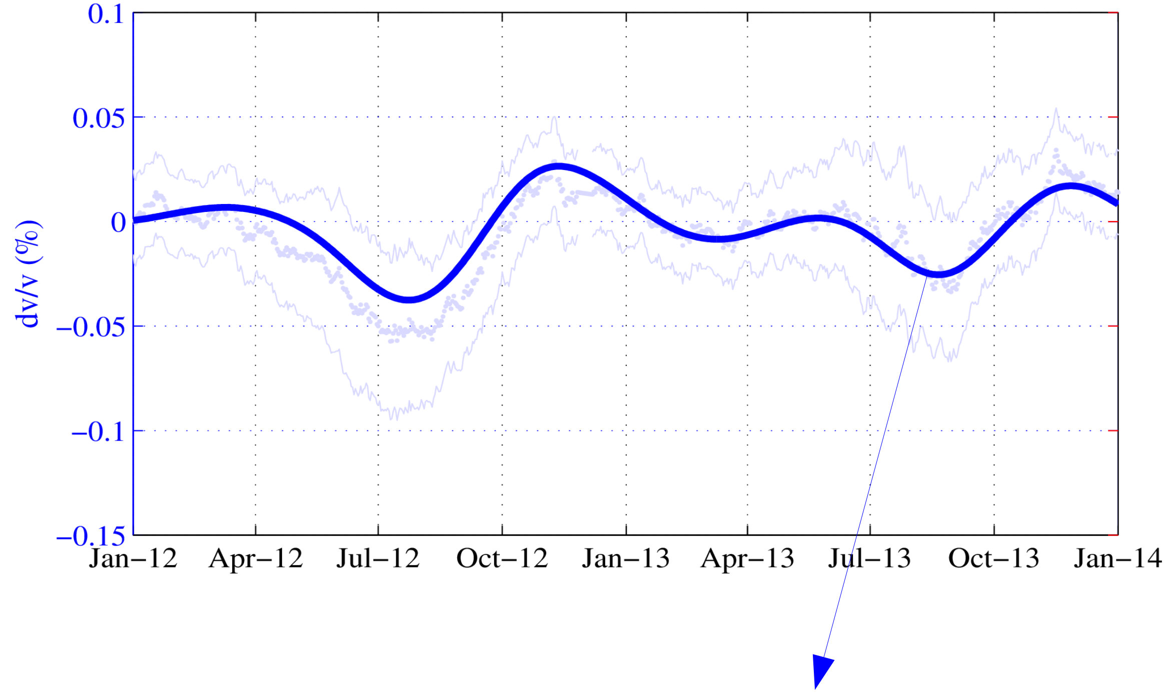
Forward modeling of the velocity variations

- Assume a **homogeneous load** change when doing the averaging



Average of the 7 pairs of stations

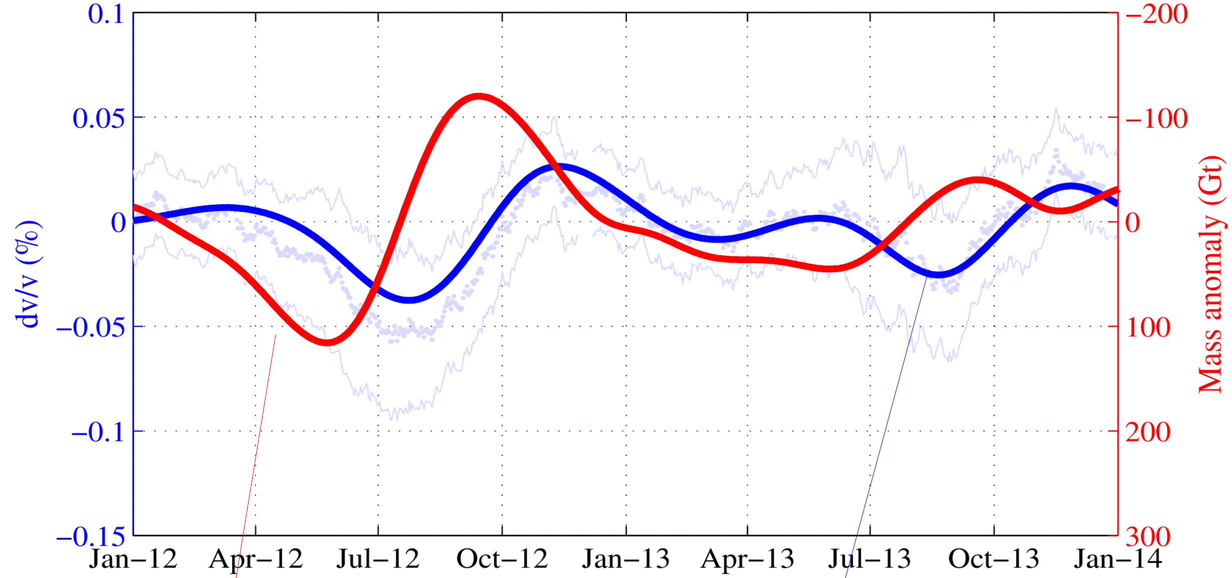
Filtered in 4-17 months period

Mordret et al. (2016, Science Advances)

Forward modeling of the velocity variations

- Assume a **homogeneous load** change when doing the averaging

Viscoelastic model



De-trended mass variations

Average of the 7 pairs of stations

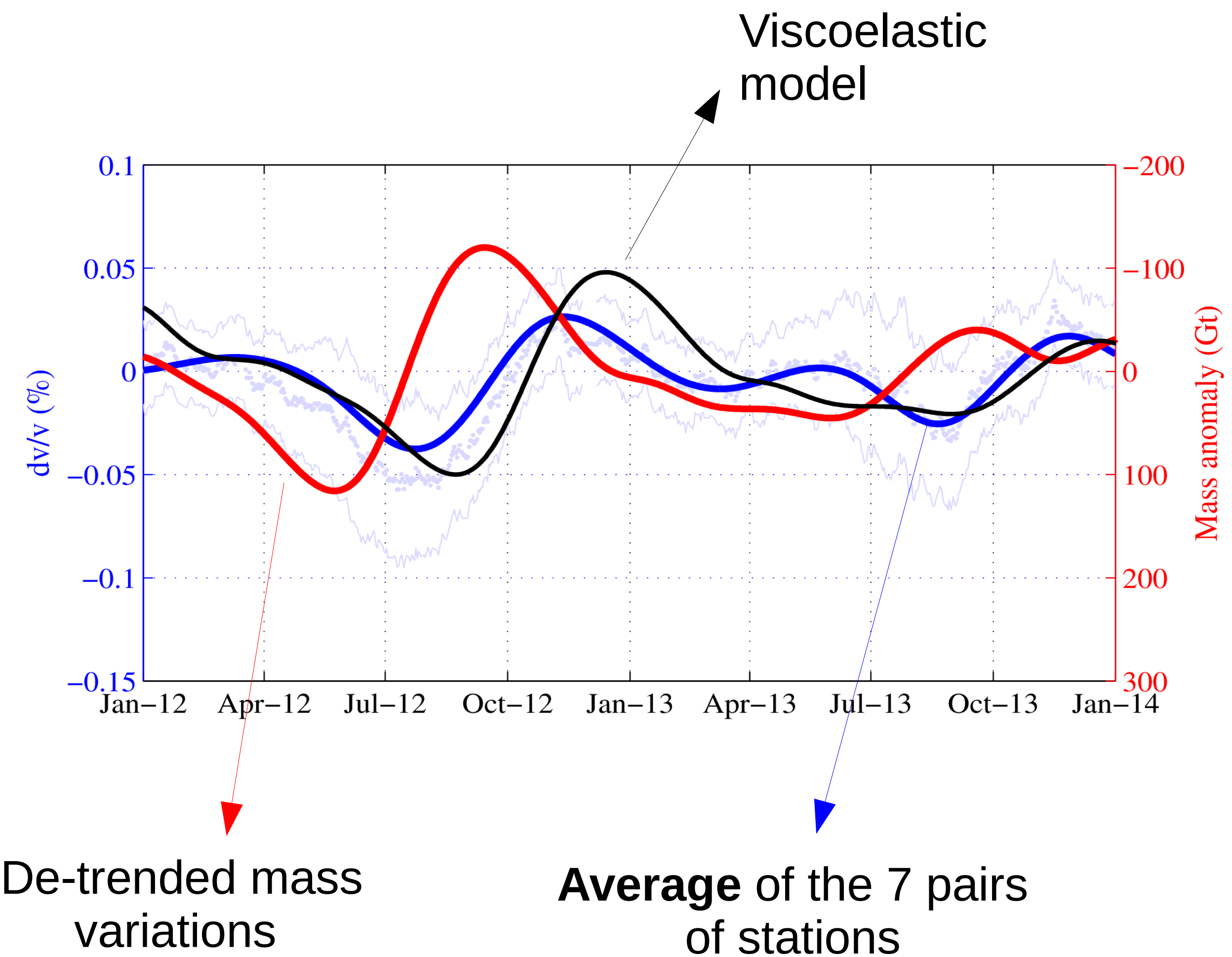
Filtered in 4-17 months period

Mordret et al. (2016, Science Advances)

Forward modeling of the velocity variations

- Assume a **homogeneous load** change when doing the averaging

- **Viscoelastic** modeling: σ ≈ ηέ
- (Dv/v)/strain = 0.5%/µstrain
- **Fit the data at 77%**



Filtered in 4-17 months period

Mordret et al. (2016, Science Advances)

Forward modeling of the velocity variations

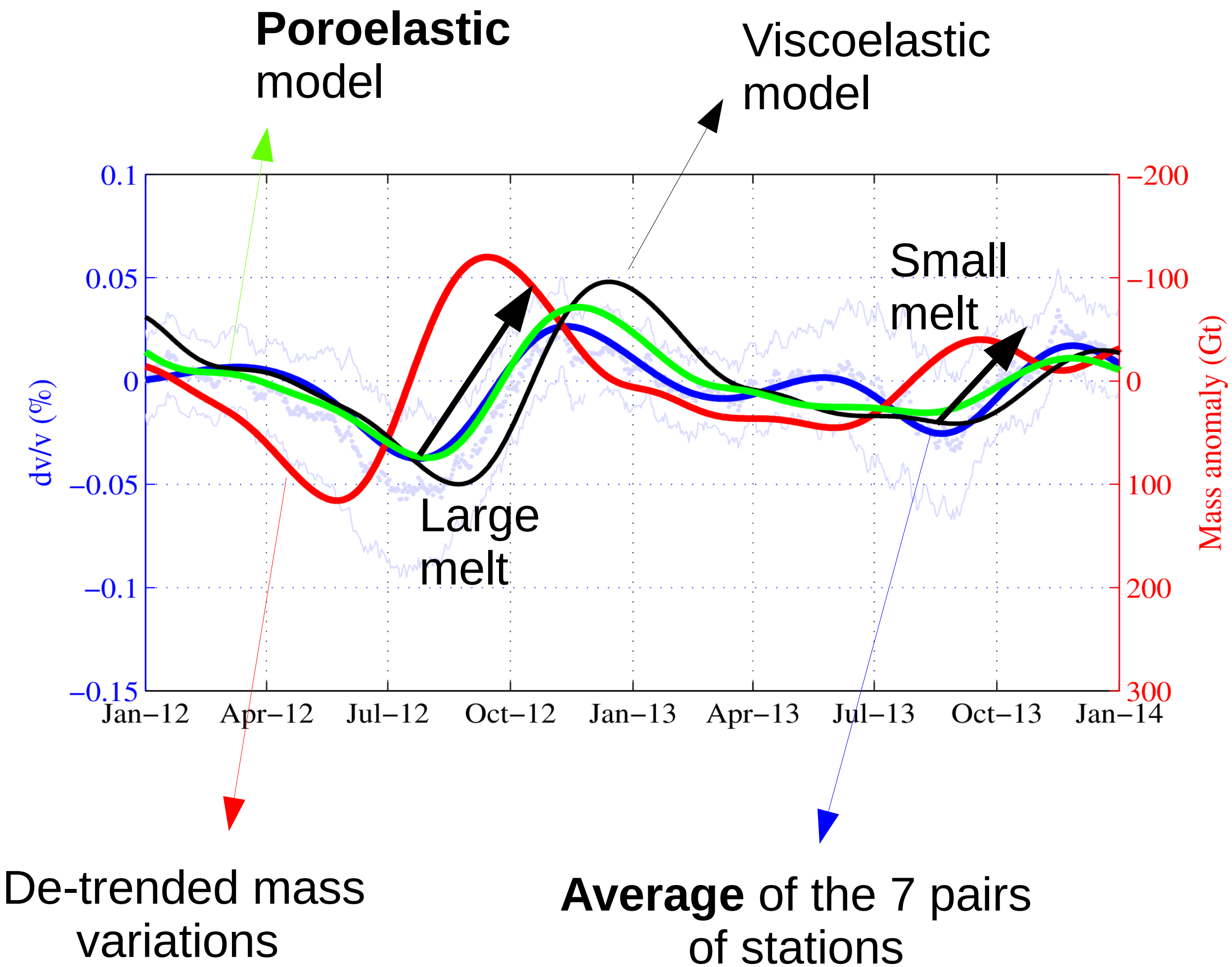
- Assume a **homogeneous load** change when doing the averaging

- **Viscoelastic** modeling: σ ≈ ηέ
- (Dv/v)/strain = 0.5%/µstrain
- **Fit the data at 77%**

- **Poroelastic** modeling of seismic velocity variations due to pore-pressure variations (Tsai 2011)

- Incorporate a **till layer** (2.85 m) to fit the delay

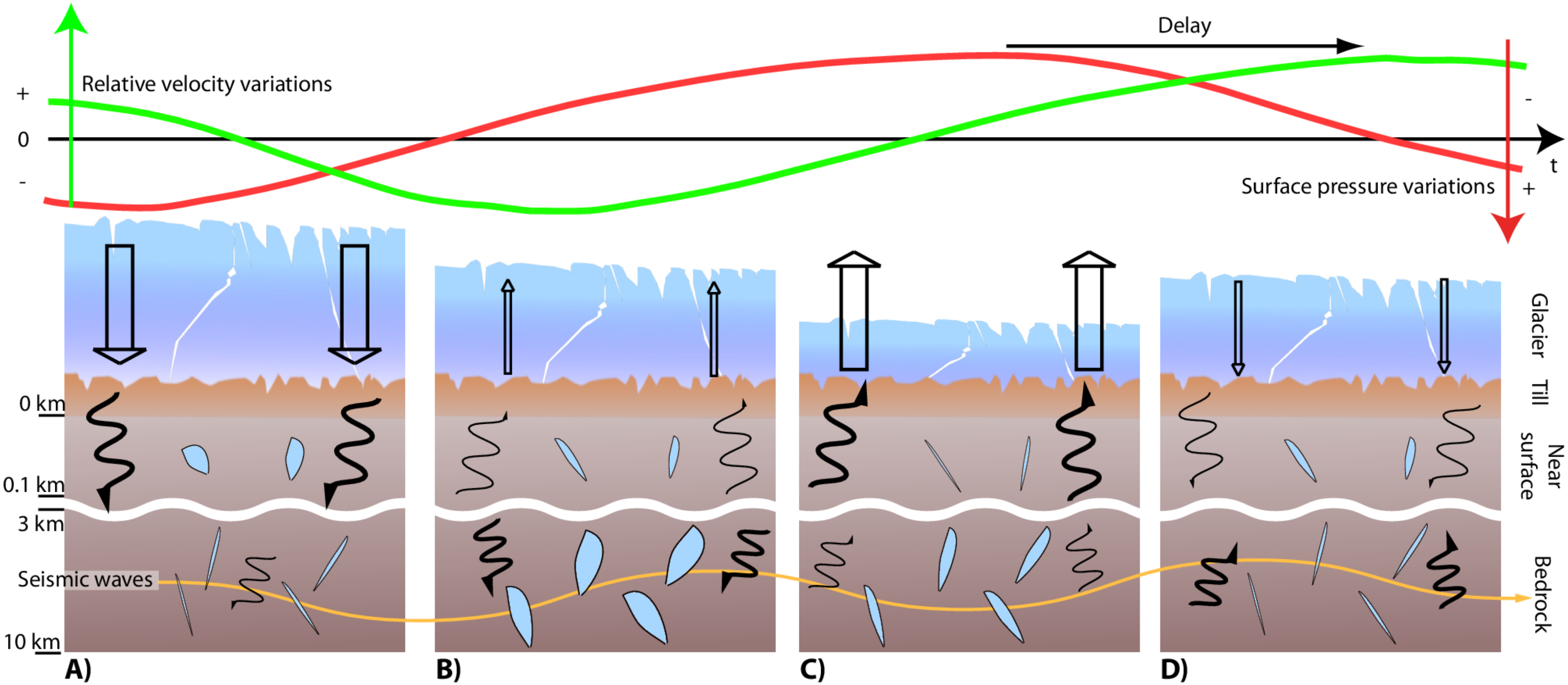
- With reasonable parameter values (from the literature), we **fit the data at 90%**



Filtered in 4-17 months period

Mordret et al. (2016, Science Advances)

Velocity changes due to pore-pressure variations



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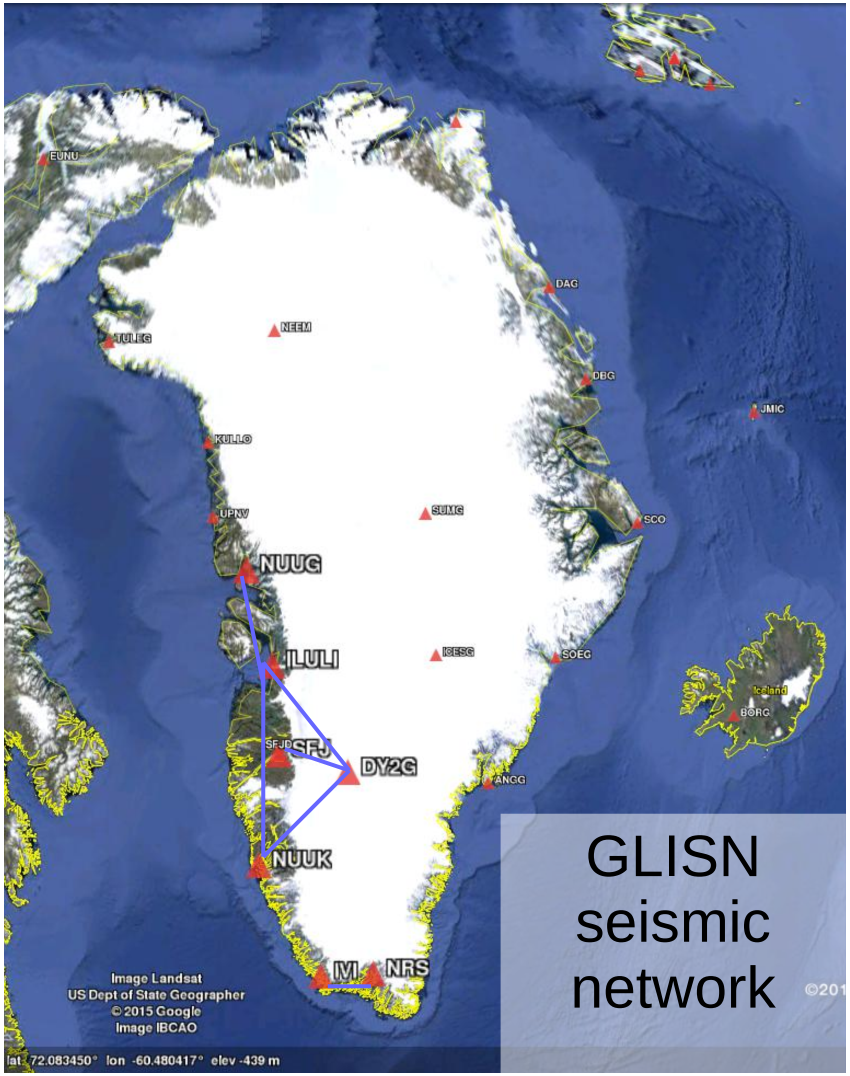
Conclusions and perspectives

- **Seismic methods** can provide **fine spatial and temporal resolution** for monitoring applications
- **Seismic waves** traveling in the crust are **sensitive to changes in the ice sheet**
- The loading and unloading of the ice induce **pore-pressure variation**s in the crust which can be detected through **seismic velocity monitoring**

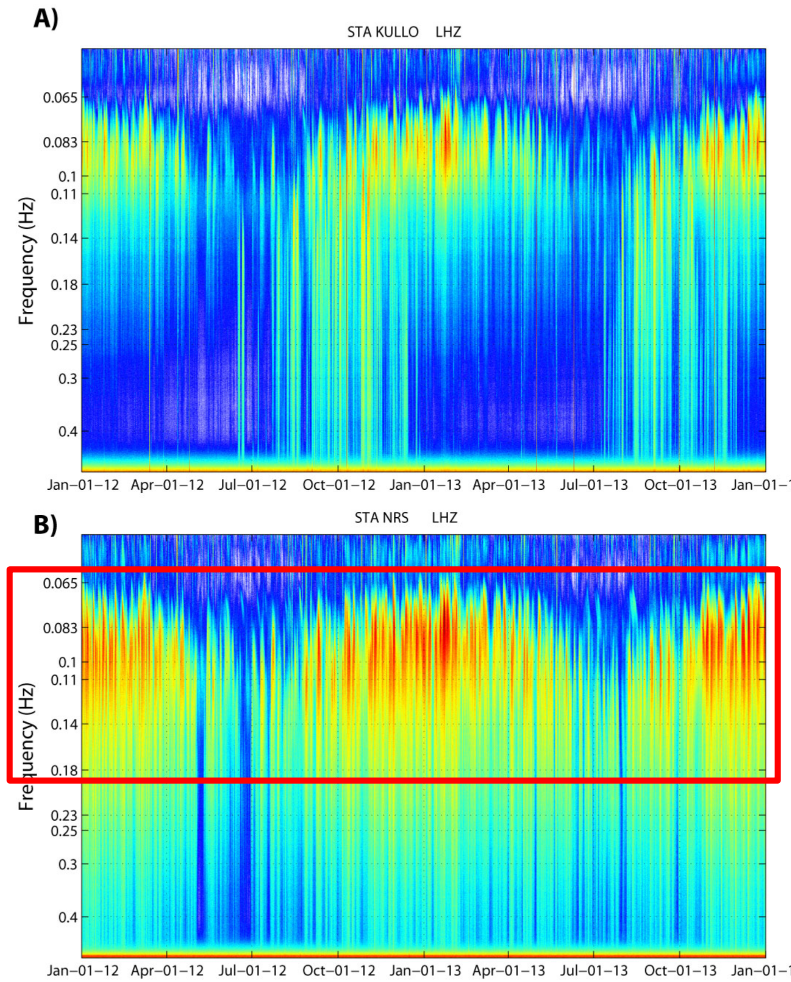
- Possibility to compute a **map of ice-mass changes** through tomographic inversion if more stations

- Future application to the **Antarctica ice sheet**

Seismic data in Greenland

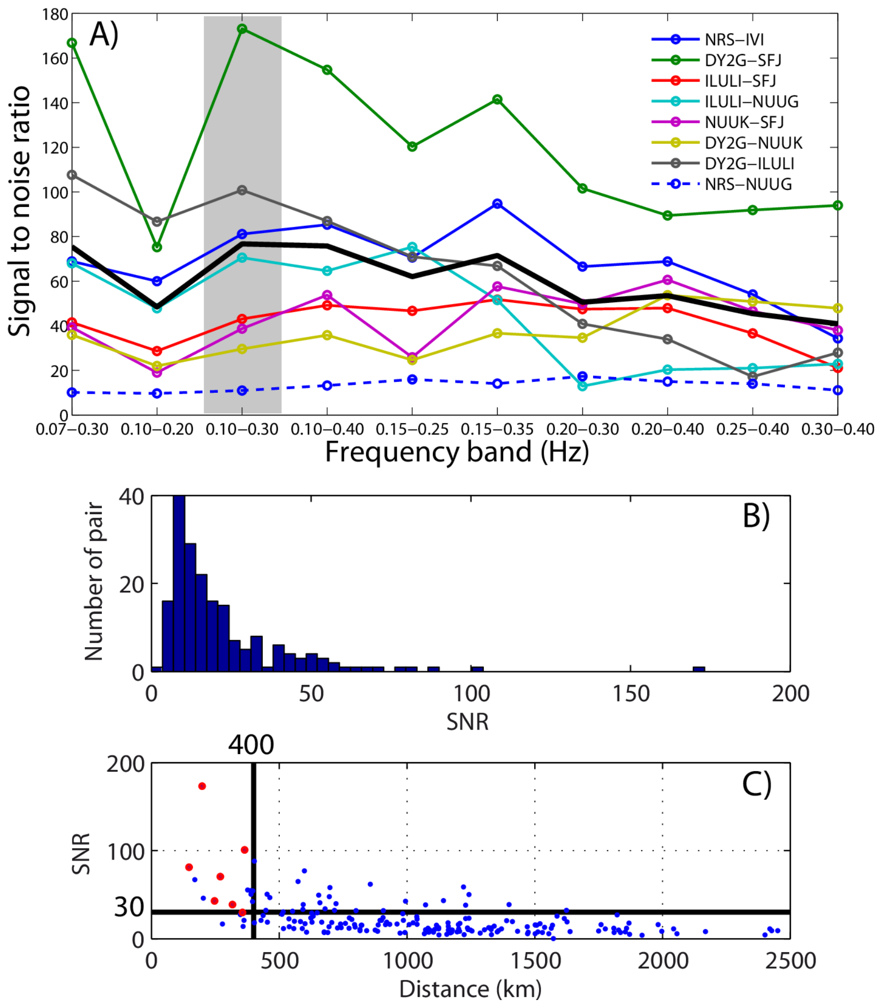


We use 7 closest stations on West coast

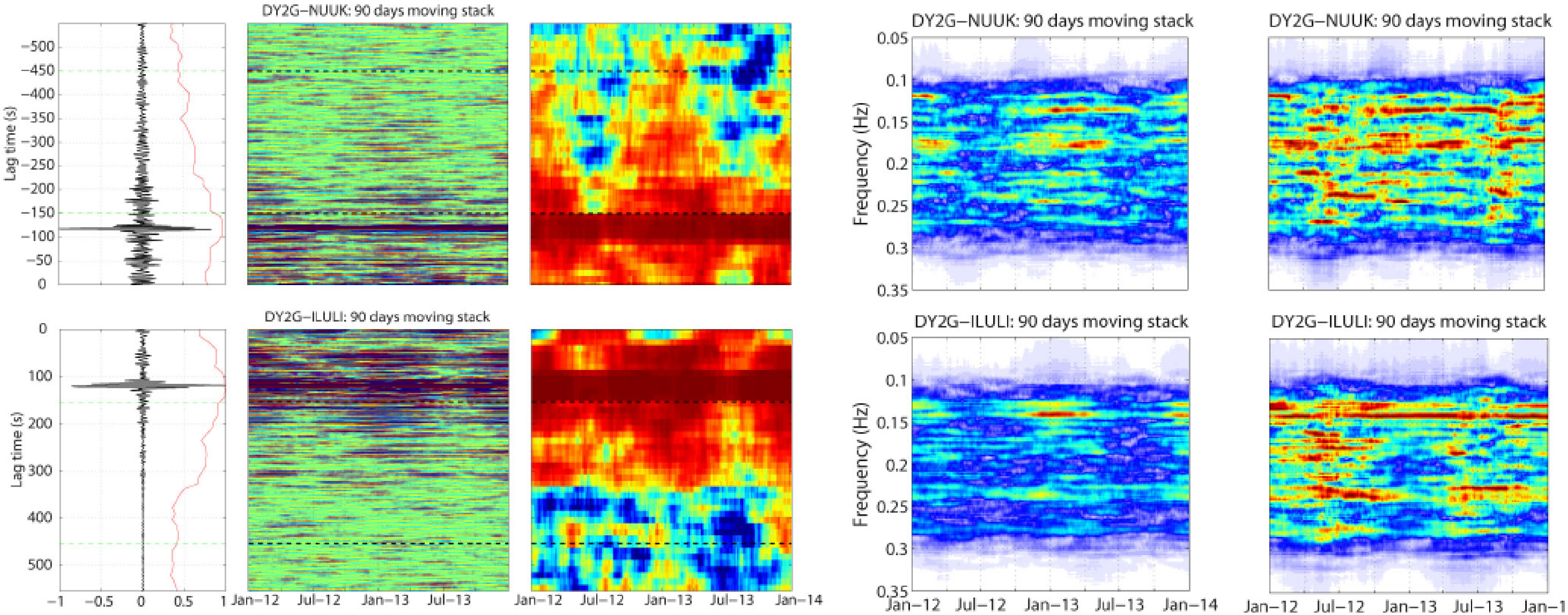


Seismic data processing

1) Demean, detrend, remove instrumental response of daily data
2) Filter between 0.1 – 0.3 Hz
3) Cut into 4 hours segments (50% overlap)
4) Clipped at 3 std of each segment
5) Spectral whitening in 0.1 - 0.3 Hz
6) Cross-correlate each segment
7) Stack for daily correlations
8) Stack daily correlations with a 90 days running average
9) Measure relative velocity variations

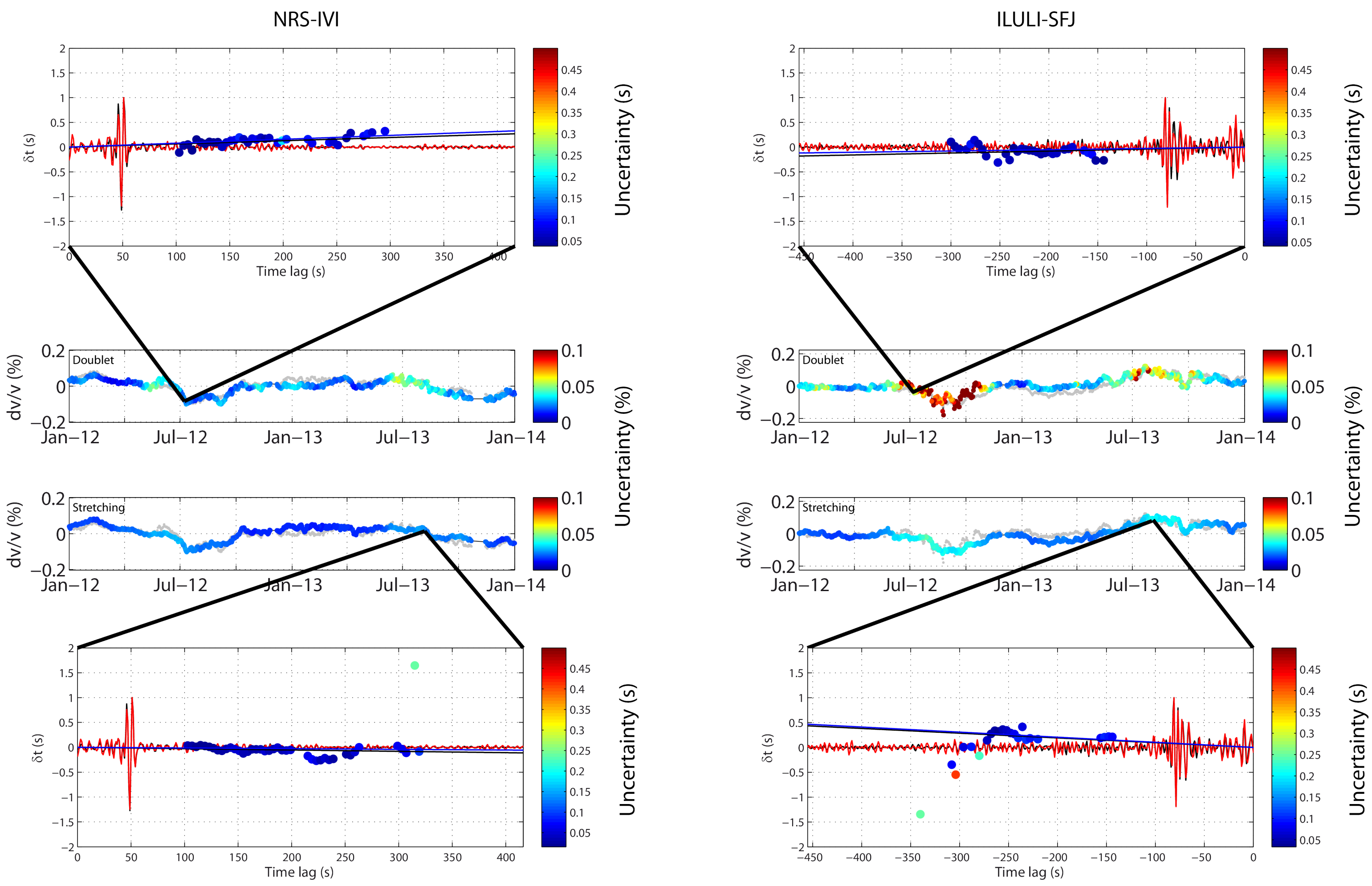


Noise correlations

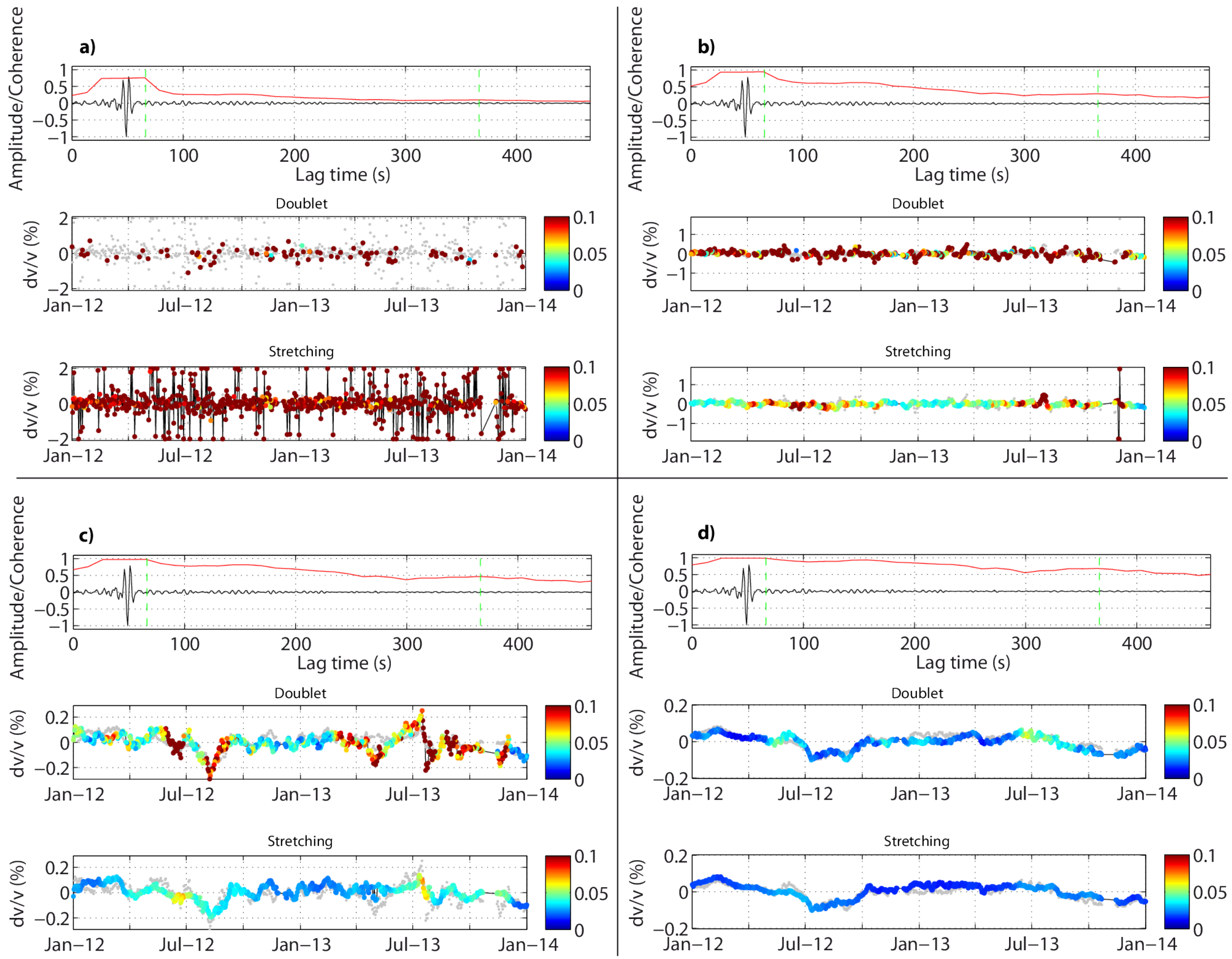


Stack | Daily Corr | Daily Coherency | Correlation spectrograms

Stretching vs. MWCS



Influence of number of days stacked



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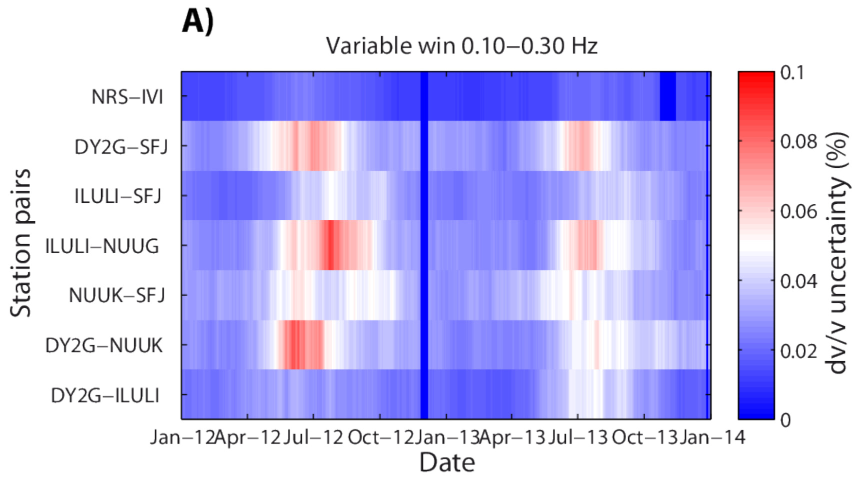
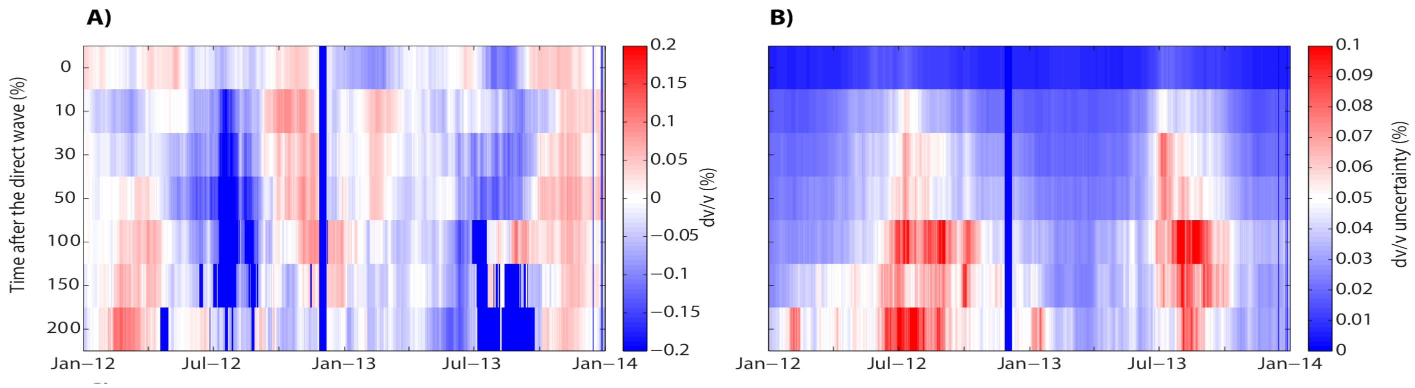
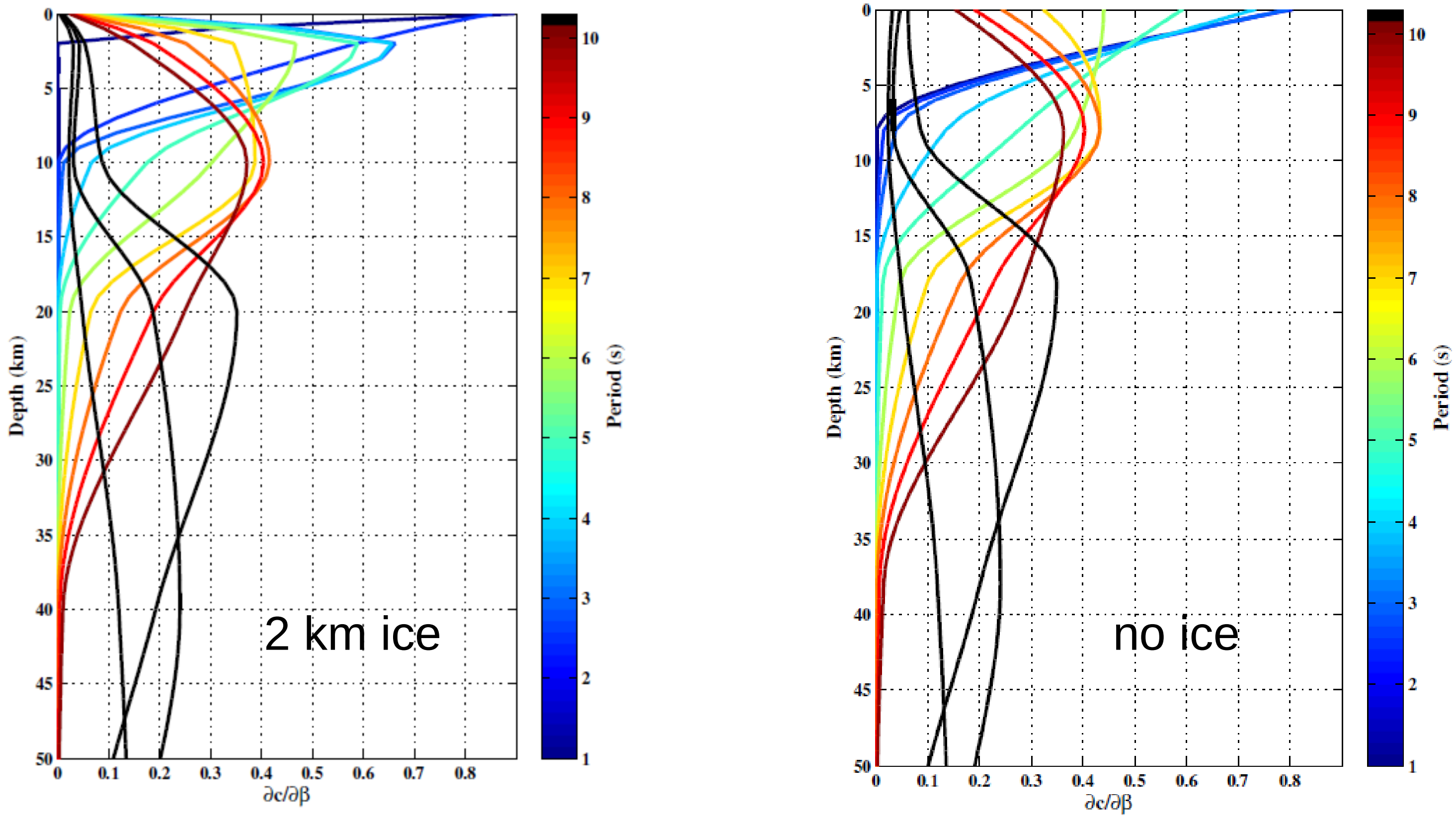
Influence of the window in the coda

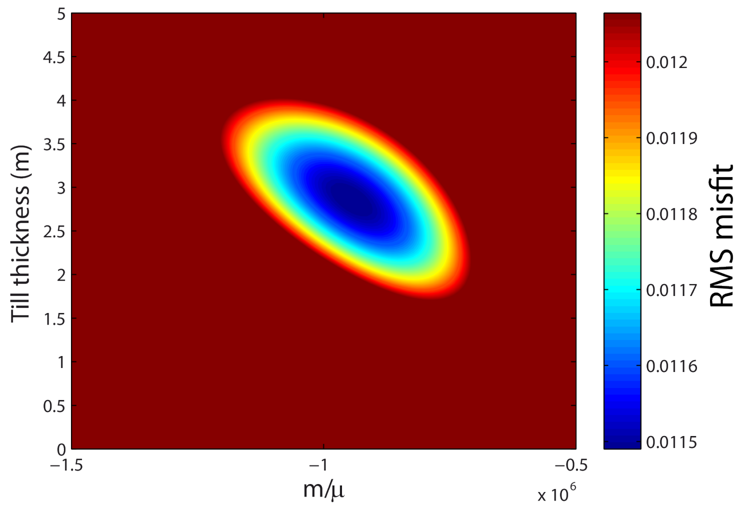




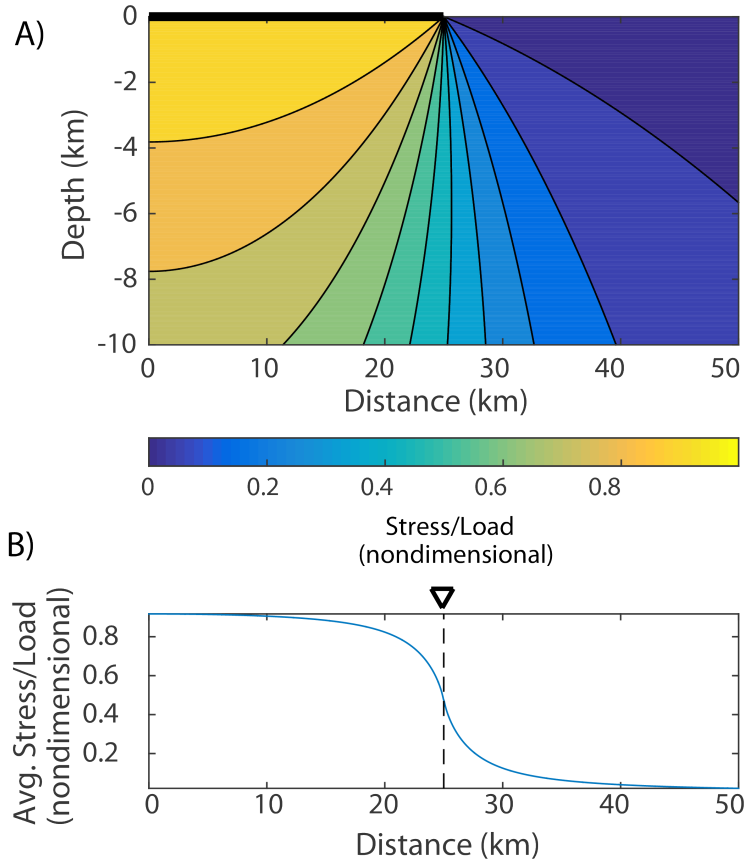
Depth sensitivity of Rayleigh waves in Greenland



Modeling



Till thickness (m)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−1.5
−1
−0.5
m/μ
x 10^6
0.012
0.0119
0.0118
0.0117
0.0116
0.0115
RMS misfit



A)
0
-2
-4
-6
-8
-10
Depth (km)
0
10
20
30
40
50
Distance (km)
0
0.2
0.4
0.6
0.8
Stress/Load
(nondimensional)
B)
Avg. Stress/Load
(nondimensional)
0.8
0.6
0.4
0.2
0
10
20
30
40
50
Distance (km)

Dv/v modeling parameters

Table 1: **Parameters used in the dv/v modelling.**

Parameter	Symbol	Value	Reference
Glaciostatic pressure	P_g	1600 Pa	from data
Ice area	S_i	$6.5 \cdot 10^{11}$ m^2	from data
Gravitational acceleration	g	9.81 m/s^2	
Pressure field wave number	k	$2\pi/(60$ km$)$	Jiang et al[11]
Depth of investigation	z	5 km	from data
S-wave velocity	Vs	3300 m/s	Kumar et al[56]
Vp/Vs ratio	Vp/Vs	1.8	Kumar et al[56]
Upper crust density	ρ_c	2700 kg/m^3	Schmidt-Aursch et al[57]
P-wave velocity	$Vp = Vs(Vp/Vs)$	5940 m/s	
Poisson's ratio	ν	0.2768	
Young's modulus	E	$7.5 \cdot 10^{10}$ Pa	
Mantle viscosity	η	10^{21} Pa·s	
Viscoelastic relaxation time	T	10^{11} s	
Lamé's first parameter	λ	$3.65 \cdot 10^{10}$ Pa	
Shear modulus	μ	$2.94 \cdot 10^{10}$ Pa	
Murnaghan constant	m	$-2.77 \cdot 10^{16}$ Pa	from inversion
Distance from the ice	x	12.5 km	
Biot's coefficient	α	0.7	Tsai[34]
Hydraulic diffusivity of the crust	K_c	0.5 m^2/s	Shapiro et al[58]
Angular frequency	ω	$2\pi/(365$ days$)$	
Till layer thickness	z_t	2.85 m	from inversion
Hydraulic diffusivity of till	K_t	$5 \cdot 10^{-6}$ m^2/s	Iverson et al[43]