Resolving subglacial hydrology network dynamics through seismic observations on an Alpine glacier.

A 3-year PhD research defended by **Ugo NANNI** on December 3rd 2020

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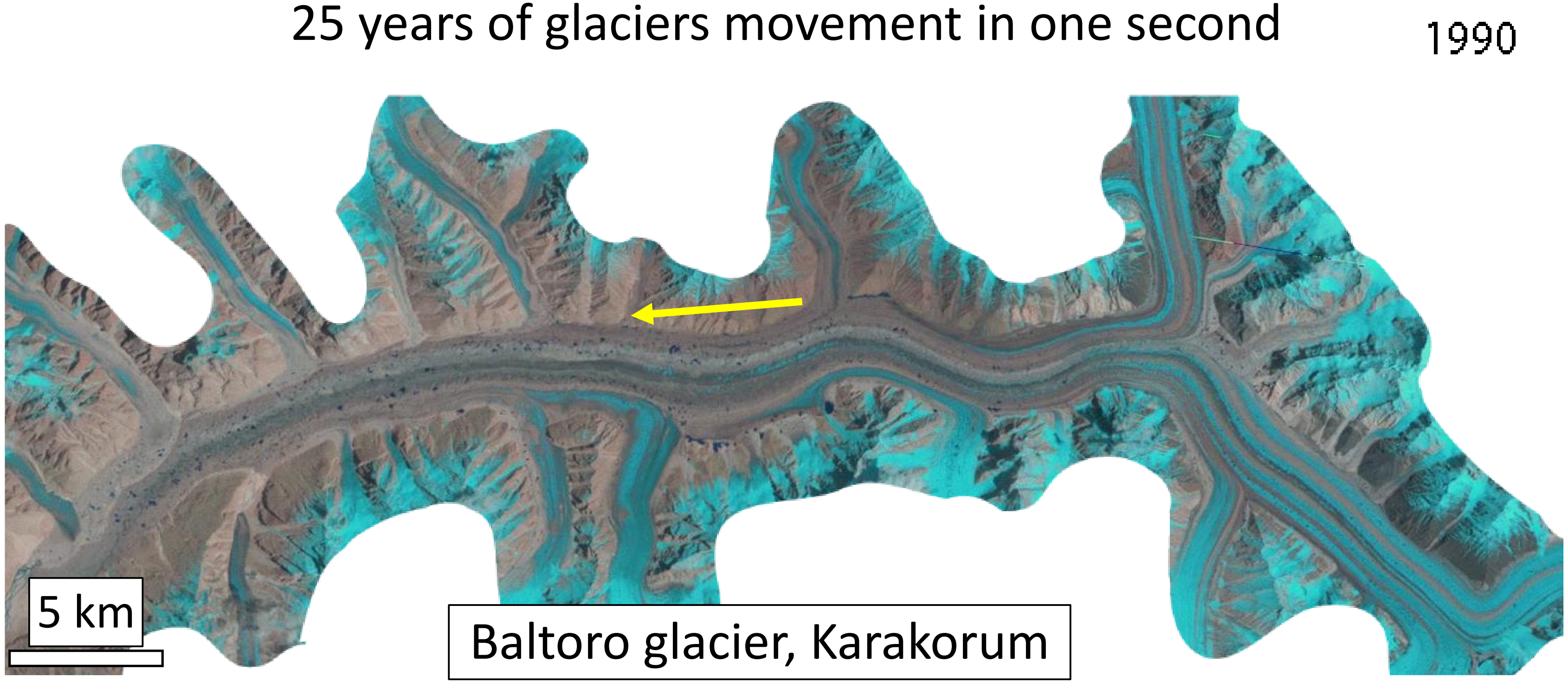
My first step in glaciology

25 years of glaciers movement in one second

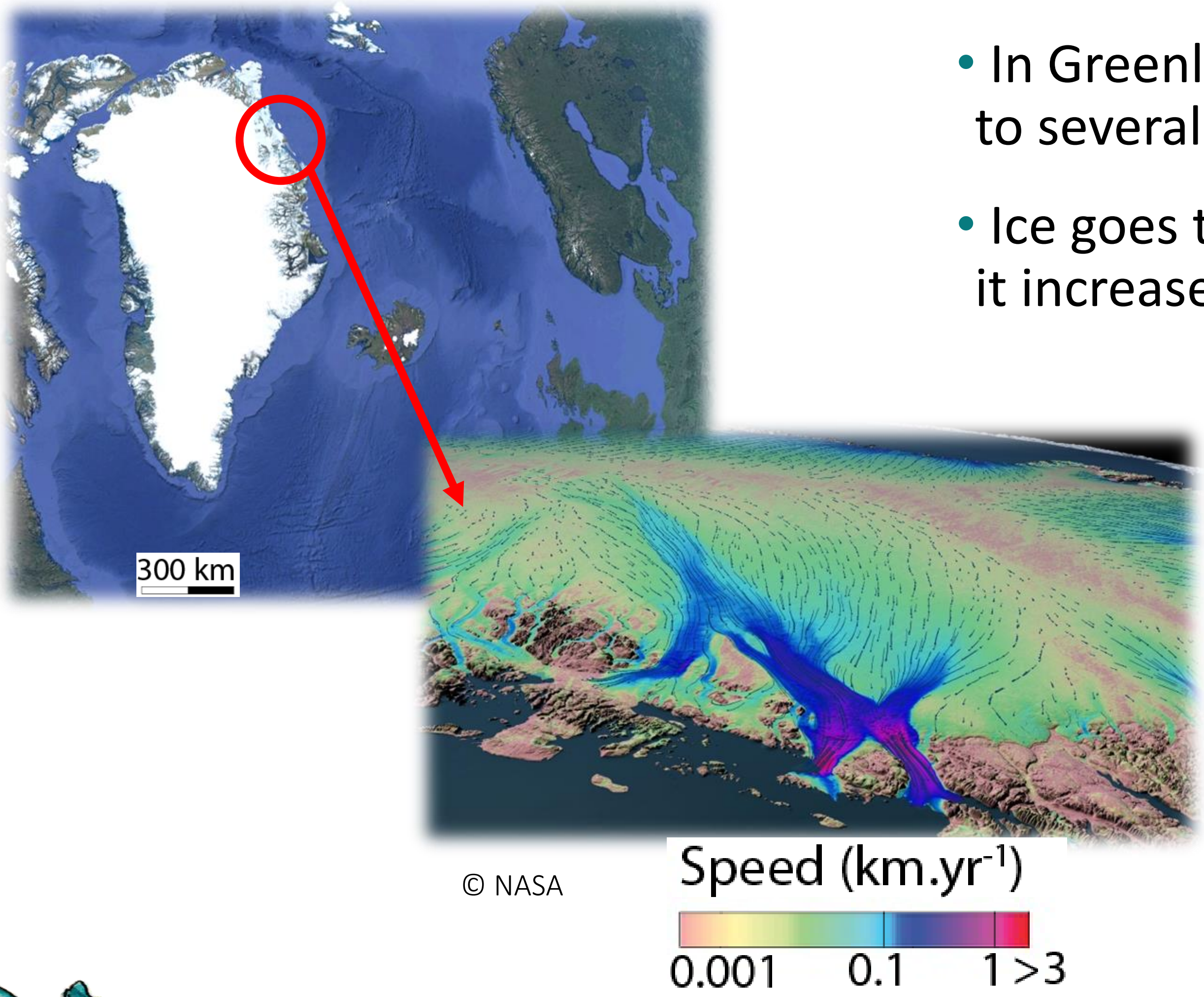


Up to 200 m/year

(Paul, 2015; Quincey et al., 2008)

Glaciers and ice sheets drive sea-level-rise

- In Greenland glaciers flow up to several kilometer per year!
- Ice goes to the ocean where it increases sea-level rise



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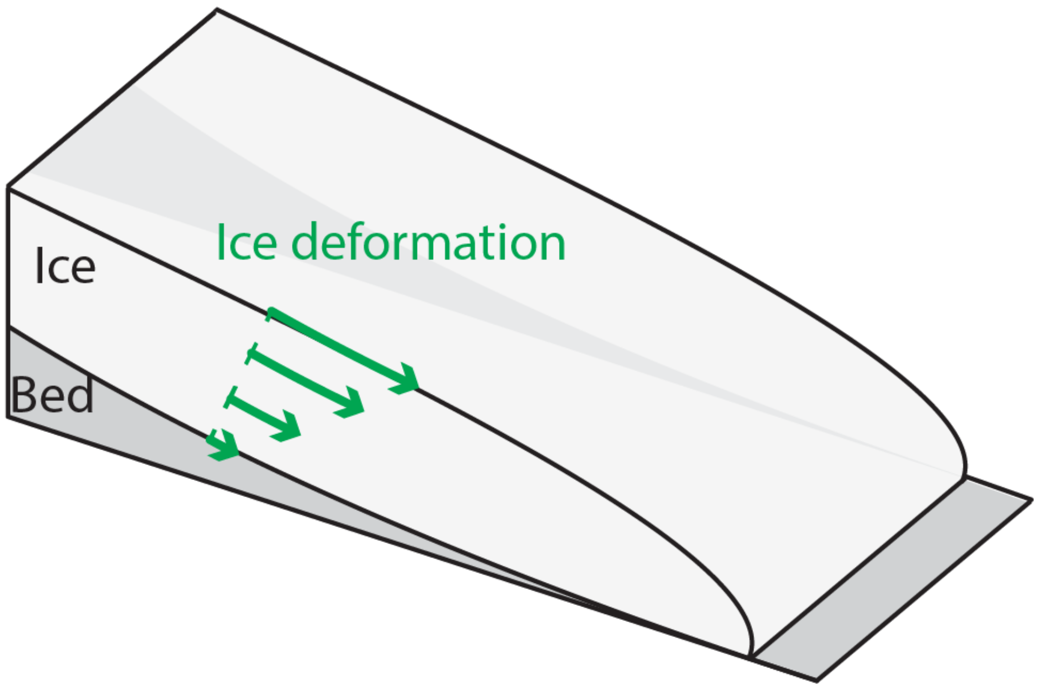
A flood in France (2016)

On the dynamics of glaciers

- Glaciers form by snow accumulation
- Ice slowly deforms and flows downhill

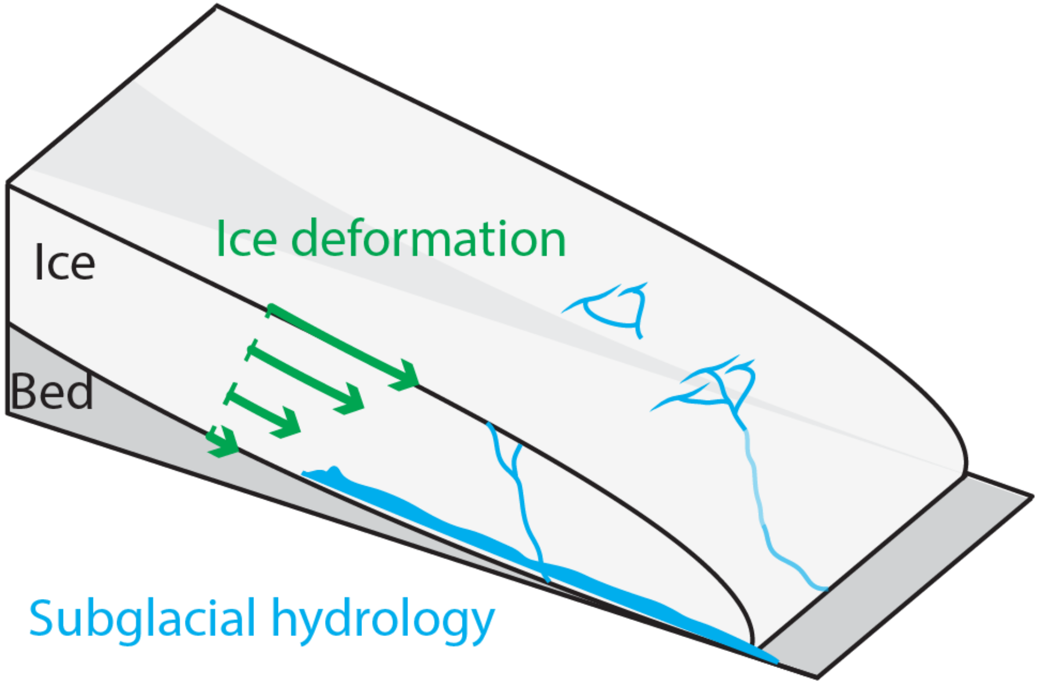


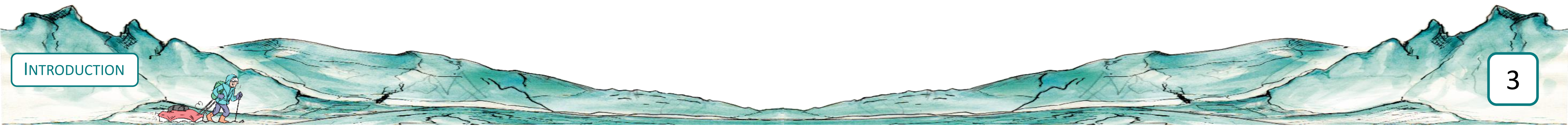
On the dynamics of glaciers

- Glaciers form by snow accumulation

- Ice slowly deforms and flows downhill

- At low altitudes surface melt occurs and meltwater penetrates glaciers

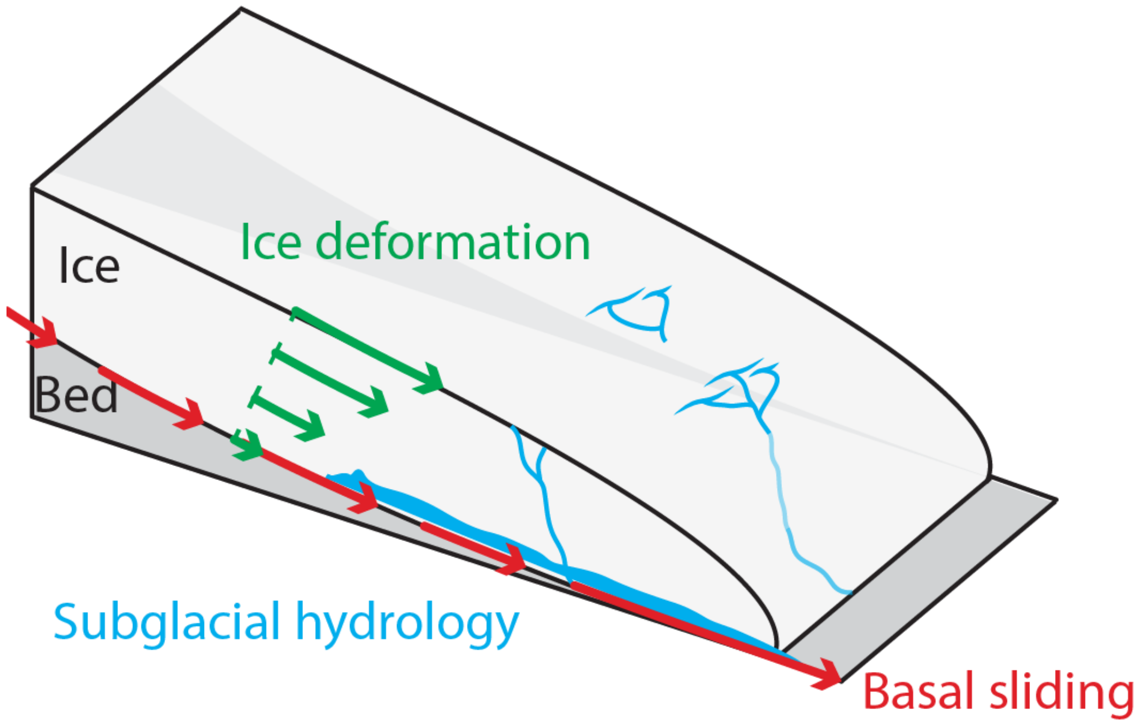




On the dynamics of glaciers

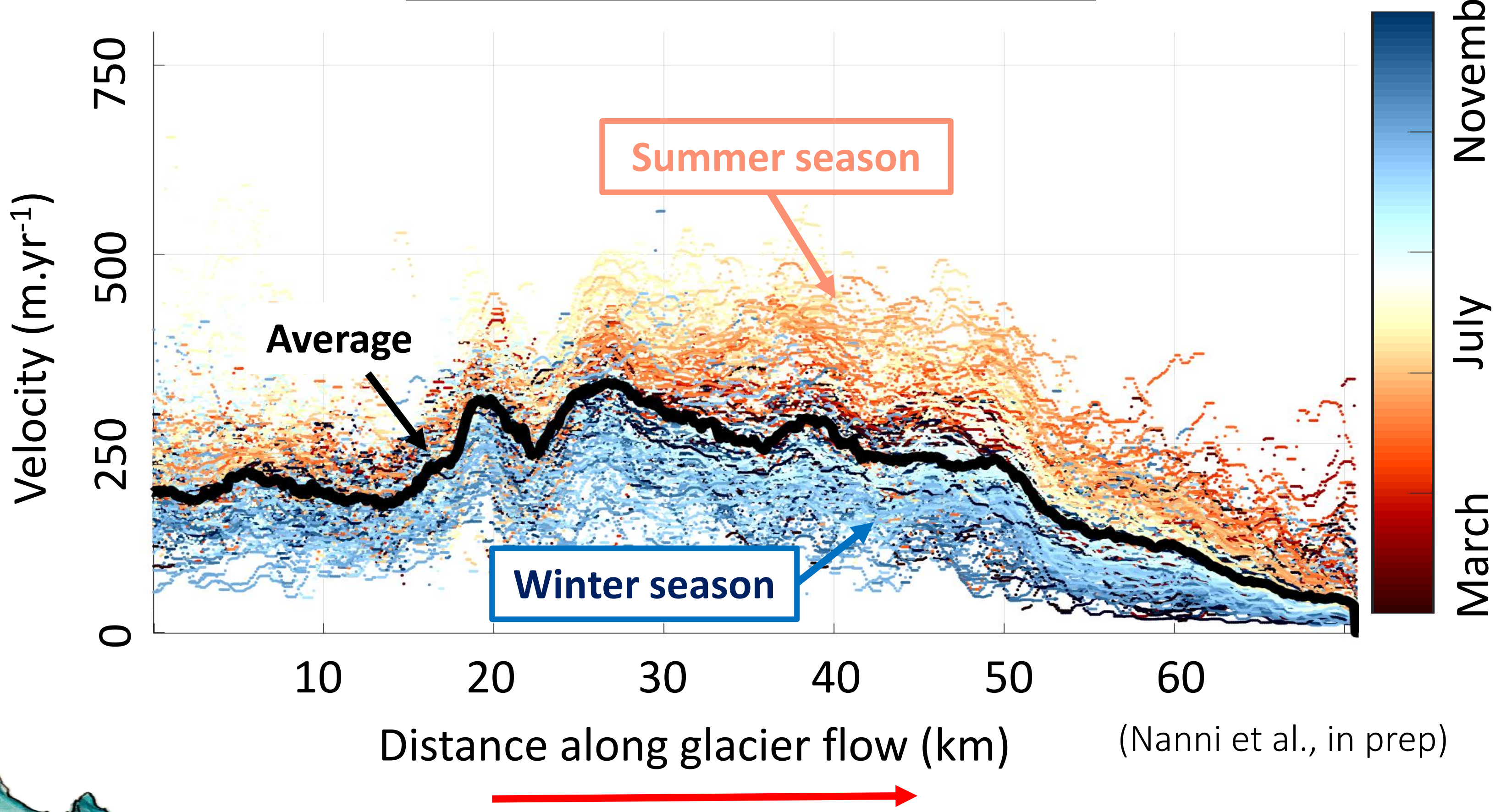
- Glaciers form by snow accumulation
- Ice slowly deforms and flows downhill
- In low altitudes surface melt occurs and meltwater penetrates glaciers
- Subglacial waterflow modulates sliding by lubrication

Up to 50 to 90% of ice flow



My second step in glaciology

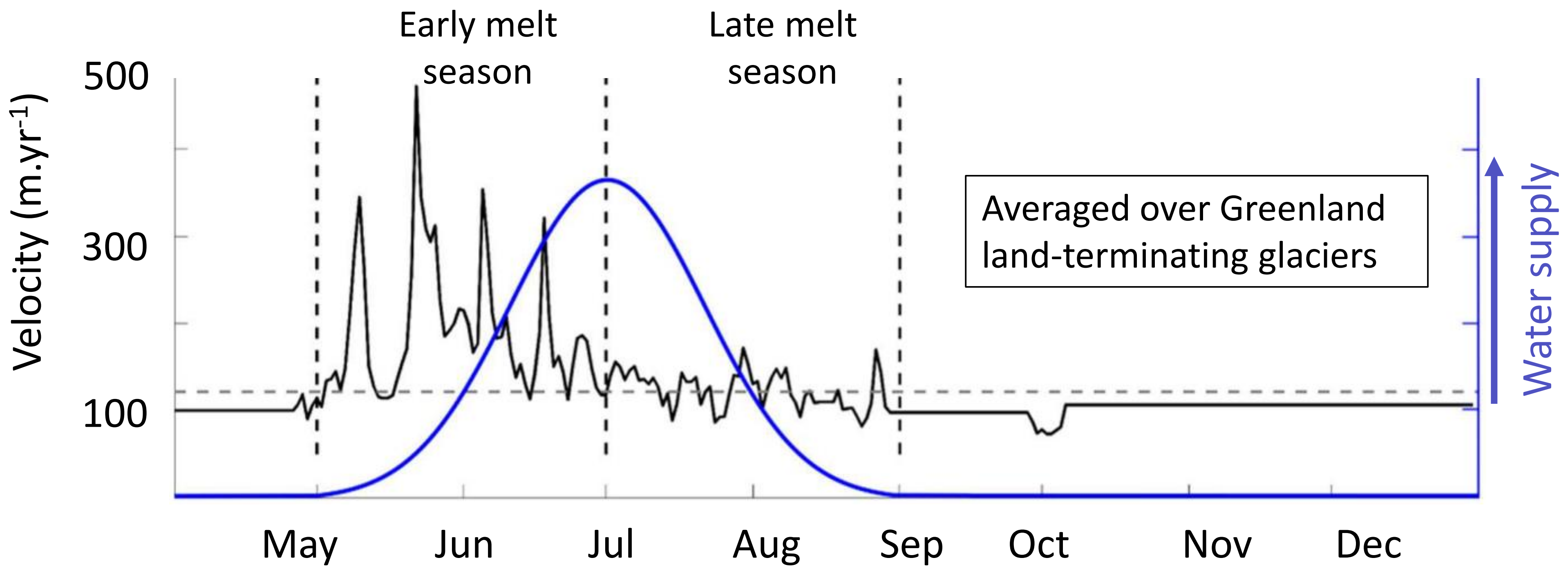
16 days profiles from 2013 to 2019



(Nanni et al., in prep)

Fedchenko glacier, Pamir

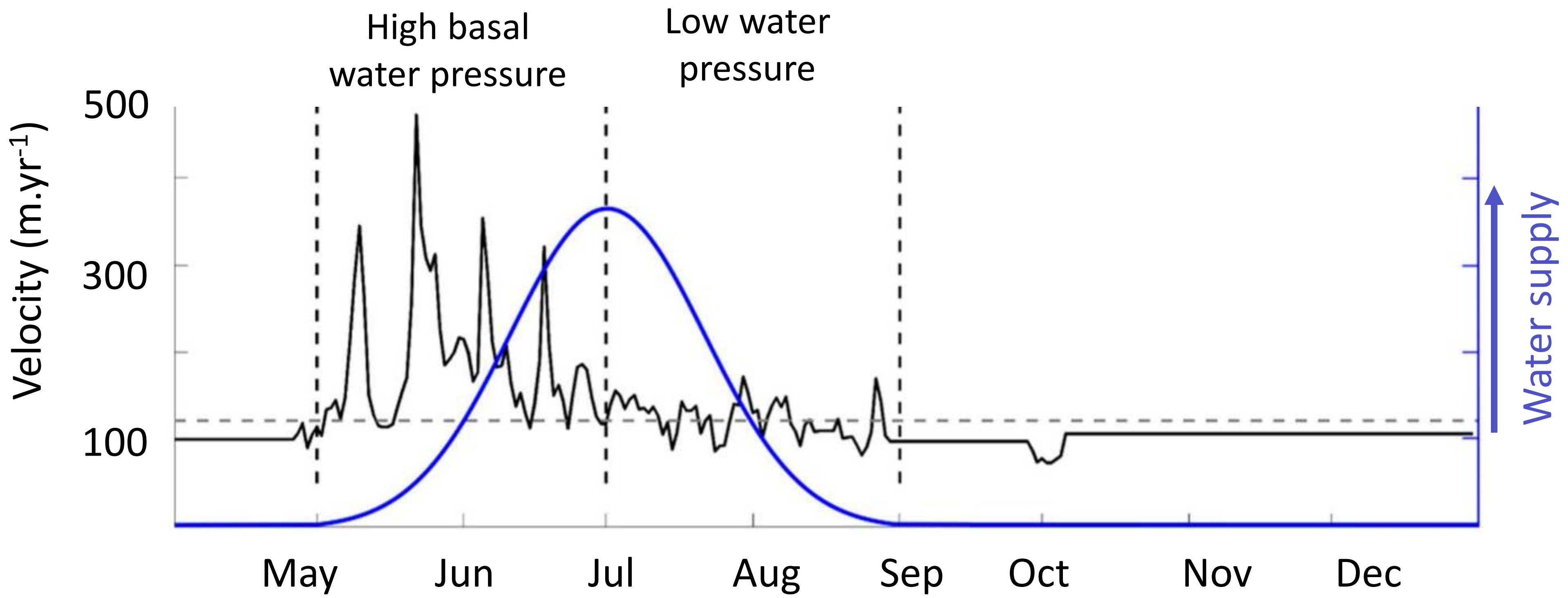
A complex response to water supply



(Davison et al., 2019)

No direct relationship water/sliding

Evolution of the subglacial drainage system

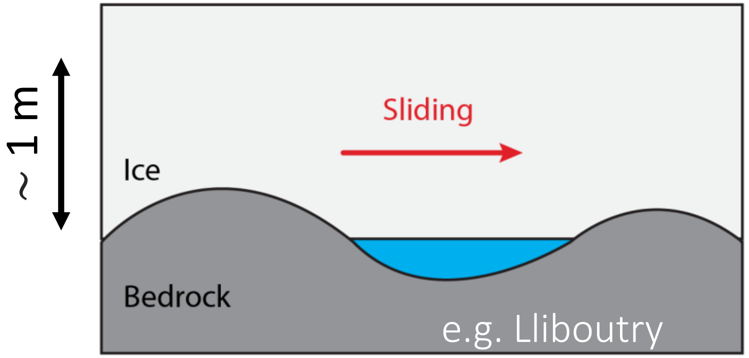


(Davison et al., 2019)

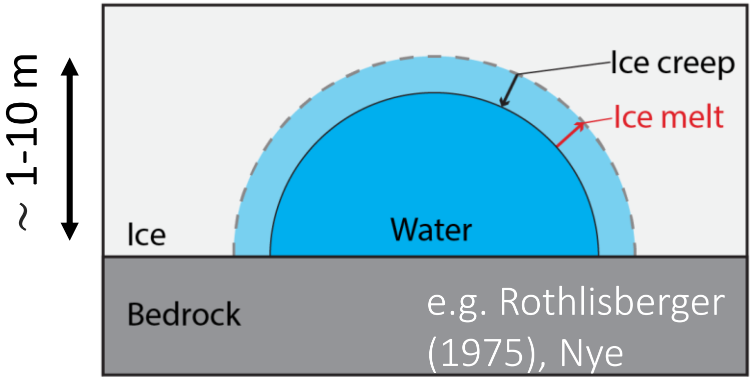
A complex drainage system

Evolution of the subglacial drainage system

<u>Inefficient and distributed</u>:
Cavities



<u>Efficient and localized</u> :
Channels



High basal water pressure

More glacier flow

Low basal water pressure

Less glacier flow

Limited measurements

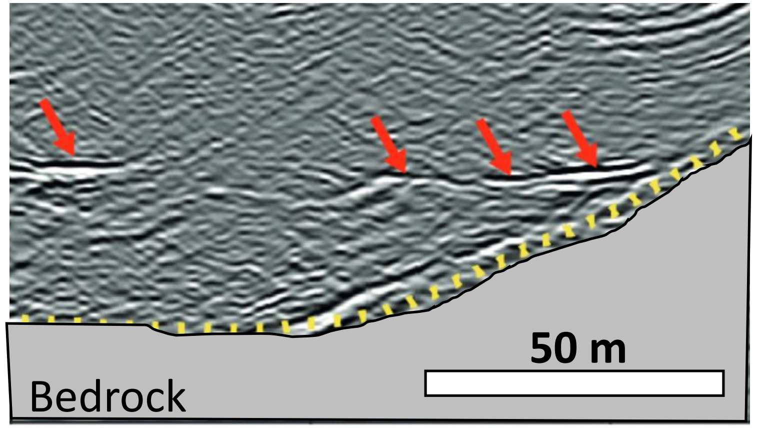
How to measure a system rapidly evolving in time and strongly heterogeneous in space?

Limited measurements

How to measure a system rapidly evolving in time and strongly heterogeneous in space?

<u>Ground penetrating radar</u>

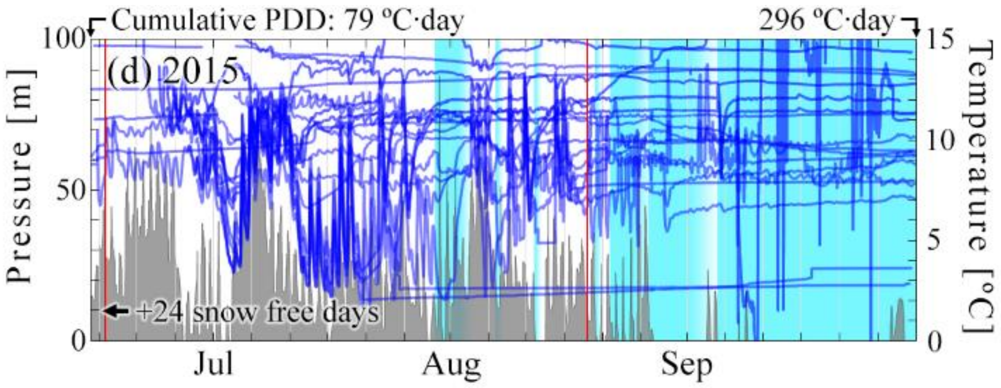
Limited access to physical properties



August 2019, Rhonegletscher
(Church et al., 2020)

<u>Basal water pressure measurements</u>

Punctual and highly heterogeneous



Results of 700+ boreholes pressure sensors
(Rada and Schoof, 2018)

Key questions remain

- Where are cavities and channels?
- How do they develop?
- What are their hydraulic properties?

Great uncertainties on the fate of glaciers

Surface Melt–Induced Acceleration of Greenland Ice-Sheet Flow 2002

H. Jay Zwally,[1*] Waleed Abdalati,[2] Tom Herring,[3] Kristine Larson,[4] Jack Saba,[5] Konrad Steffen[6]

ARTICLE 2019

https://doi.org/10.1038/s41467-019-12039-2 OPEN

Rapid accelerations of Antarctic Peninsula outlet glaciers driven by surface melt

Peter A. Tuckett[1], Jeremy C. Ely[1*], Andrew J. Sole[1], Stephen J. Livingstone[1], Benjamin J. Davison[2], J. Melchior van Wessem[3] & Joshua Howard[1]

Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming 2015

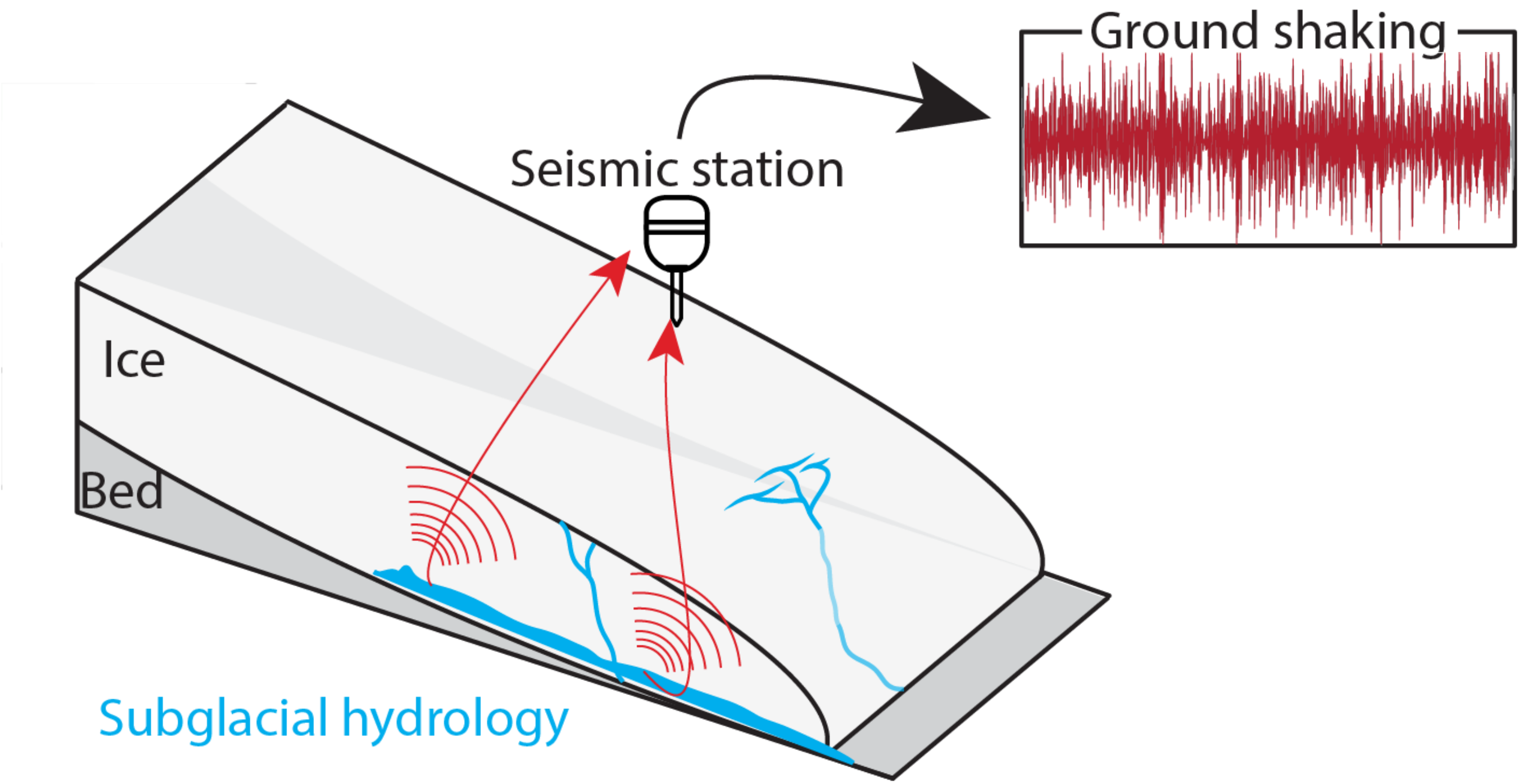
Andrew J. Tedstone[1], Peter W. Nienow[1], Noel Gourmelen[1], Amaury Dehecq[1,2], Daniel Goldberg[1] & Edward Hanna[3]

Dominant **inefficient** drainage system?

Dominant **efficient** drainage system?

Time to find a **new way** to observe subglacial hydrology

Can seismology help?

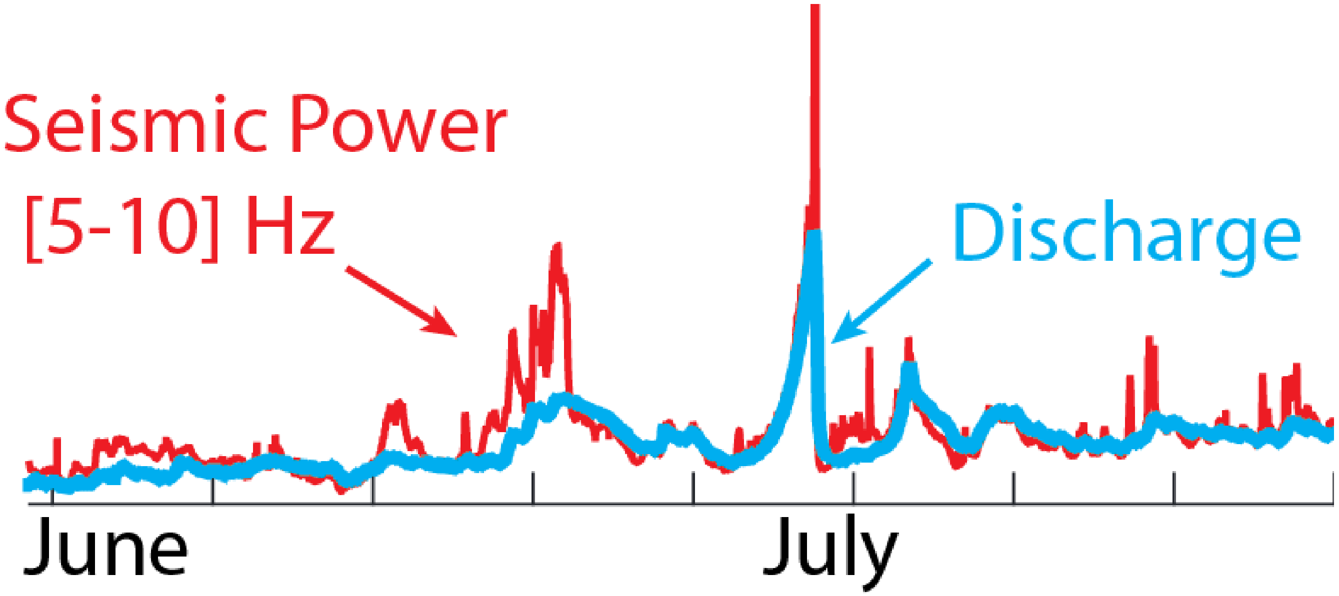


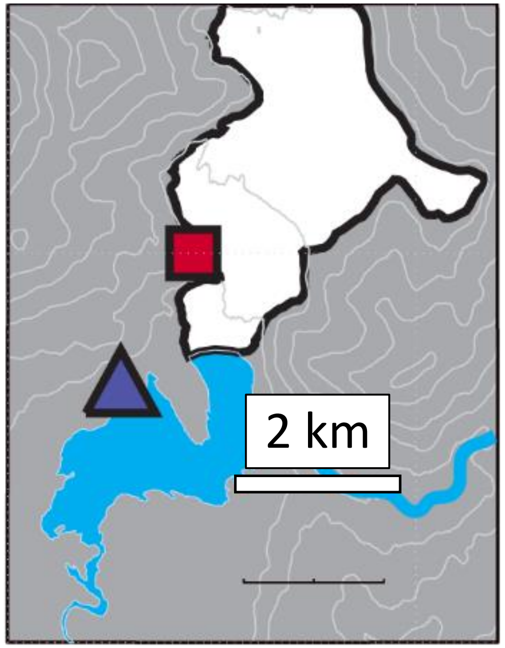
A new-born tool to study subglacial hydrology

Subglacial discharge at tidewater glaciers revealed by seismic tremor

2015

Timothy C. Bartholomaus[1], Jason M. Amundson[2], Jacob I. Walter[1], Shad O'Neel[3], Michael E. West[4] and Christopher F. Larsen[4]





Mendenhall glacier, Alaska

A promising physical framework

Gimbert et al., (2014, 2016):

- Seismic power scales with hydraulic **RADIUS** and hydraulic **PRESSURE** gradient

Study and invert subglacial hydraulic properties

Limitations at the beginning of my PhD

When/where can we apply it

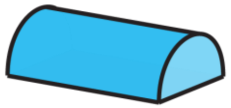
- To other glaciers?
- To complete melt-season?
  (*at lower discharge?*)

What can we observe?

- Only sensitive to channels?
- Spatial information?

My questions

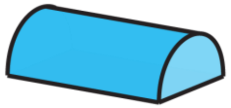
#1 Can we **MEASURE** subglacial-water-flow-induced seismicity over complete melt-seasons?



#2 What is the **TEMPORAL** dynamics of subglacial hydraulic properties over complete melt-seasons?

Part I

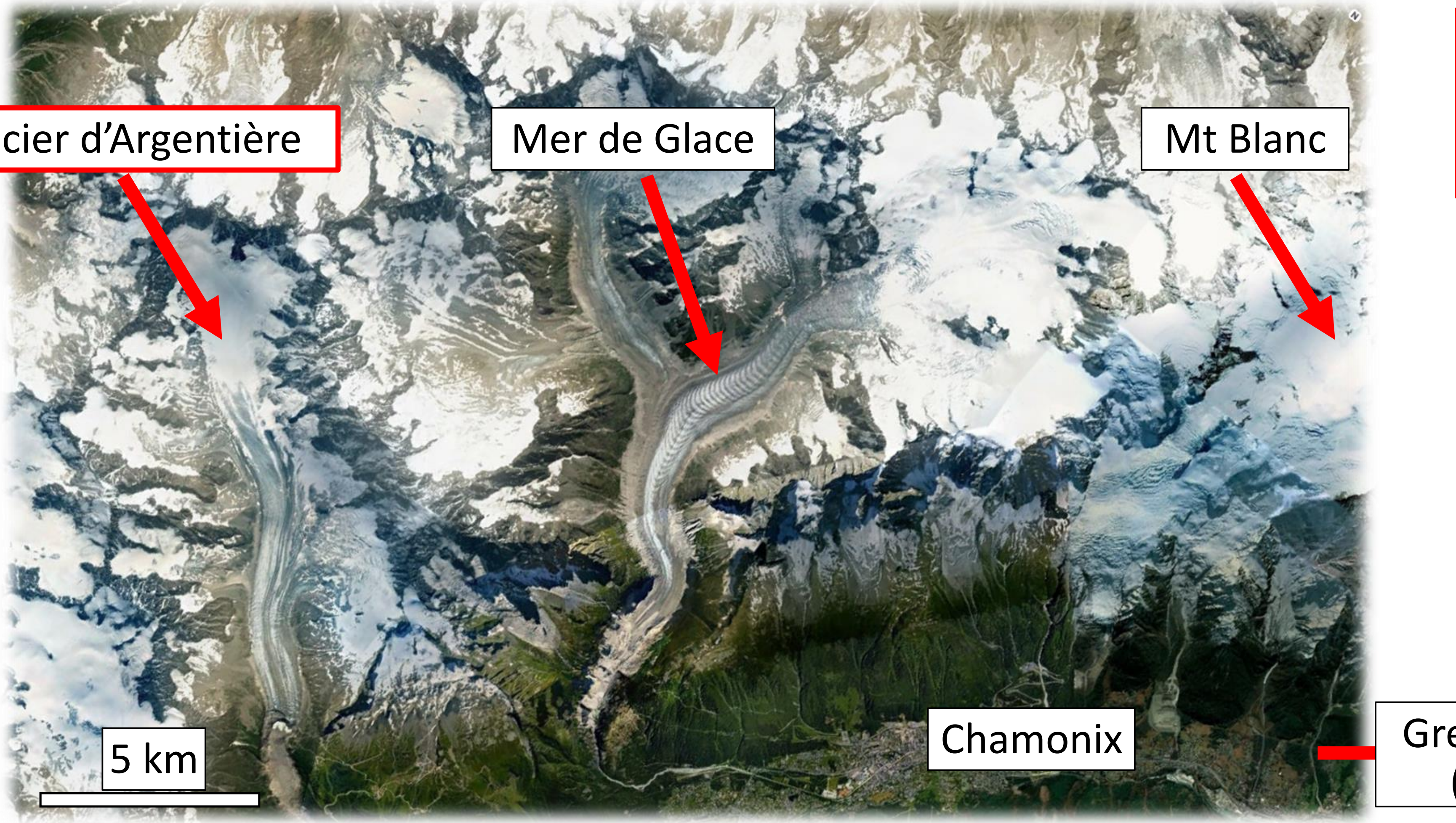
#3 Can we **LOCATE** distributed sources of seismic noise?



#4 What is the **SPATIAL** dynamics of cavities and channels?

Part II

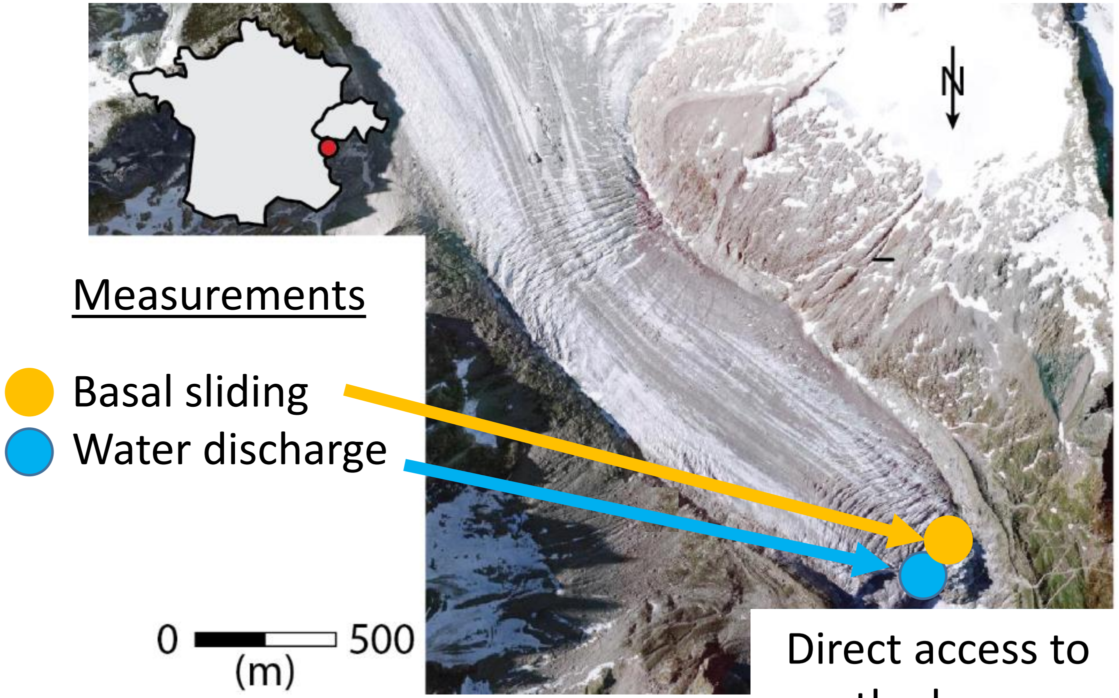
Glacier d'Argentière: a field-scale laboratory

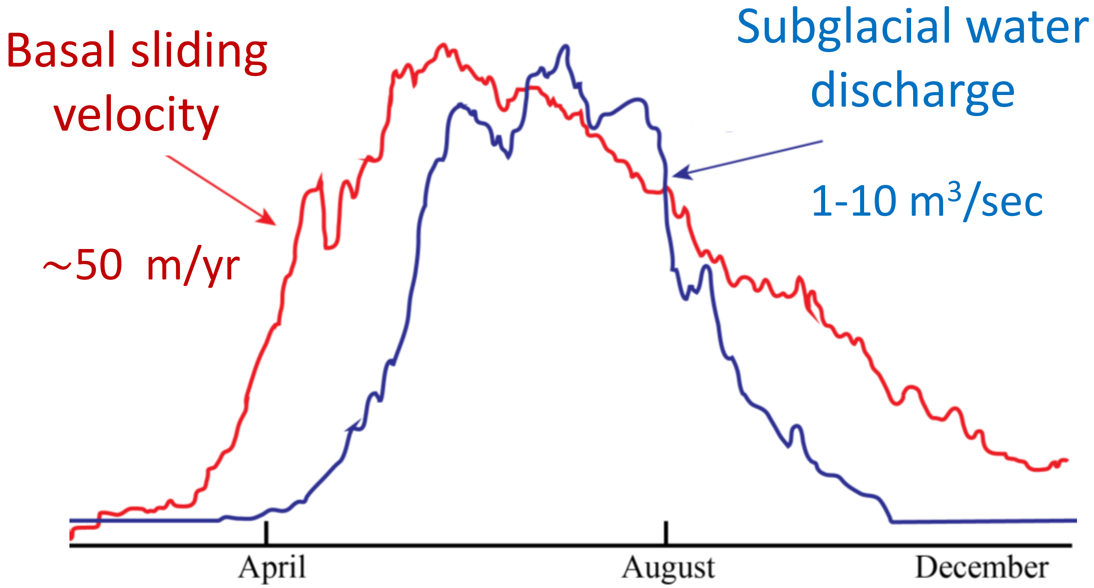


Unique measurements

- 30+ years of measurements of water discharge and **sliding**
- High sensitivity to subglacial water flow

©L. Moreau

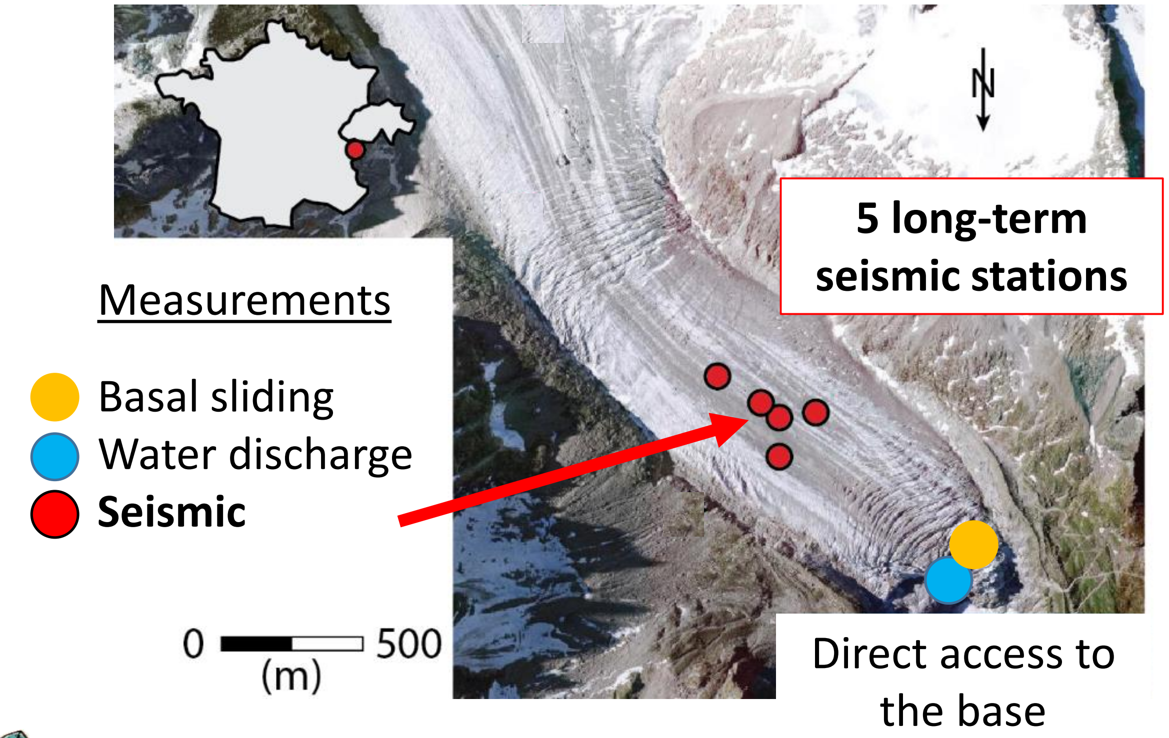




2000-2016 average

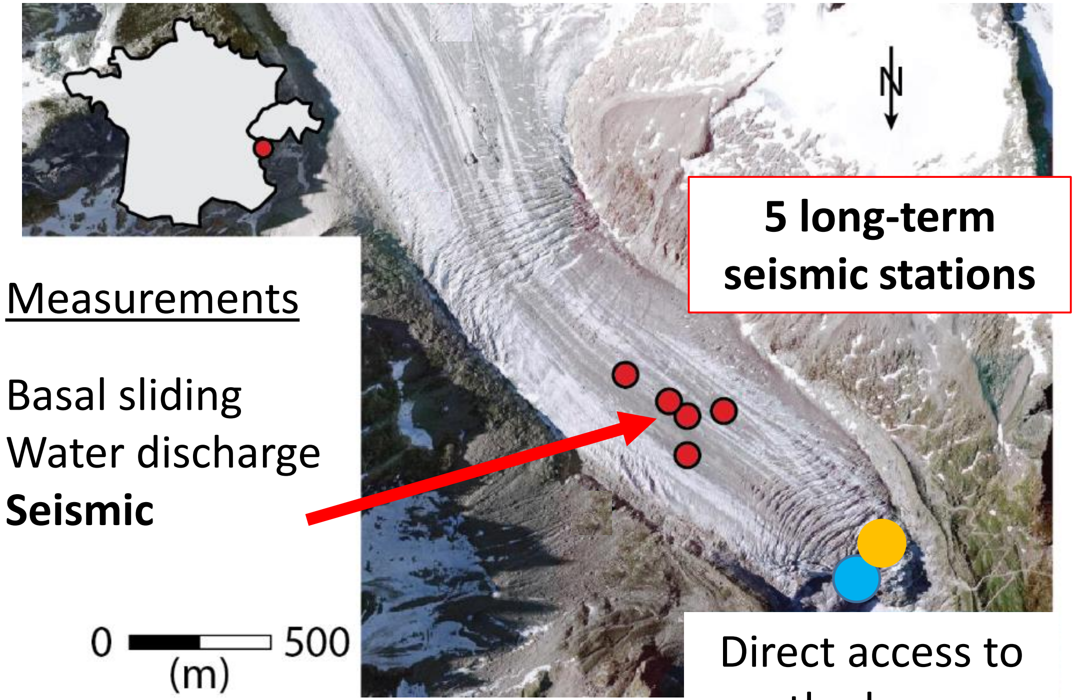
Seismic measurements: **temporal**

- Up to 7 seismic stations maintained from spring **2016** to winter **2020**
  - Collaboration with Fabian Walter and Dominik Graeff from ETH Zurich



In collaboration with the SAUSSURE project: a multidisciplinary investigation of the subglacial processes on glacier d'Argentière.

Seismic measurements: **temporal**



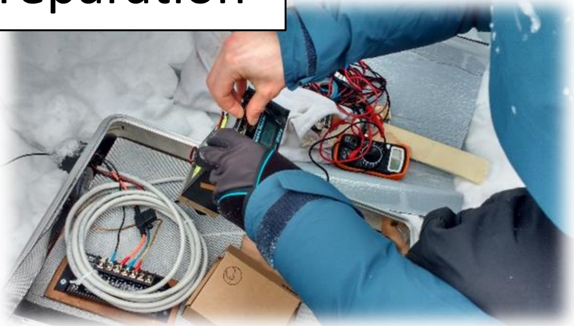
Measurements

- Basal sliding
- Water discharge
- **Seismic**

5 long-term seismic stations

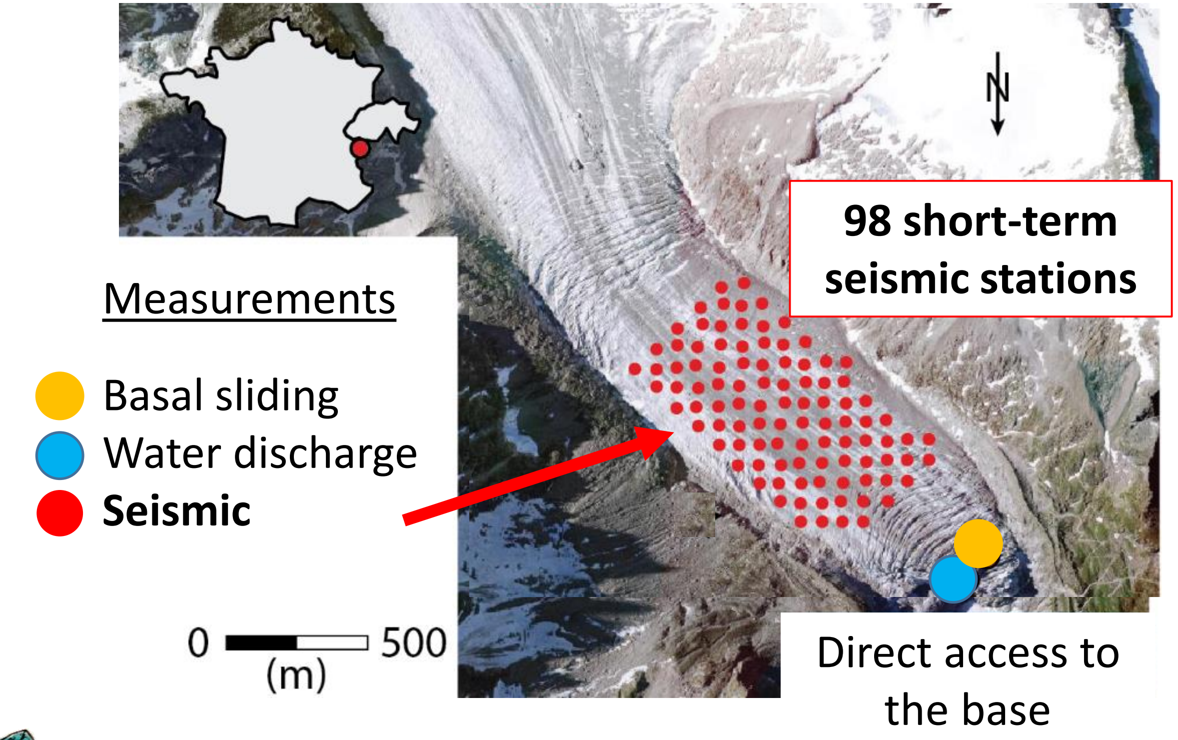
Direct access to the base

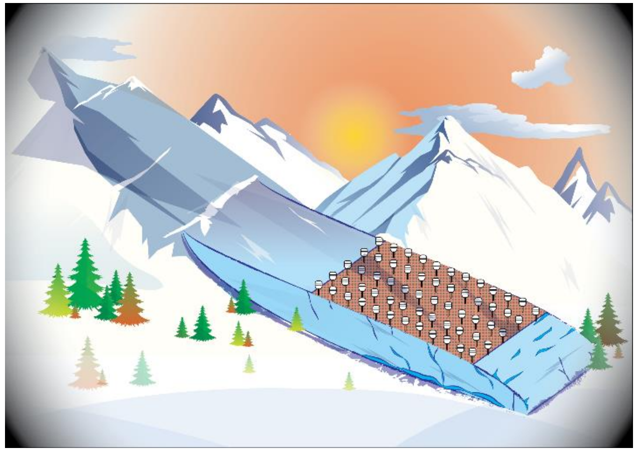
~ 70 days of maintenance + casing and cabling preparation



Seismic measurements: **spatial**

- 98 seismic stations maitained for one-month in spring 2018
- A cross-disciplinary and cross-institutes collaboration





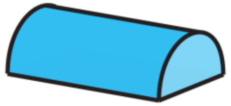
ISTerre

In collaboration with the RESOLVE project: a development of a multi-instrument platform for interdisciplinary research.

So what did I observe?

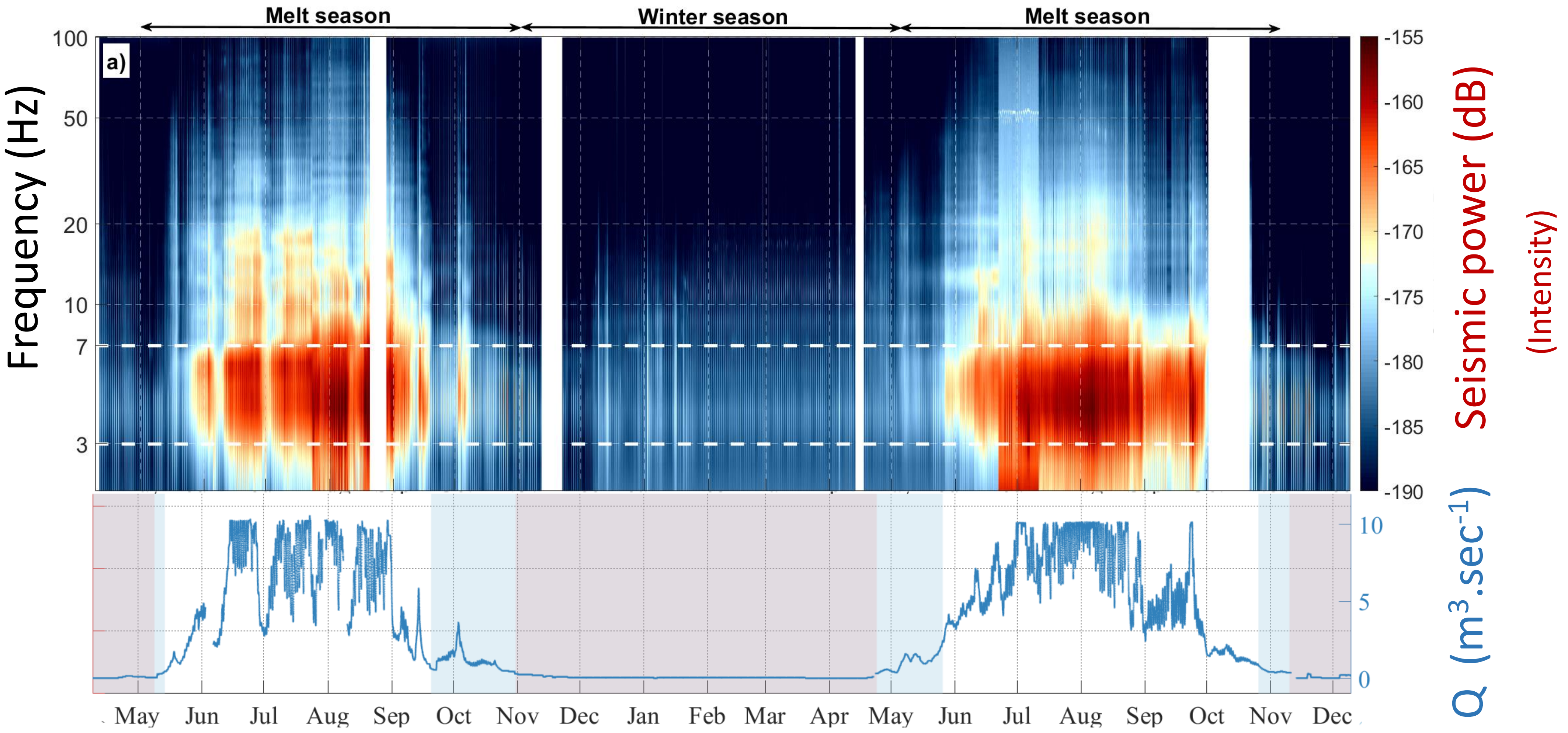
Part I: Temporal investigation of subglacial water flow

#1 Can we **MEASURE** subglacial-water-flow-induced seismicity over complete melt seasons?



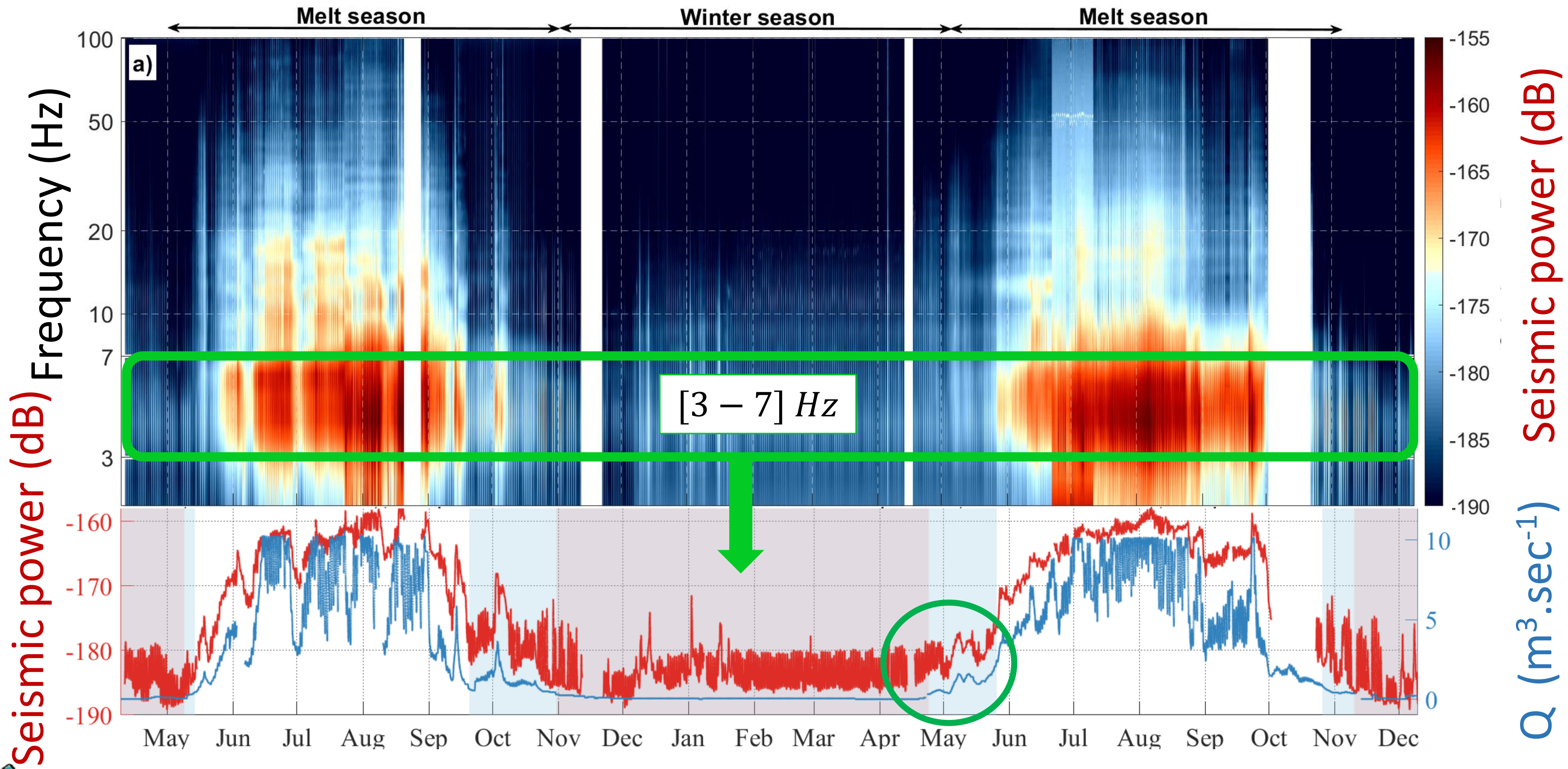
#2 What is the **TEMPORAL** dynamics of subglacial hydraulic properties over complete melt seasons?

Seismic measurements



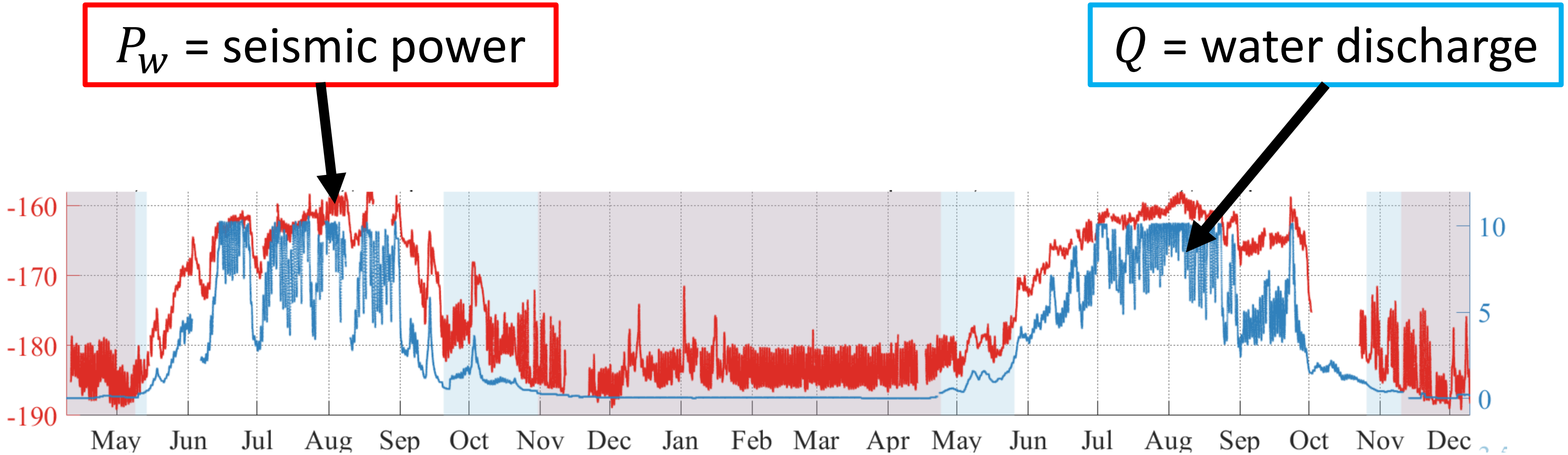
(Nanni et al., 2020)

Seismic measurements



(Nanni et al., 2020)

Notations

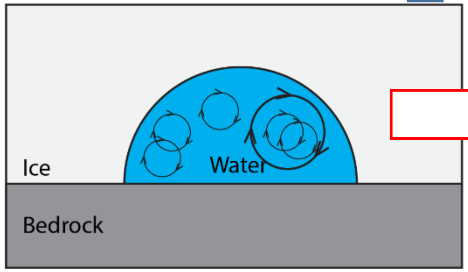


(Nanni et al., 2020)

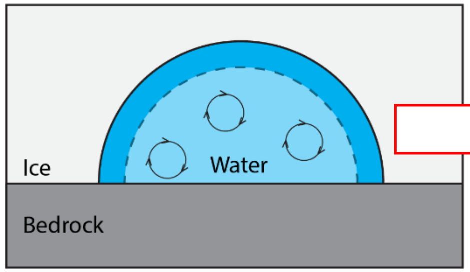
Theoretical end-members

(Gimbert et al., 2016)

2 predicted responses

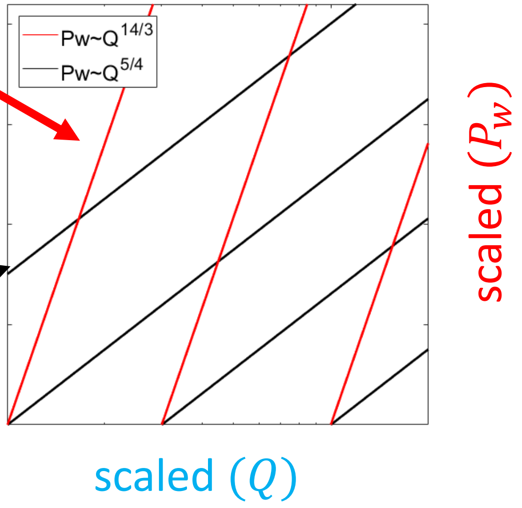


Only **Pressure gradient S** varies → $P_w \propto Q^{14/3}$

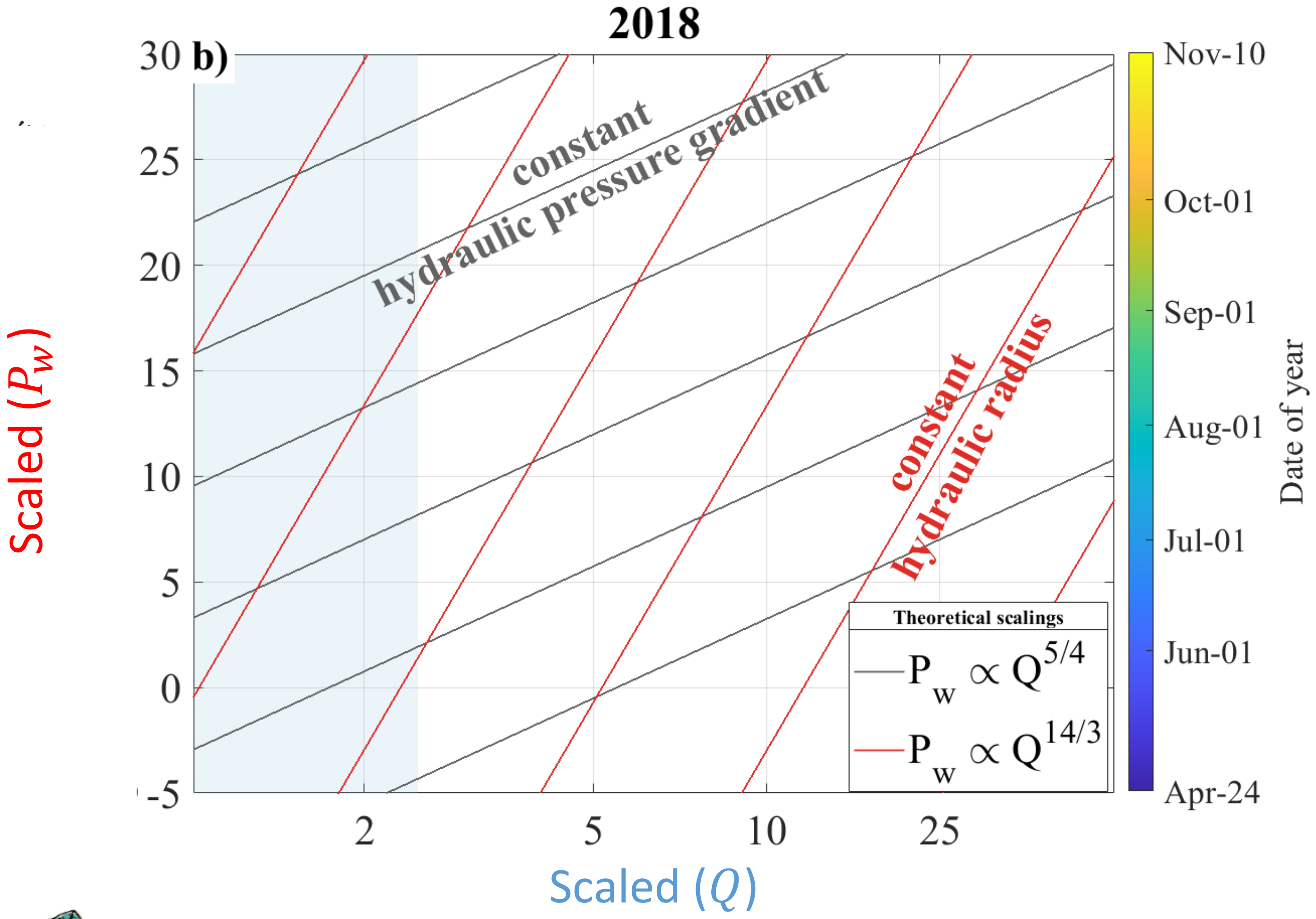


Only **Hydraulic radius R** varies → $P_w \propto Q^{5/4}$

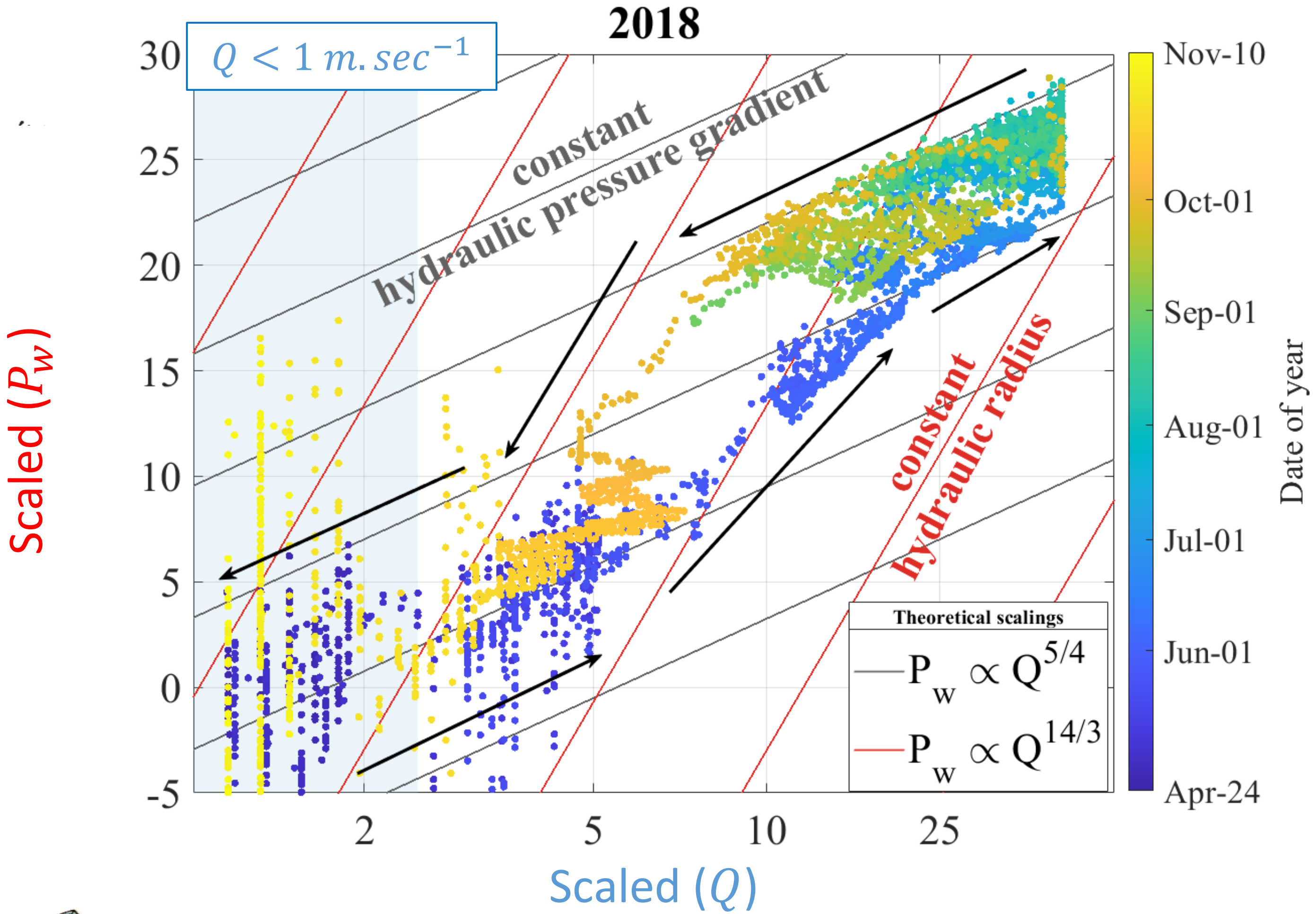
Log-Log representation



Trends at seasonal scales



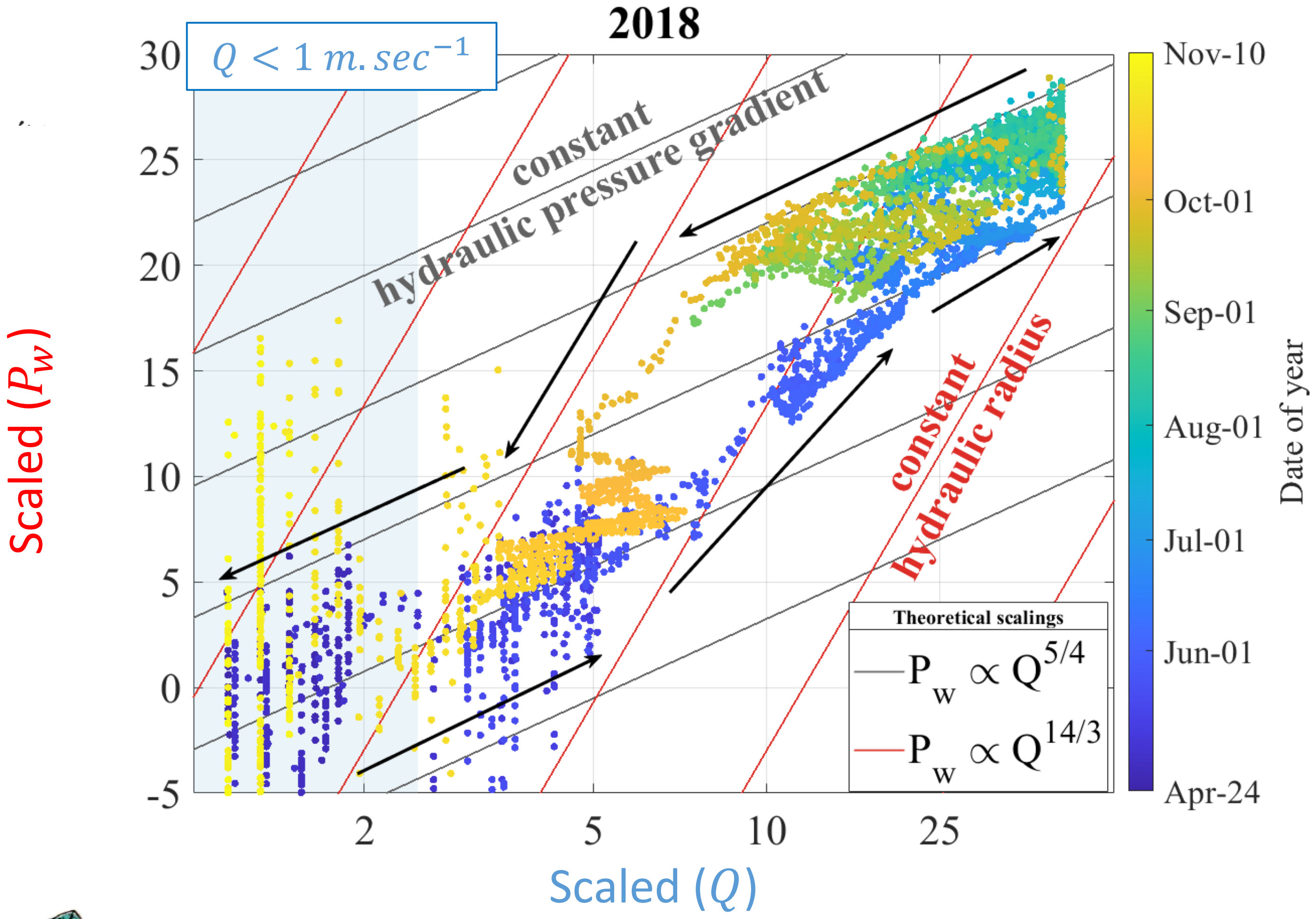
Trends at seasonal scales



- Consistency between observations and predictions

(Nanni et al., 2020)

#1 I USED SEISMOLOGY TO STUDY COMPLETE MELT SEASON



- Consistency between observations and predictions

Now invert hydraulic properties ***S*** and ***R***

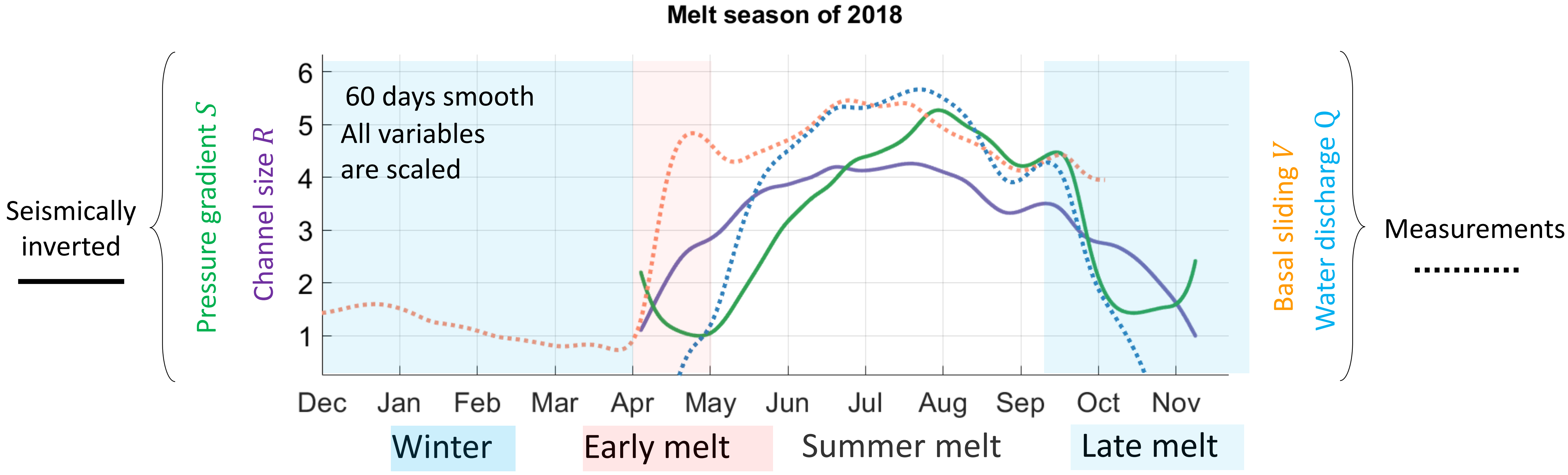
$$Q \sim R^{2/3} S^{1/2}$$

$$P_w \sim R^{7/3} S^{7/3}$$

(Gimbert et al., 2016)

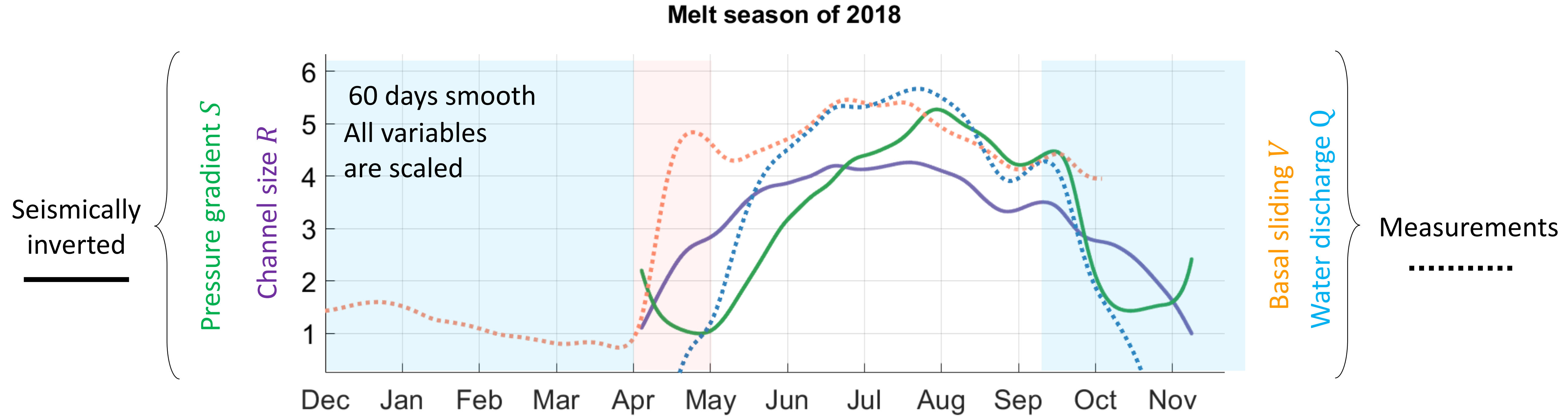
(Nanni et al., 2020)

Inversion of hydraulic properties



(Nanni et al., 2020)

Inversion of hydraulic properties



Winter | Early melt | Summer melt | Late melt

Well−marked seasonality

Winter: V →

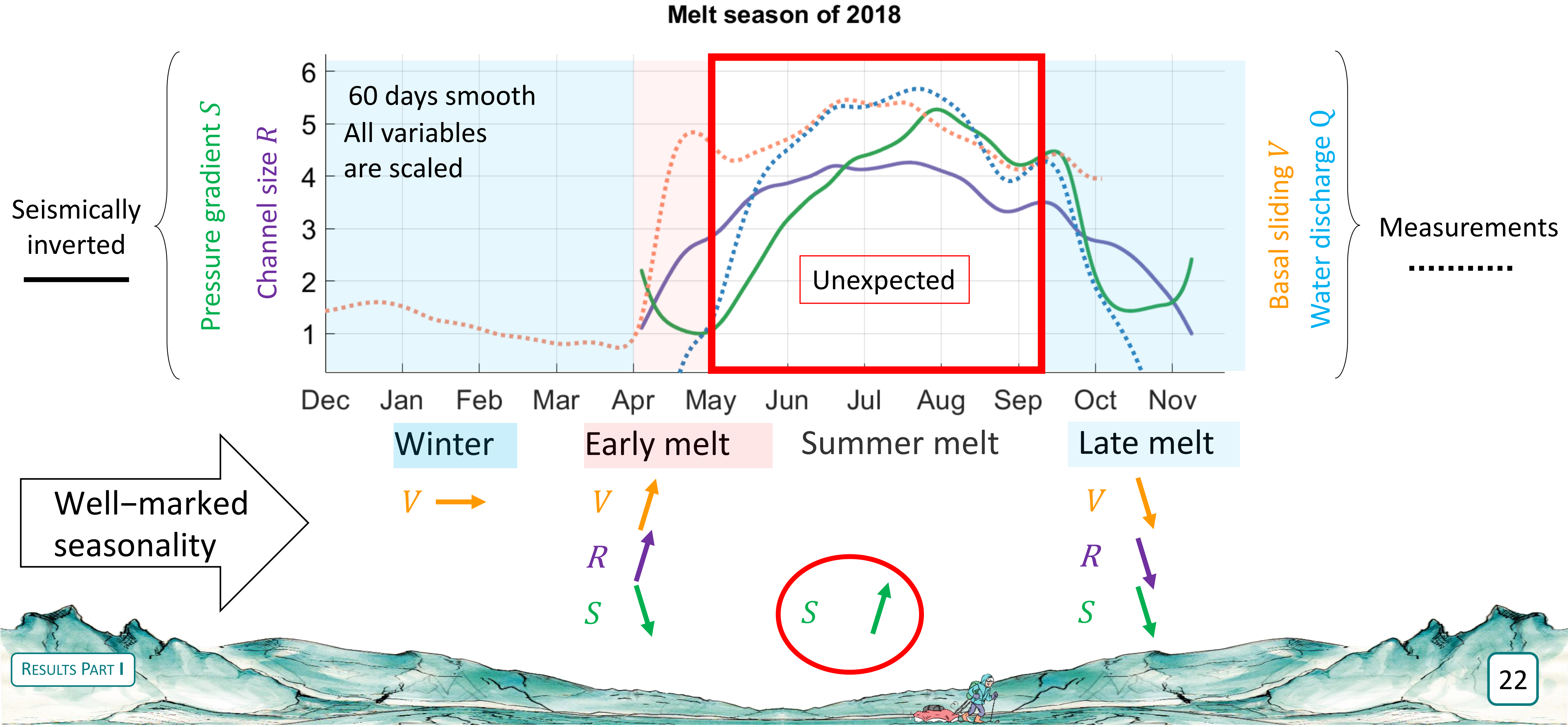
Early melt: V ↑, R ↑, S ↓

Summer melt: V →, R →, S ↑

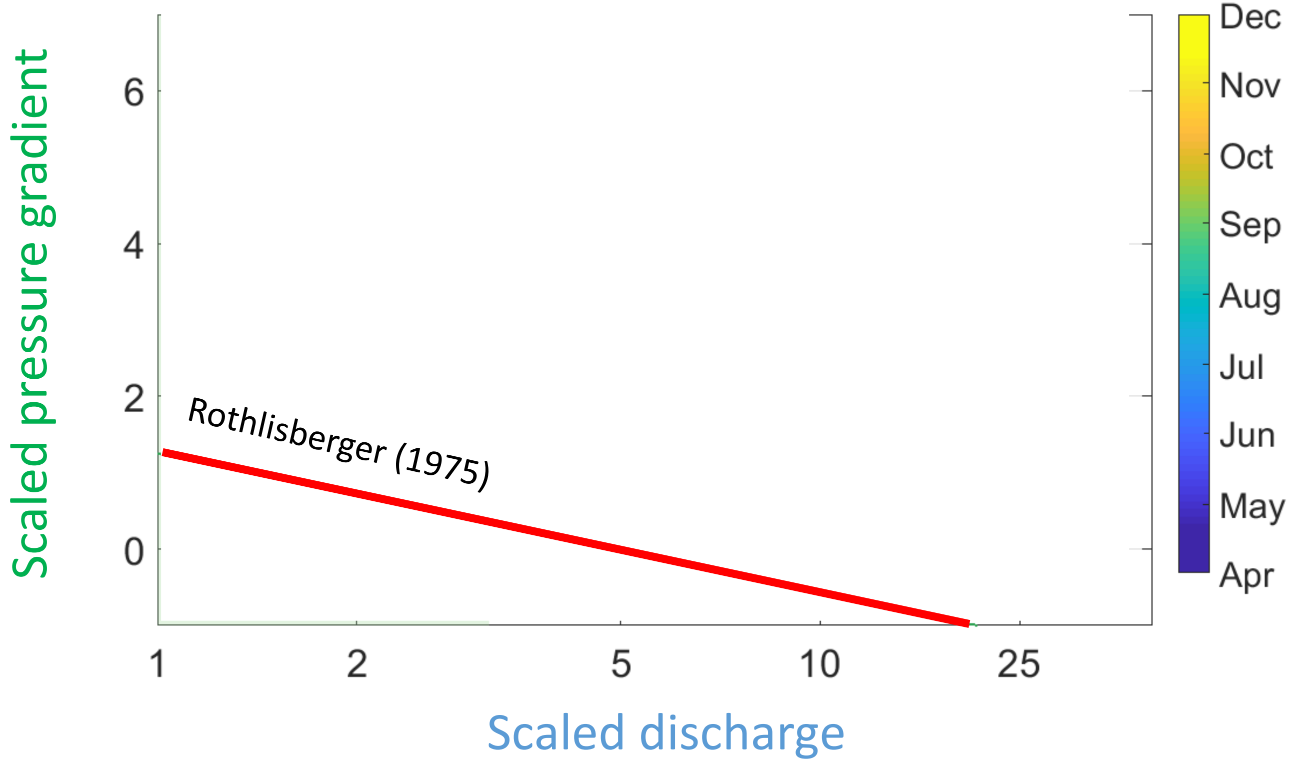
Late melt: V ↓, R ↓, S ↓

(Nanni et al., 2020)

#2 I SUCCESSFULLY INVERTED HYDRAULIC PROPERTIES

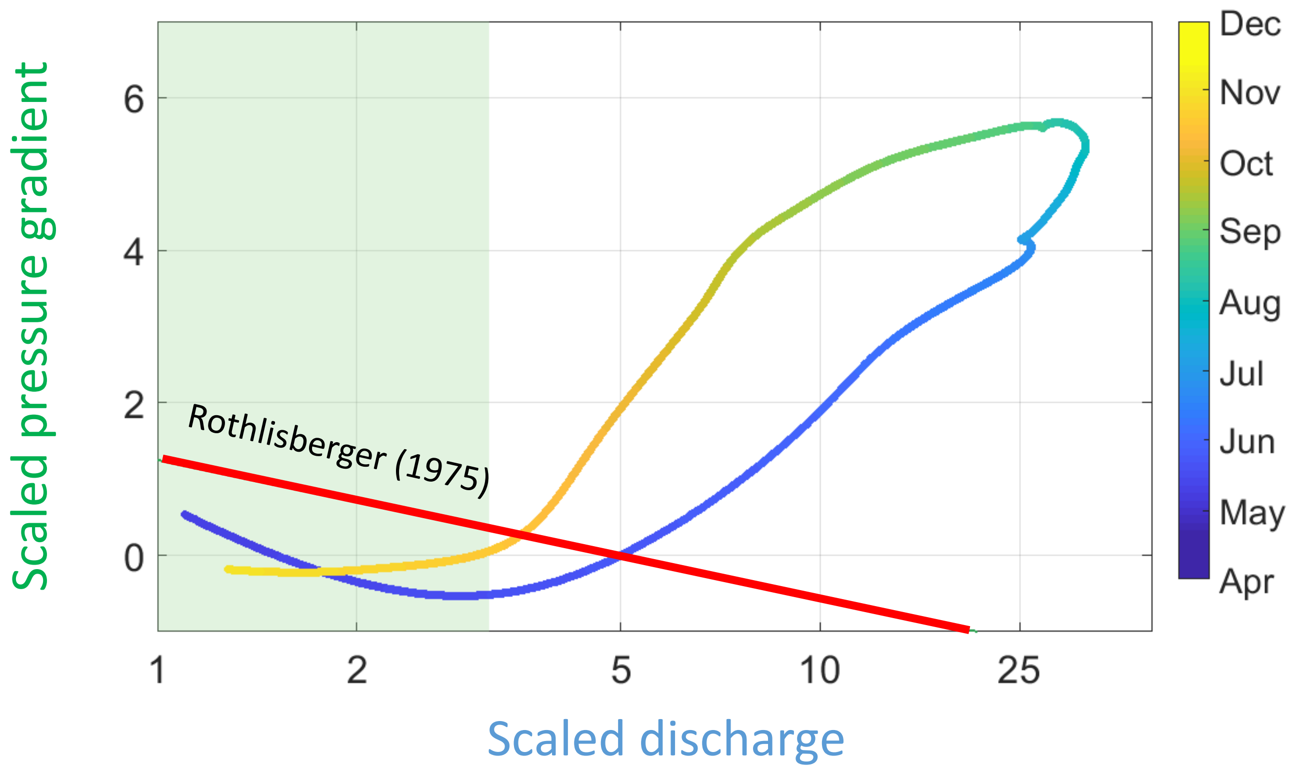


Channel dynamics: theory



- Steady-state and equilibirum prediction for channel dynamics by Rothlisberger (1975)

Channel dynamics: theory VS observation



- Steady-state and equilibirum prediction for channel dynamics by Rothlisberger (1975)
- Out of equilibrium and **pressurized** at high discharge

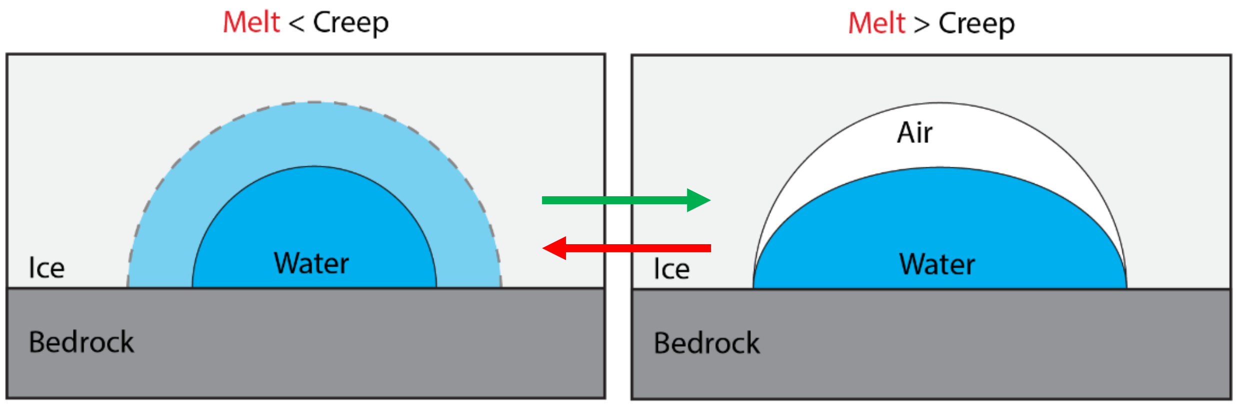
(Nanni et al., 2020)

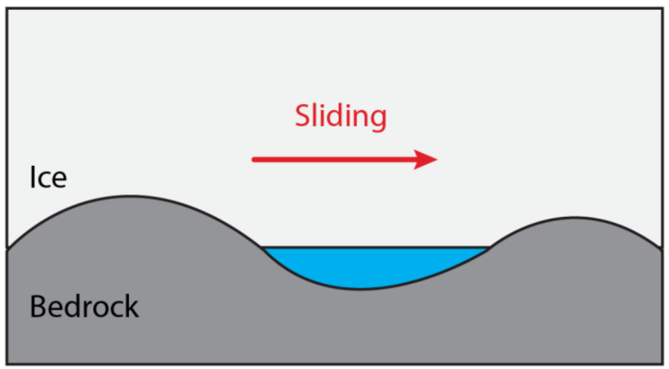
Potential cause(s) for high pressure in summer

Short term water input = Transient state

or/and

Cavities dominate the seismic power ?





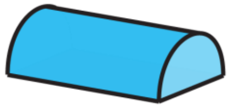
Kinetics of water supply > channel's response time

Cavities might be pressurized

Previously thought to be noise-free

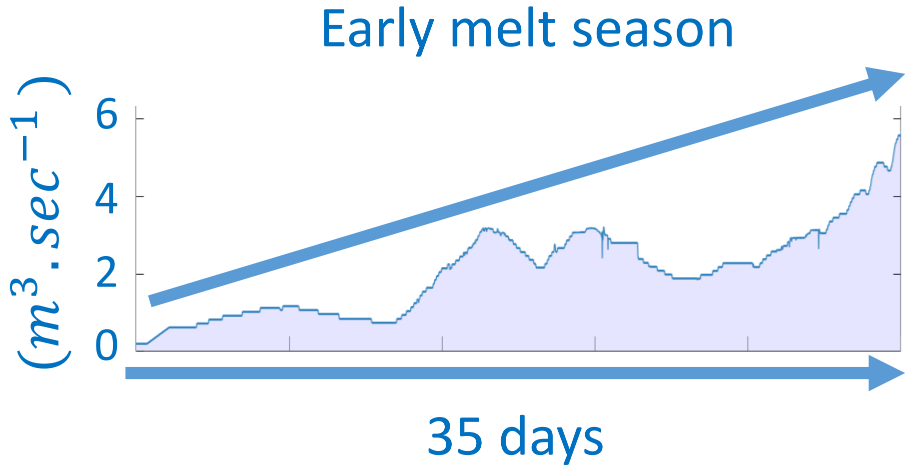
Part II: Spatial investigation of subglacial water flow

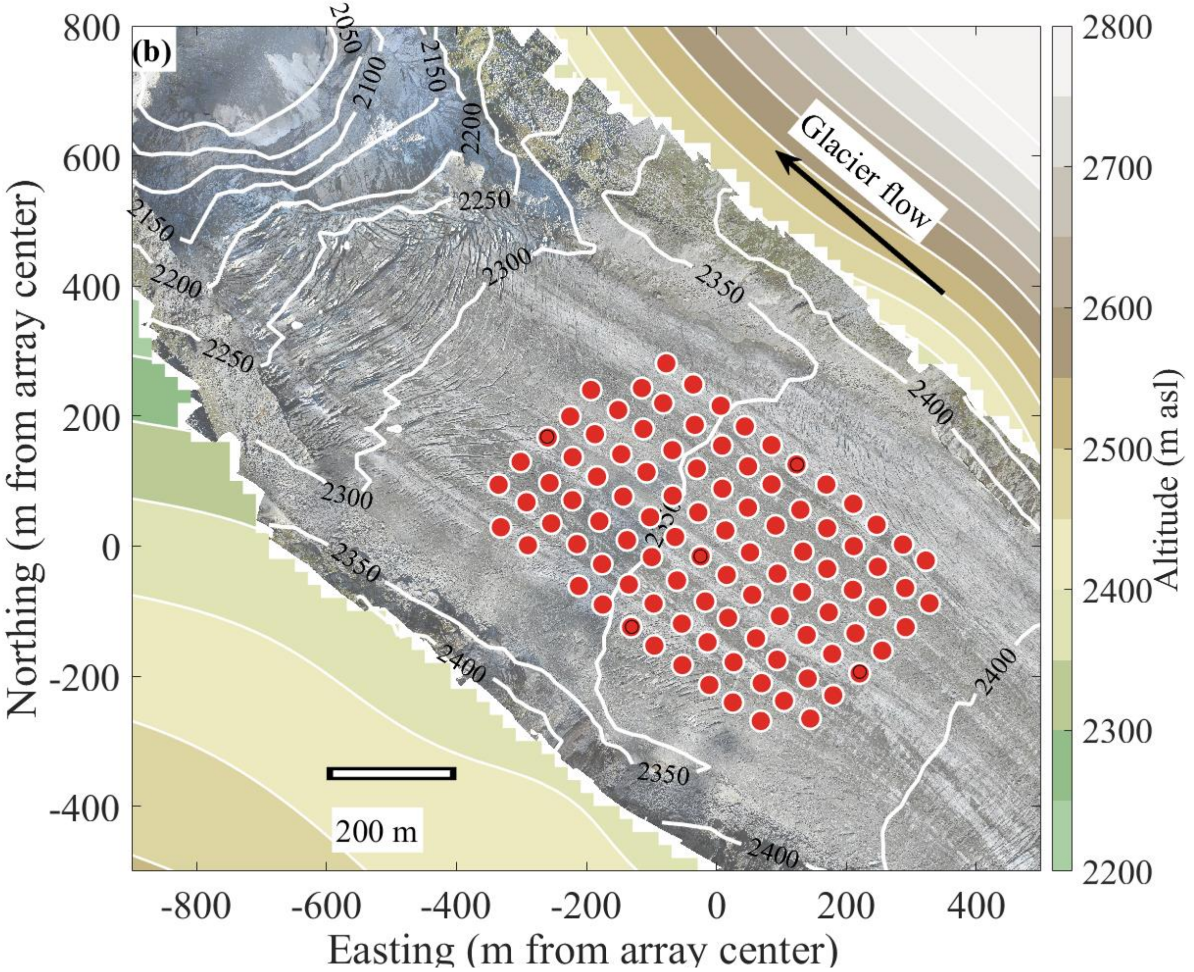
#3 Can we **LOCATE** distributed sources of seismic noise?



#4 What is the **SPATIAL** dynamics of cavities and channels?

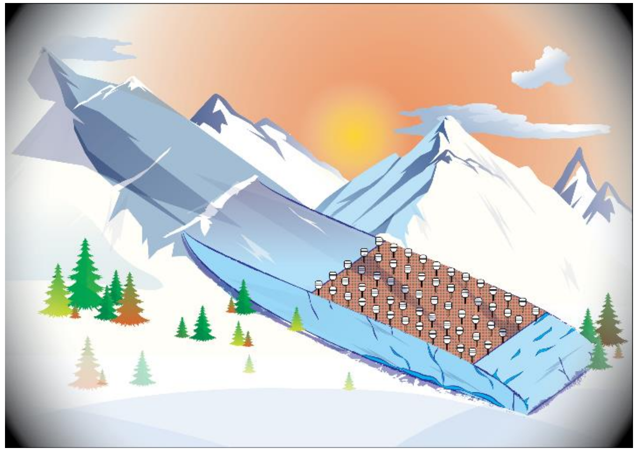
Measurements: 98 seismic sensors





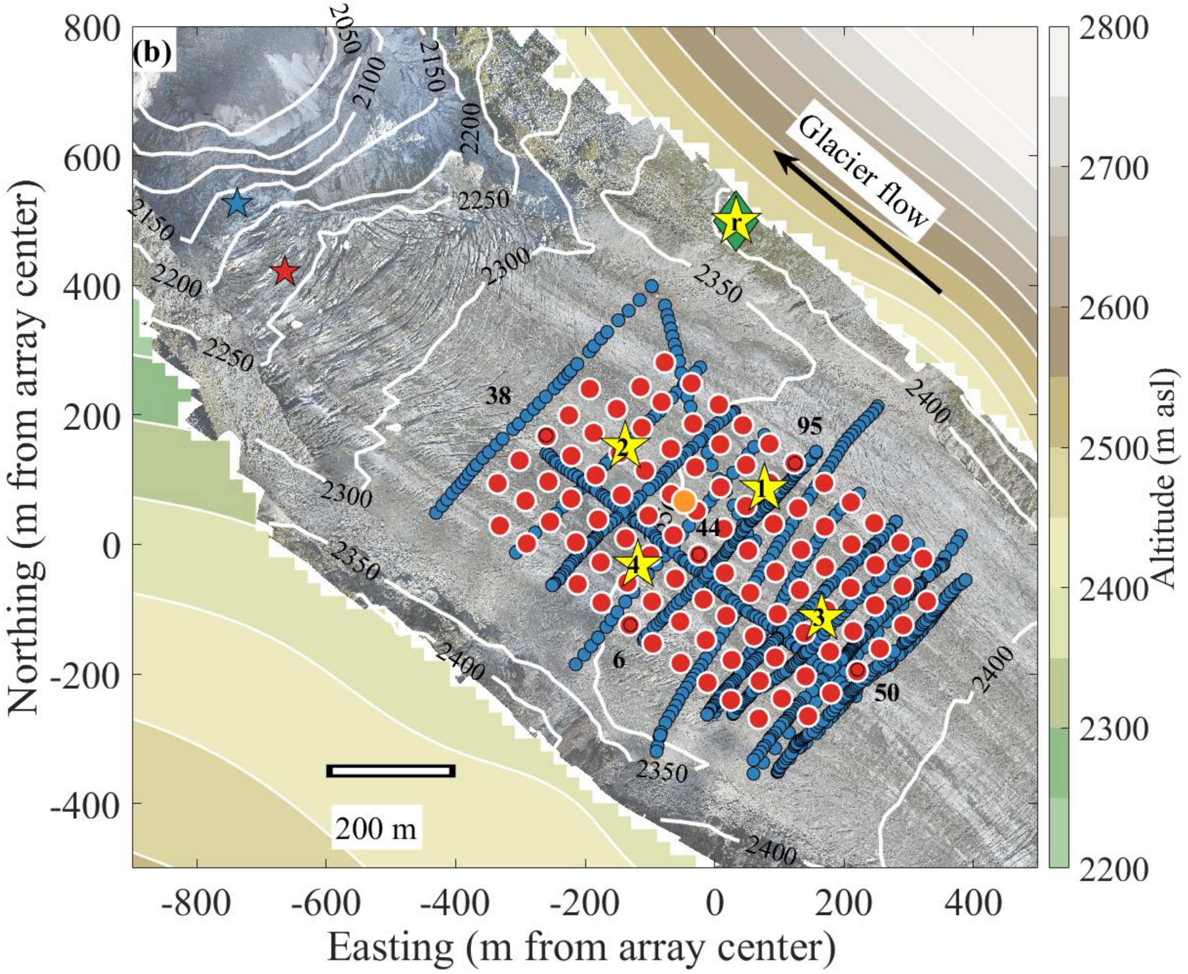
(Gimbert, **Nanni**, Roux et al., 2020)

The RESOLVE-Argentière project



Seismic measurements
- Nodes sensors
- Surface borehole seismometer

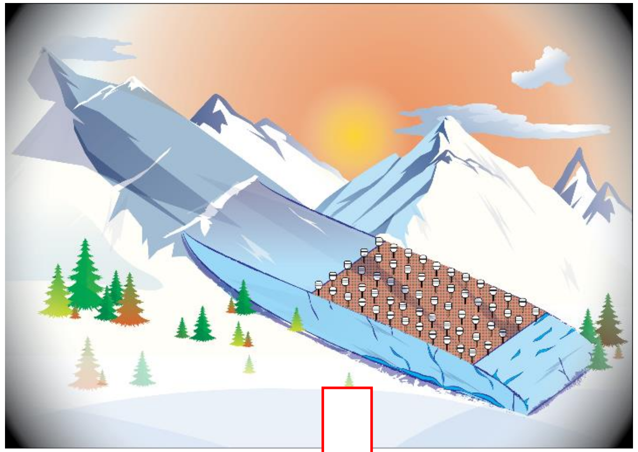
Complementary measurements
- GNSS antennas
- GPR tracks
- Subglacial wheel
- Weather station
- Water discharge gauge



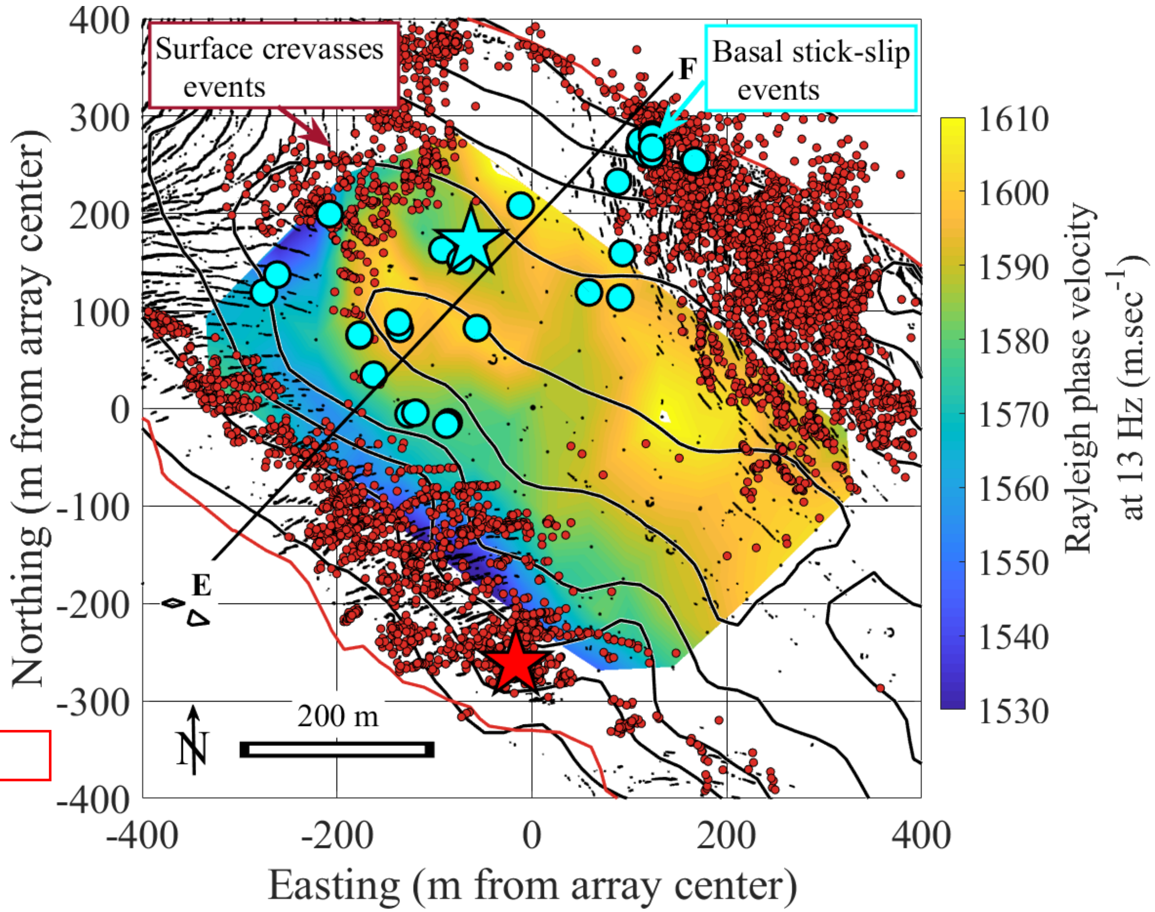
Add RESOLVE paper

(Gimbert, **Nanni**, Roux et al., 2020)

The RESOLVE-Argentière project

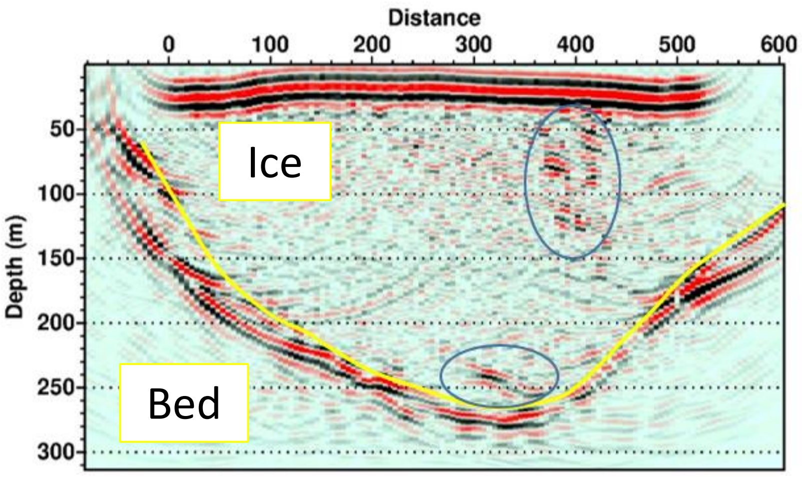


A wide range of **seismic analysis** presented in our community paper.

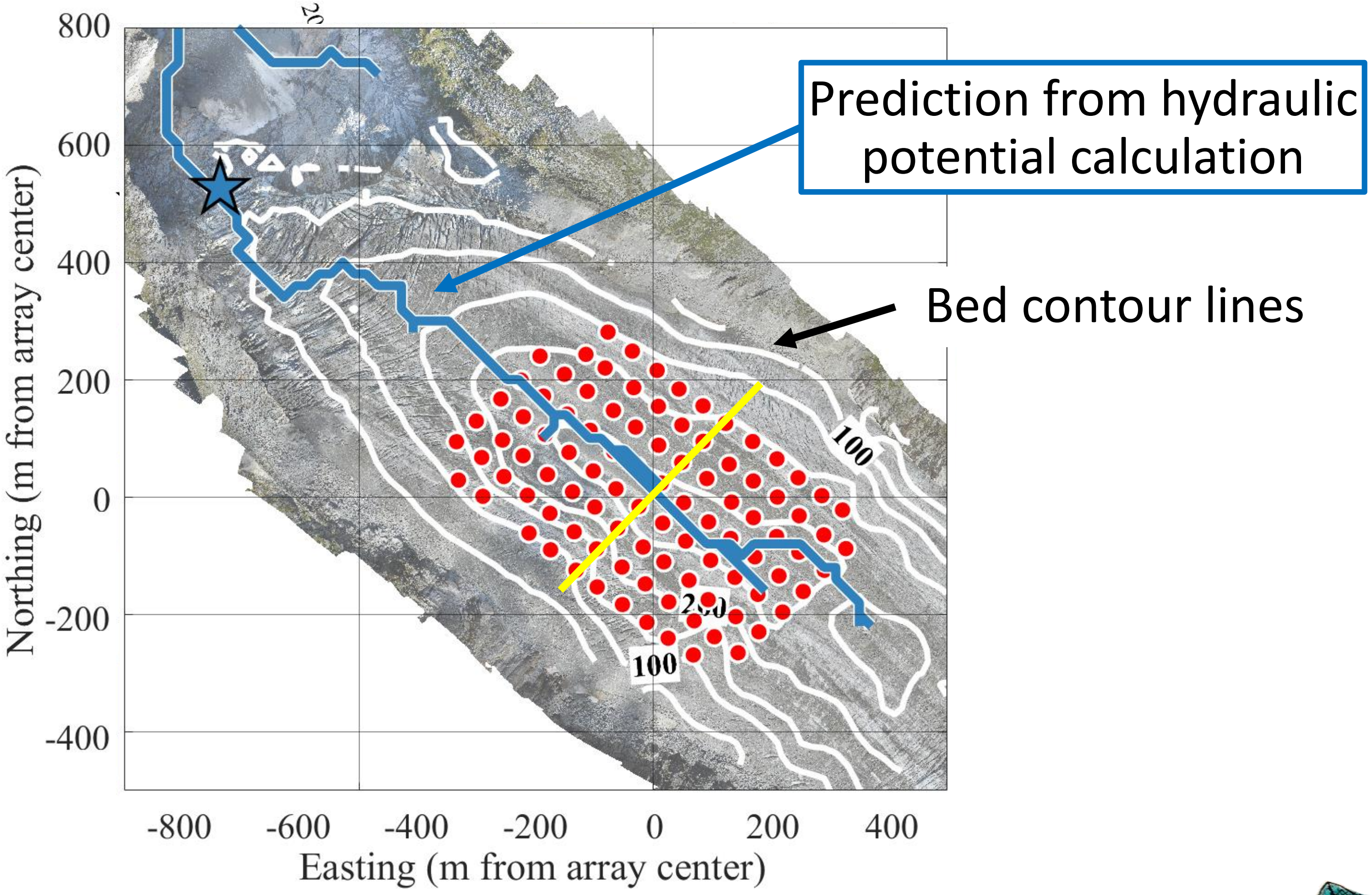


(Gimbert, **Nanni**, Roux et al., 2020)

Glacier geometry and waterways



GPR imaging results



(Gimbert, **Nanni**, Roux et al., 2020)

How to locate **distributed** noise sources ?

Very few studies …

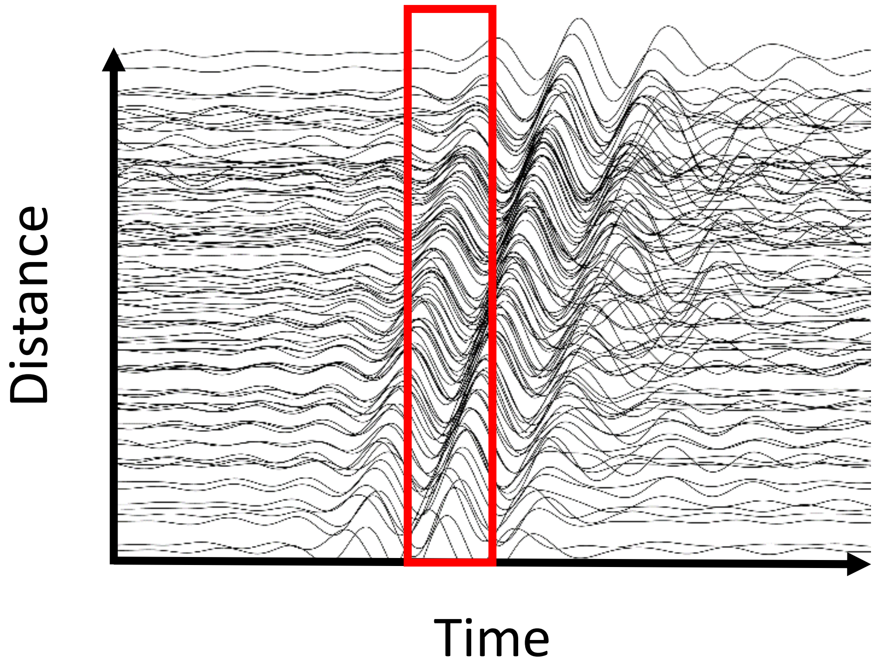
Venkatesh et al., 2003; Stehly et al., 2006; Burtin et al., 2010; Corciulo et al., 2013; Chmiel et al., 2019

How to locate **punctual** sources ?

$$u(t) = Ae^{i\omega t}$$

Amplitude **Phase**

Phase differences ~ time delays

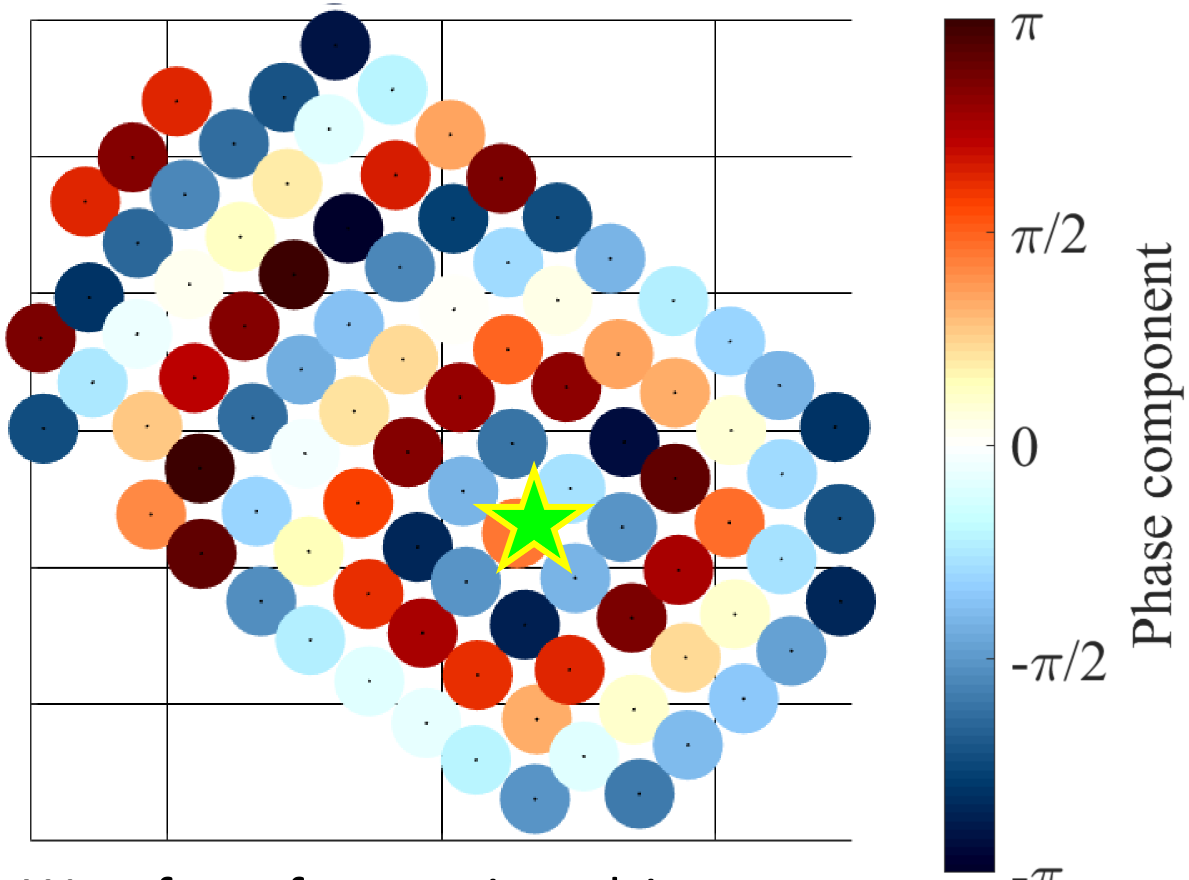


Phase coherence for a punctual source

Wavefront when throwing a stone in a lake

Phase coherence for a punctual source

Wavefront when throwing a stone in a lake

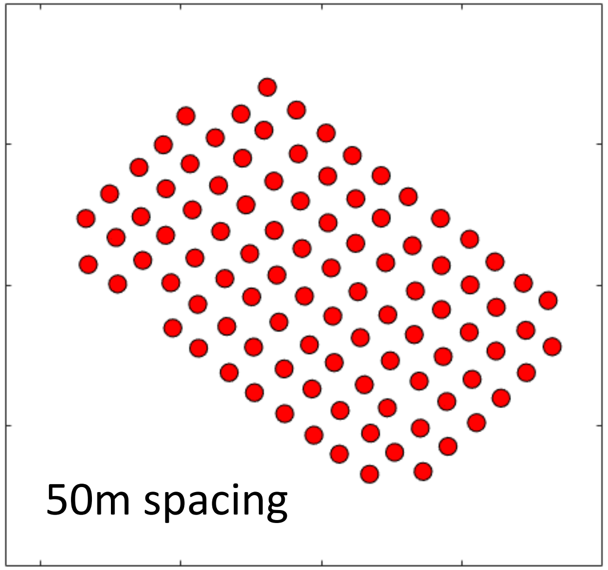


Wavefront from an impulsive event

MFP: the Match-field-processing method

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)

Seismic array



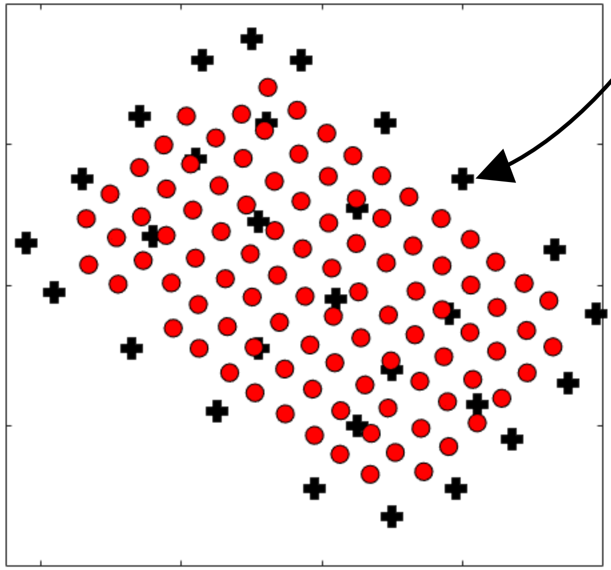
(e.g. Kuperman et al., 1997; Corciulo et al., 2013; Chmiel et al., 2019)

MFP: the Match-field-processing method

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)

Find local and global minima

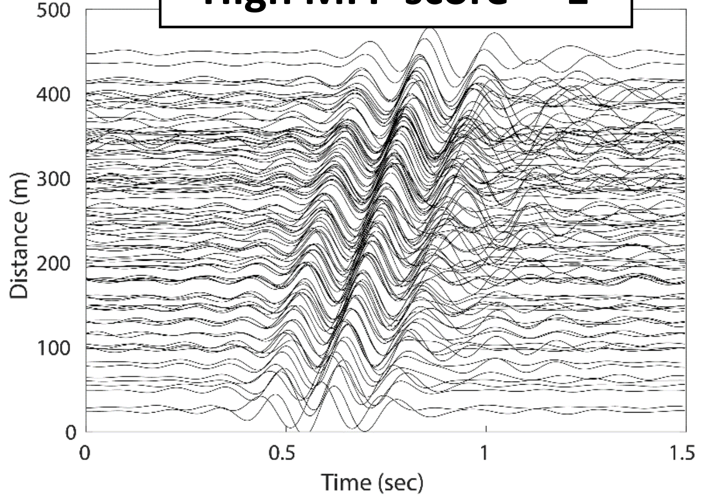
29 starting points



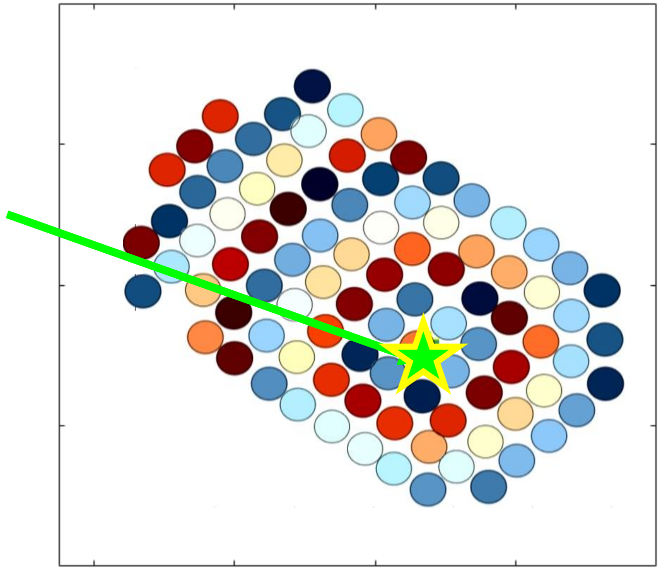
Punctual source: easy

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)
- MFP score $\propto$ phase coherency over the array

Impulsional signal:
High MFP score ~ 1



<u>Unique location</u>



Distributed sources: tricky

- Assume a unique source over 1 second-signal
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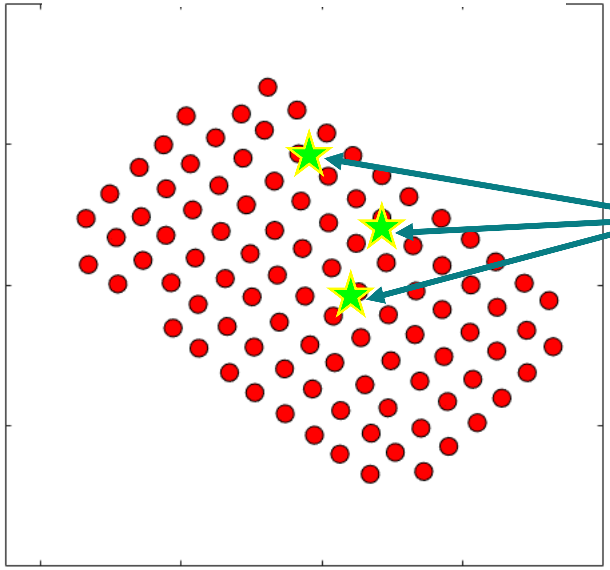
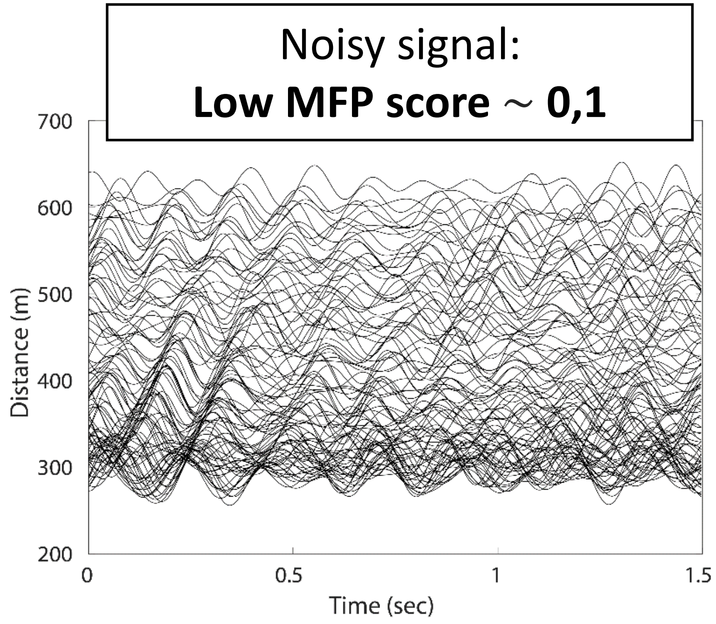
Multiple locations





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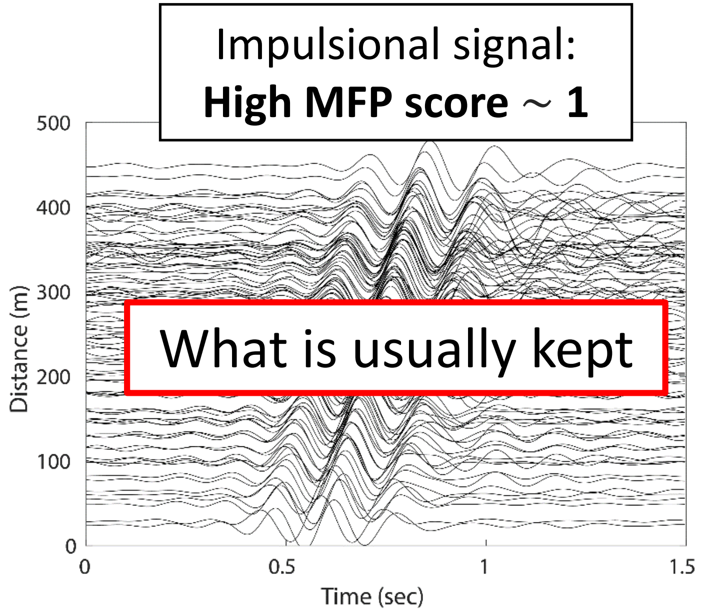

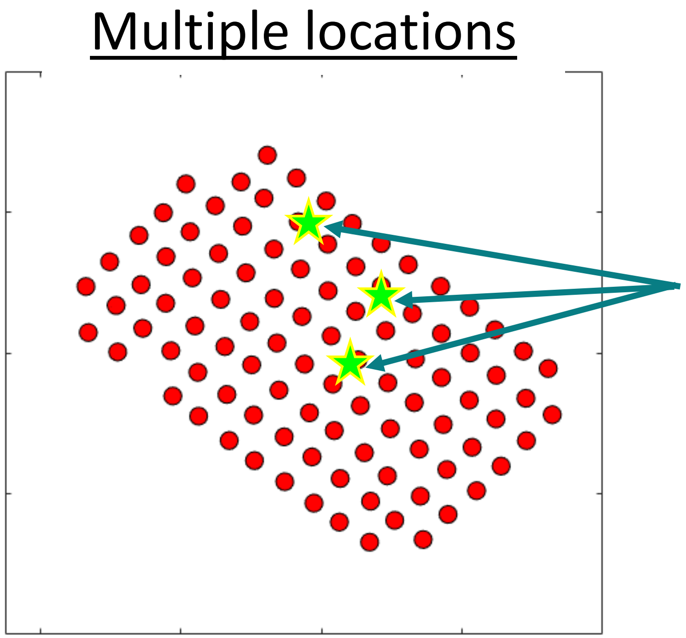

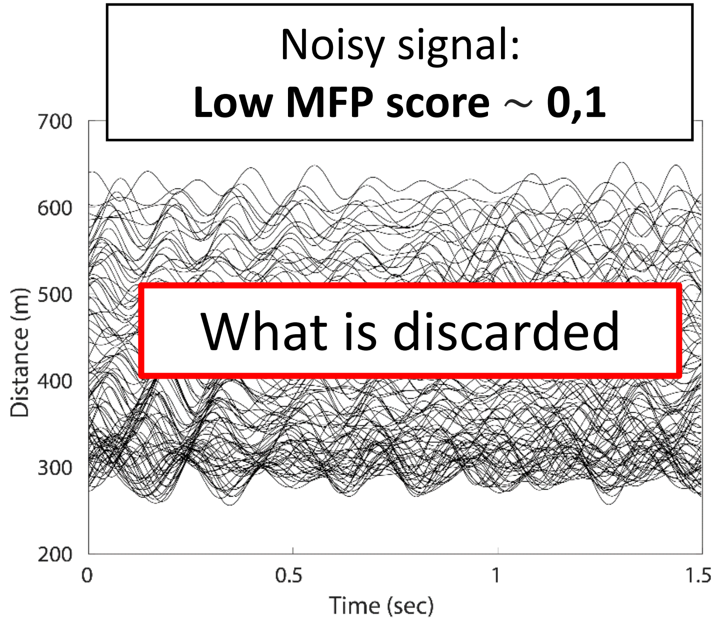

A CONCEPTUAL ADVANCE!

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)
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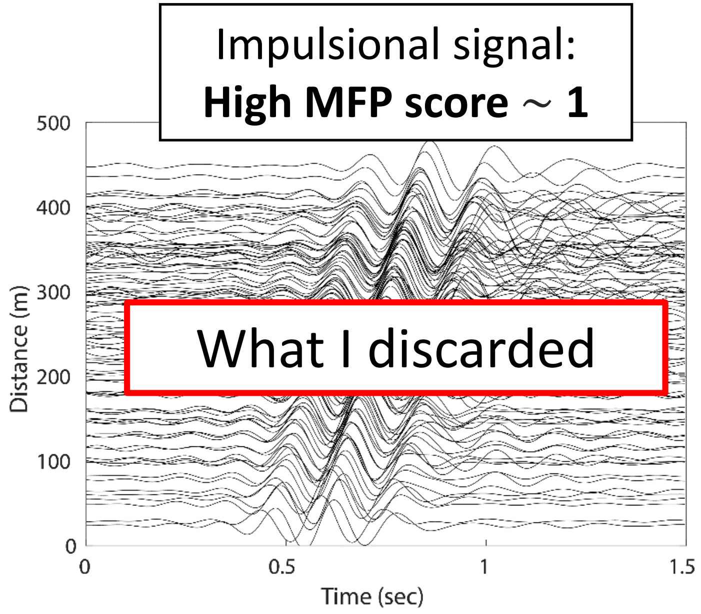
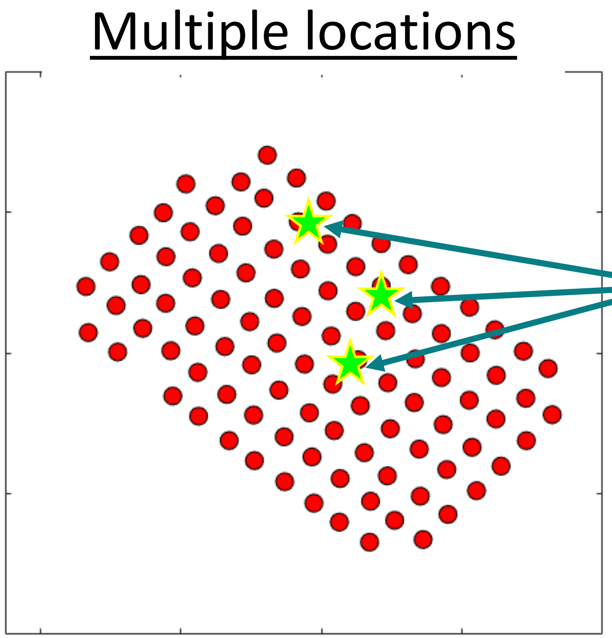
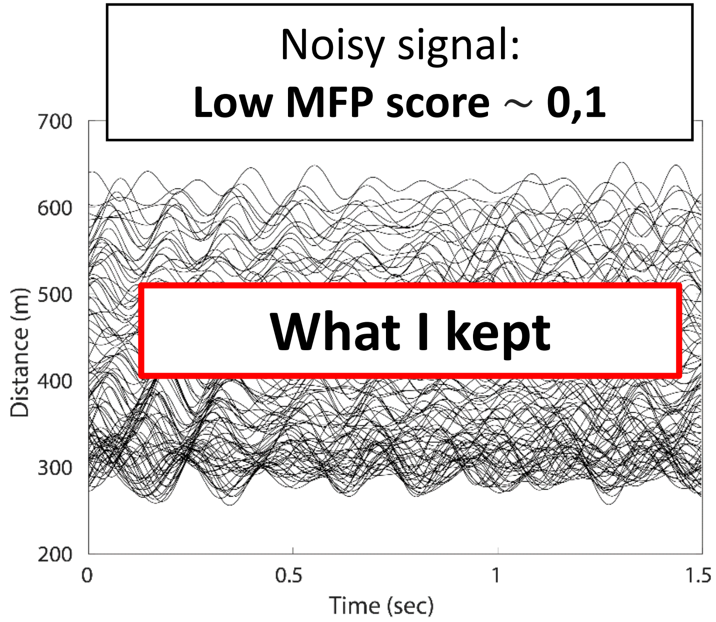
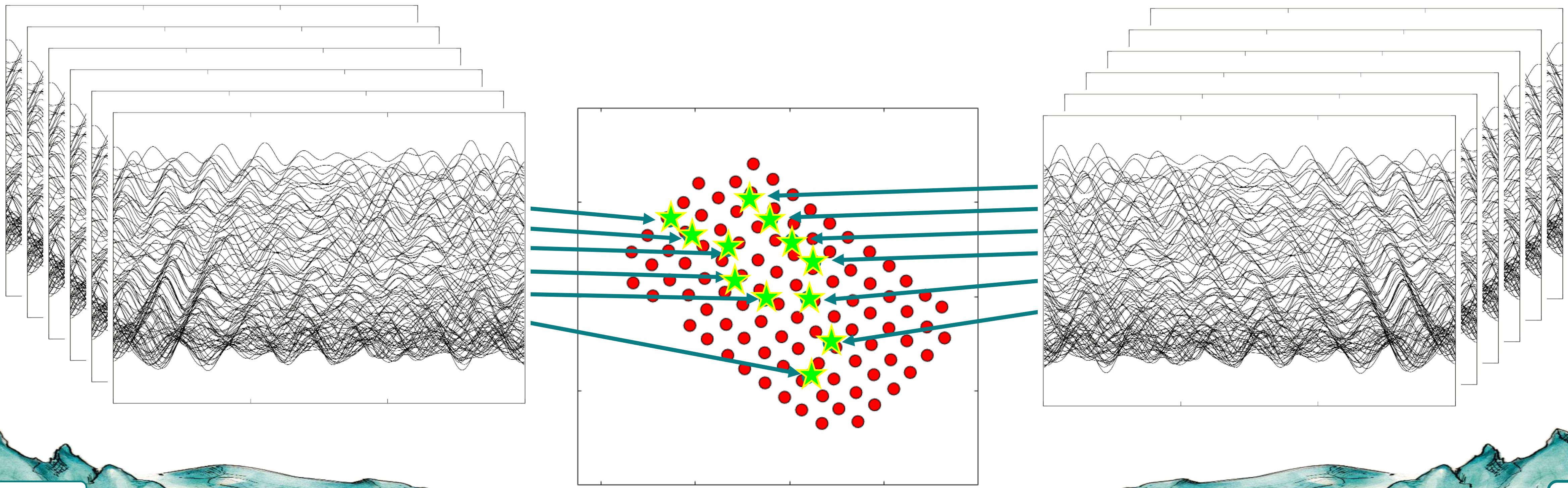




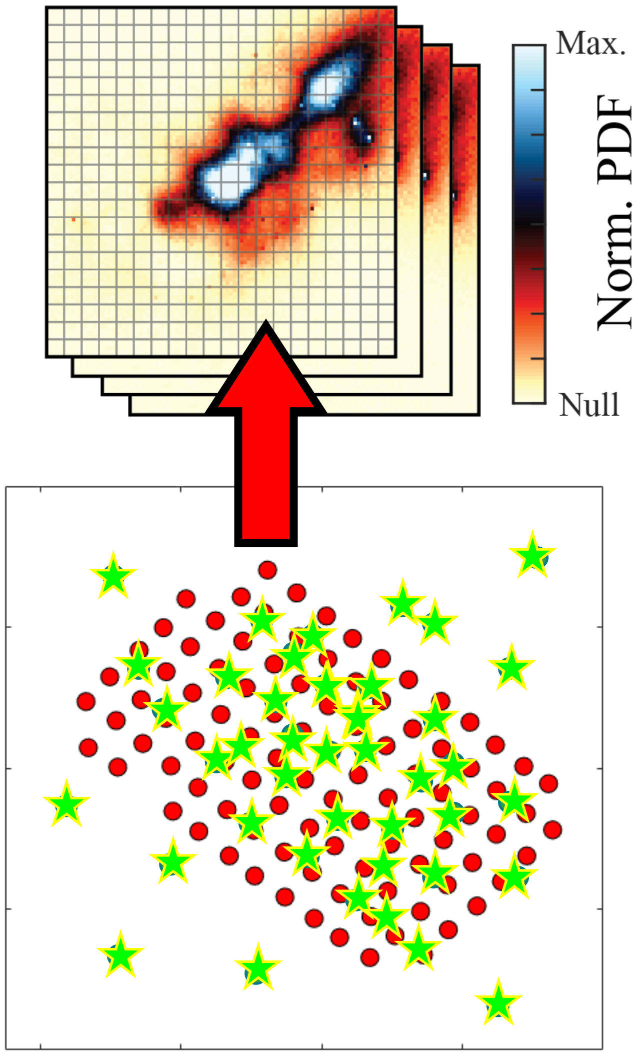


A CONCEPTUAL ADVANCE!

- Subglacial water flow: **low MFP** score (several sources are active simultaneously)
- I stack each 1 second-location over long time periods (~ days)



Making density probability maps



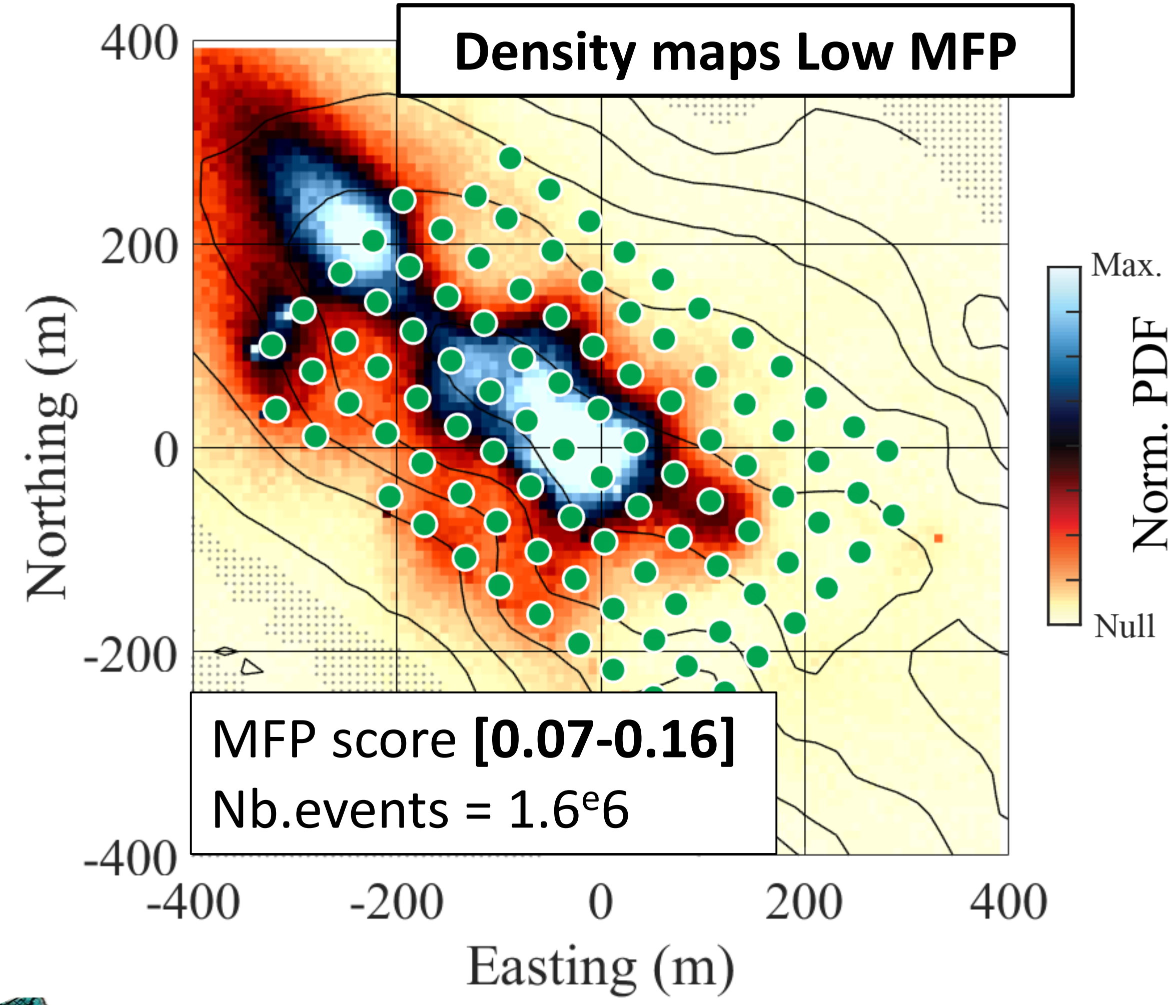
Up to 50+ millions potential locations per day

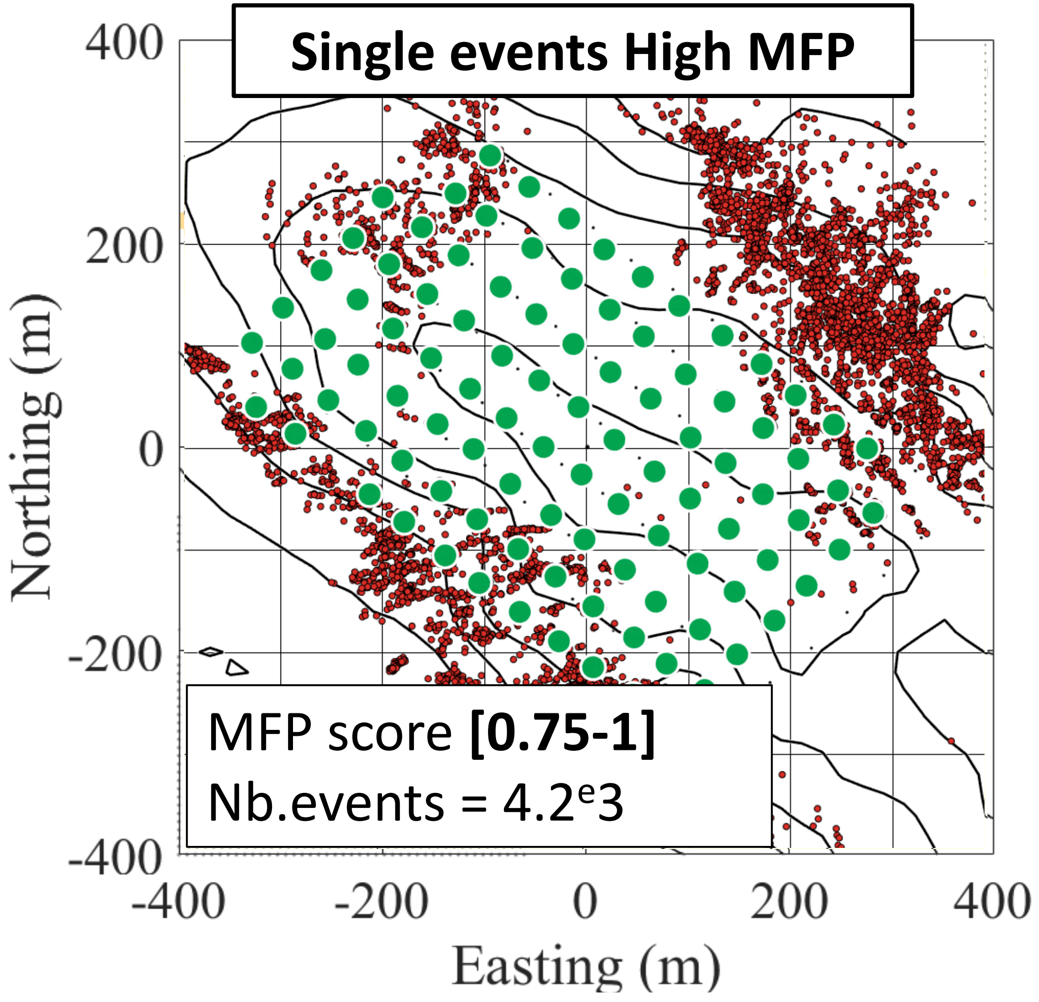
I selected realistic values:

- Phase velocity
  [1500-3600 m.sec^{-1}]

- Source positions
  ± 400m from array center in (x,y,z)

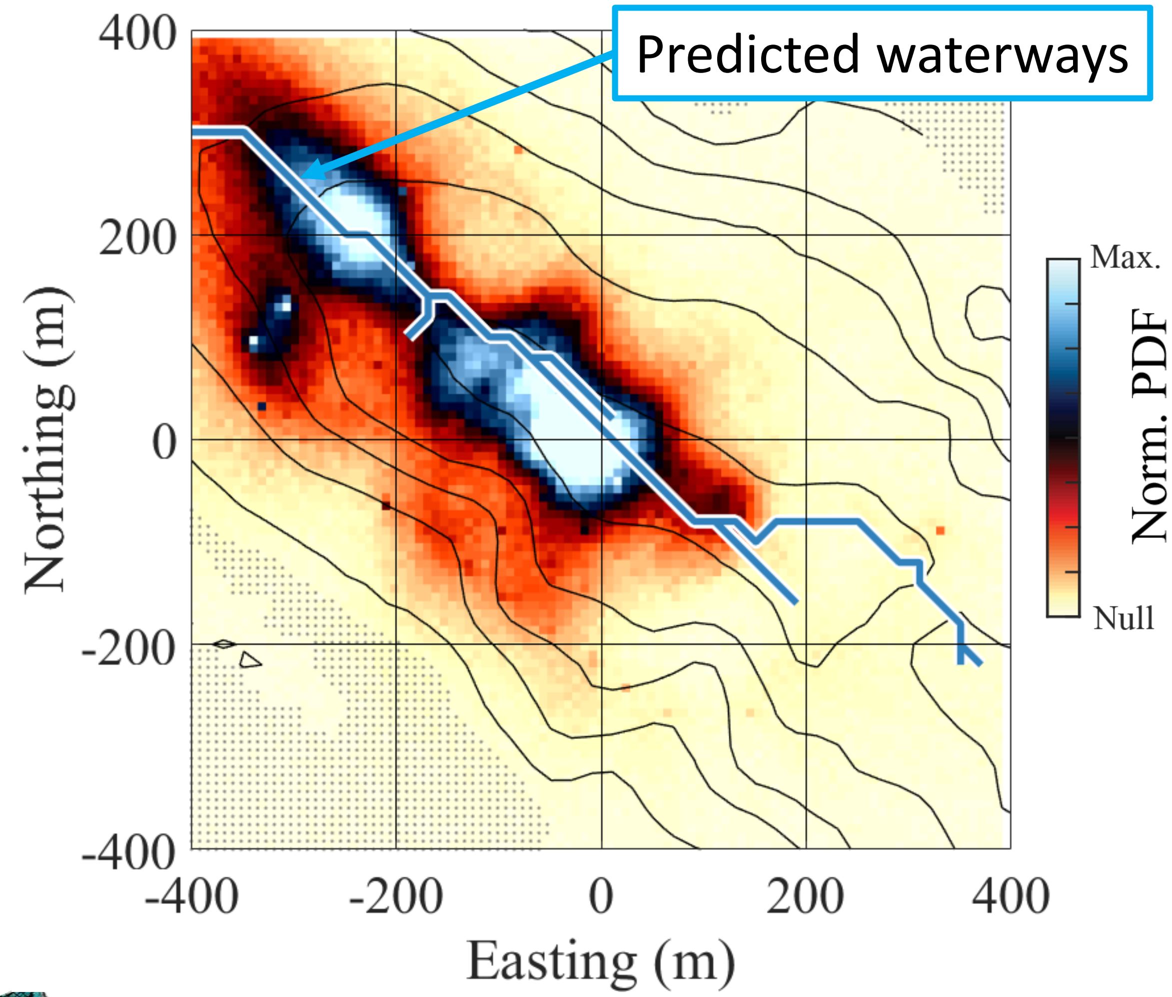
Patterns of noise and punctual sources

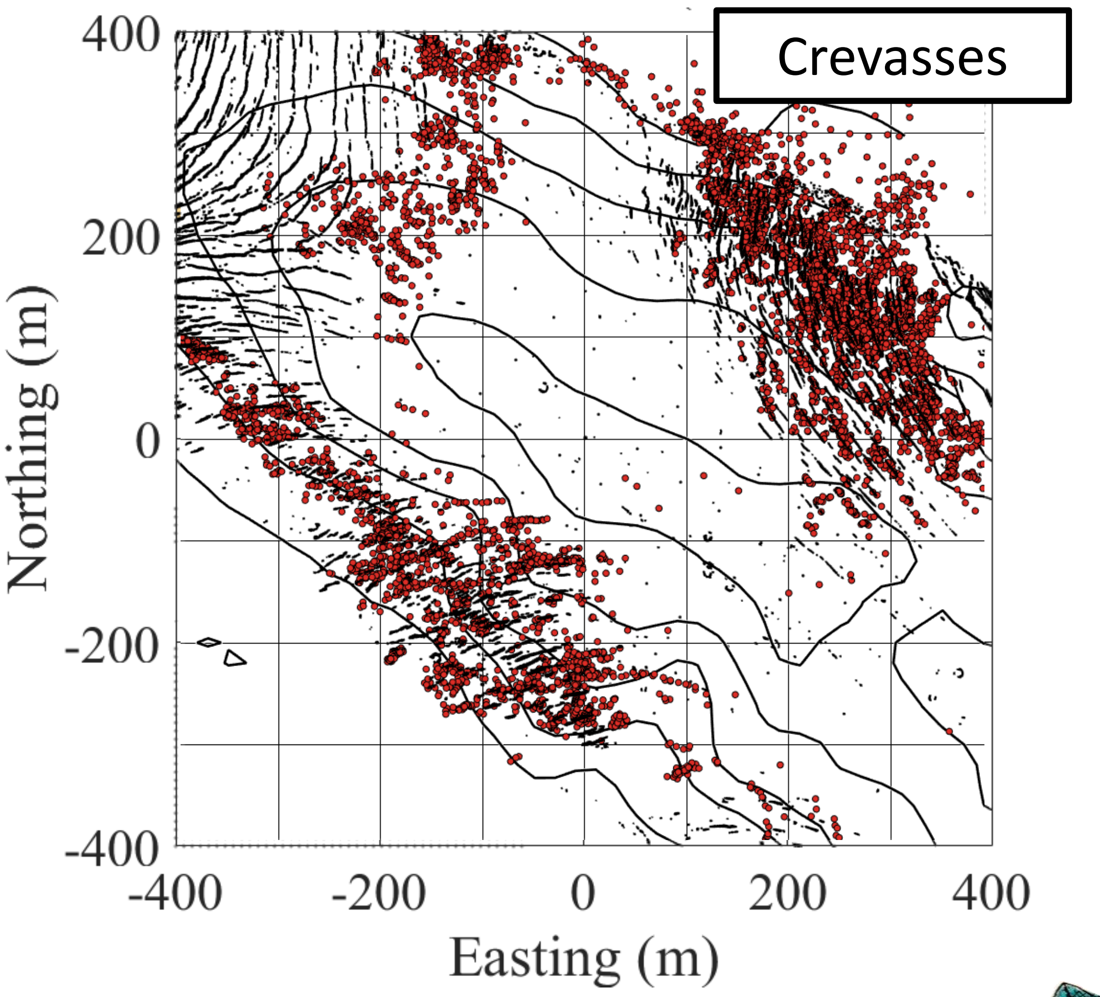




(Nanni et al., subm.)

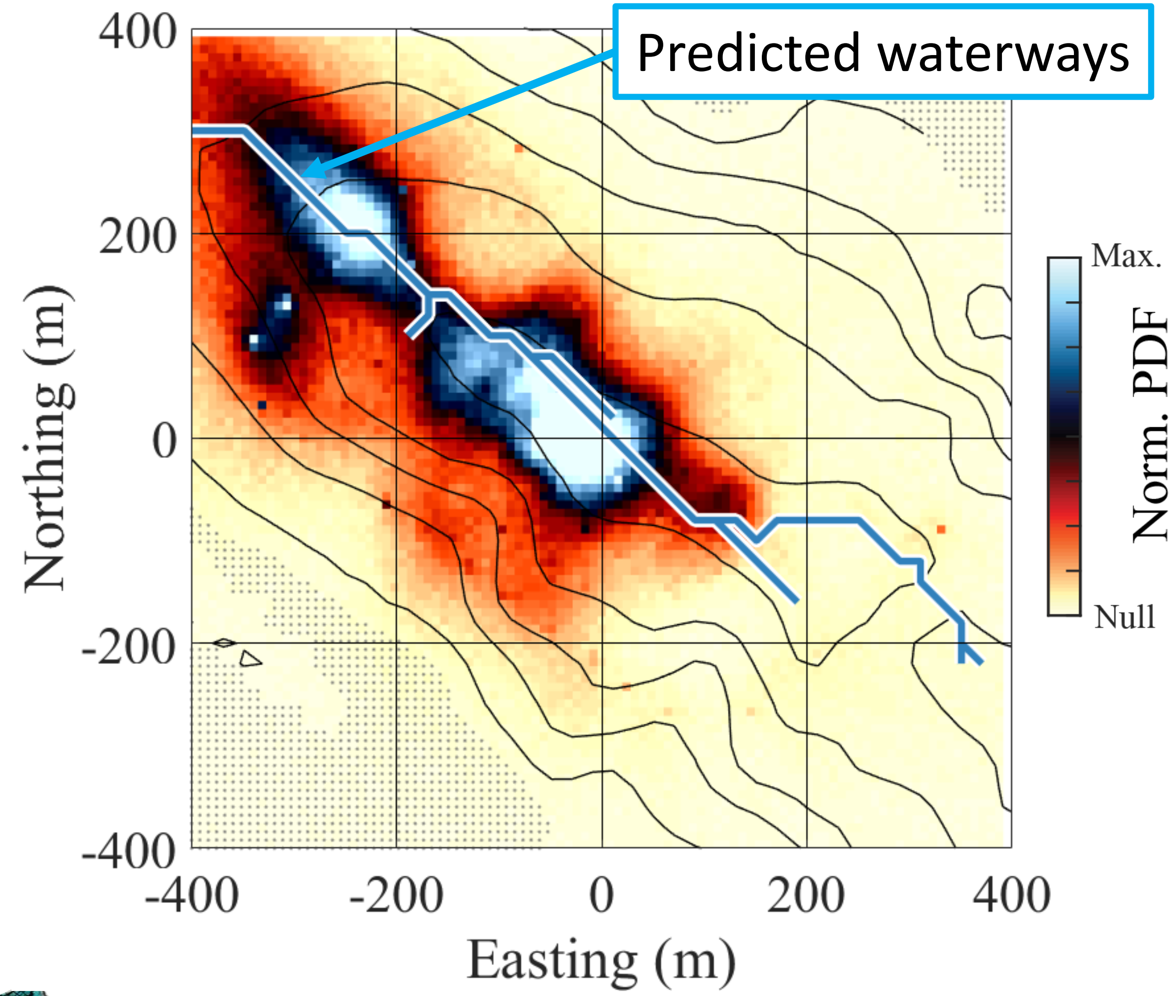
Patterns of noise and punctual sources





(Nanni et al., subm.)

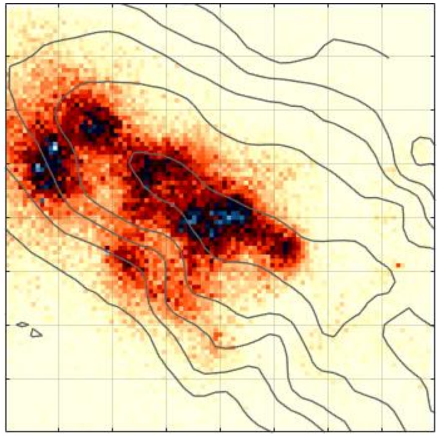
#3 I AM CAPABLE OF LOCATING SUBGLACIAL WATER FLOW

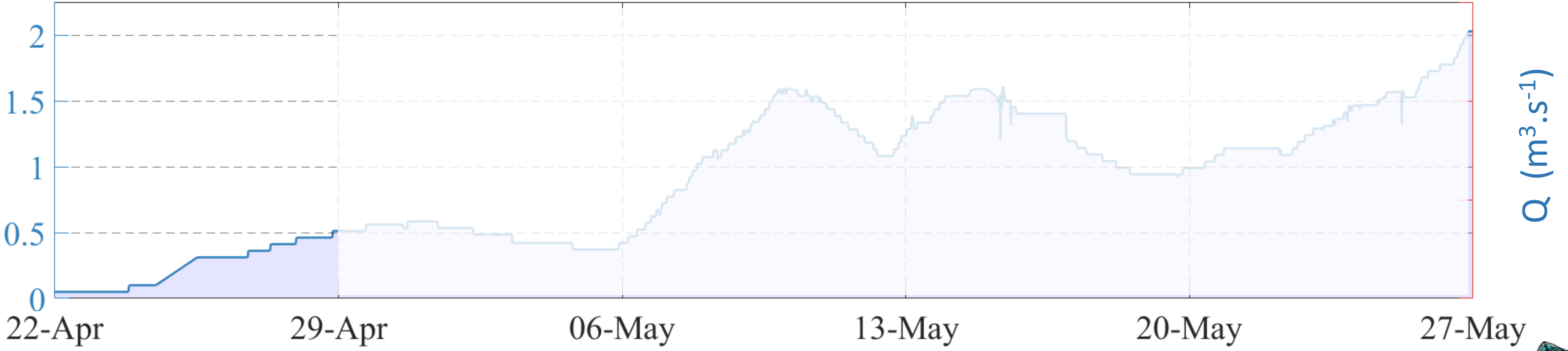


- Along-flow geometry
- ~ 50m width of source location
  - Due to seismic wavelength? (300m at 5Hz)
  - Spread sources?

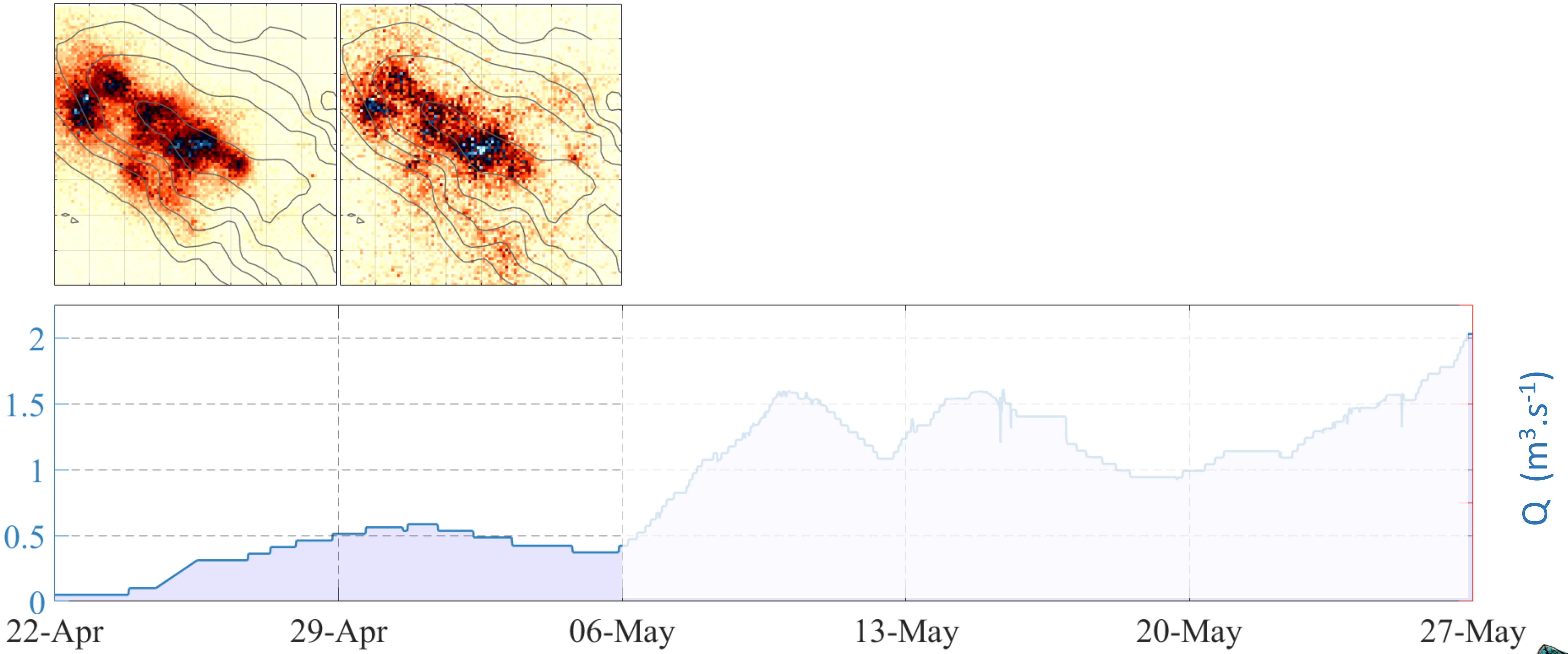
(Nanni et al., subm.)

Spatio-temporal dynamics

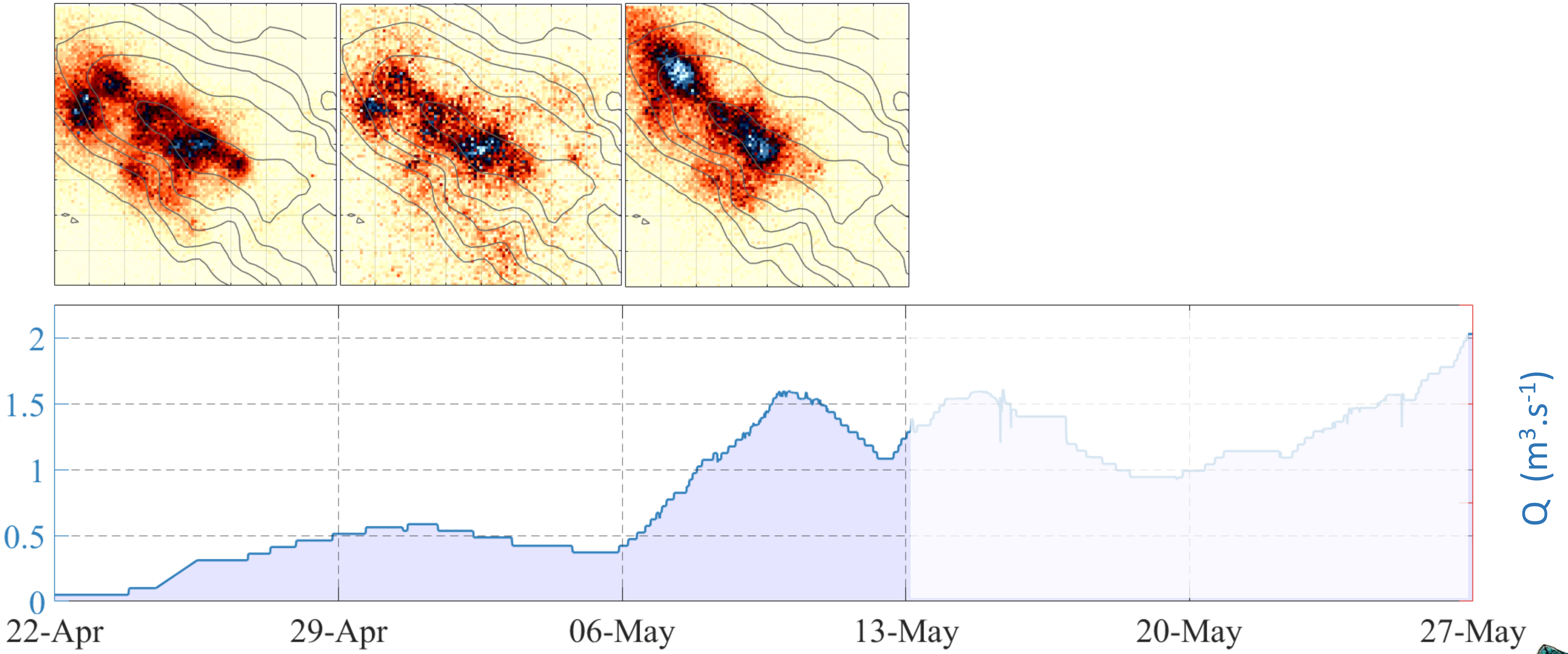




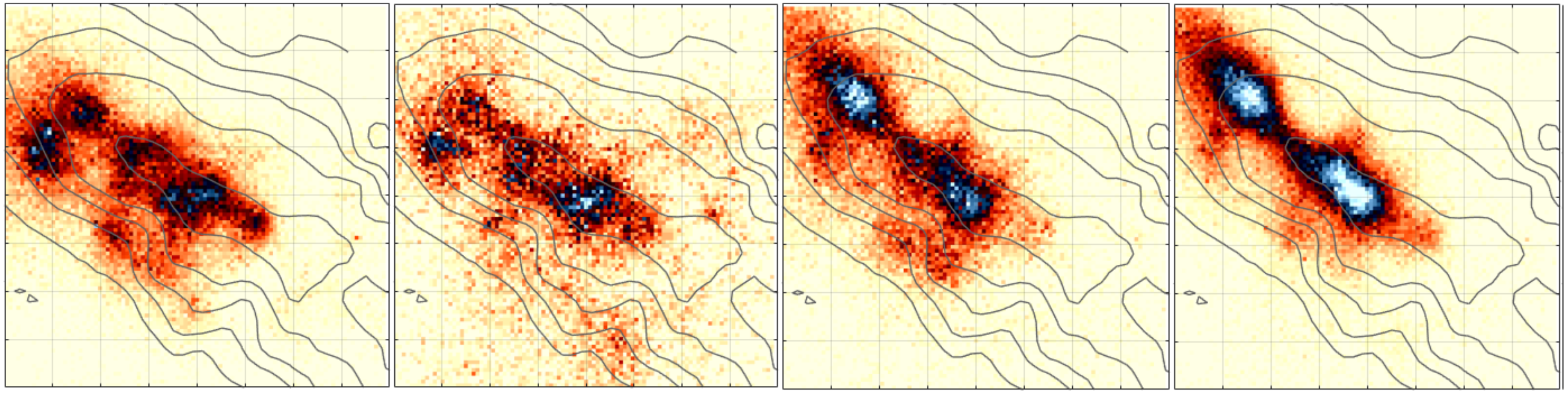
From distributed …

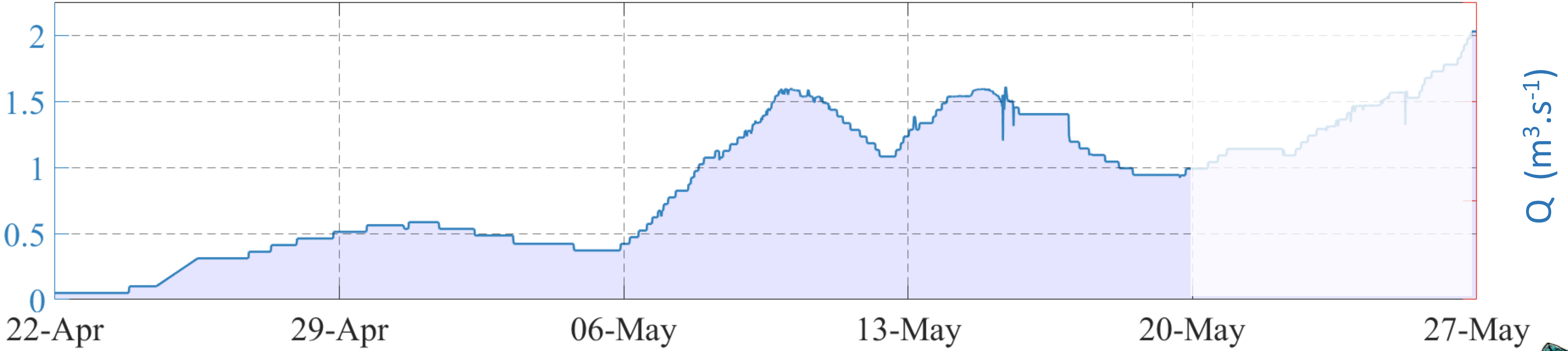


From distributed …

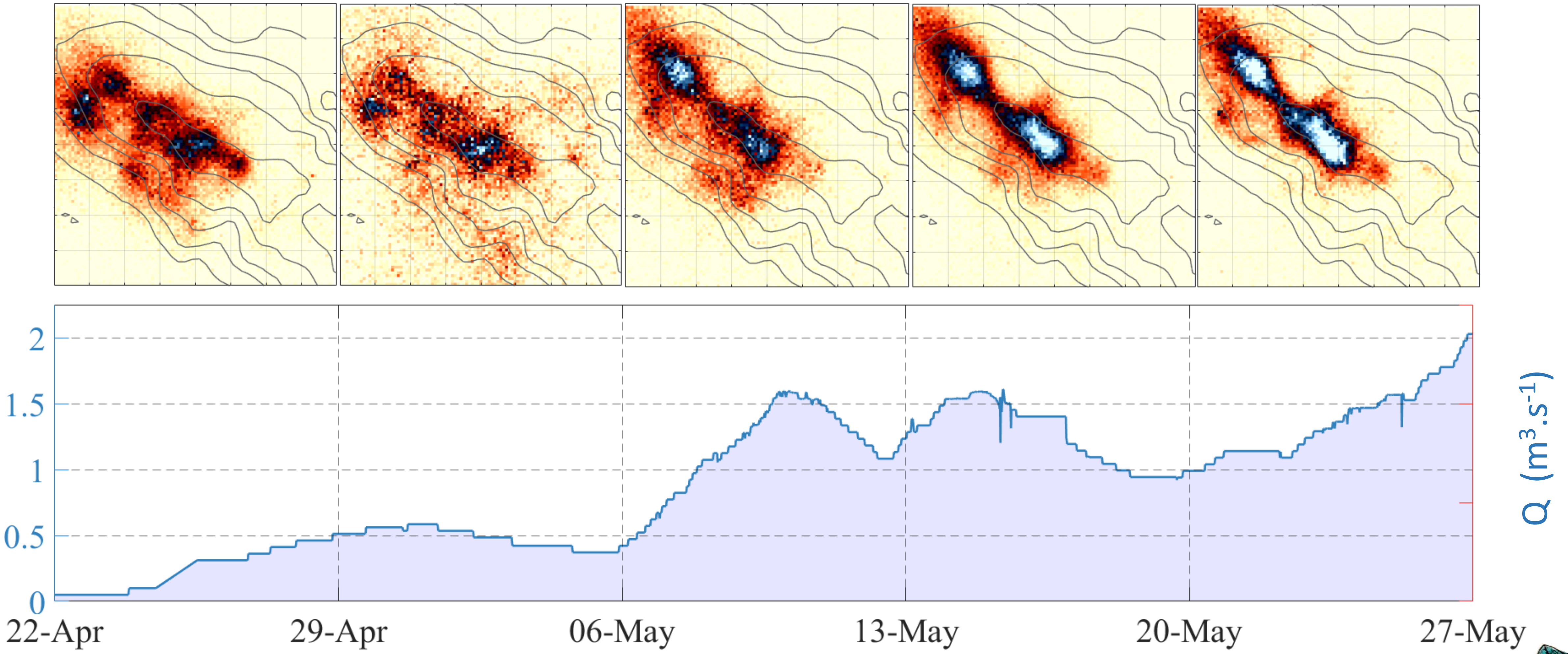


From distributed … to localized

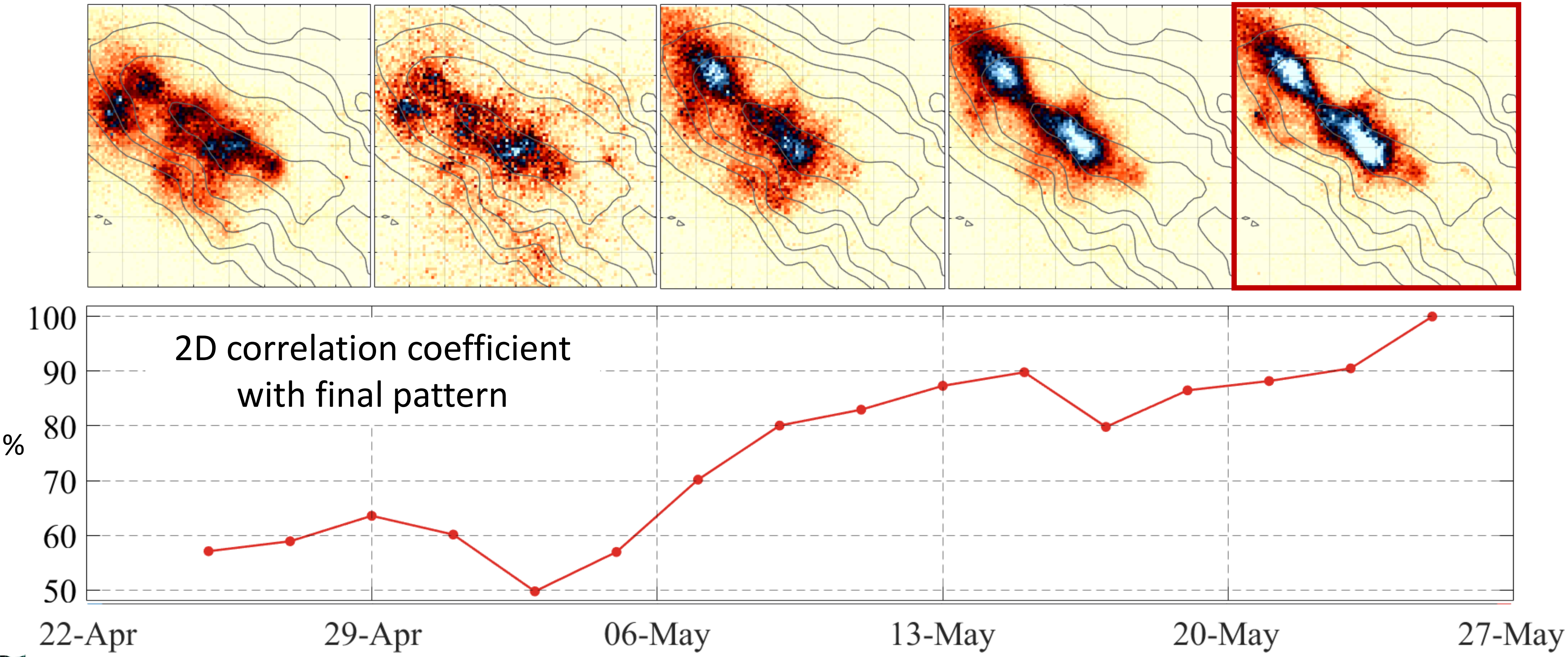




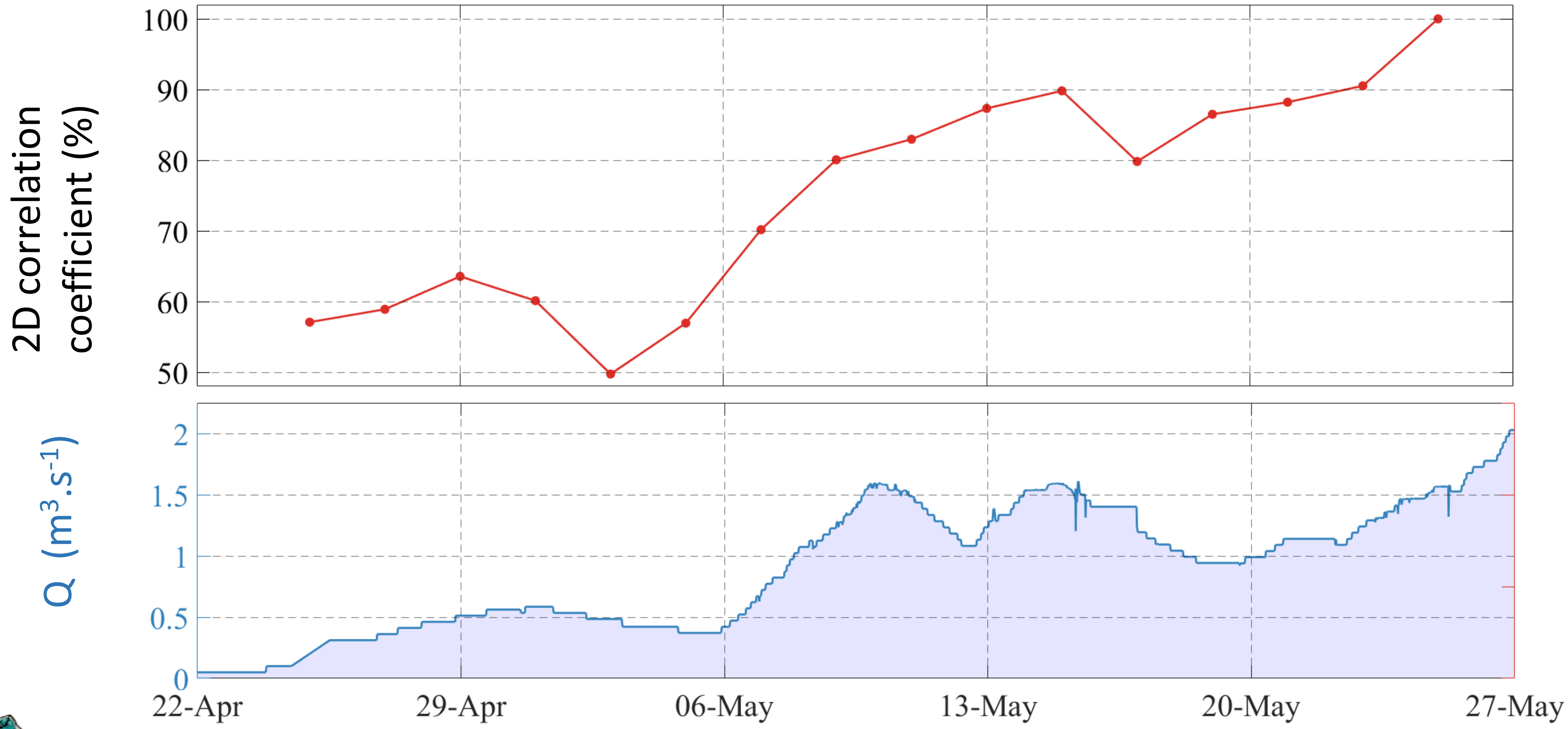
From distributed … to localized



#4 I AM CAPABLE OF CAPTURING SUBGLACIAL HYDROLOGY DYNAMICS

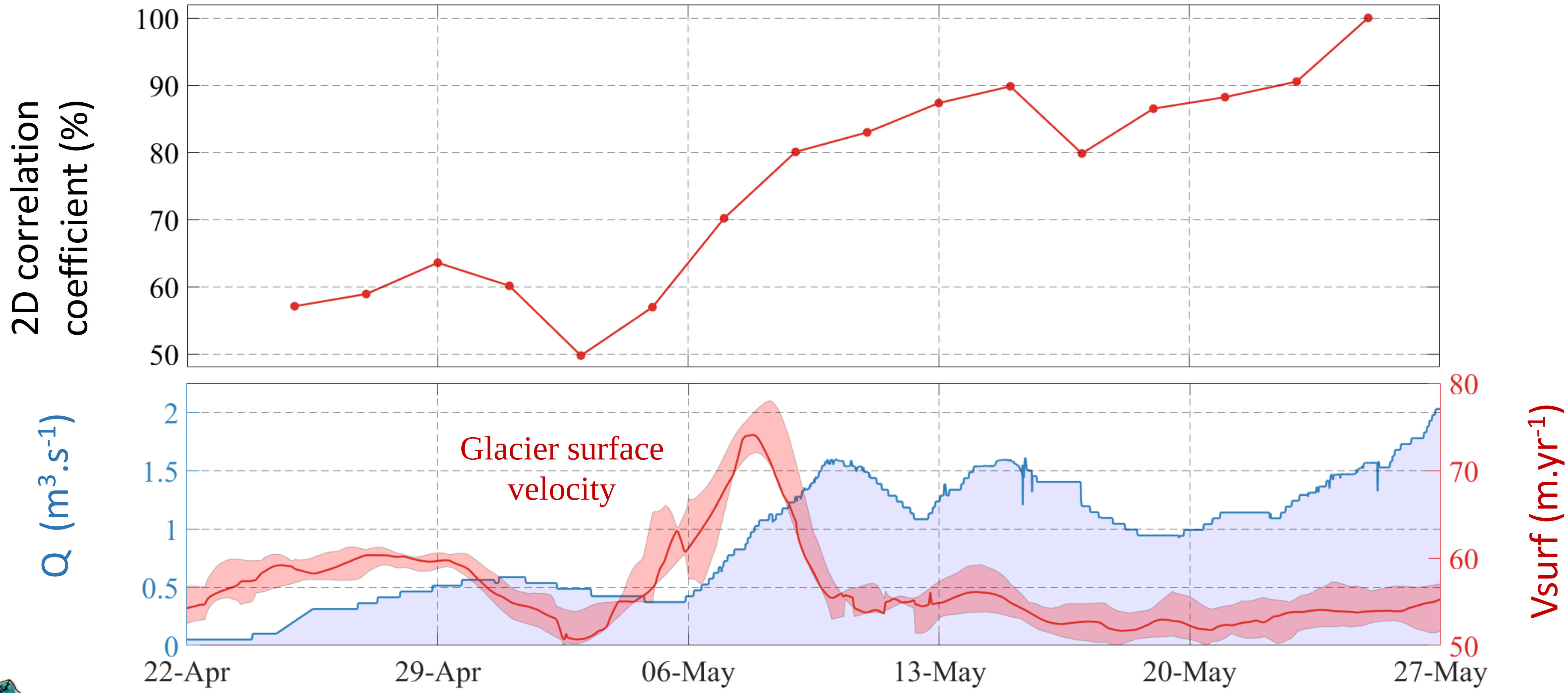


Spatial dynamics and hydraulic properties



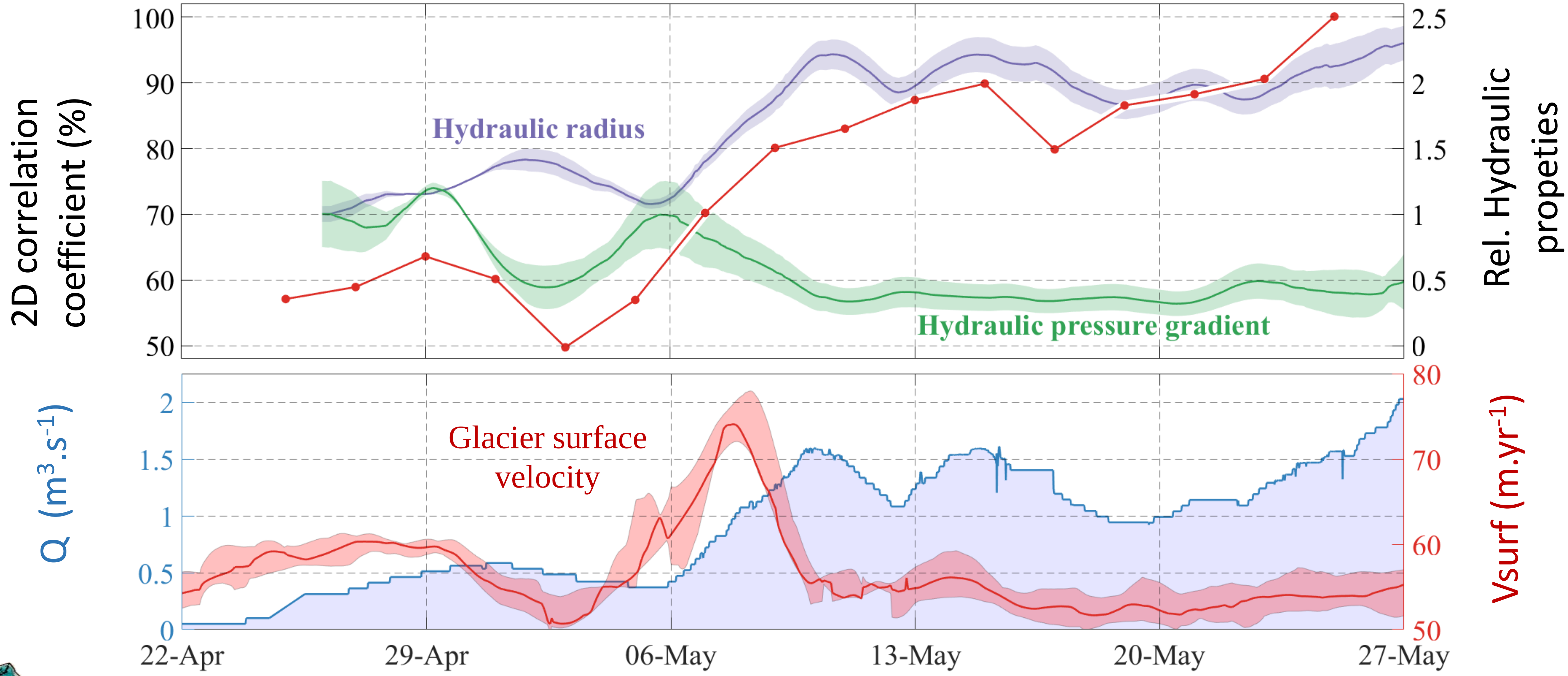
(Nanni et al., subm.)

Spatial dynamics and hydraulic properties



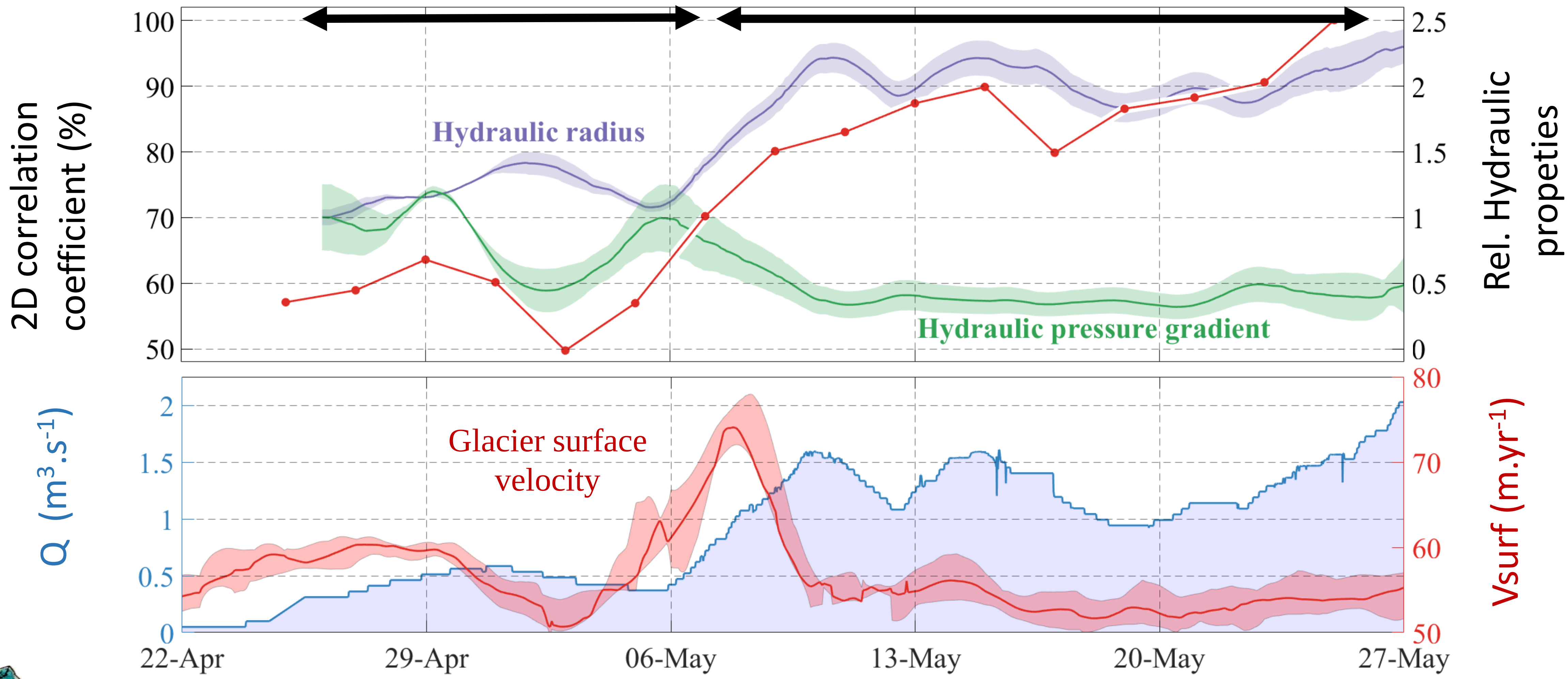
(Nanni et al., subm.)

Spatial dynamics and hydraulic properties



(Nanni et al., subm.)

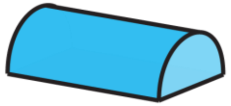
From inefficient to efficient?



(Nanni et al., subm.)

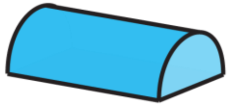
My questions on the methodology

#1 Can we MEASURE subglacial-water-flow-induced seismicity over complete melt-seasons?



#2 What is the TEMPORAL dynamics of subglacial hydraulic properties over complete melt-seasons?

#3 Can we LOCATE distributed sources of seismic noise?



#4 What is the SPATIAL dynamics of cavities and channels?

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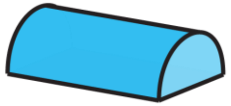

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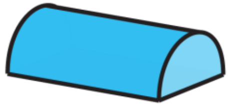
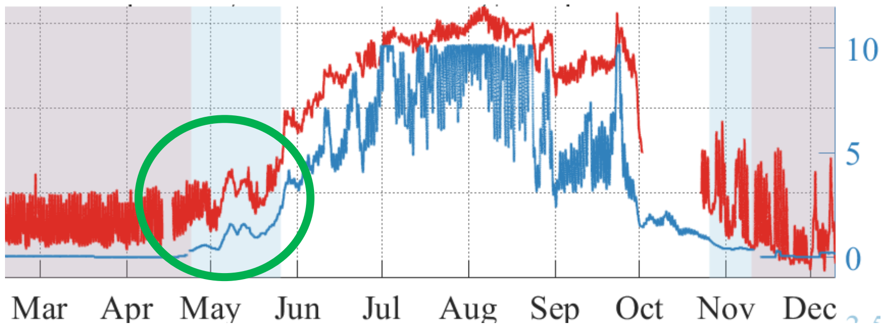


#4 What is the **SPATIAL** dynamics of cavities and channels?

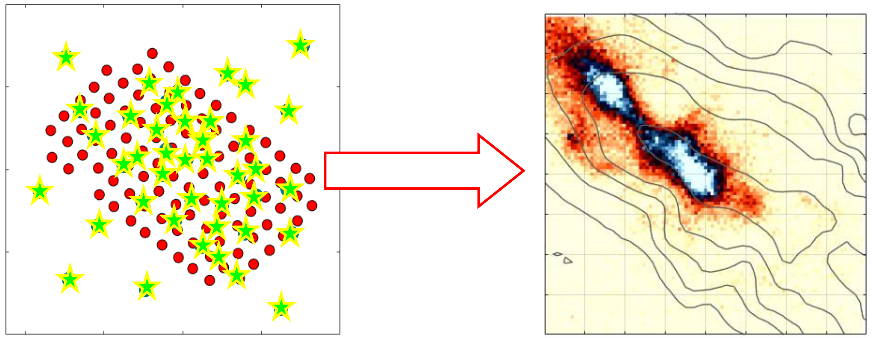
My conclusions on methodological aspects

I USED SEISMOLOGY TO STUDY COMPLETE MELT-SEASON

I WAS CAPABLE OF SPATIALLY LOCATING SUBGLACIAL WATER FLOW



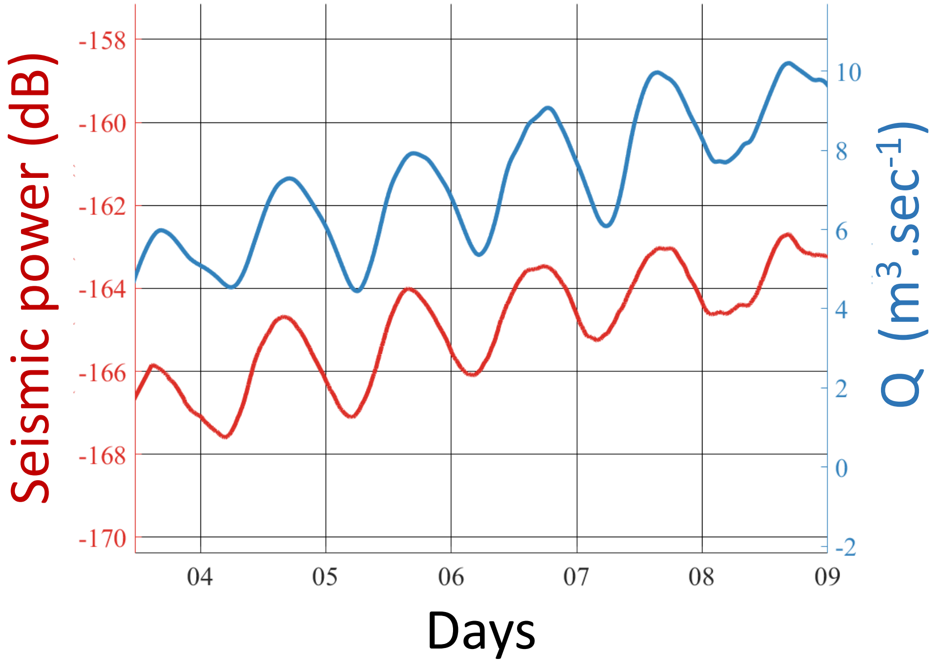
Published in The Cryosphere



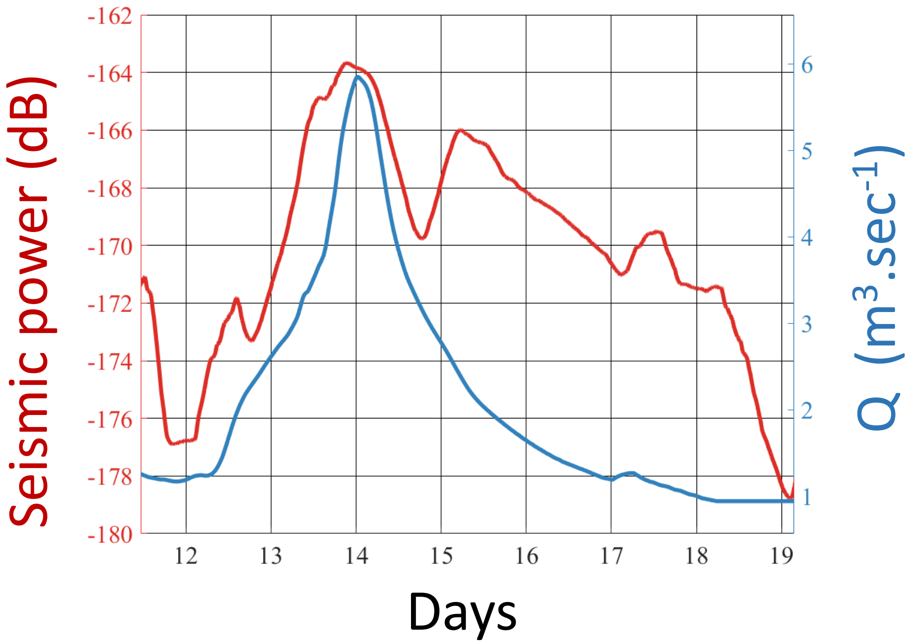
Submitted to PNAS + published in SRL

Perspectives: different timescales

Daily variations



Storm event



Investigate kinetic effect and transient states

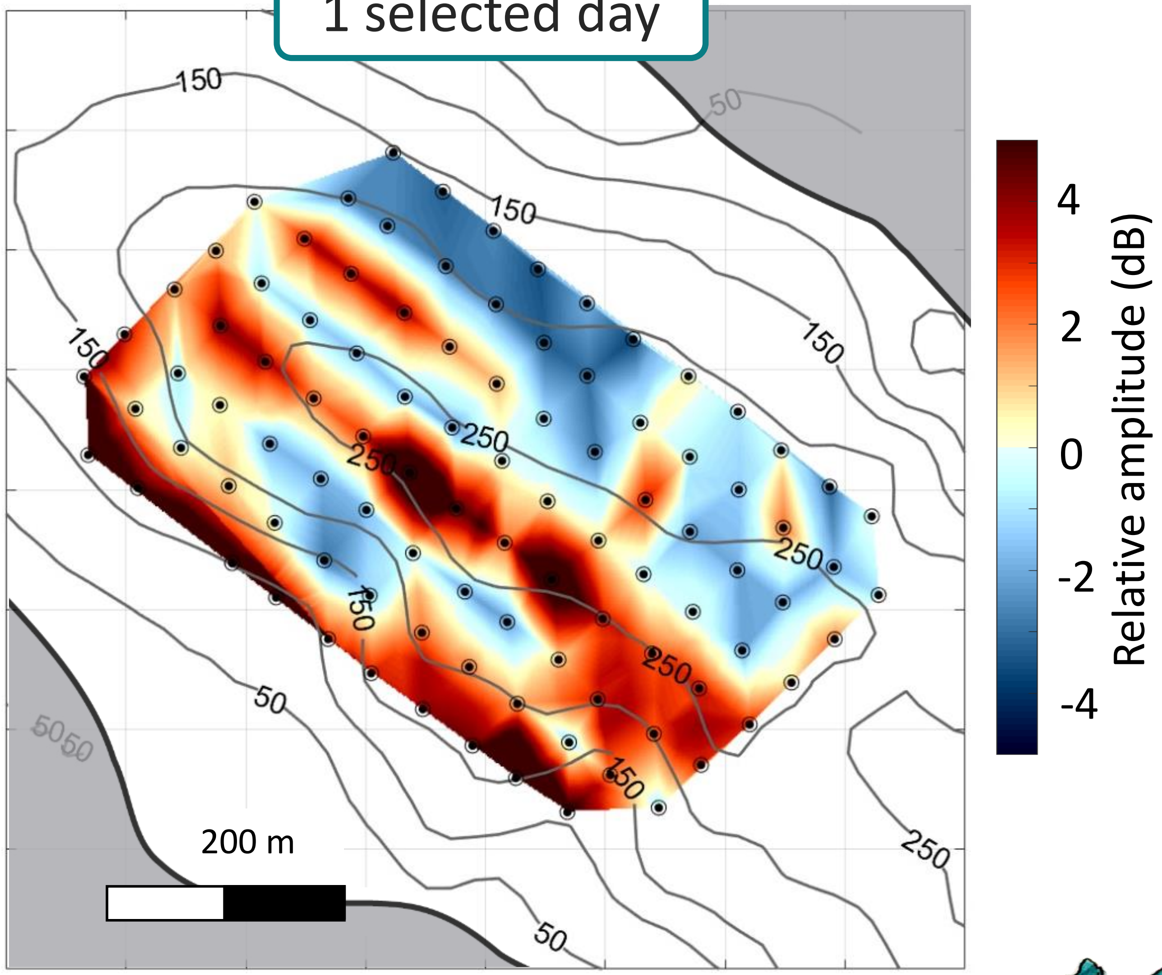
Perspectives: spatial variations of amplitudes

$$u(t) = Ae^{i\omega t}$$

Amplitude Phase

- Might allow to spatialized hydraulic properties
- Complex effect of attenuation/amplification

1 selected day



(Nanni et al., in prep.)

My questions on the studied processes

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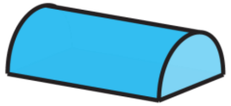

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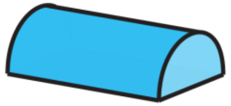

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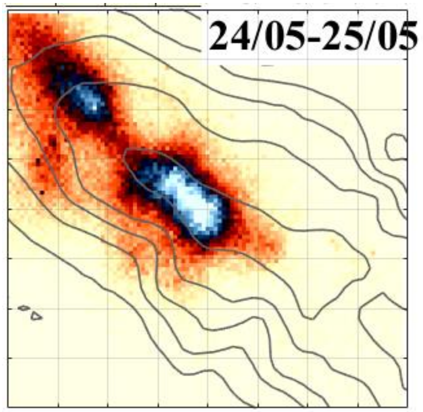
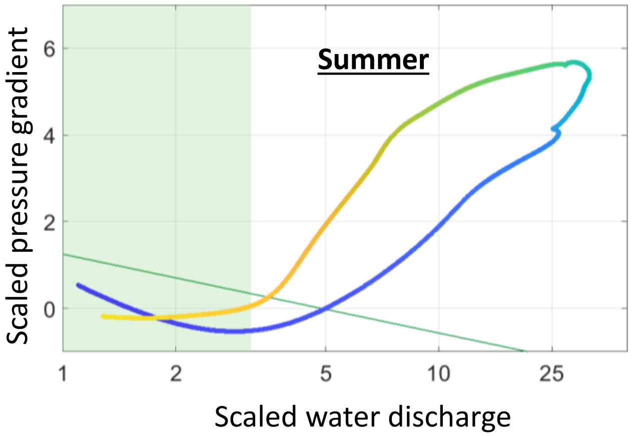
My conclusions on the studied processes

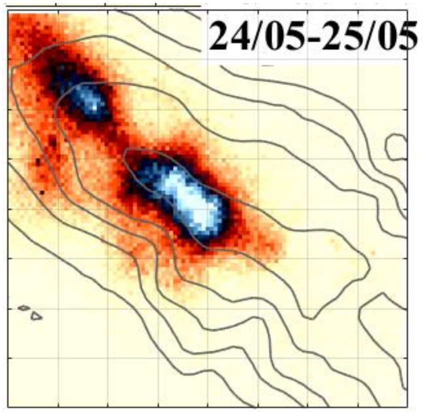


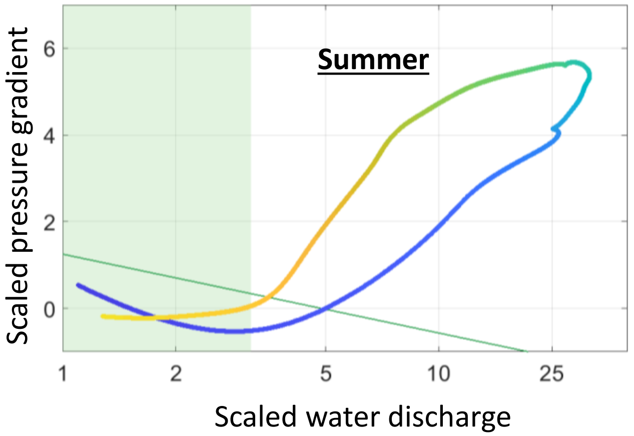


Localized water flow

High pressure gradient in summer!

My conclusions on the studied processes





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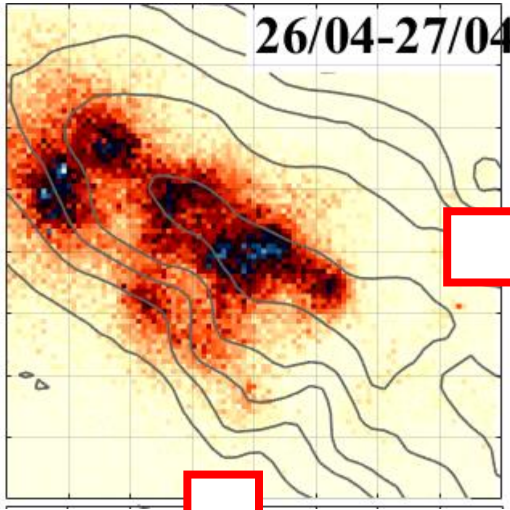
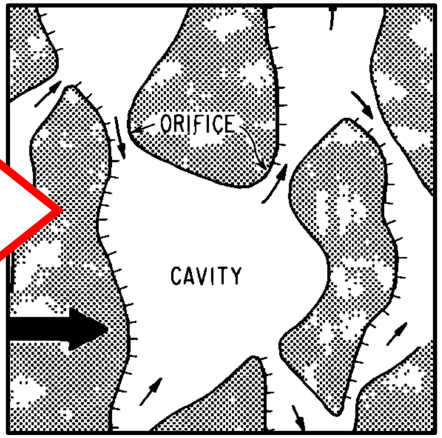


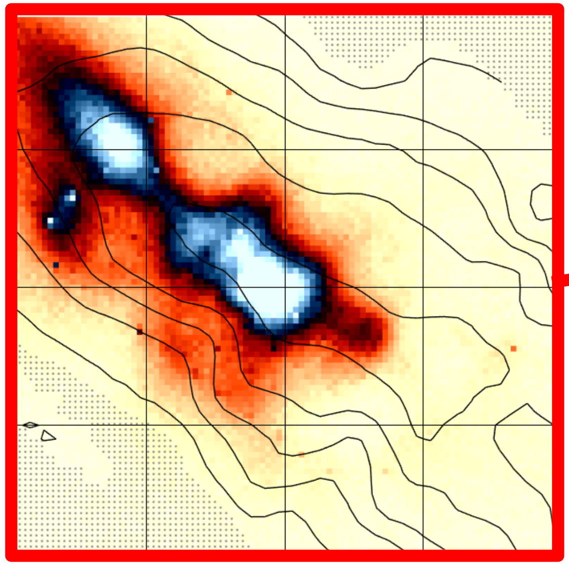


Linked cavity
(Kamb, 1987)

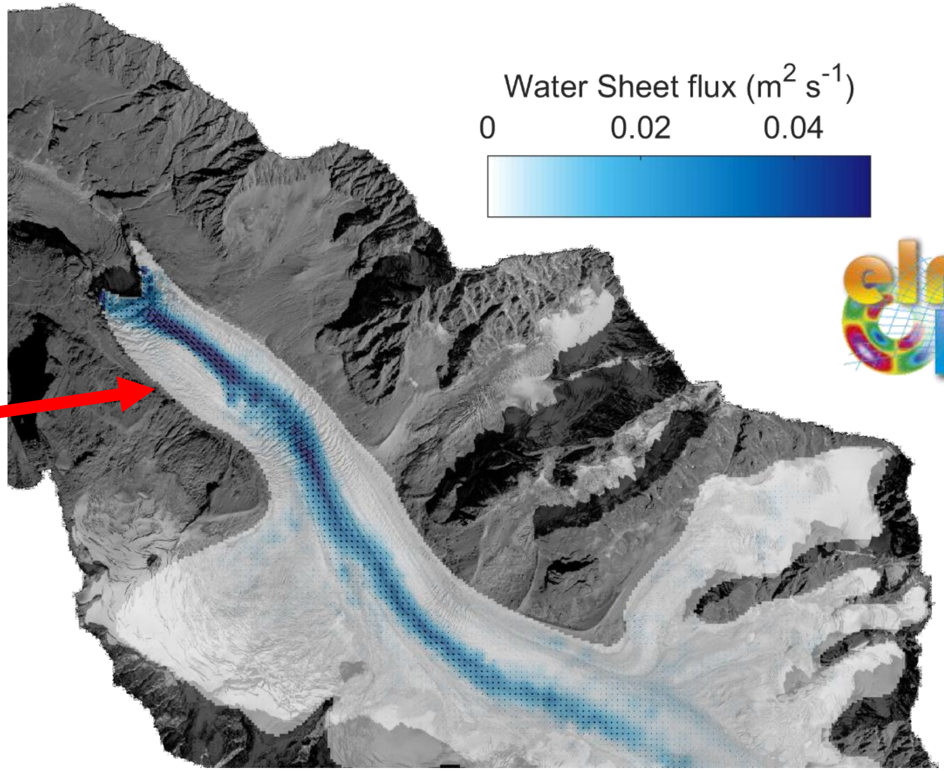
I can observe **distributed** water flow in the cavities with seismology

Implication for subglacial hydrology dynamics

- Do we observe cavities only?
- Do cavities domiantes the drainage system?



Modelling subglacial hydrology with Elmer/Ice-GlaDS coupling by A. Gilbert



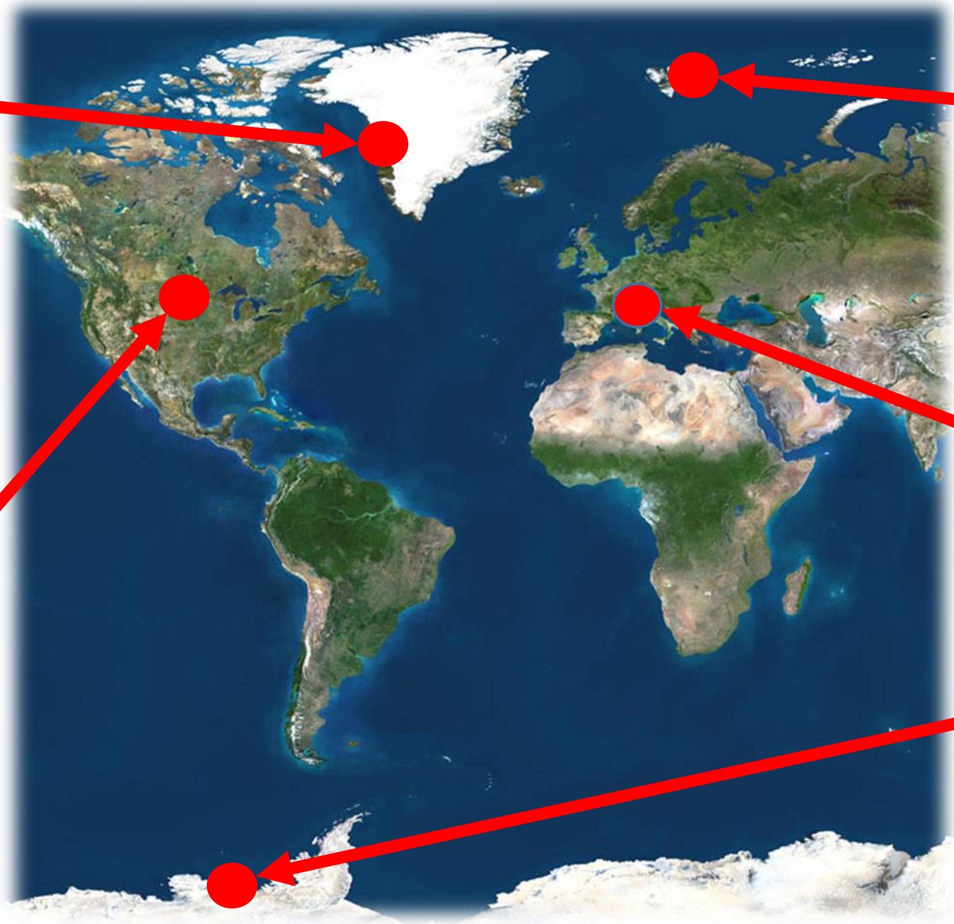
Perspectives: we need to study other settings

Current (or soon) dense seismic experiments

Subglacial lakes in Greenland
(S. Livingstone, A. Booth and others - **UK**)

My post-doc?

Subglacial hydrology and stick-slips in Canada
(N. Stevens, L. Zoet and others - **USA**)



Soft-bedded glaciers and surges in Spitzberg
(T. Schuler, A. Kholer, and others - **Norway**) *My post-doc?*

My PhD

Grounding line dynamics and subglacial hydrology in Antarctica – <u>1,000 sensors</u>
(The International Thwaites Glacier collaboration)

Perspectives: continue sharing beyond academia

An artistic collaboration with EdZ

Making comics with 12 other PhD students

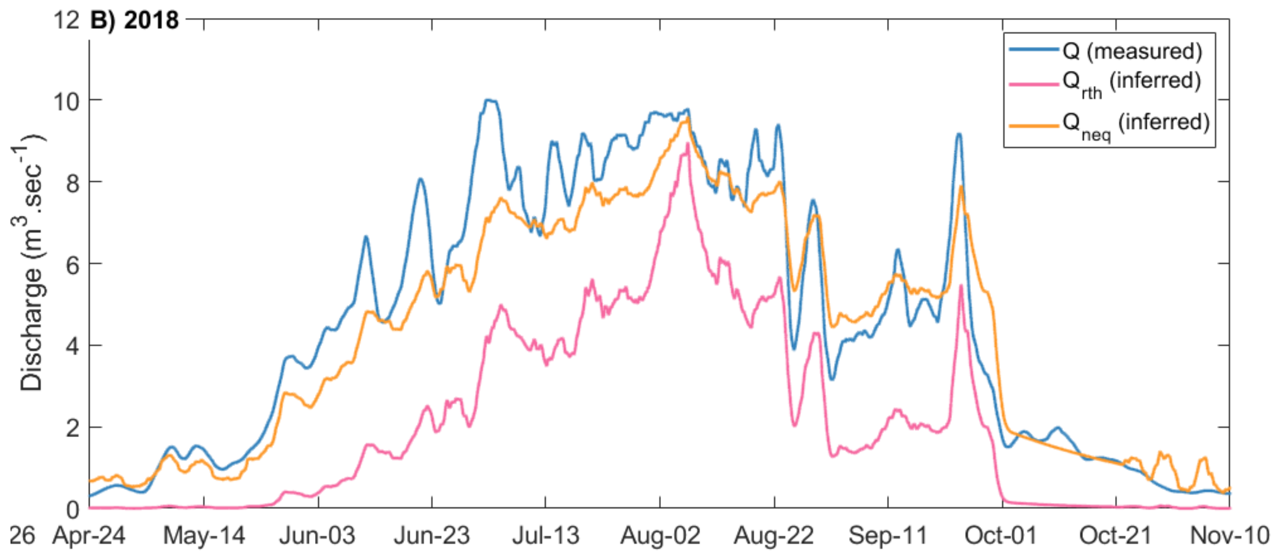
Presenting my works during the « Week of science»

A collaboration during the Grenoble Scientific Game Jam

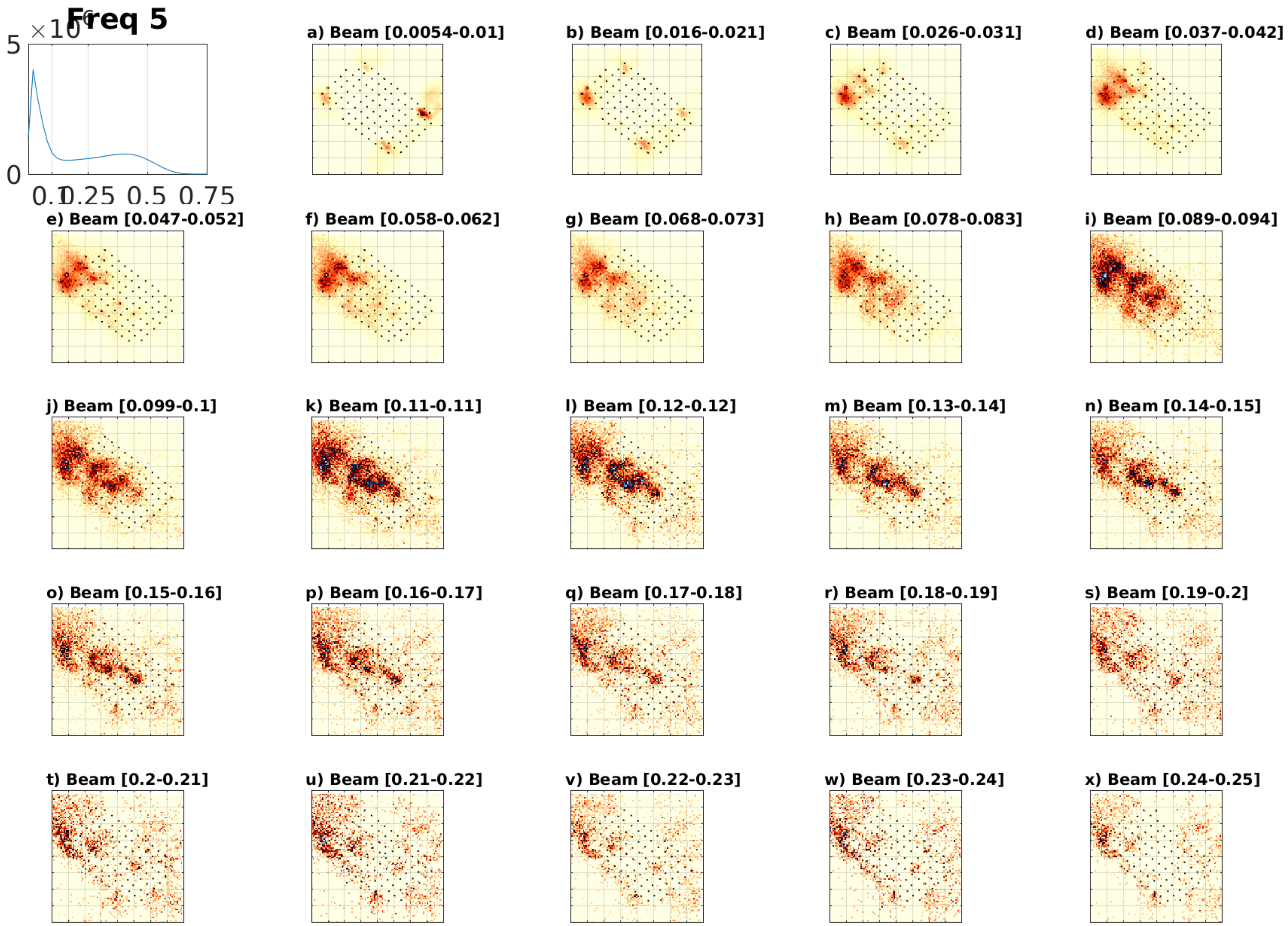
THANK YOU ALL

AND COLLEAGUES, LAB MEMBERS, FAMILY ...

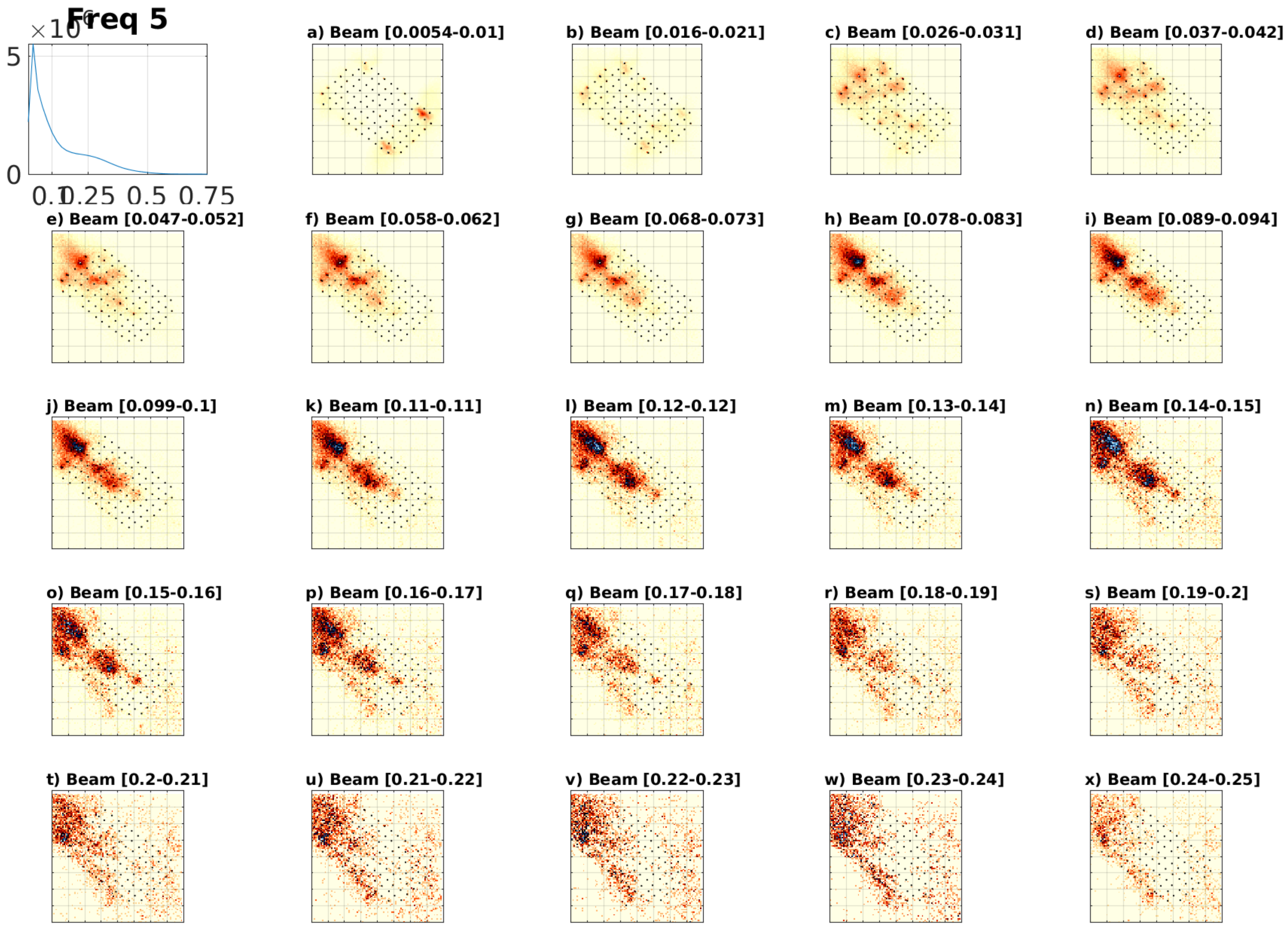
Implication for monitoring Q



- Using the relation between Q and Pw for channels out-of-equilibrium allow to estimate Q from Pw with less than 10% error compared to more than 65% if channels are assumed to be at equilibrium.



Freq 5
×10^6
5
0
0.1
0.25
0.5
0.75
a) Beam [0.0054-0.01]
b) Beam [0.016-0.021]
c) Beam [0.026-0.031]
d) Beam [0.037-0.042]
e) Beam [0.047-0.052]
f) Beam [0.058-0.062]
g) Beam [0.068-0.073]
h) Beam [0.078-0.083]
i) Beam [0.089-0.094]
j) Beam [0.099-0.1]
k) Beam [0.11-0.11]
l) Beam [0.12-0.12]
m) Beam [0.13-0.14]
n) Beam [0.14-0.15]
o) Beam [0.15-0.16]
p) Beam [0.16-0.17]
q) Beam [0.17-0.18]
r) Beam [0.18-0.19]
s) Beam [0.19-0.2]
t) Beam [0.2-0.21]
u) Beam [0.21-0.22]
v) Beam [0.22-0.23]
w) Beam [0.23-0.24]
x) Beam [0.24-0.25]



Freq 5
×10
5
0
0.1
0.25
0.5
0.75
a) Beam [0.0054-0.01]
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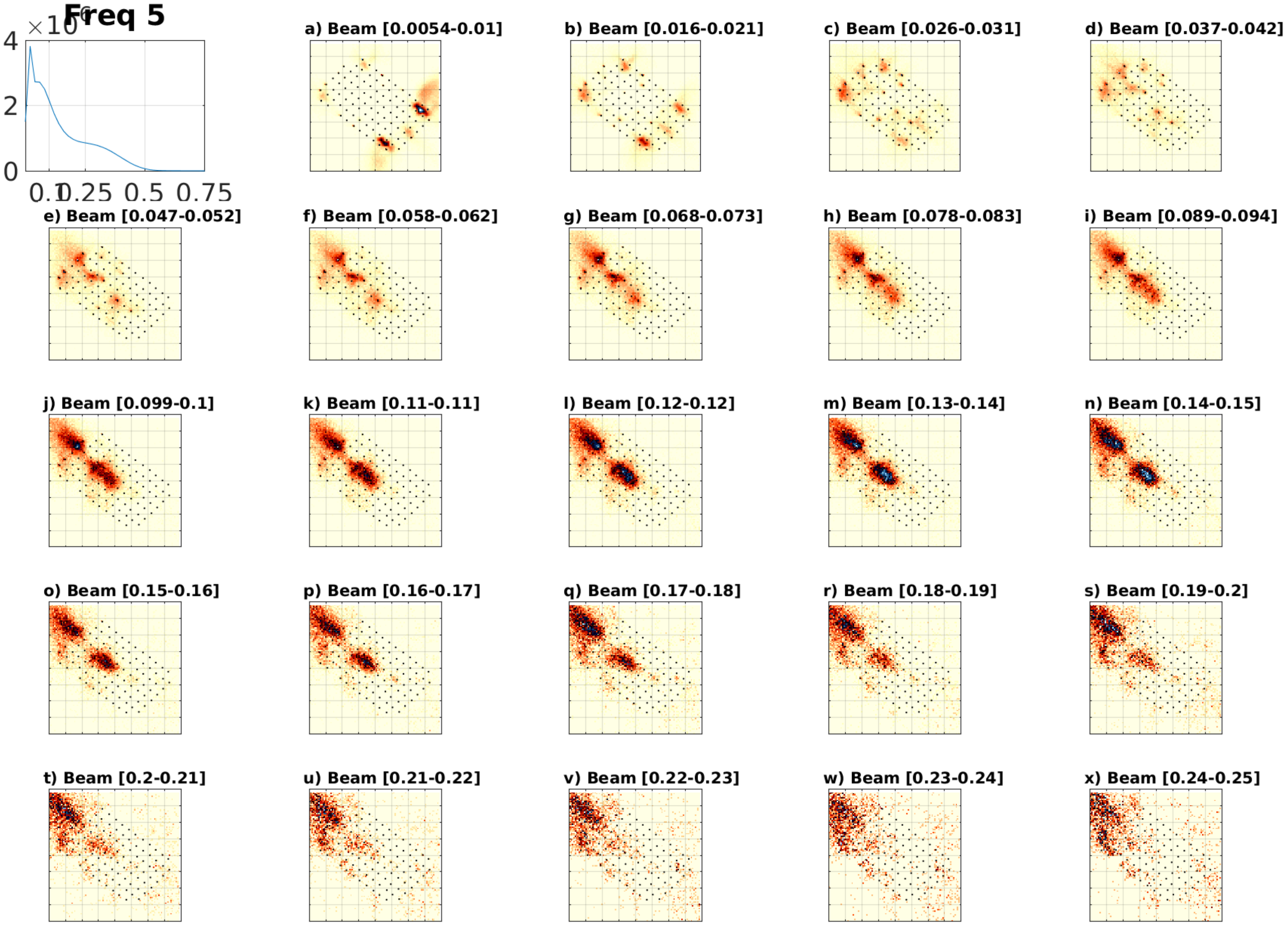
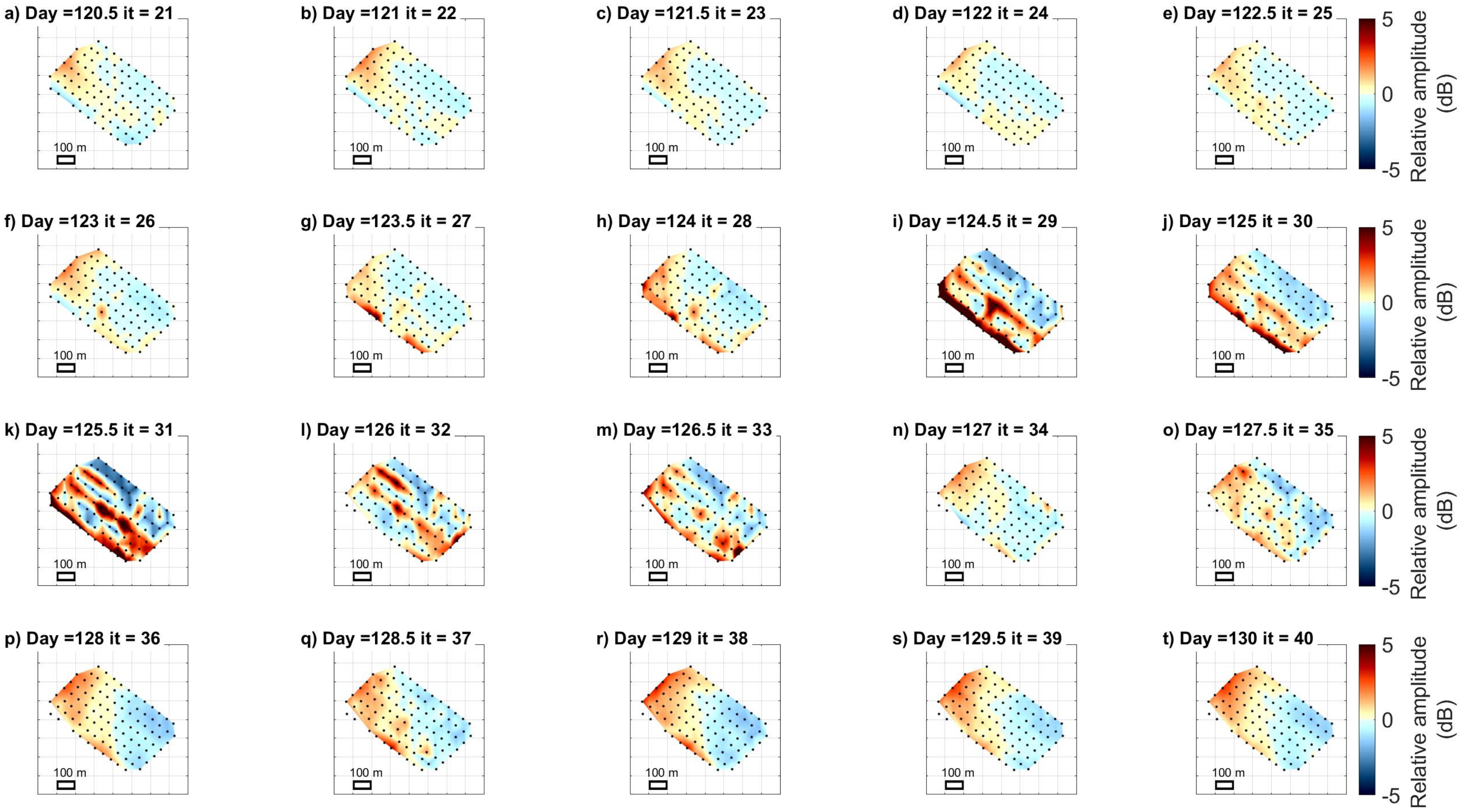
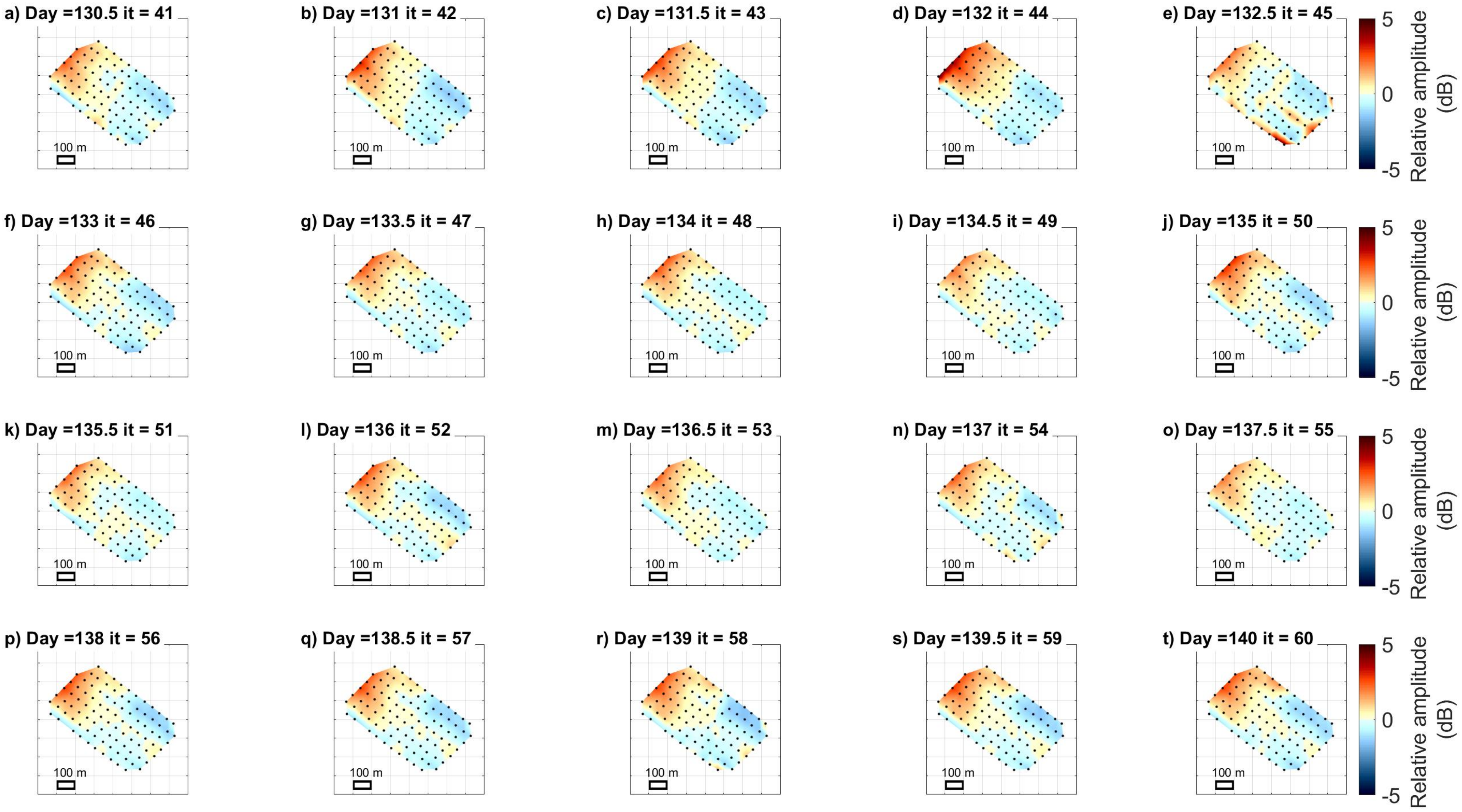
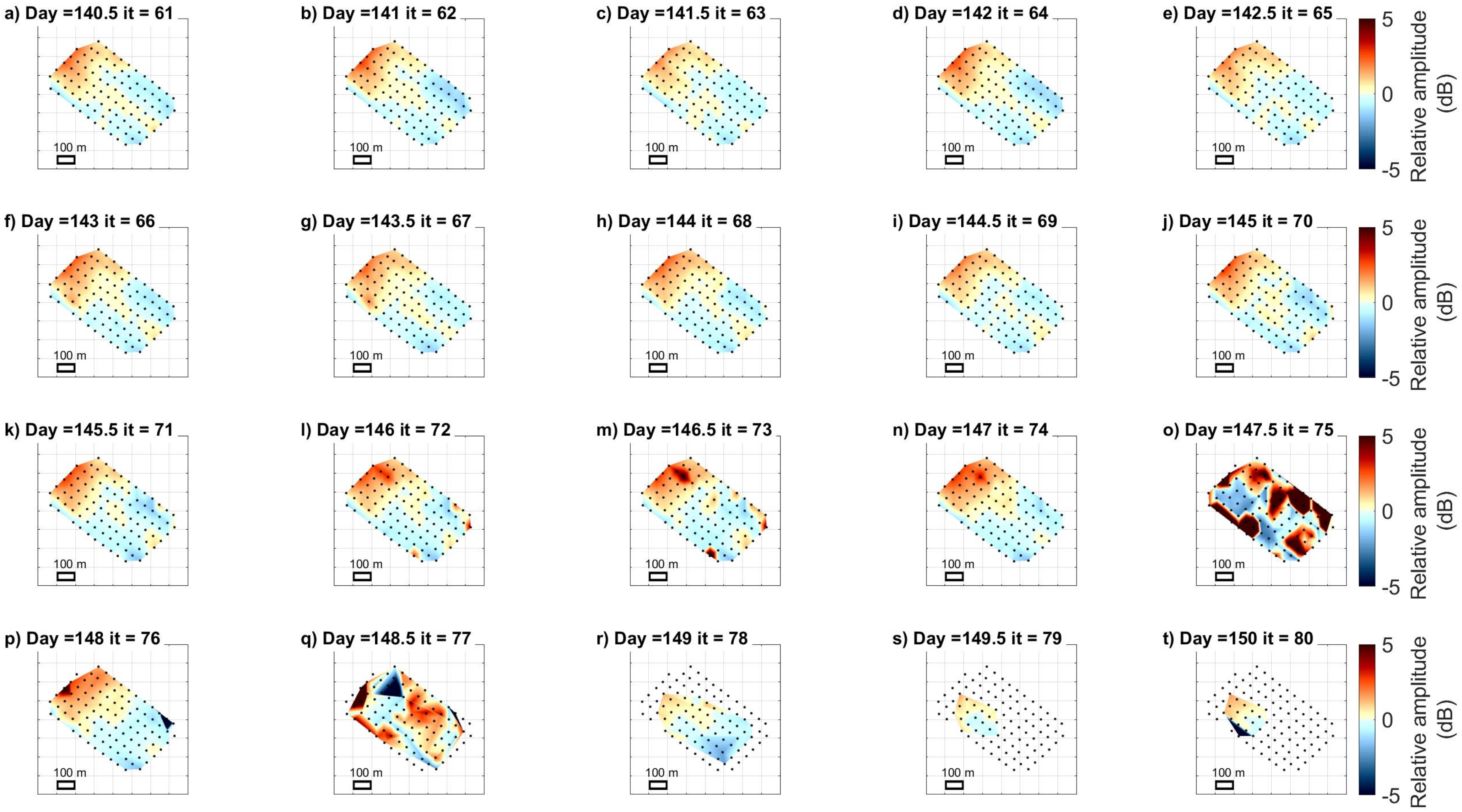
p) Beam [0.16-0.17]
q) Beam [0.17-0.18]
r) Beam [0.18-0.19]
s) Beam [0.19-0.2]
t) Beam [0.2-0.21]
u) Beam [0.21-0.22]
v) Beam [0.22-0.23]
w) Beam [0.23-0.24]
x) Beam [0.24-0.25]


Freq 5
×10
4
2
0
0.1
0.25
0.5
0.75
a) Beam [0.0054-0.01]
b) Beam [0.016-0.021]
c) Beam [0.026-0.031]
d) Beam [0.037-0.042]
e) Beam [0.047-0.052]
f) Beam [0.058-0.062]
g) Beam [0.068-0.073]
h) Beam [0.078-0.083]
i) Beam [0.089-0.094]
j) Beam [0.099-0.1]
k) Beam [0.11-0.11]
l) Beam [0.12-0.12]
m) Beam [0.13-0.14]
n) Beam [0.14-0.15]
o) Beam [0.15-0.16]
p) Beam [0.16-0.17]
q) Beam [0.17-0.18]
r) Beam [0.18-0.19]
s) Beam [0.19-0.2]
t) Beam [0.2-0.21]
u) Beam [0.21-0.22]
v) Beam [0.22-0.23]
w) Beam [0.23-0.24]
x) Beam [0.24-0.25]


a) Day =120.5 it = 21
b) Day =121 it = 22
c) Day =121.5 it = 23
d) Day =122 it = 24
e) Day =122.5 it = 25
f) Day =123 it = 26
g) Day =123.5 it = 27
h) Day =124 it = 28
i) Day =124.5 it = 29
j) Day =125 it = 30
k) Day =125.5 it = 31
l) Day =126 it = 32
m) Day =126.5 it = 33
n) Day =127 it = 34
o) Day =127.5 it = 35
p) Day =128 it = 36
q) Day =128.5 it = 37
r) Day =129 it = 38
s) Day =129.5 it = 39
t) Day =130 it = 40
100 m
Relative amplitude (dB)
5
0
-5


a) Day =130.5 it = 41
b) Day =131 it = 42
c) Day =131.5 it = 43
d) Day =132 it = 44
e) Day =132.5 it = 45
f) Day =133 it = 46
g) Day =133.5 it = 47
h) Day =134 it = 48
i) Day =134.5 it = 49
j) Day =135 it = 50
k) Day =135.5 it = 51
l) Day =136 it = 52
m) Day =136.5 it = 53
n) Day =137 it = 54
o) Day =137.5 it = 55
p) Day =138 it = 56
q) Day =138.5 it = 57
r) Day =139 it = 58
s) Day =139.5 it = 59
t) Day =140 it = 60
100 m
Relative amplitude (dB)
5
0
-5


a) Day =140.5 it = 61
b) Day =141 it = 62
c) Day =141.5 it = 63
d) Day =142 it = 64
e) Day =142.5 it = 65
f) Day =143 it = 66
g) Day =143.5 it = 67
h) Day =144 it = 68
i) Day =144.5 it = 69
j) Day =145 it = 70
k) Day =145.5 it = 71
l) Day =146 it = 72
m) Day =146.5 it = 73
n) Day =147 it = 74
o) Day =147.5 it = 75
p) Day =148 it = 76
q) Day =148.5 it = 77
r) Day =149 it = 78
s) Day =149.5 it = 79
t) Day =150 it = 80
100 m
Relative amplitude (dB)
5
0
-5

Deriving seismic power – discharge scalings

From (Gimbert et al., 2016)

- Noise power from turbulent flow scales as $P_w \propto \zeta W u_*^{14/3}$
  - with $\zeta = \left(\frac{H}{k_s}\right)$, k_s the wall roughness and H the flow depth
  - and u_* the shear velocity and W the river width

For subglacial channels we assume:

- Uniform pressure fluctuations along the walls
  - so $W = \Gamma$ the wetted perimeter
- $H \ll k_s$ so we can neglect variations in ζ
- Subglacial channel flow is steady and uniform at large scale
  - so $u_* = \sqrt{gRS}$
  - with $R = \frac{A}{\Gamma}$ the Hydraulic radius and $S = -\frac{1}{\rho g}\frac{\partial p}{\partial x} + \tan\theta$ the pressure gradient

Deriving seismic power – discharge scalings

From (Gimbert et al., 2016)

- We then define the flow discharge as $Q = AU$
  - with $U = \frac{R^{2/3}S^{1/2}}{n}$ the Manning's formulation

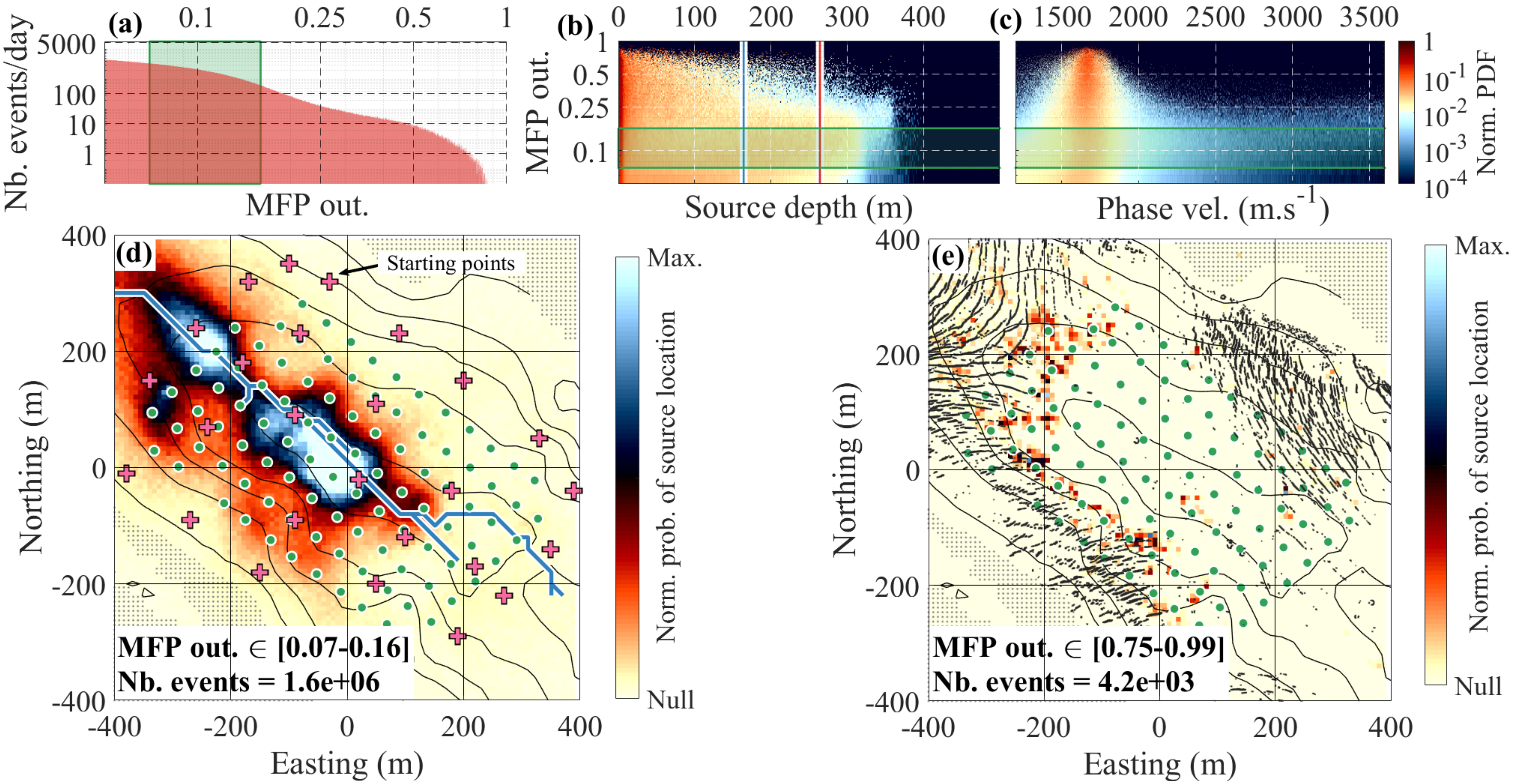
- Noise power becomes: $P_w \propto \Gamma R^{7/3} S^{7/3}$ and $Q \propto AR^{2/3}S^{1/2}$

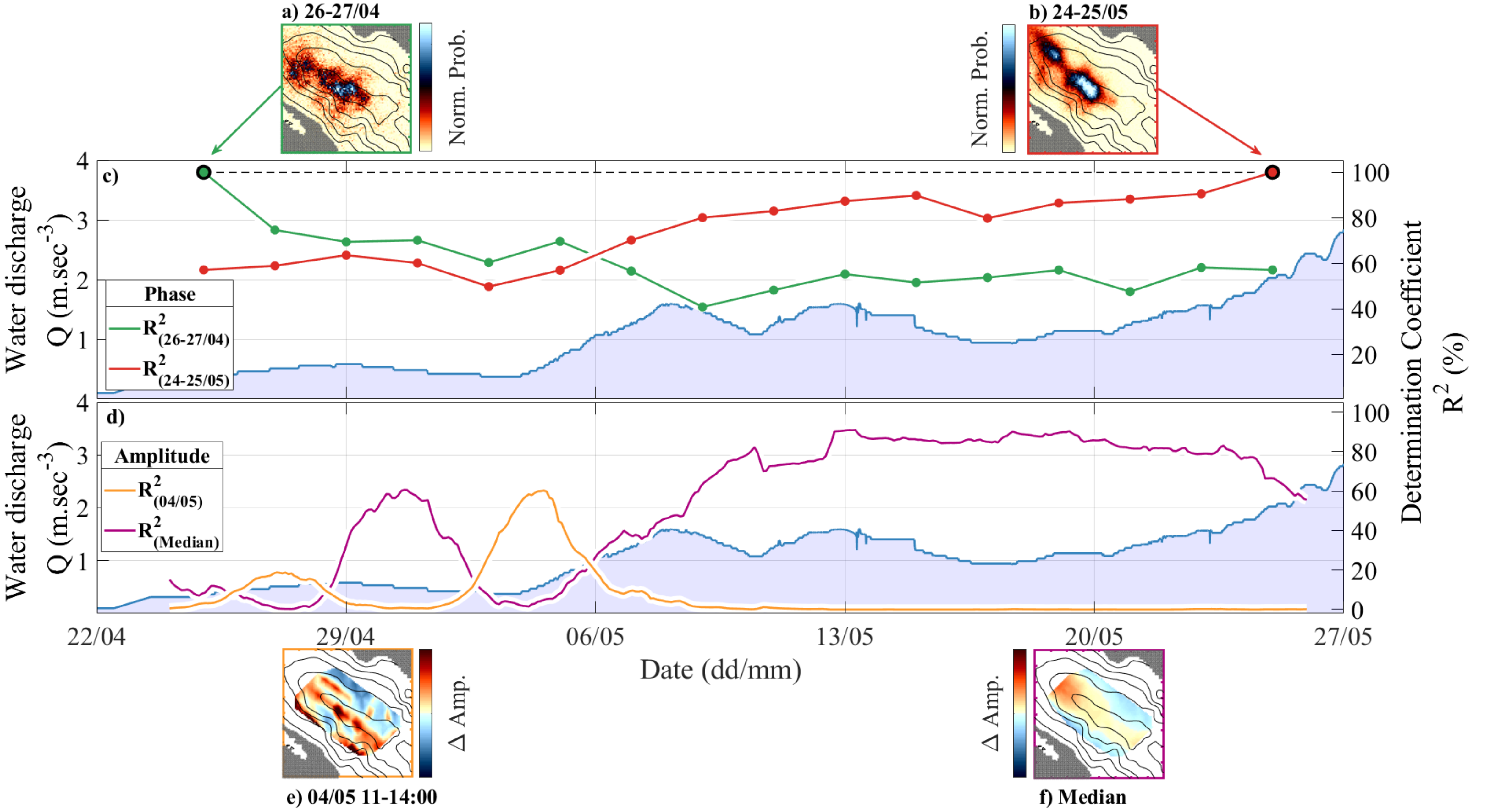
- Defining β the shape function with $\Gamma = \beta R$ and $A = \beta R^2$ we can define:

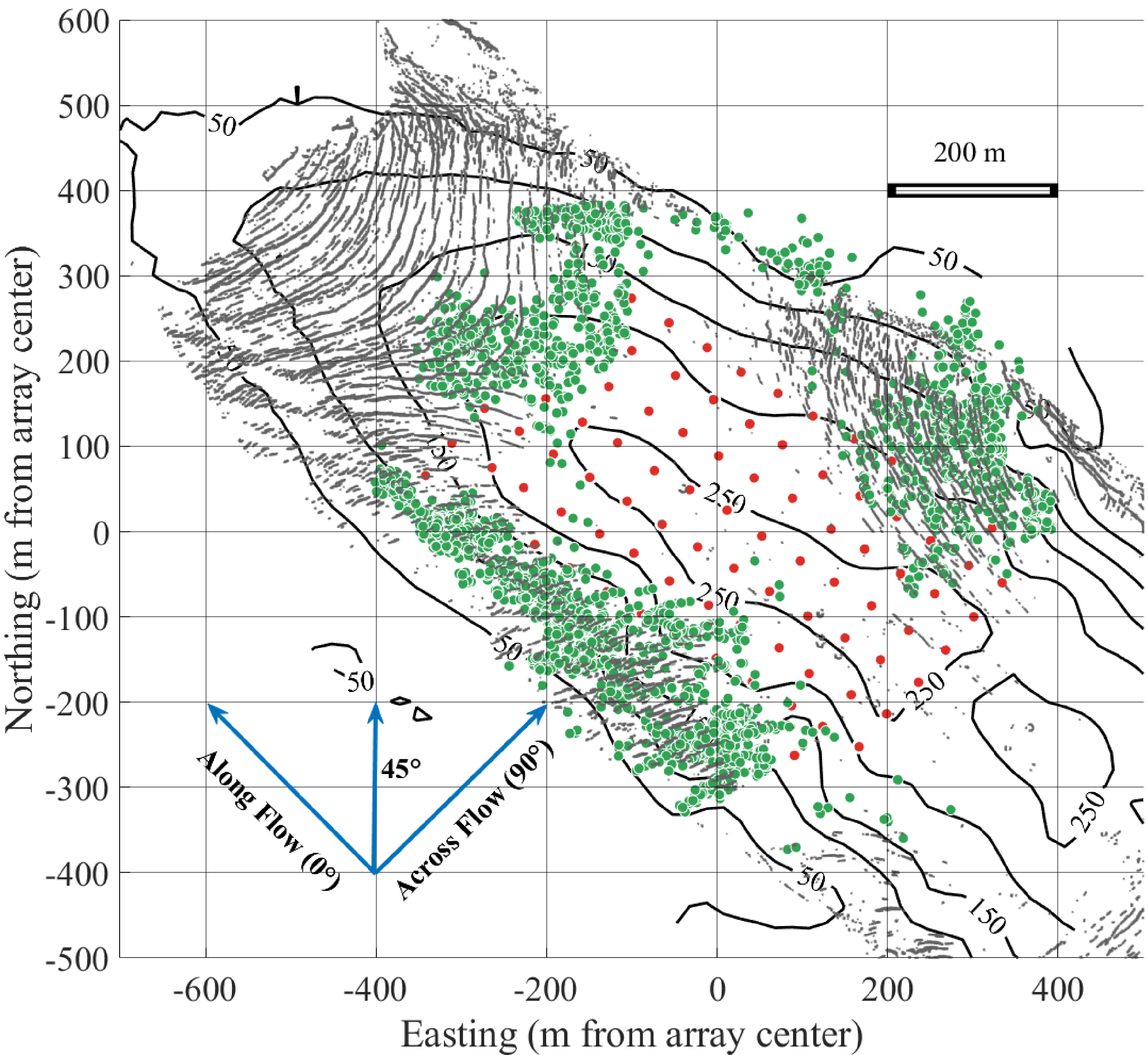
$$P_w \propto \beta^{-11/3} R^{-82/9} Q^{14/3}$$
$$P_w \propto \beta^{-1/4} S^{41/24} Q^{5/4}$$

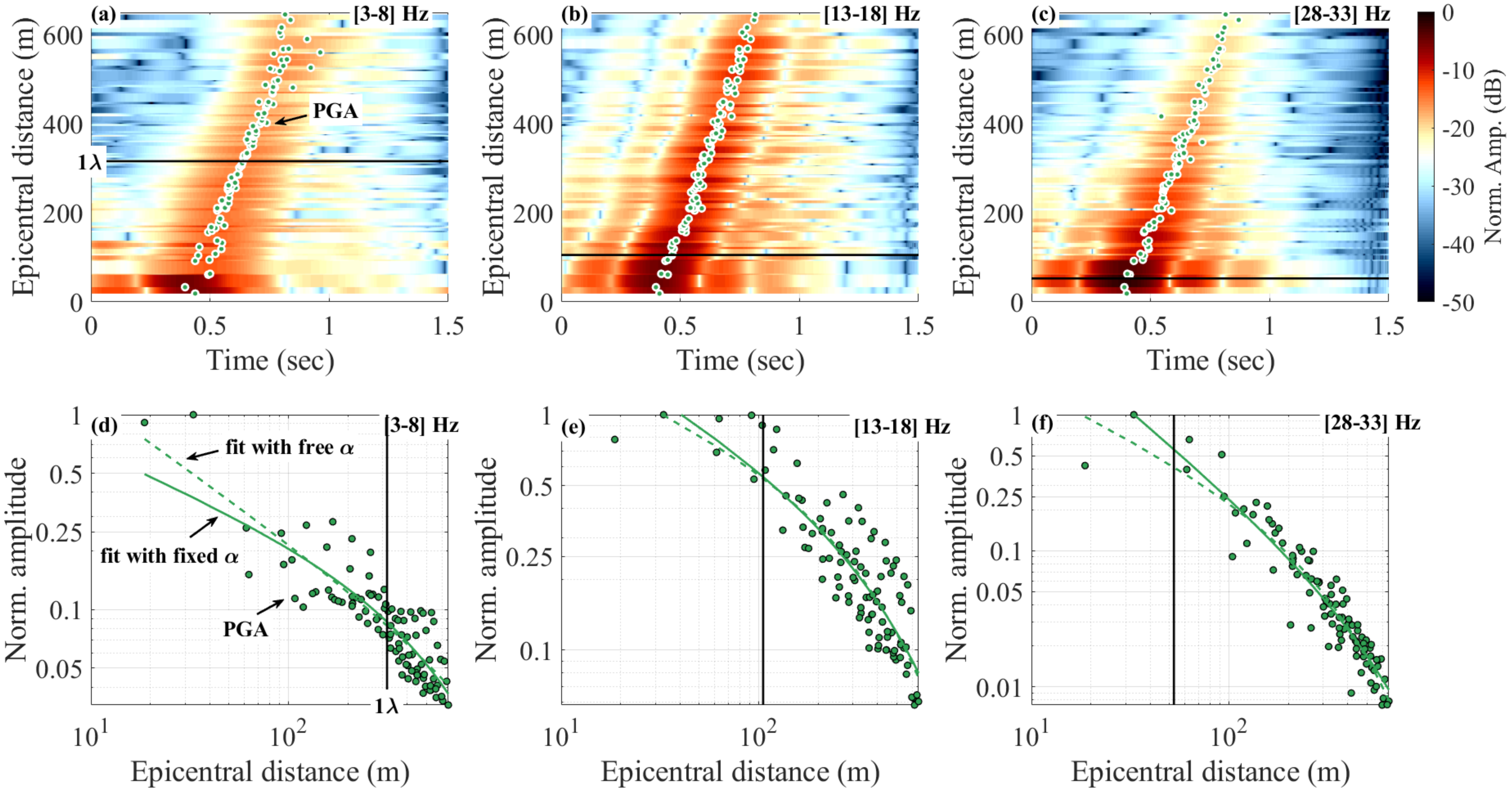
→

$$P_w \propto Q^{14/3}$$
$$P_w \propto Q^{5/4}$$

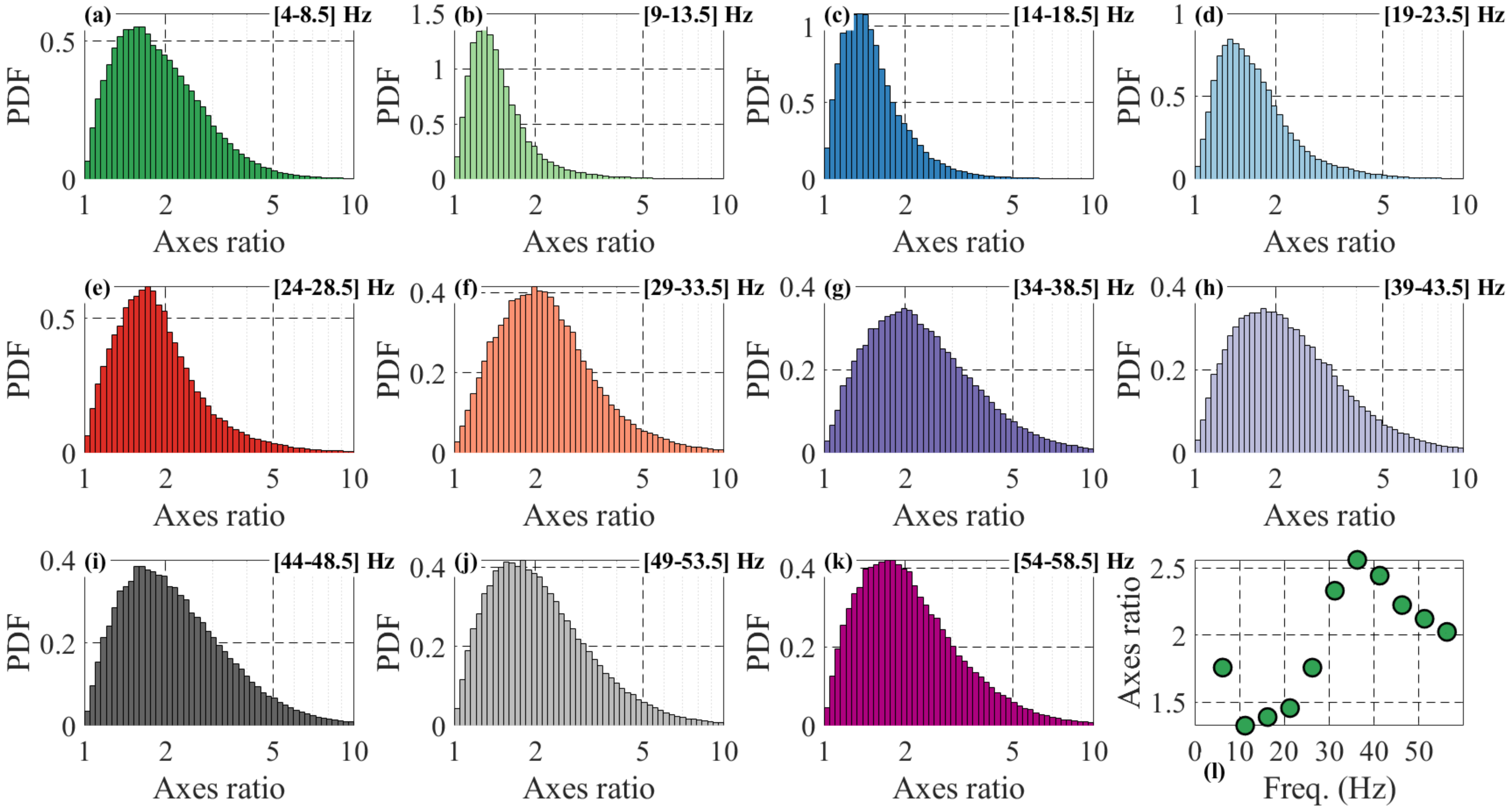

(a)
0.1
0.25
0.5
1
Nb. events/day
5000
100
10
1
MFP out.
(b)
0
100
200
300
400
MFP out.
1
0.5
0.25
0.1
Source depth (m)
(c)
1500
2000
2500
3000
3500
Phase vel. (m.s^{-1})
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Norm. PDF
(d)
Starting points
Northing (m)
400
200
0
-200
-400
Easting (m)
-400
-200
0
200
400
MFP out. ∈ [0.07-0.16]
Nb. events = 1.6e+06
Max.
Null
Norm. prob. of source location
(e)
Northing (m)
Easting (m)
MFP out. ∈ [0.75-0.99]
Nb. events = 4.2e+03
Max.
Null
Norm. prob. of source location


a) 26-27/04
Norm. Prob.
b) 24-25/05
Norm. Prob.
c)
Phase
$R^2_{(26-27/04)}$
$R^2_{(24-25/05)}$
d)
Amplitude
$R^2_{(04/05)}$
$R^2_{(Median)}$
Water discharge Q (m.sec^{-3})
Determination Coefficient R^2 (%)
22/04
29/04
06/05
13/05
20/05
27/05
Date (dd/mm)
Δ Amp.
e) 04/05 11-14:00
Δ Amp.
f) Median

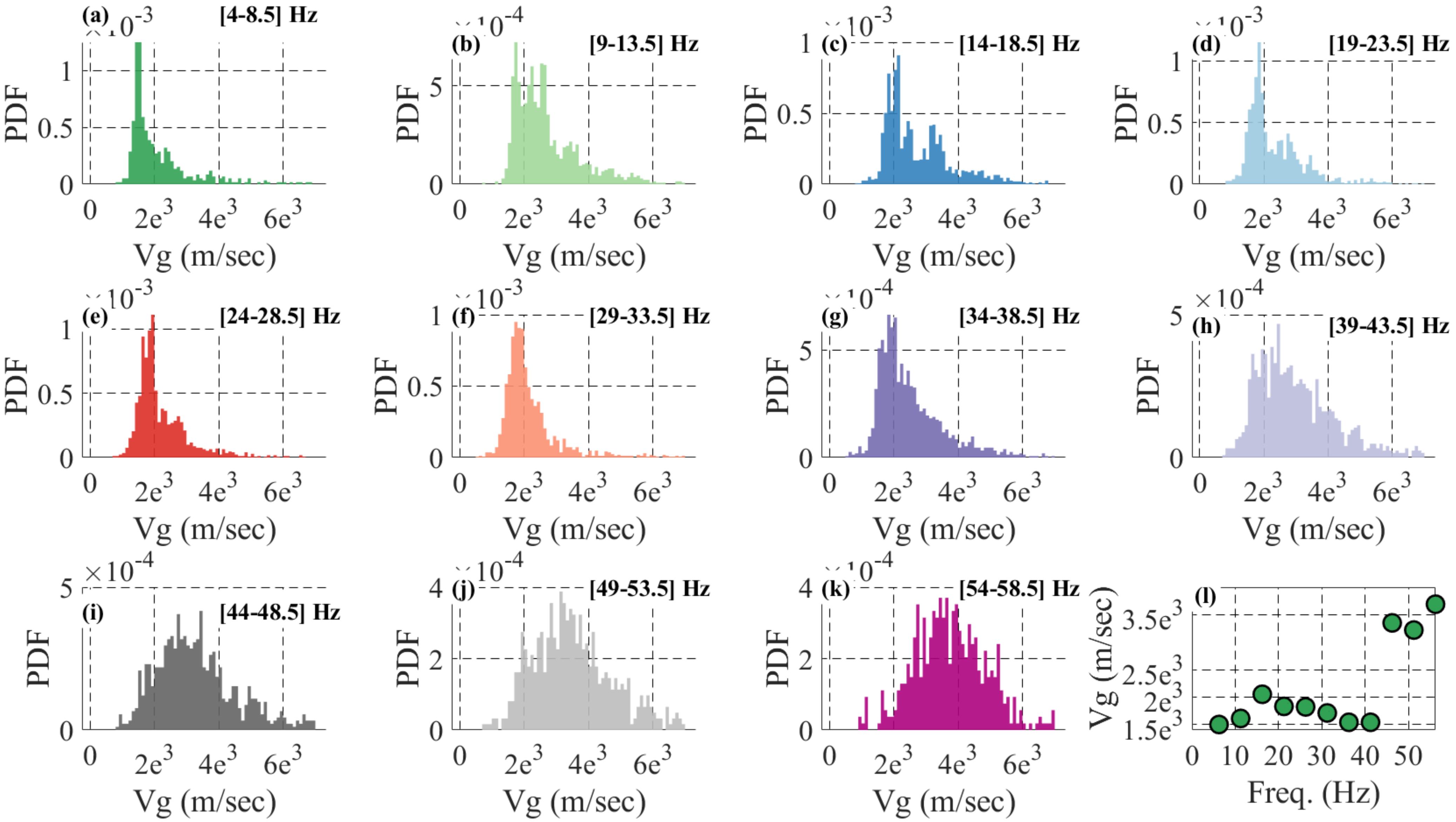

Northing (m from array center)
Easting (m from array center)
200 m
Along Flow (0°)
45°
Across Flow (90°)
50
150
250
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-400
-200
0
200
400



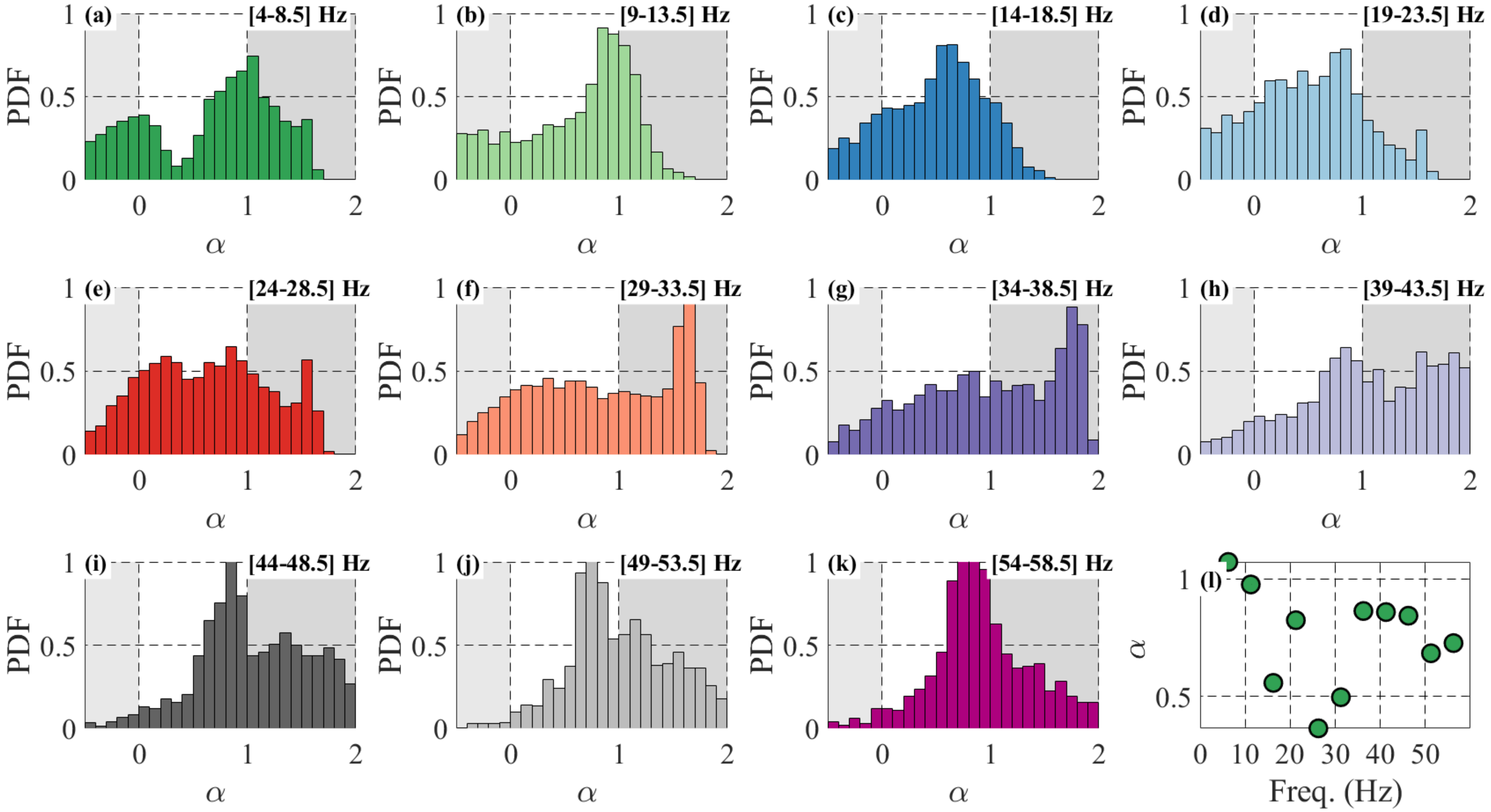
(a)
[3-8] Hz
(b)
[13-18] Hz
(c)
[28-33] Hz
Epicentral distance (m)
Time (sec)
PGA
1λ
Norm. Amp. (dB)
(d)
(e)
(f)
fit with free α
fit with fixed α
Norm. amplitude
Epicentral distance (m)



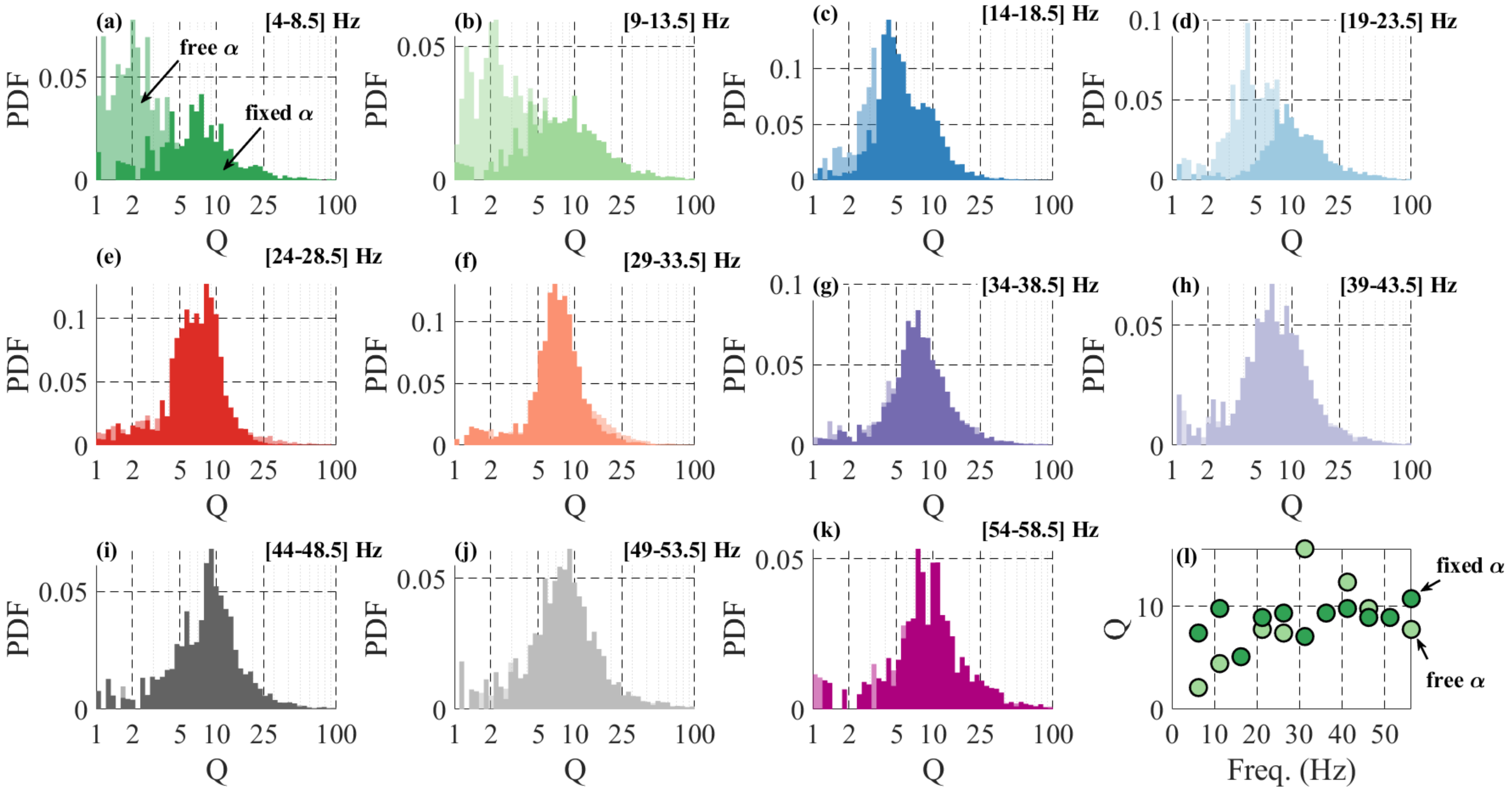
(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
(l)
PDF
Axes ratio
Freq. (Hz)

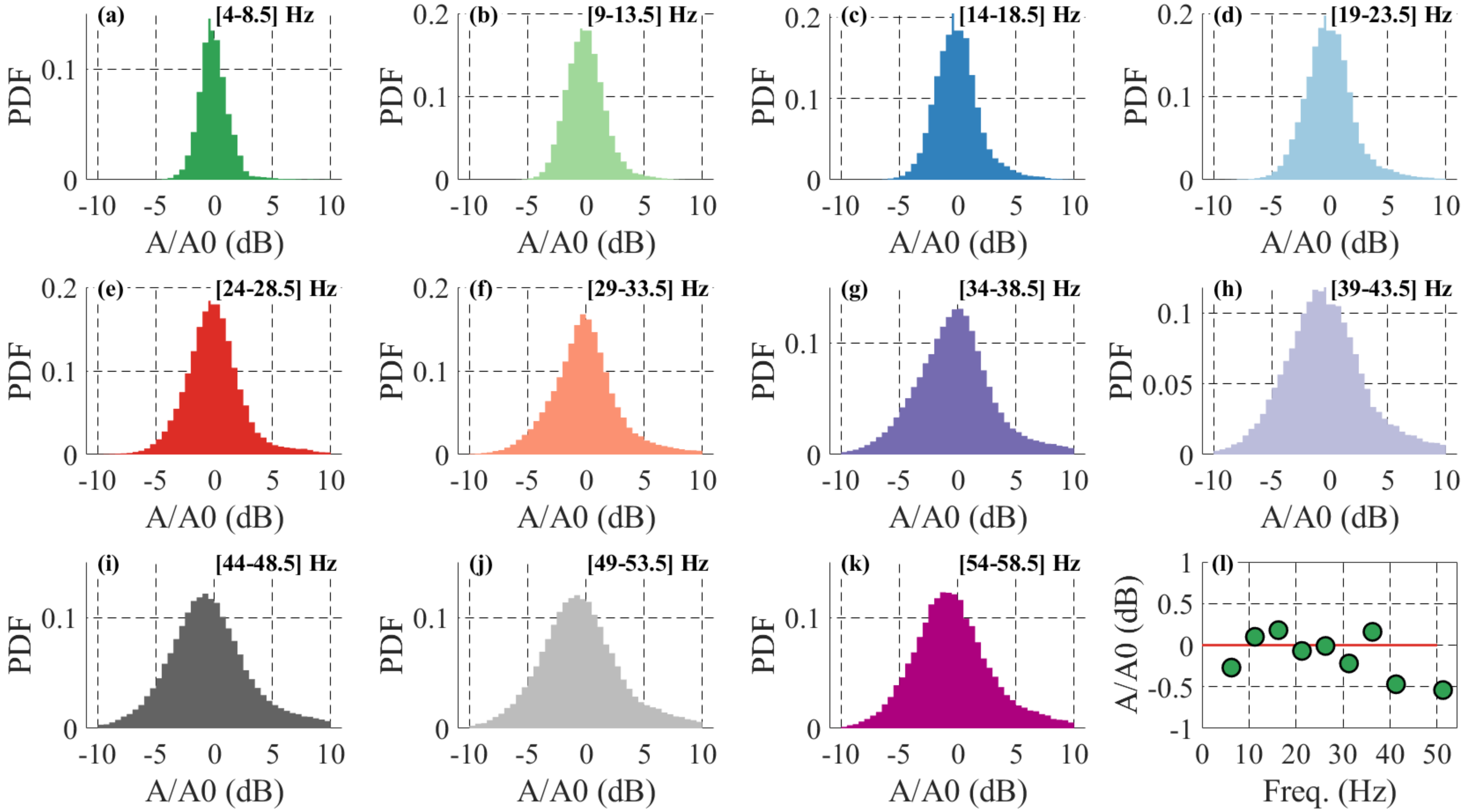


(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
(l)
PDF
Vg (m/sec)
0
2e3
4e3
6e3
Freq. (Hz)
10
20
30
40
50
1.5e3
2e3
2.5e3
3.5e3

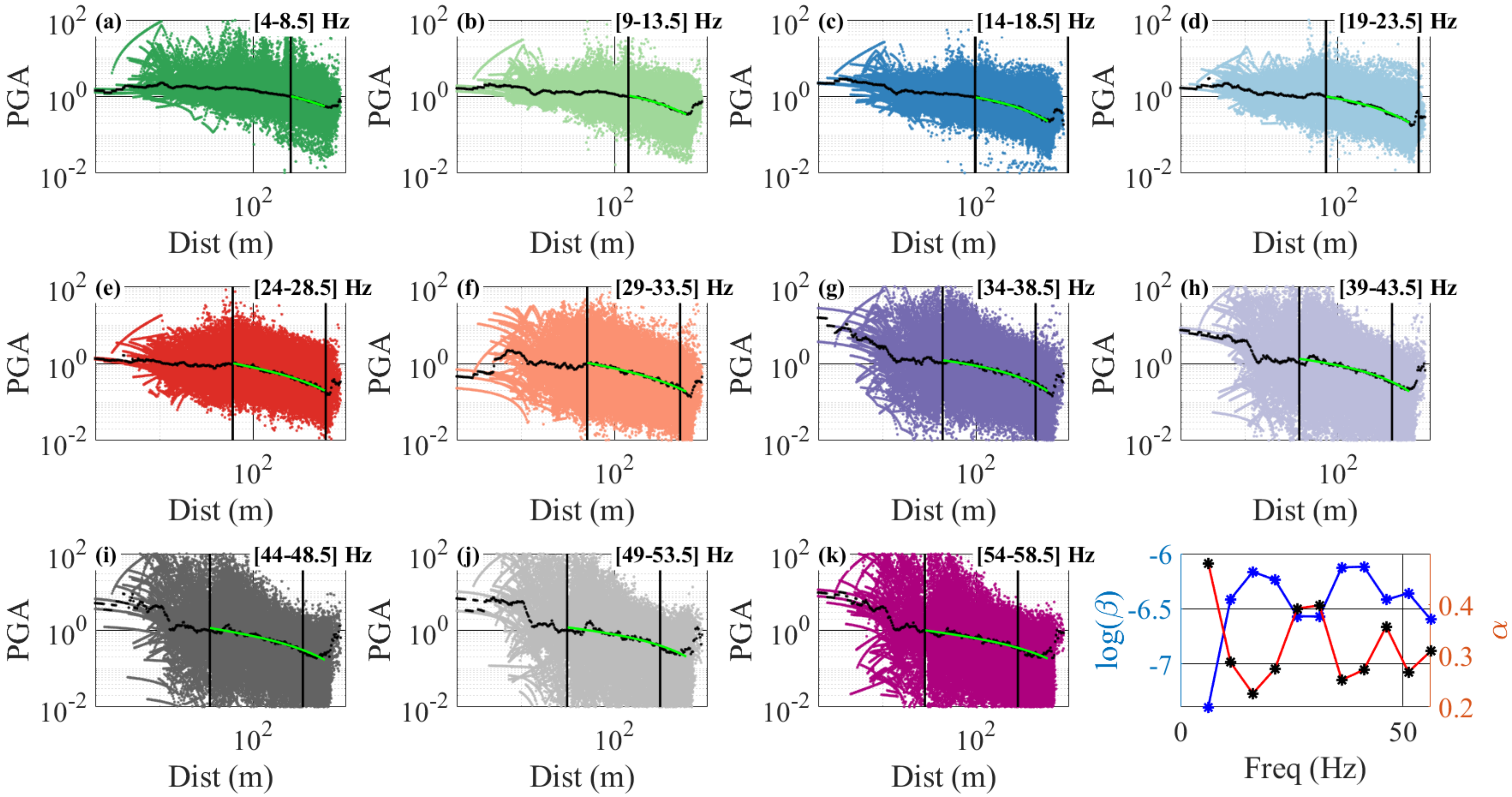


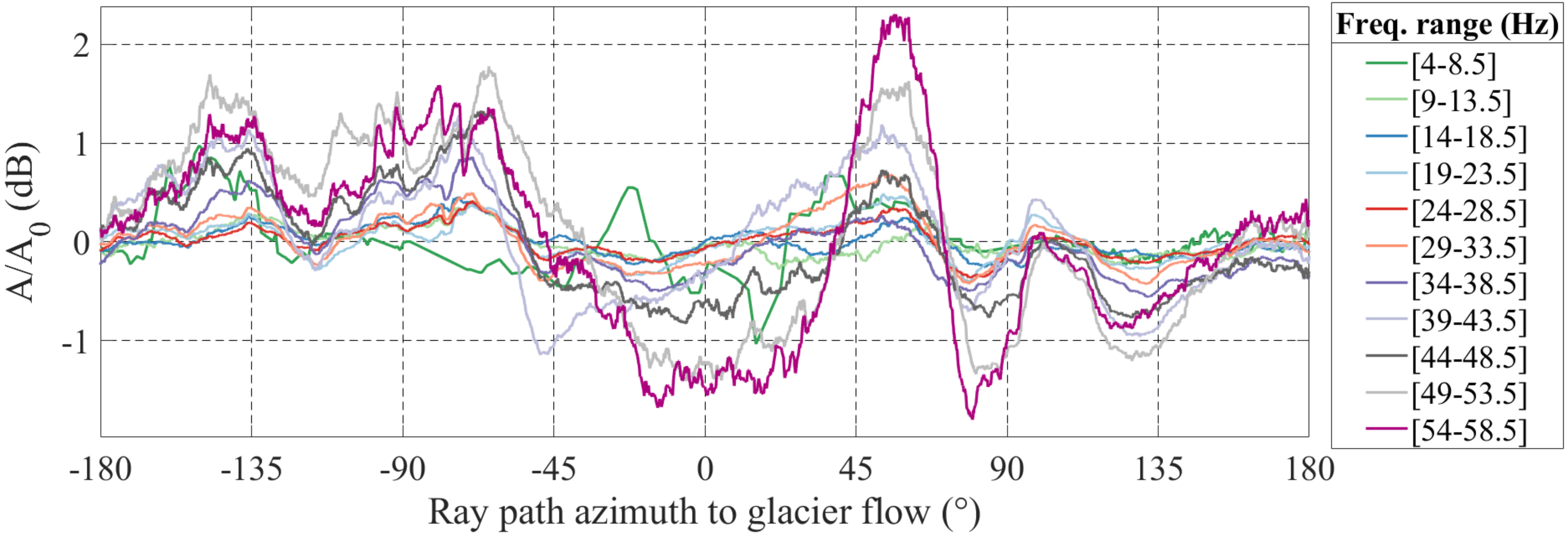
(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
(l)
PDF
α
Freq. (Hz)


(a)
[4-8.5] Hz
free α
fixed α
(b)
[9-13.5] Hz
(c)
[14-18.5] Hz
(d)
[19-23.5] Hz
(e)
[24-28.5] Hz
(f)
[29-33.5] Hz
(g)
[34-38.5] Hz
(h)
[39-43.5] Hz
(i)
[44-48.5] Hz
(j)
[49-53.5] Hz
(k)
[54-58.5] Hz
(l)
fixed α
free α
PDF
Q
Freq. (Hz)

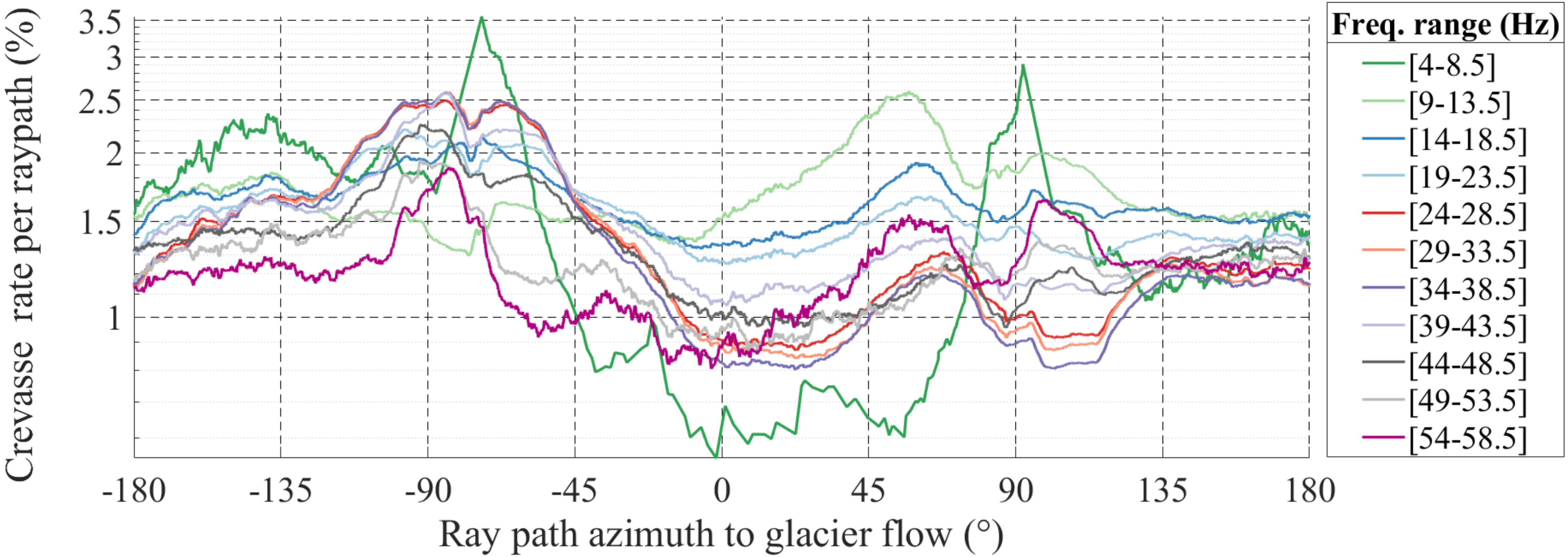


(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
(l)
PDF
A/A0 (dB)
Freq. (Hz)

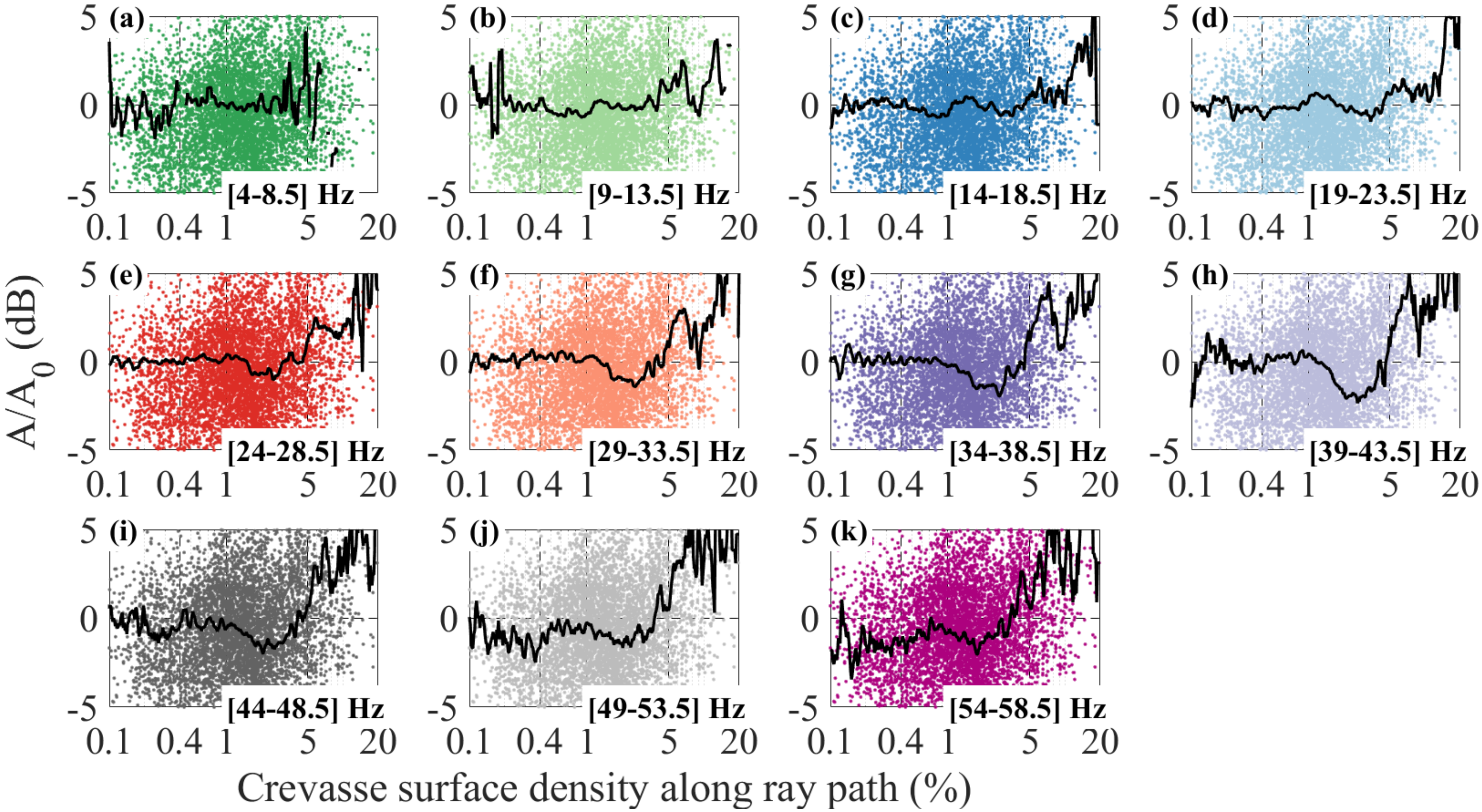

(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
PGA
Dist (m)
10^{2}
10^{0}
10^{-2}
$\log(\beta)$
α
Freq (Hz)
-6
-6.5
-7
0.4
0.3
0.2
0
50



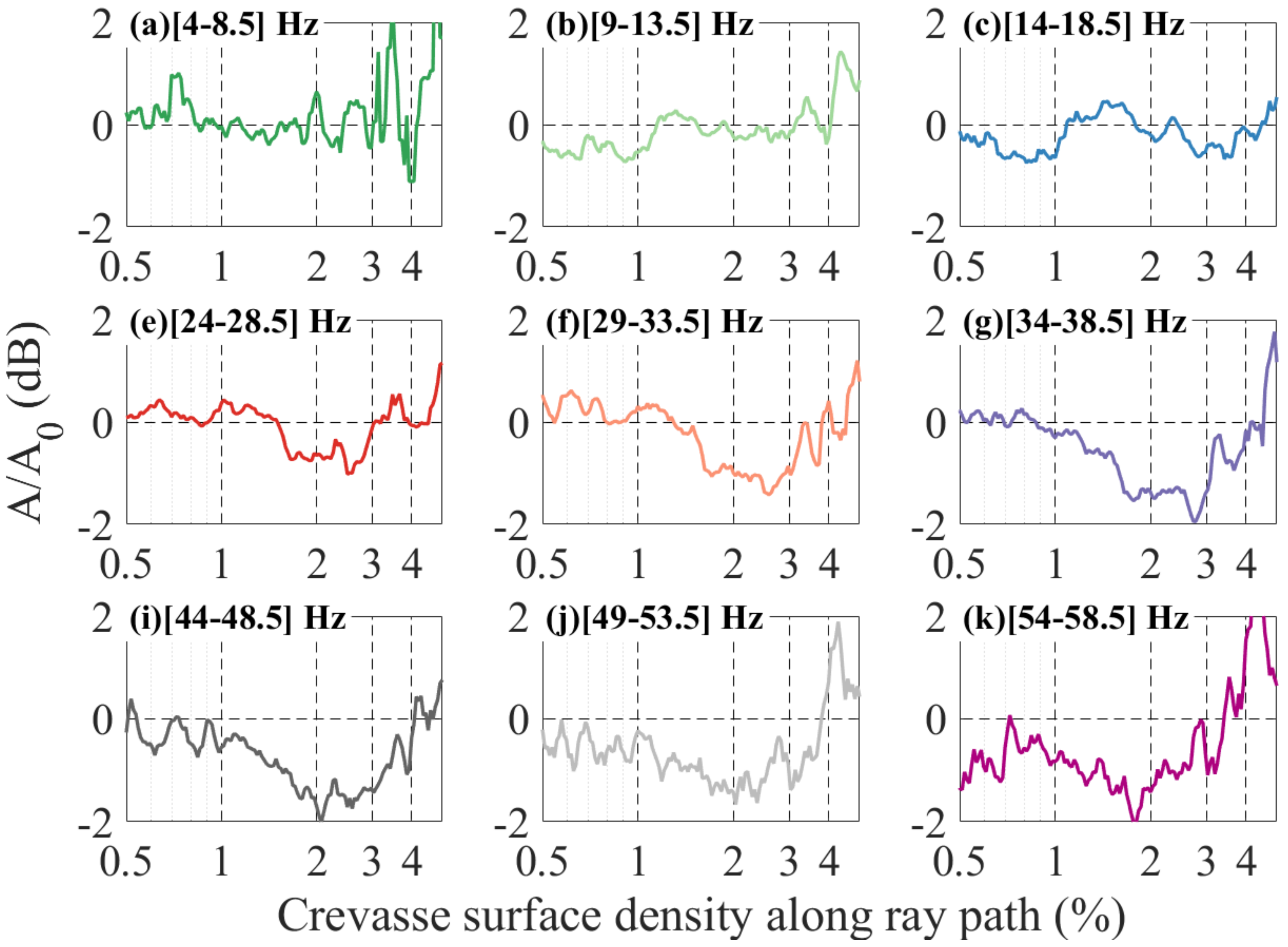
A/A0 (dB)
2
1
0
-1
-180
-135
-90
-45
0
45
90
135
180
Ray path azimuth to glacier flow (°)
Freq. range (Hz)
[4-8.5]
[9-13.5]
[14-18.5]
[19-23.5]
[24-28.5]
[29-33.5]
[34-38.5]
[39-43.5]
[44-48.5]
[49-53.5]
[54-58.5]



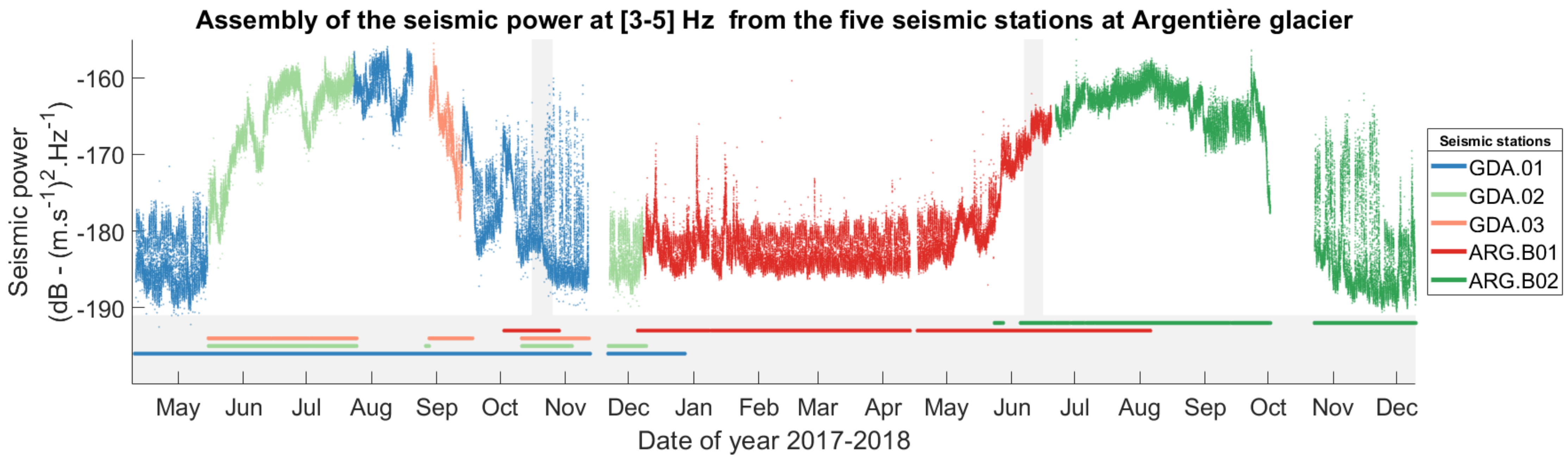
Crevasse rate per raypath (%)
3.5
3
2.5
2
1.5
1
-180
-135
-90
-45
0
45
90
135
180
Ray path azimuth to glacier flow (°)
Freq. range (Hz)
[4-8.5]
[9-13.5]
[14-18.5]
[19-23.5]
[24-28.5]
[29-33.5]
[34-38.5]
[39-43.5]
[44-48.5]
[49-53.5]
[54-58.5]

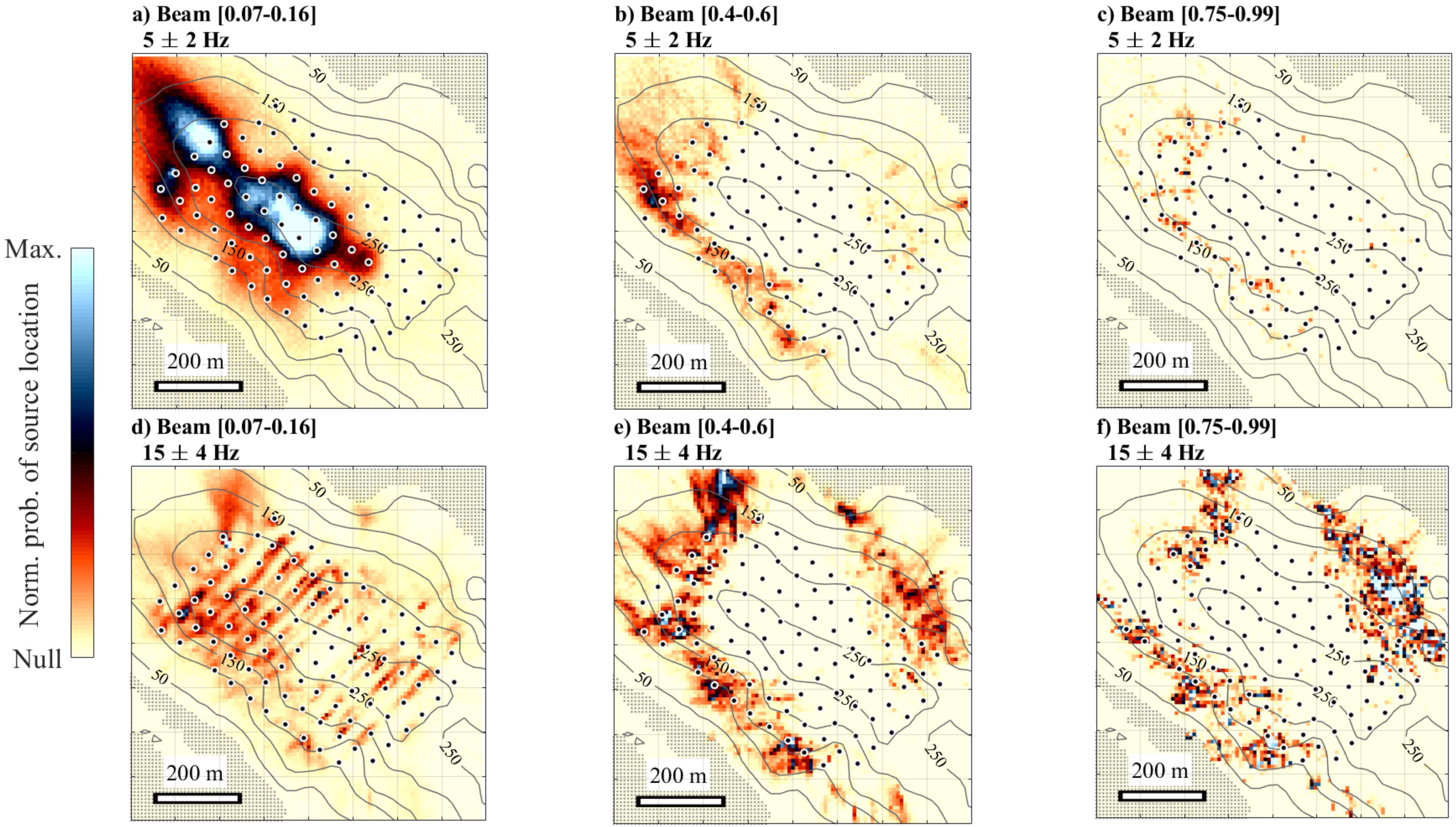


(a)
[4-8.5] Hz
(b)
[9-13.5] Hz
(c)
[14-18.5] Hz
(d)
[19-23.5] Hz
(e)
[24-28.5] Hz
(f)
[29-33.5] Hz
(g)
[34-38.5] Hz
(h)
[39-43.5] Hz
(i)
[44-48.5] Hz
(j)
[49-53.5] Hz
(k)
[54-58.5] Hz
5
0
-5
0.1 0.4 1 5 20
A/A0 (dB)
Crevasse surface density along ray path (%)

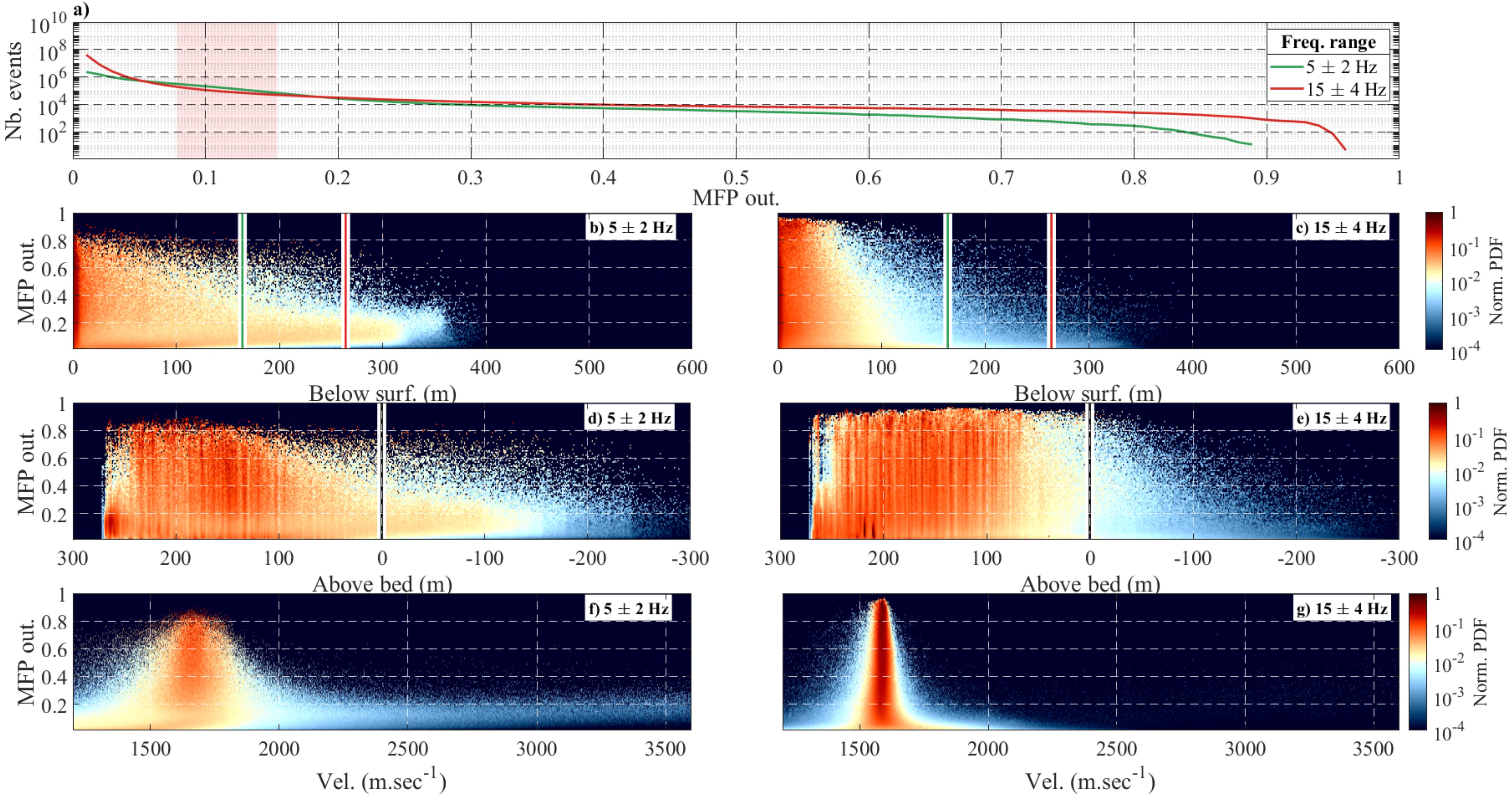


(a)[4-8.5] Hz
(b)[9-13.5] Hz
(c)[14-18.5] Hz
(d)[19-23.5] Hz
(e)[24-28.5] Hz
(f)[29-33.5] Hz
(g)[34-38.5] Hz
(h)[39-43.5] Hz
(i)[44-48.5] Hz
(j)[49-53.5] Hz
(k)[54-58.5] Hz
2
0
-2
0.5
1
2
3
4
A/A0 (dB)
Crevasse surface density along ray path (%)

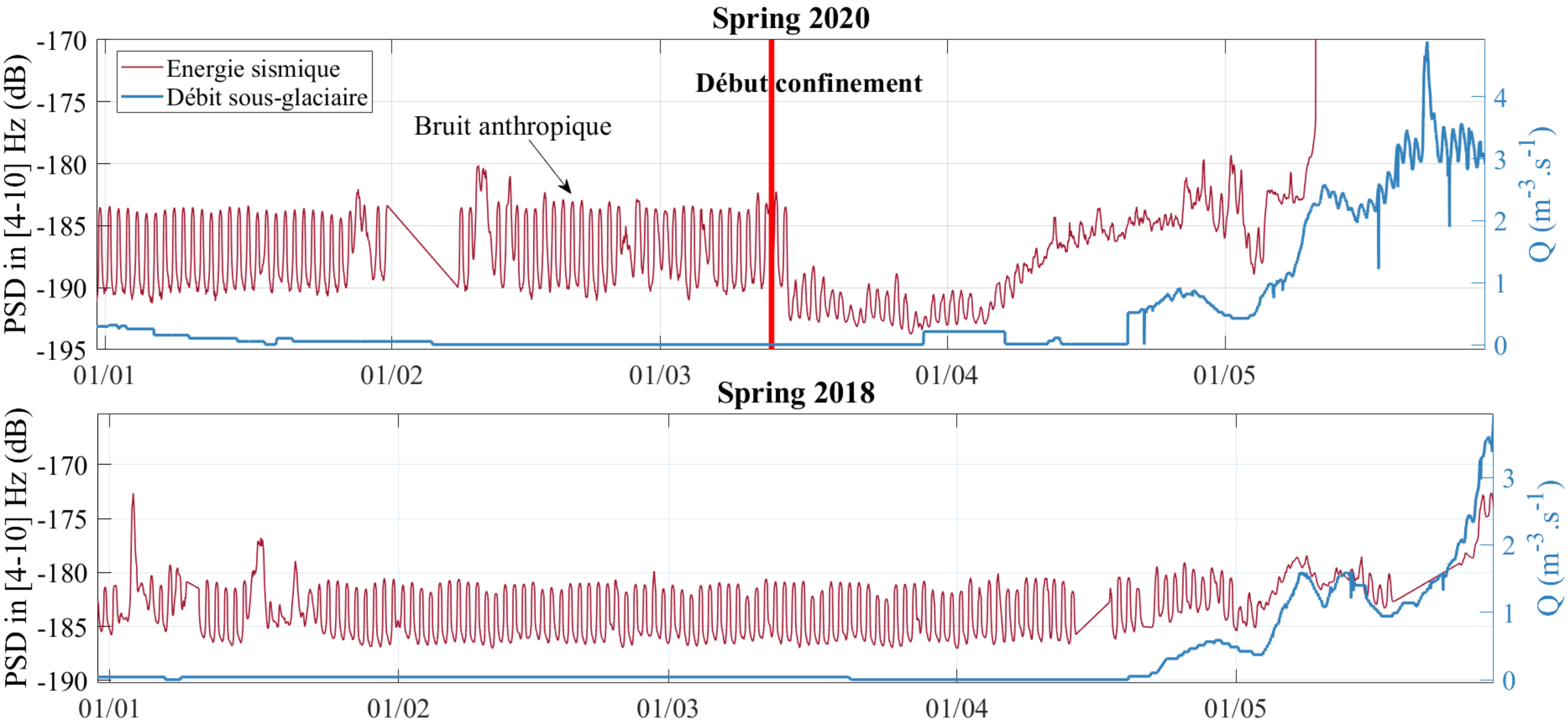

Assembly of the seismic power at [3-5] Hz from the five seismic stations at Argentière glacier
Seismic power
(dB - (m.s-1)2.Hz-1)
-160
-170
-180
-190
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Date of year 2017-2018
Seismic stations
GDA.01
GDA.02
GDA.03
ARG.B01
ARG.B02



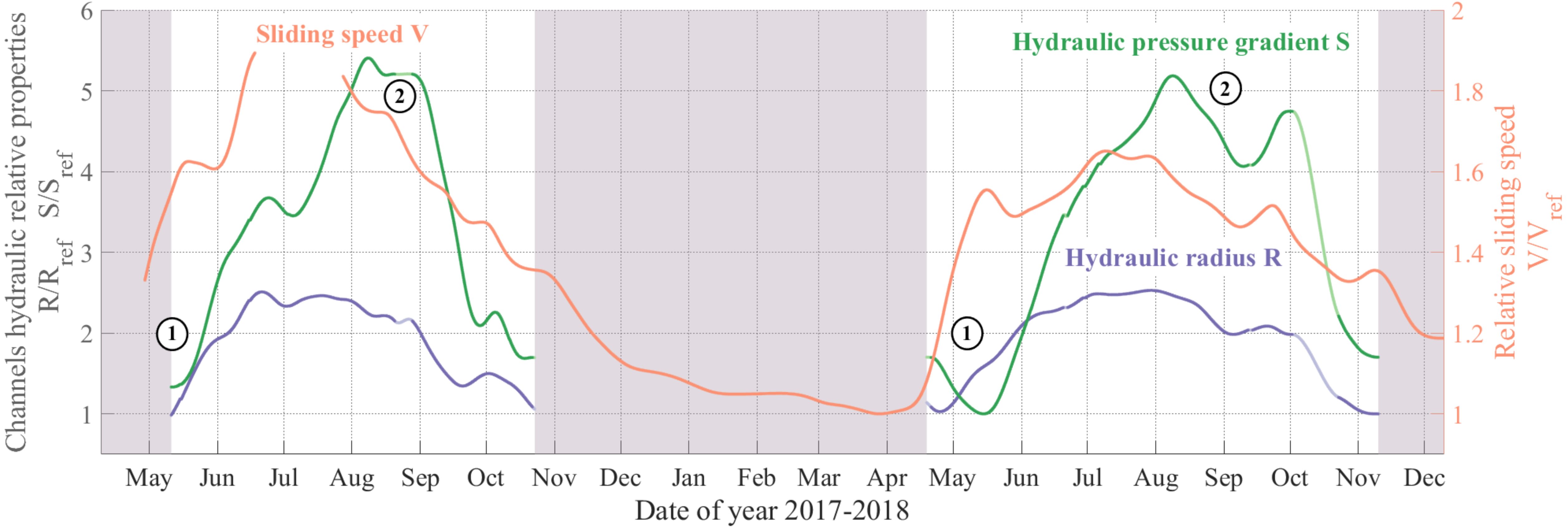
a) Beam [0.07-0.16]
5 ± 2 Hz
b) Beam [0.4-0.6]
5 ± 2 Hz
c) Beam [0.75-0.99]
5 ± 2 Hz
d) Beam [0.07-0.16]
15 ± 4 Hz
e) Beam [0.4-0.6]
15 ± 4 Hz
f) Beam [0.75-0.99]
15 ± 4 Hz
Max.
Norm. prob. of source location
Null
200 m
50
150
250



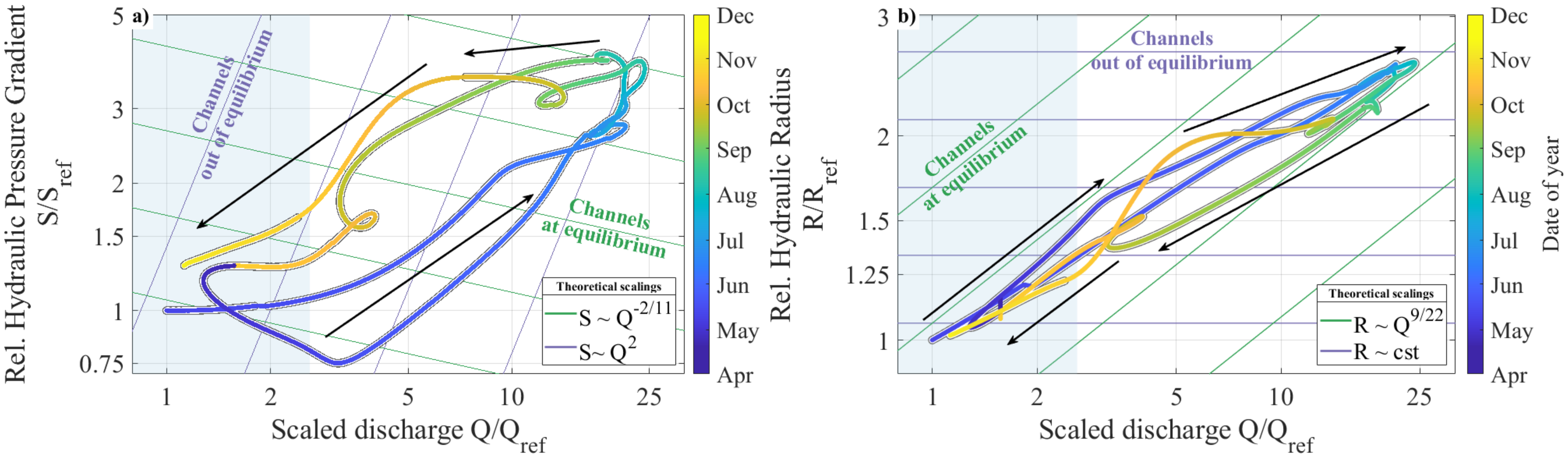
a)
Nb. events
MFP out.
Freq. range
5 ± 2 Hz
15 ± 4 Hz
b) 5 ± 2 Hz
c) 15 ± 4 Hz
Below surf. (m)
d) 5 ± 2 Hz
e) 15 ± 4 Hz
Above bed (m)
f) 5 ± 2 Hz
g) 15 ± 4 Hz
Vel. (m.sec-1)
Norm. PDF

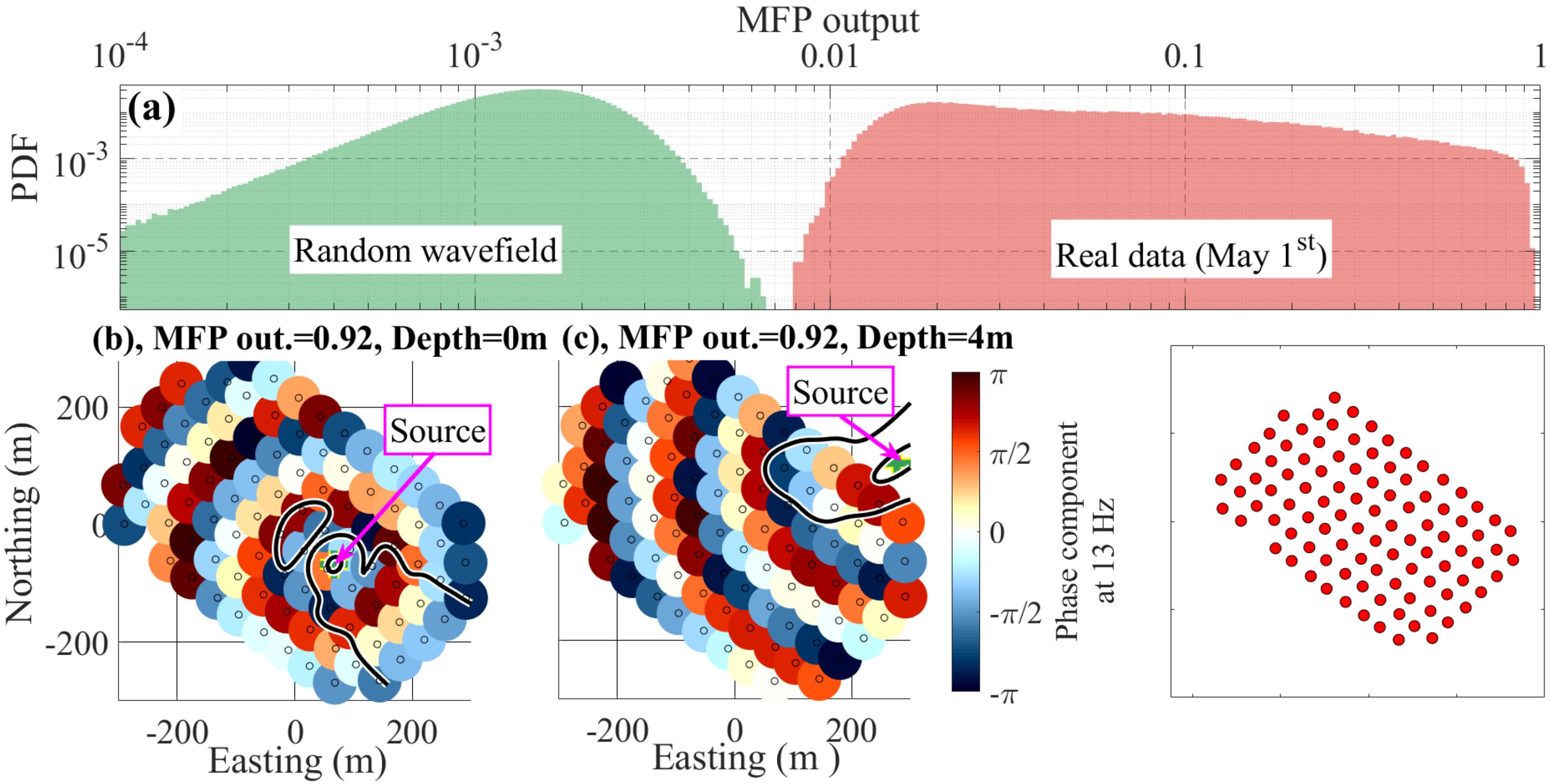


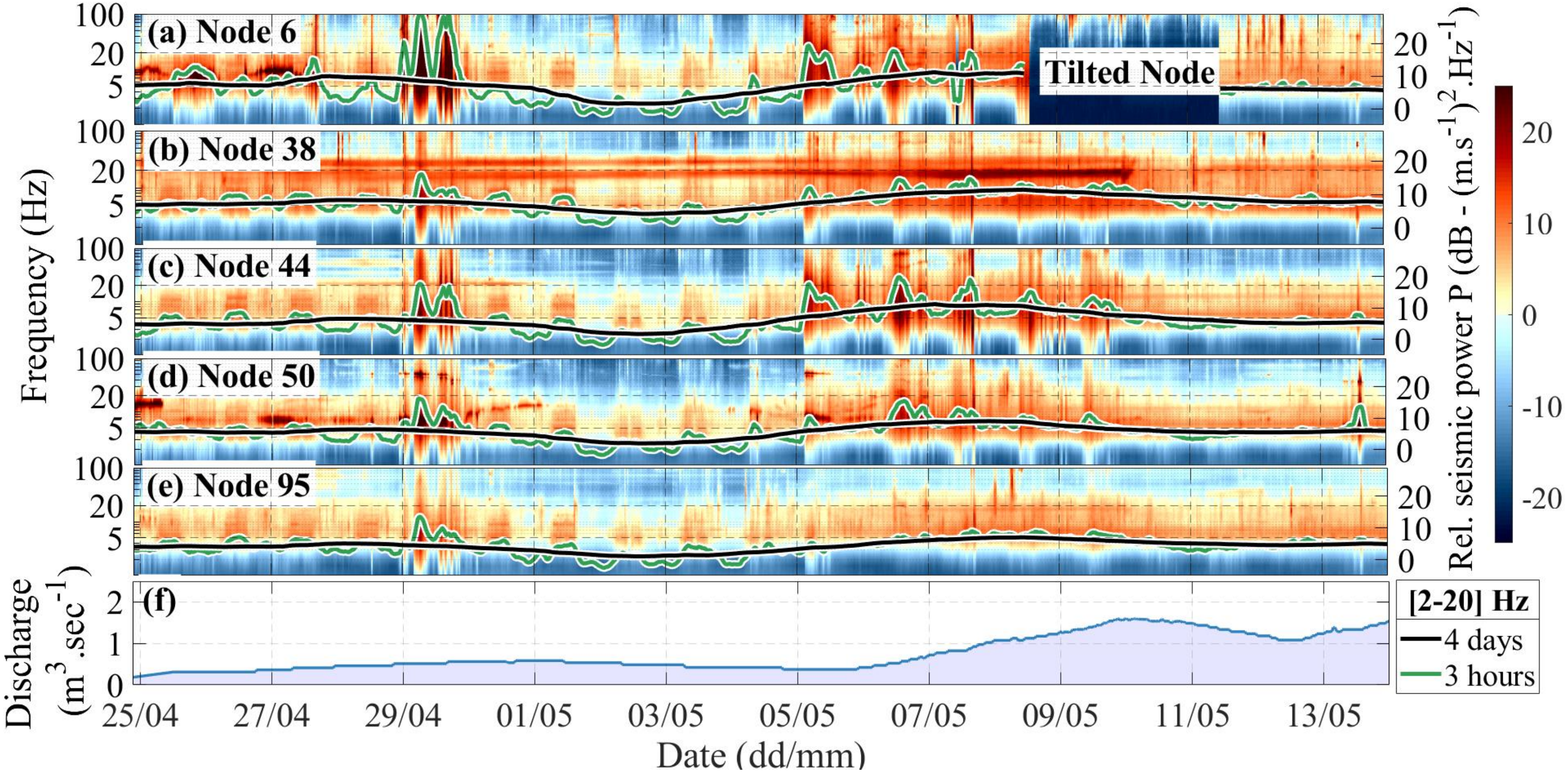
Spring 2020
Energie sismique
Débit sous-glaciaire
Début confinement
Bruit anthropique
PSD in [4-10] Hz (dB)
-170
-175
-180
-185
-190
-195
Q (m-3.s-1)
4
3
2
1
0
01/01
01/02
01/03
01/04
01/05
Spring 2018
PSD in [4-10] Hz (dB)
-170
-175
-180
-185
-190
Q (m-3.s-1)
3
2
1
0
01/01
01/02
01/03
01/04
01/05

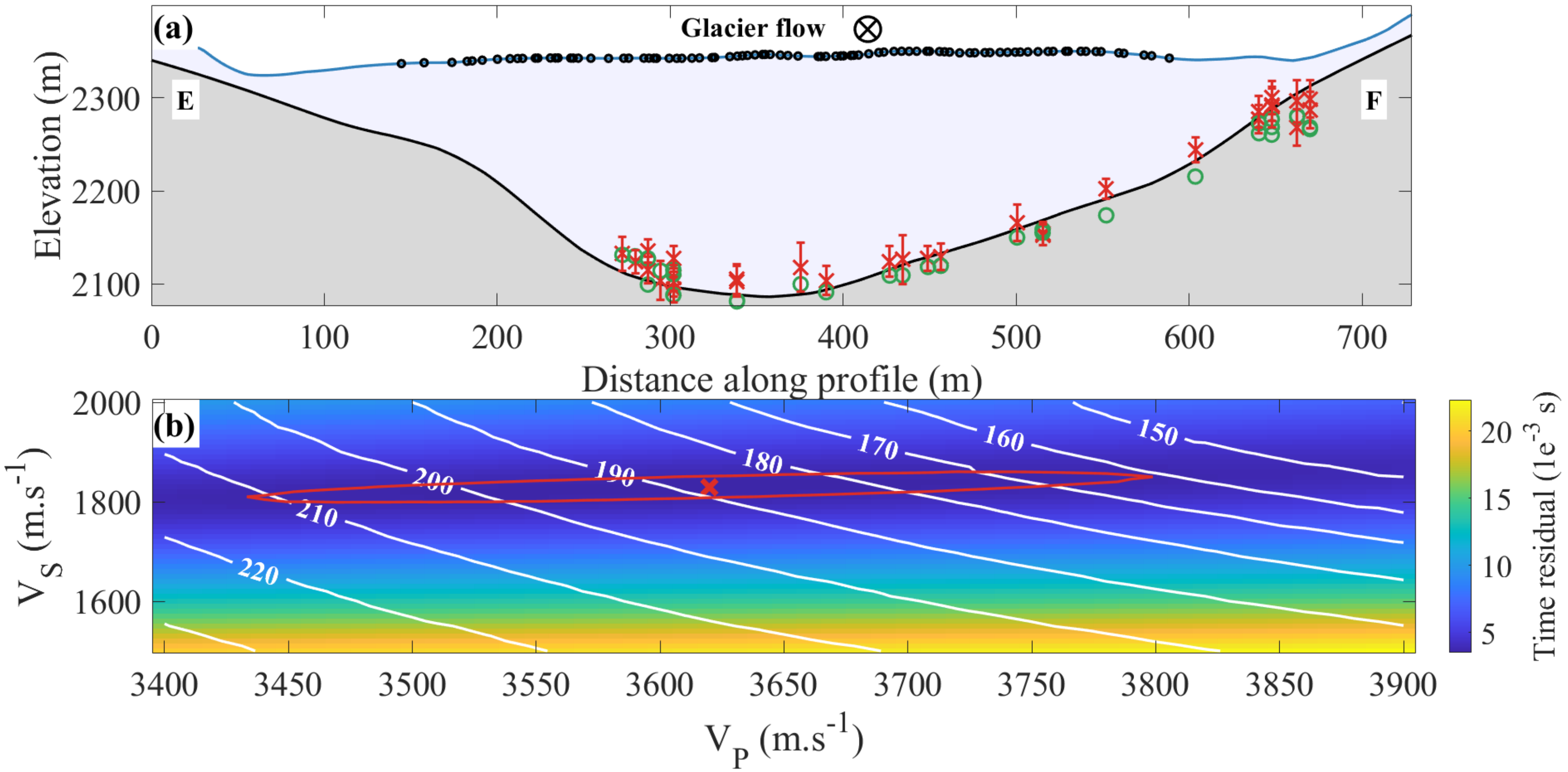


Sliding speed V
Hydraulic pressure gradient S
Hydraulic radius R
Channels hydraulic relative properties
R/R_ref S/S_ref
Relative sliding speed
V/V_ref
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Date of year 2017-2018

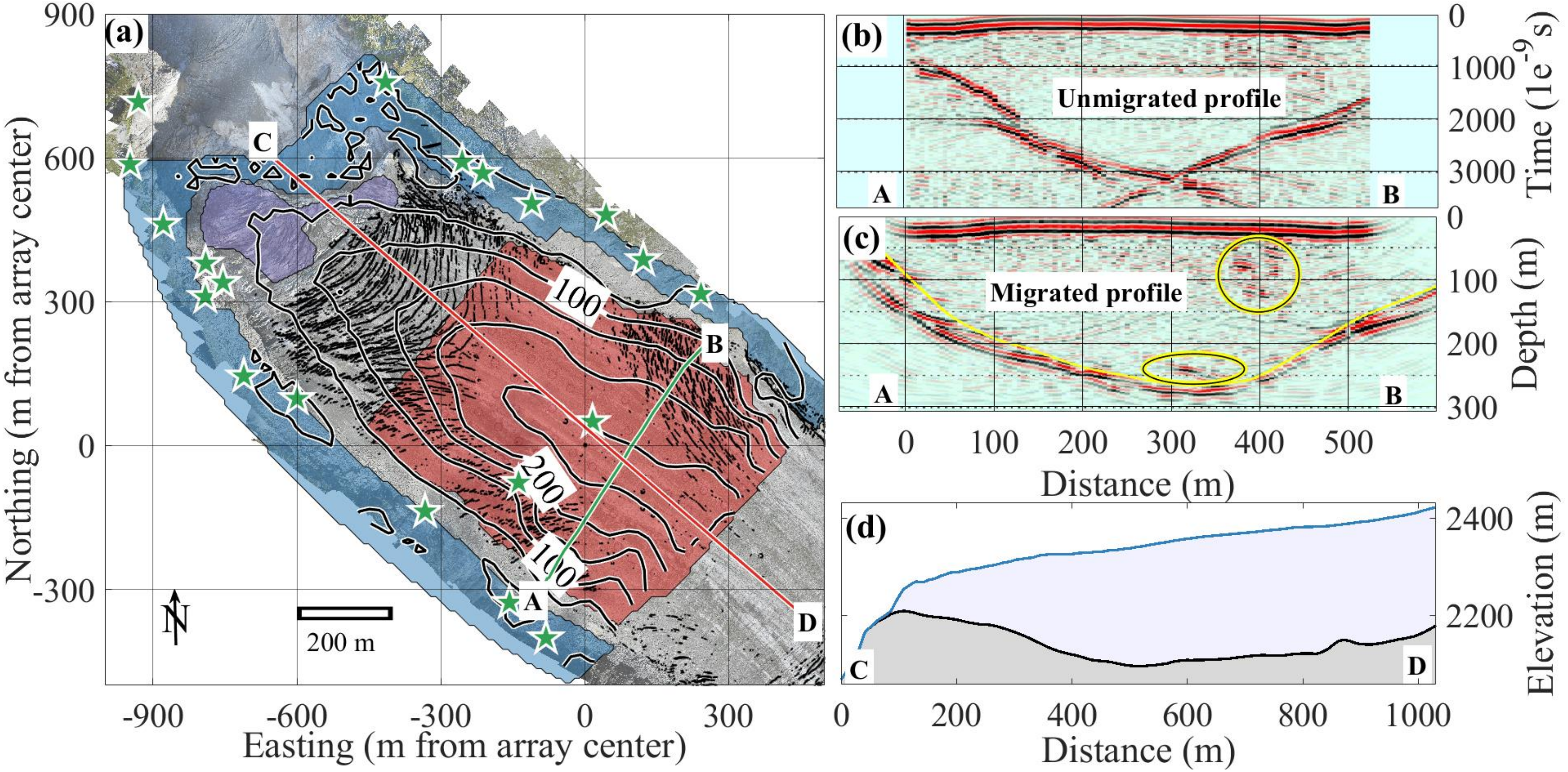

a)
Rel. Hydraulic Pressure Gradient
S/S_ref
Scaled discharge Q/Q_ref
Channels
out of equilibrium
Channels
at equilibrium
Theoretical scalings
S ~ Q^-2/11
S~ Q^2
5
3
2
1.5
1
0.75
1
2
5
10
25
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
b)
Rel. Hydraulic Radius
R/R_ref
Scaled discharge Q/Q_ref
Channels
out of equilibrium
Channels
at equilibrium
Theoretical scalings
R ~ Q^9/22
R ~ cst
3
2
1.5
1.25
1
1
2
5
10
25
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Date of year

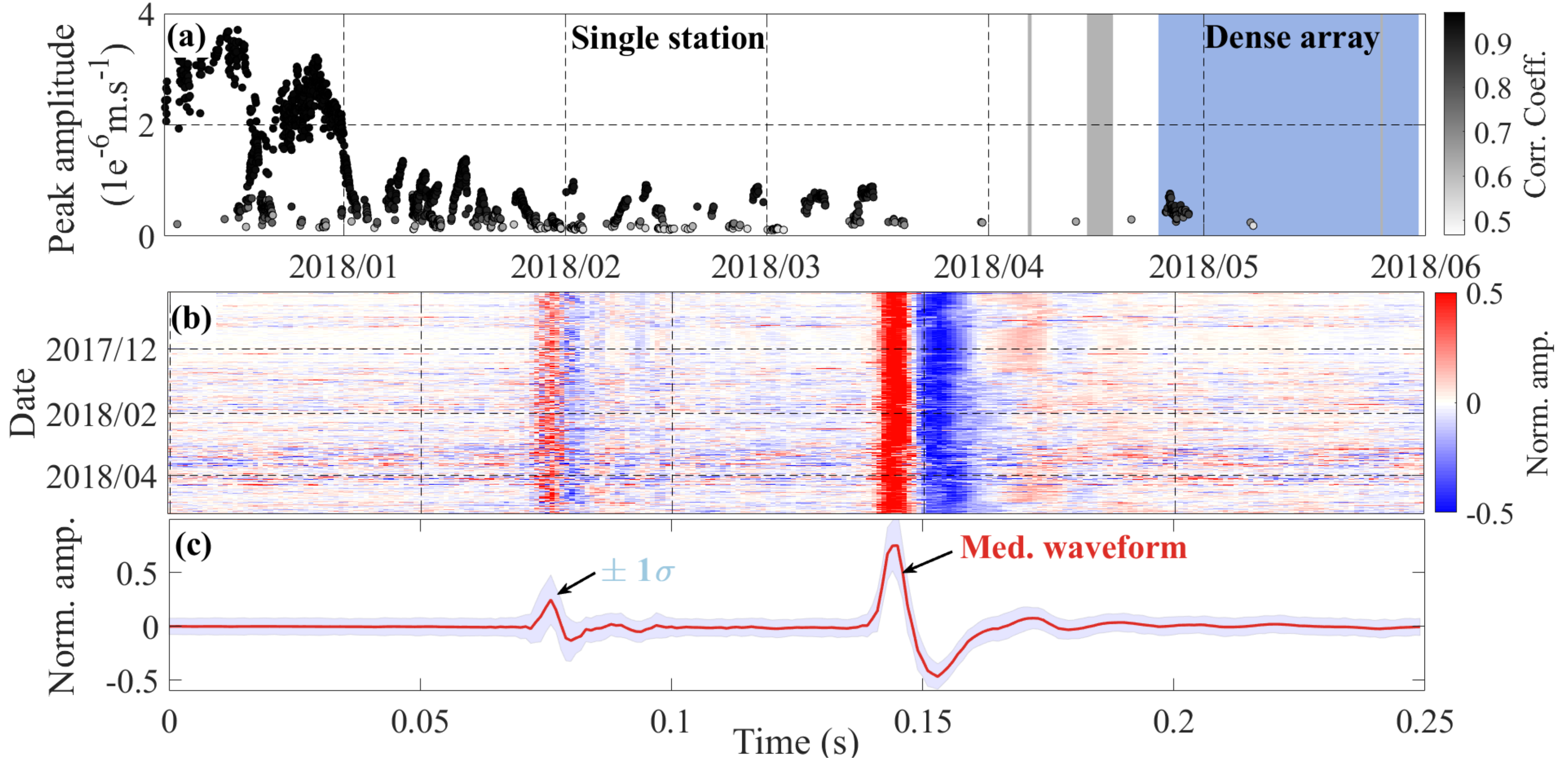

MFP output
(a)
PDF
Random wavefield
Real data (May 1st)
(b), MFP out.=0.92, Depth=0m
(c), MFP out.=0.92, Depth=4m
Source
Northing (m)
Easting (m)
Phase component at 13 Hz


(a) Node 6
Tilted Node
(b) Node 38
(c) Node 44
(d) Node 50
(e) Node 95
(f)
Frequency (Hz)
Rel. seismic power P (dB - (m.s^{-1})^2.Hz^{-1})
Discharge (m^3.sec^{-1})
Date (dd/mm)
25/04
27/04
29/04
01/05
03/05
05/05
07/05
09/05
11/05
13/05
[2-20] Hz
4 days
3 hours

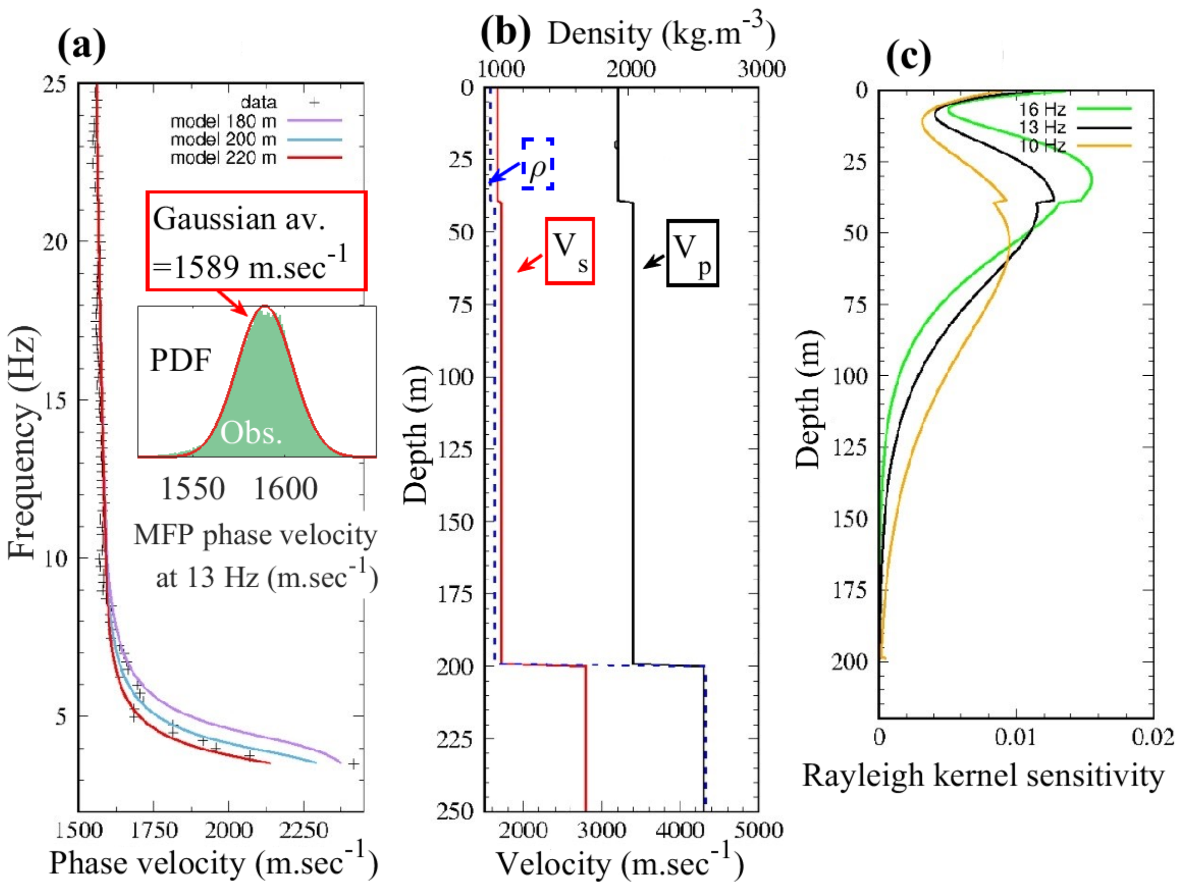


(a)
Glacier flow
E
F
Elevation (m)
2300
2200
2100
0
100
200
300
400
500
600
700
Distance along profile (m)
(b)
2000
1800
1600
V_S (m.s^{-1})
200
190
180
170
160
150
210
220
3400
3450
3500
3550
3600
3650
3700
3750
3800
3850
3900
V_P (m.s^{-1})
20
15
10
5
Time residual (1e^{-3} s)

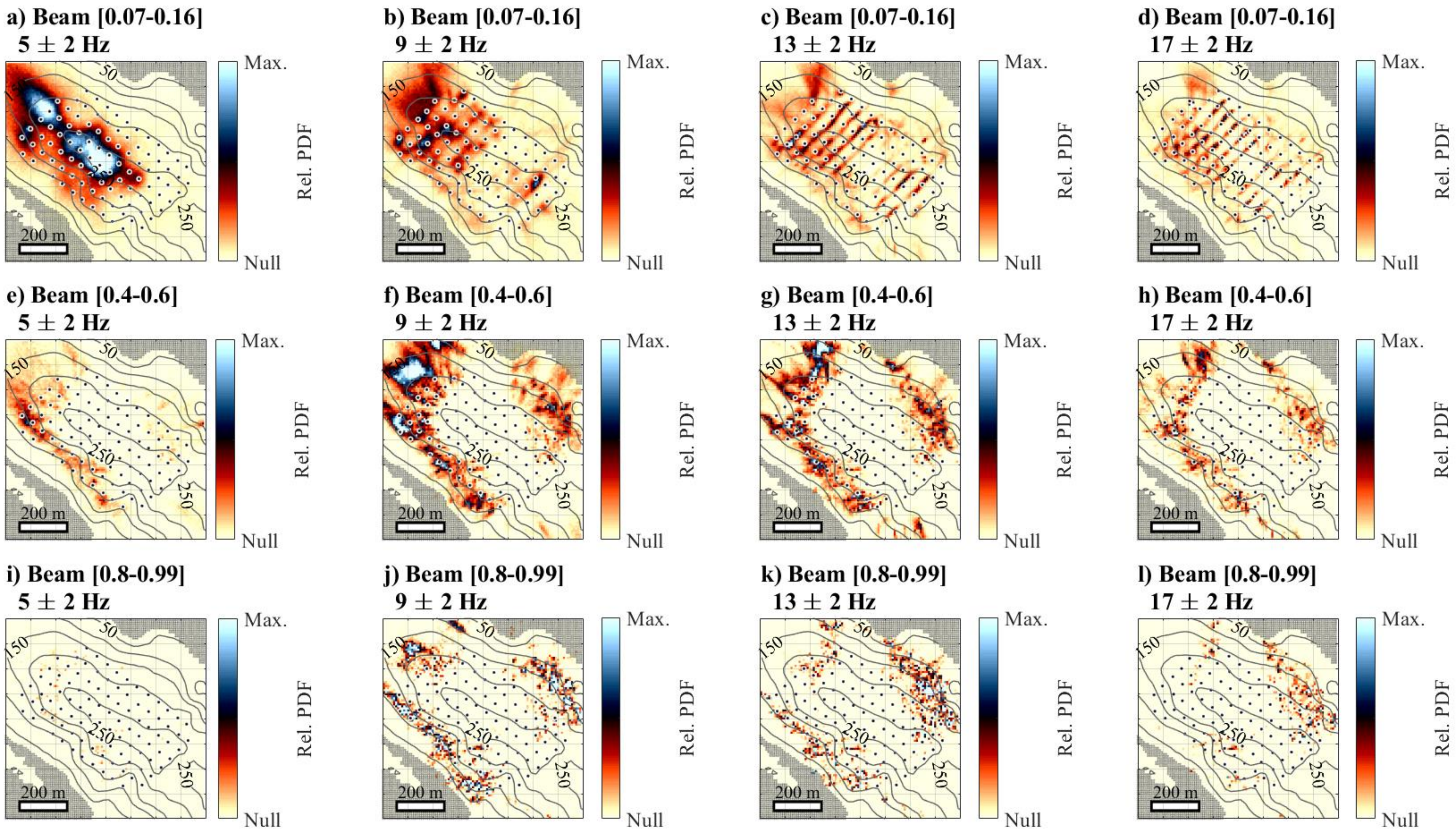

(a)
900
600
300
0
-300
Northing (m from array center)
-900
-600
-300
0
300
Easting (m from array center)
C
D
A
B
100
200
100
N
200 m
(b)
Unmigrated profile
A
B
0
1000
2000
3000
Time (1e^-9 s)
(c)
Migrated profile
A
B
0
100
200
300
Depth (m)
0
100
200
300
400
500
Distance (m)
(d)
C
D
2400
2200
Elevation (m)
0
200
400
600
800
1000
Distance (m)

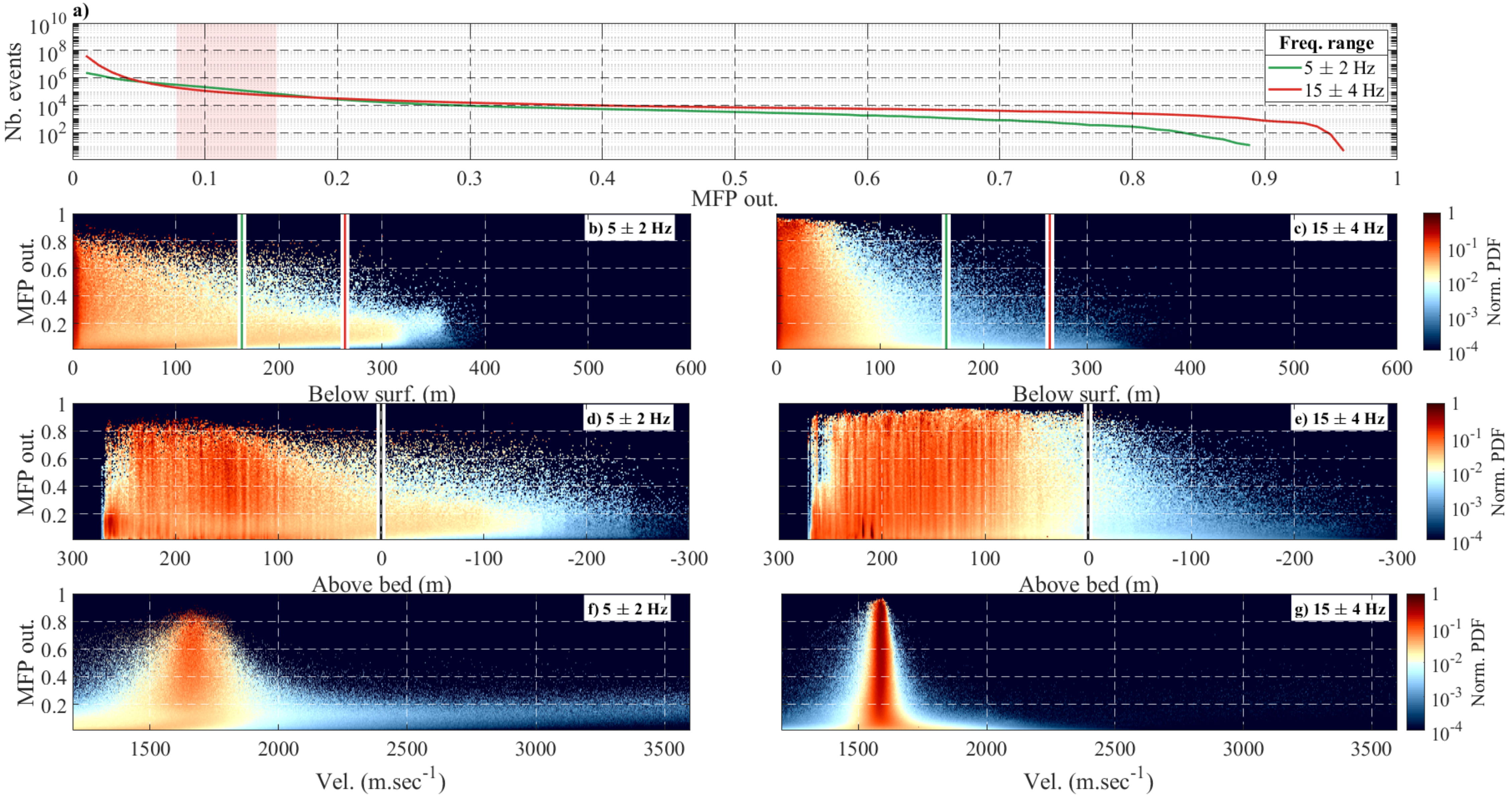


(a)
Single station
Dense array
Peak amplitude (1e-6 m.s-1)
Corr. Coeff.
2018/01
2018/02
2018/03
2018/04
2018/05
2018/06
(b)
Date
2017/12
2018/02
2018/04
Norm. amp.
(c)
± 1σ
Med. waveform
Norm. amp.
Time (s)

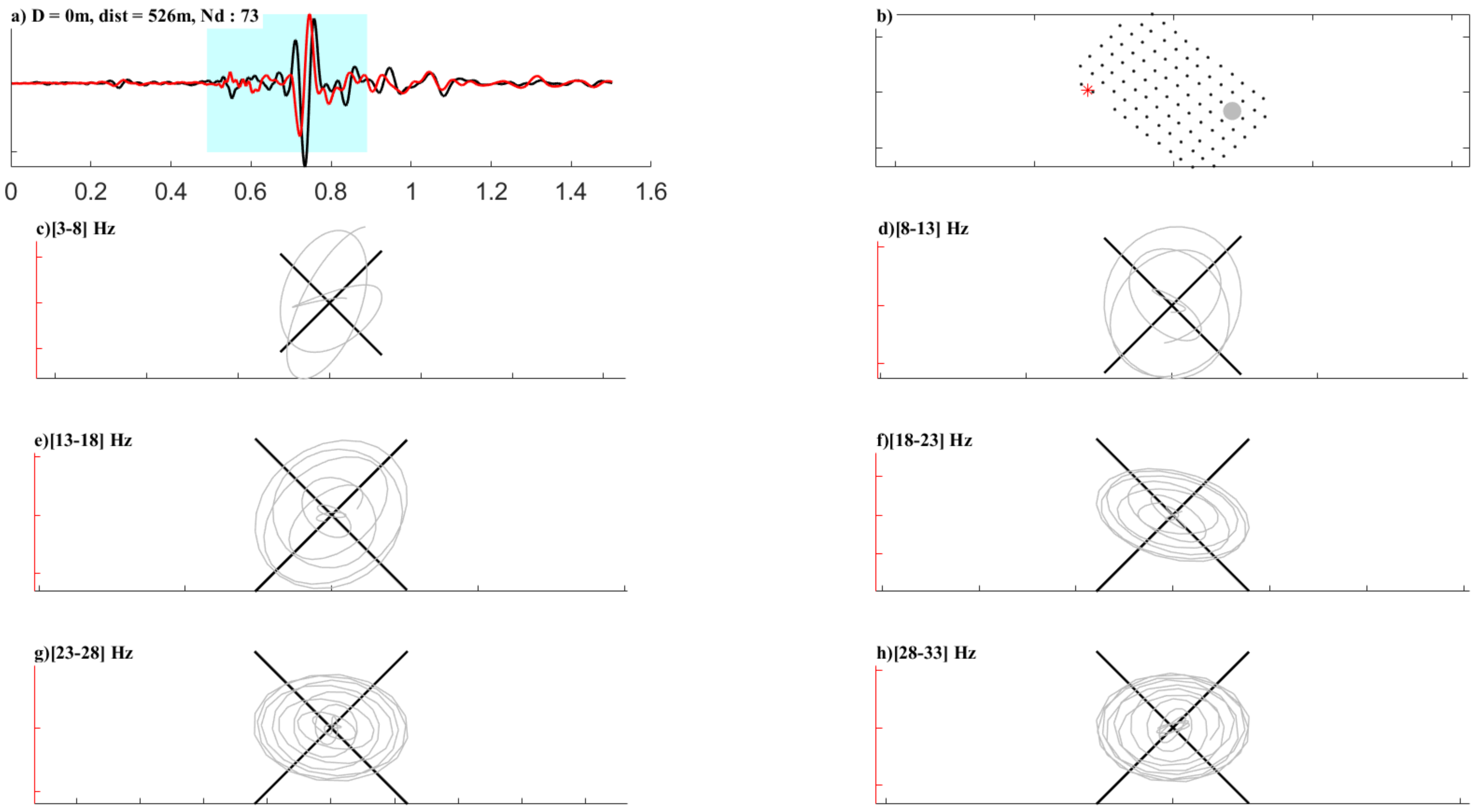


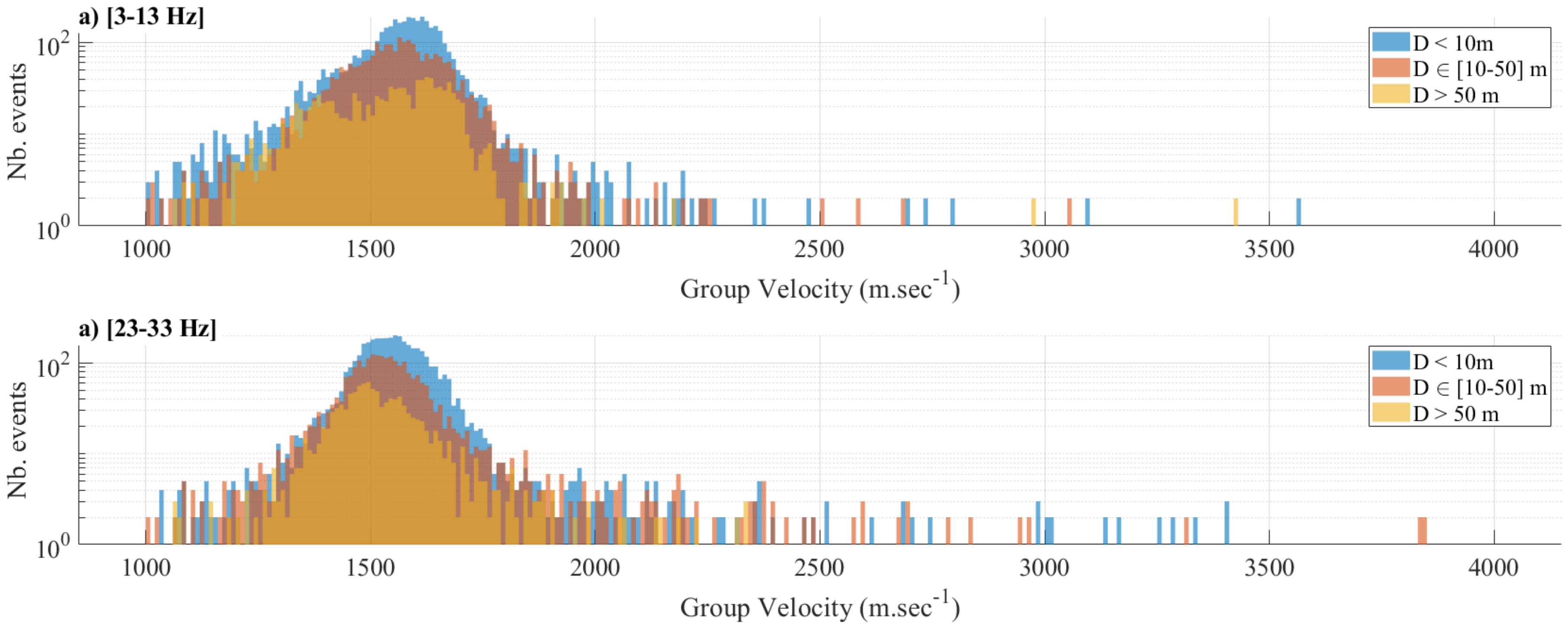
(a)
data
model 180 m
model 200 m
model 220 m
Gaussian av.
=1589 m.sec-1
PDF
Obs.
1550 1600
MFP phase velocity
at 13 Hz (m.sec-1)
Frequency (Hz)
Phase velocity (m.sec-1)
(b) Density (kg.m-3)
ρ
Vs
Vp
Depth (m)
Velocity (m.sec-1)
(c)
16 Hz
13 Hz
10 Hz
Depth (m)
Rayleigh kernel sensitivity


a) Beam [0.07-0.16] 5 ± 2 Hz
b) Beam [0.07-0.16] 9 ± 2 Hz
c) Beam [0.07-0.16] 13 ± 2 Hz
d) Beam [0.07-0.16] 17 ± 2 Hz
e) Beam [0.4-0.6] 5 ± 2 Hz
f) Beam [0.4-0.6] 9 ± 2 Hz
g) Beam [0.4-0.6] 13 ± 2 Hz
h) Beam [0.4-0.6] 17 ± 2 Hz
i) Beam [0.8-0.99] 5 ± 2 Hz
j) Beam [0.8-0.99] 9 ± 2 Hz
k) Beam [0.8-0.99] 13 ± 2 Hz
l) Beam [0.8-0.99] 17 ± 2 Hz
Max.
Rel. PDF
Null
50
150
250
200 m

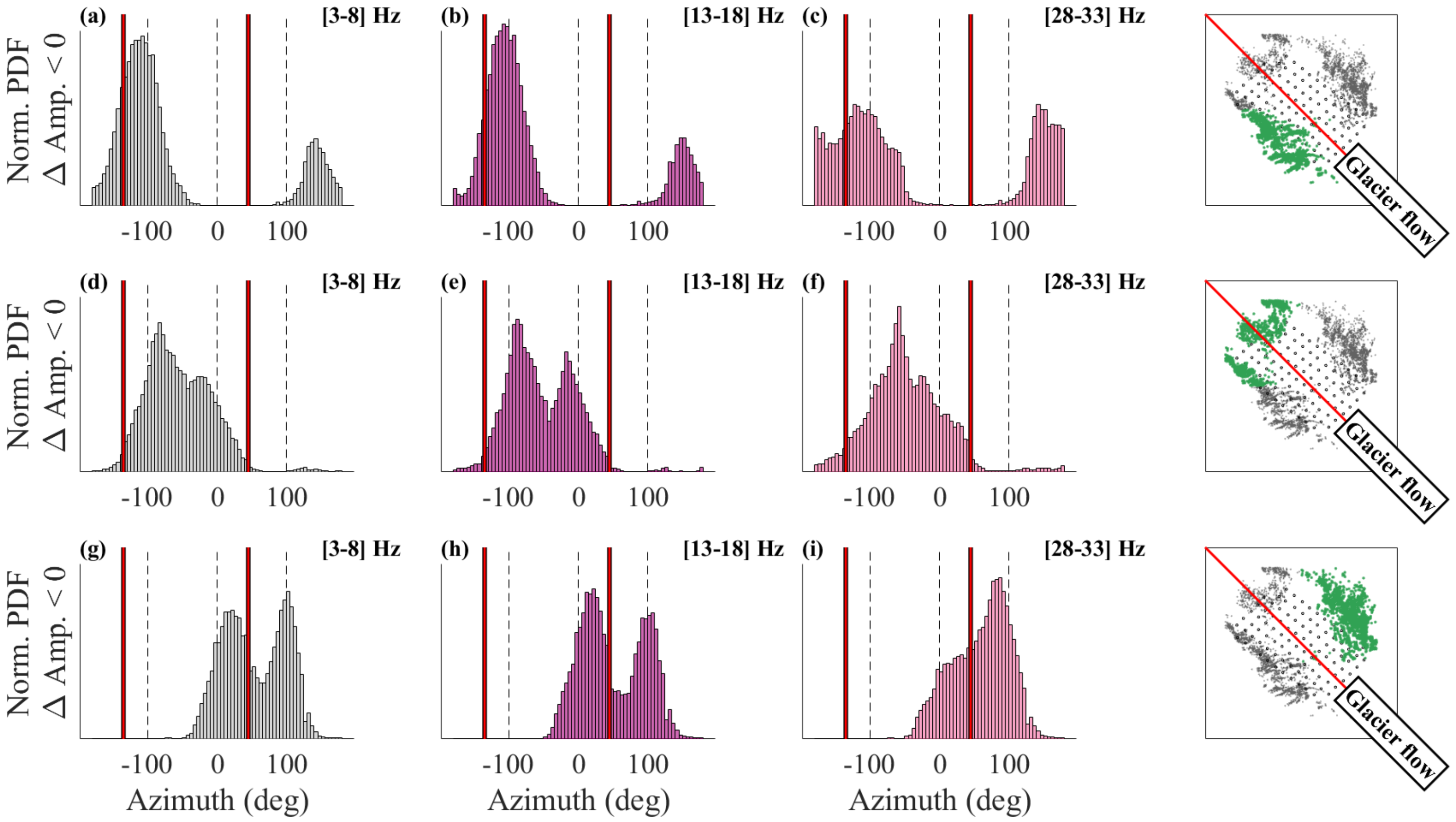


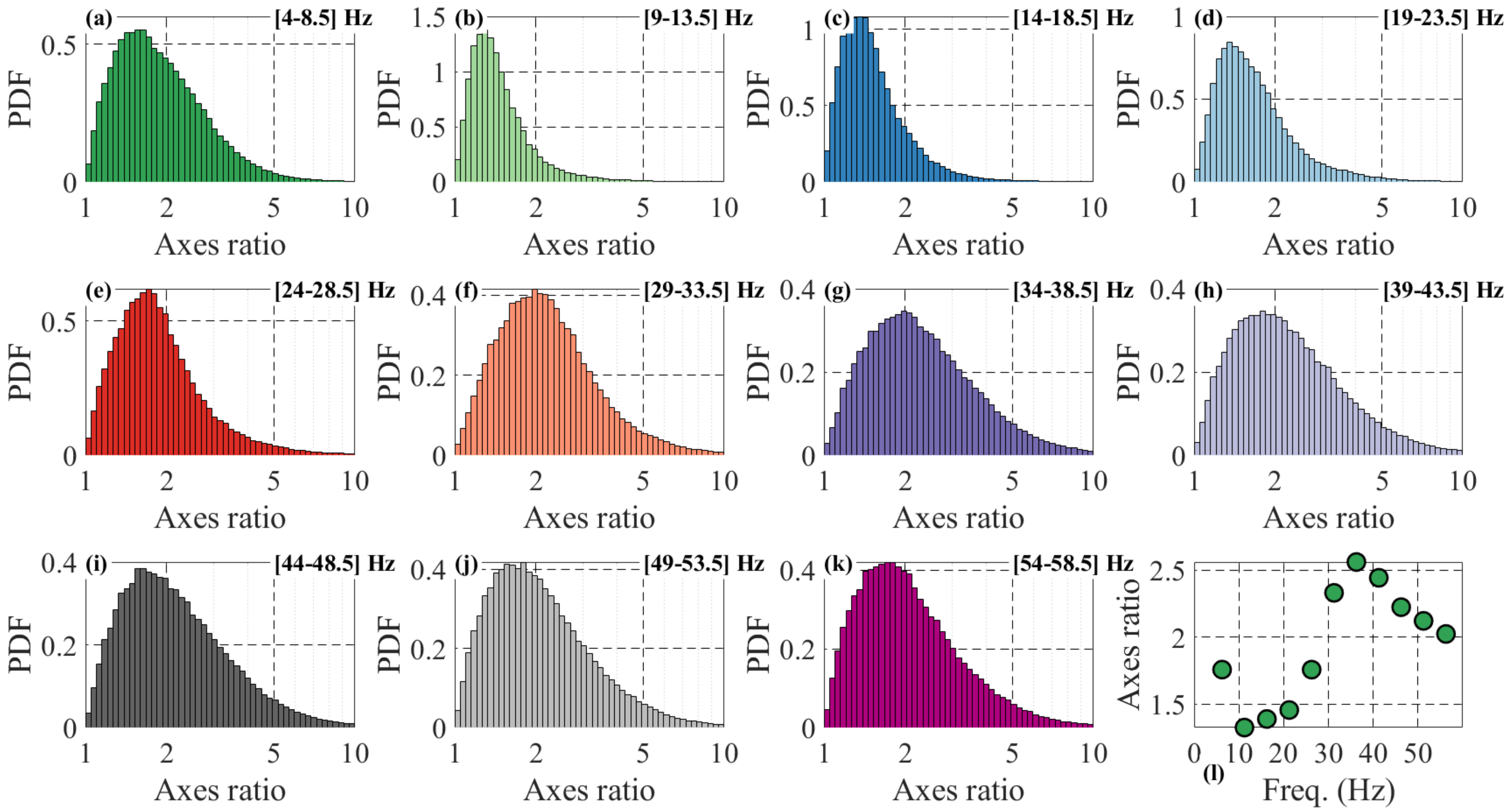
a)
Nb. events
MFP out.
Freq. range
5 ± 2 Hz
15 ± 4 Hz
b) 5 ± 2 Hz
c) 15 ± 4 Hz
Below surf. (m)
d) 5 ± 2 Hz
e) 15 ± 4 Hz
Above bed (m)
f) 5 ± 2 Hz
g) 15 ± 4 Hz
Vel. (m.sec-1)
Norm. PDF


a) D = 0m, dist = 526m, Nd : 73
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
b)
c)[3-8] Hz
d)[8-13] Hz
e)[13-18] Hz
f)[18-23] Hz
g)[23-28] Hz
h)[28-33] Hz

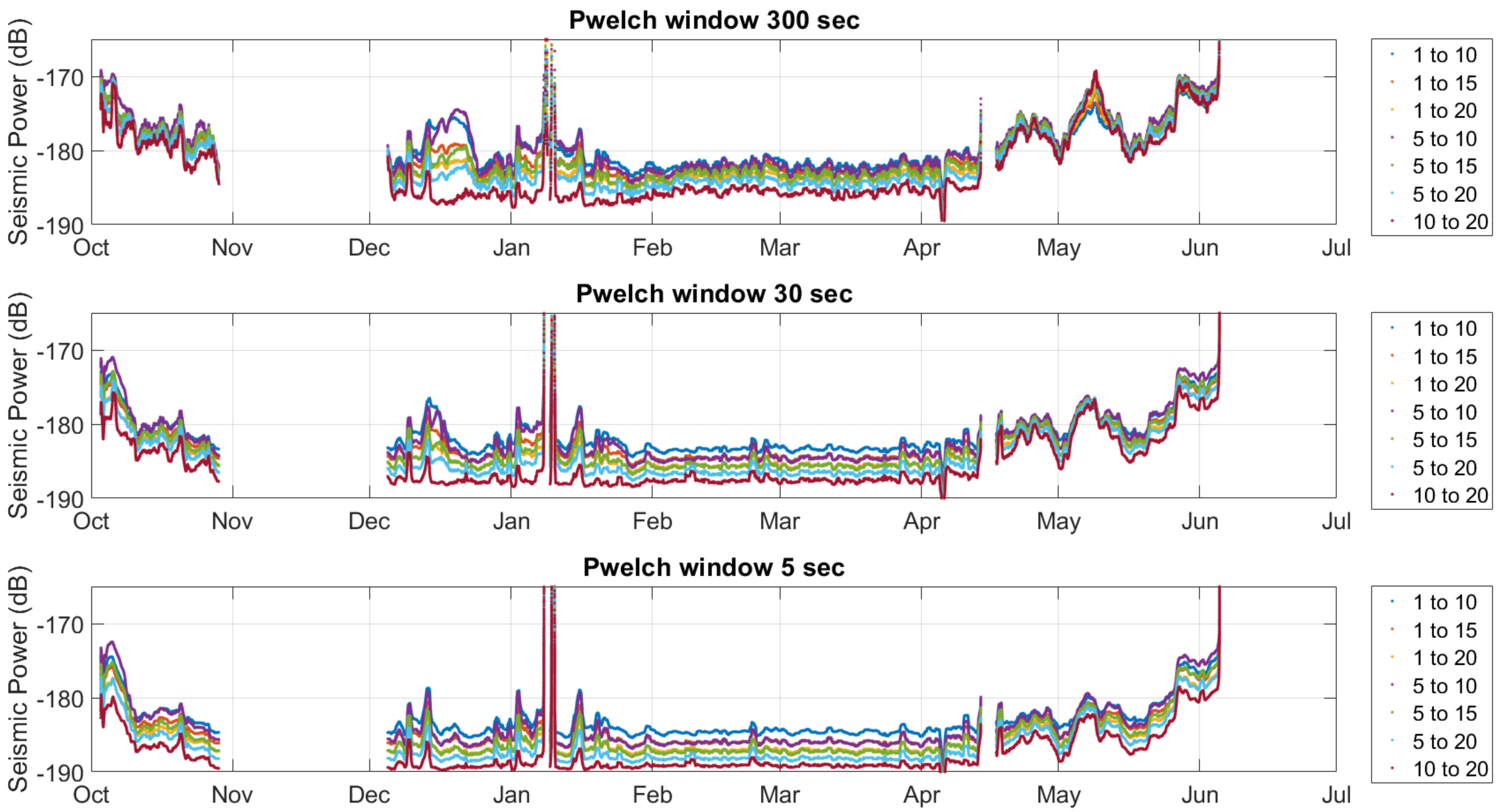


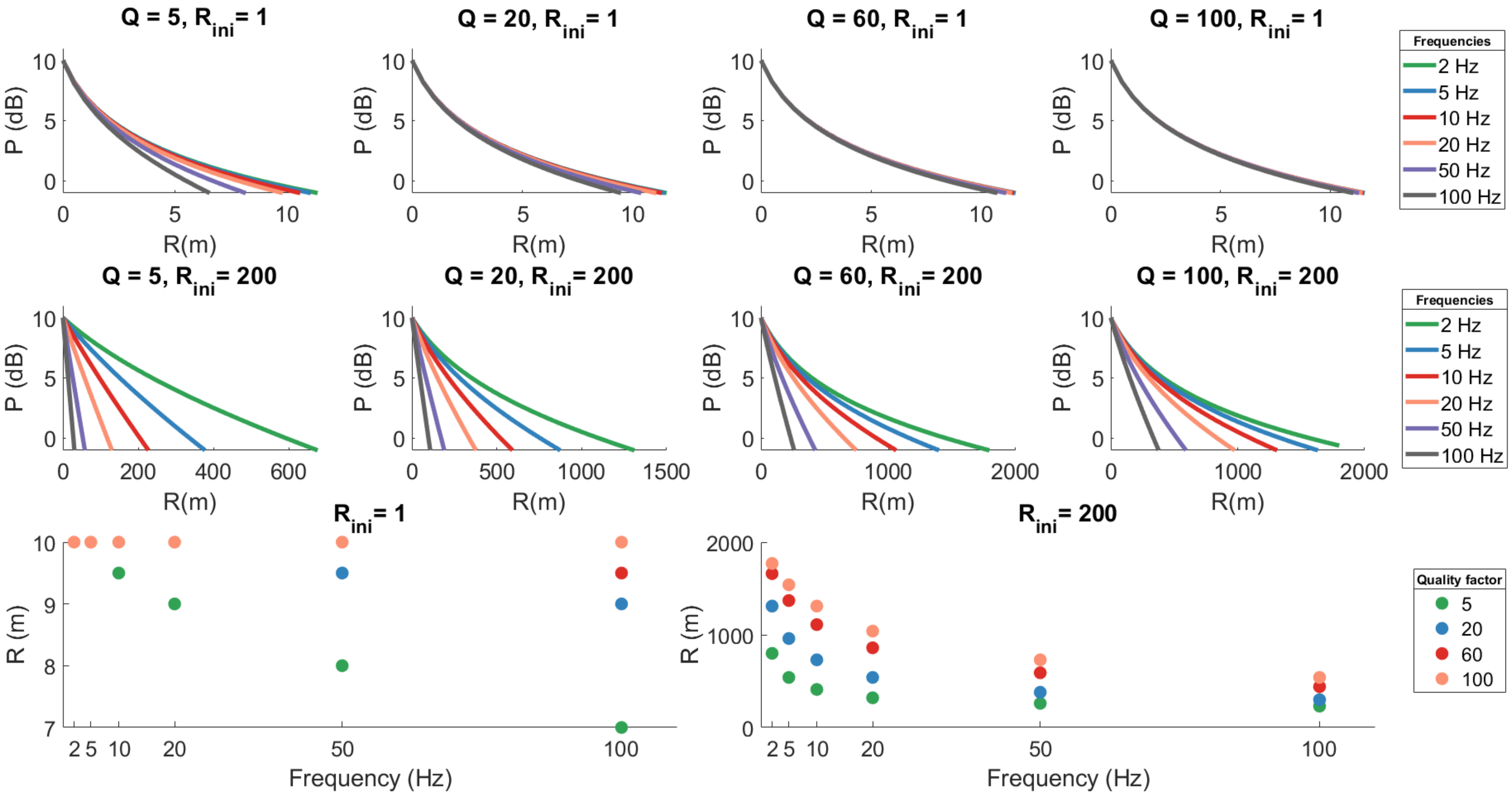
a) [3-13 Hz]
Nb. events
10^2
10^0
1000
1500
2000
2500
3000
3500
4000
Group Velocity (m.sec^{-1})
D < 10m
D ∈ [10-50] m
D > 50 m
a) [23-33 Hz]
Nb. events
10^2
10^0
1000
1500
2000
2500
3000
3500
4000
Group Velocity (m.sec^{-1})
D < 10m
D ∈ [10-50] m
D > 50 m


(a)
[3-8] Hz
(b)
[13-18] Hz
(c)
[28-33] Hz
(d)
[3-8] Hz
(e)
[13-18] Hz
(f)
[28-33] Hz
(g)
[3-8] Hz
(h)
[13-18] Hz
(i)
[28-33] Hz
Norm. PDF
Δ Amp. < 0
-100
0
100
Azimuth (deg)
Glacier flow

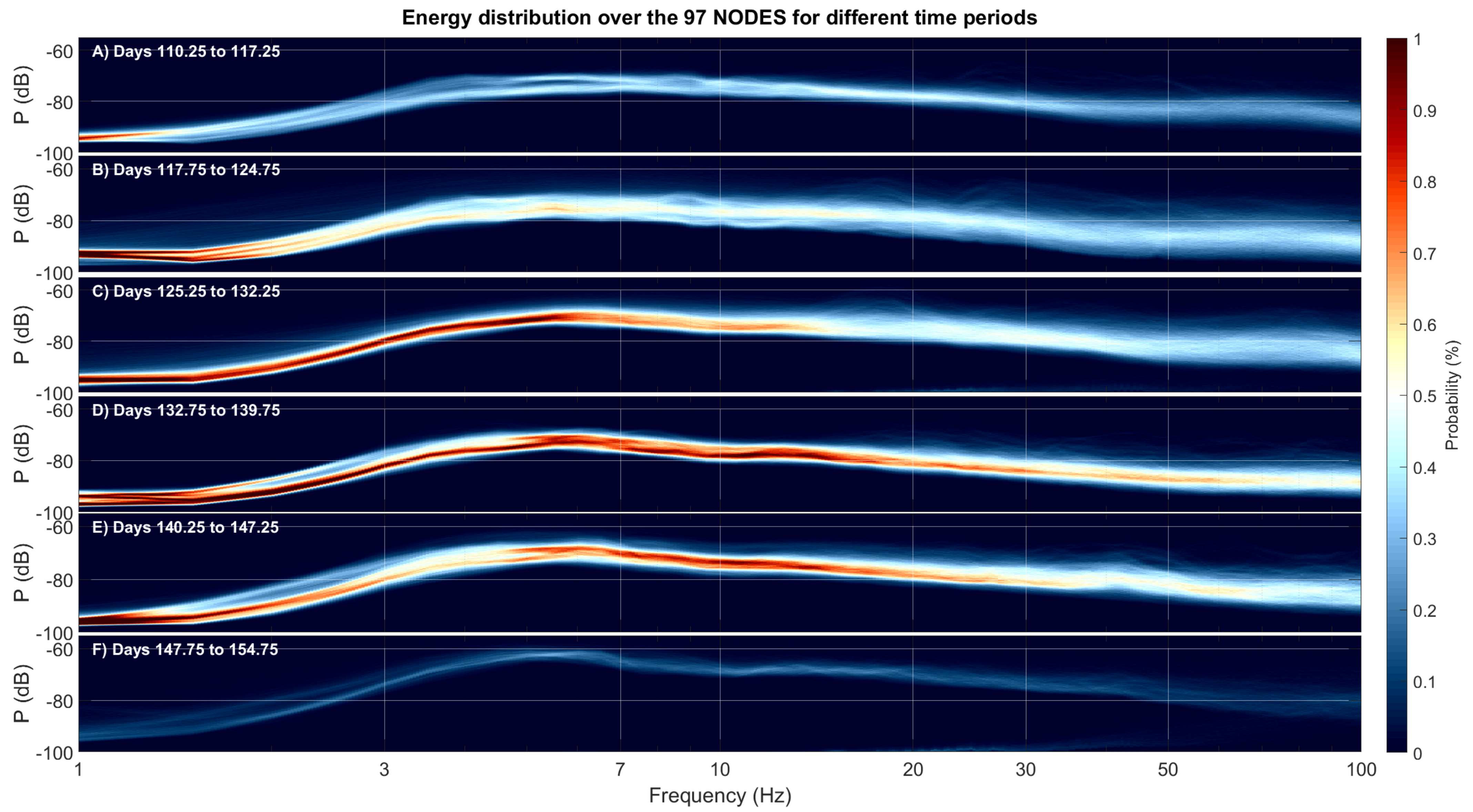


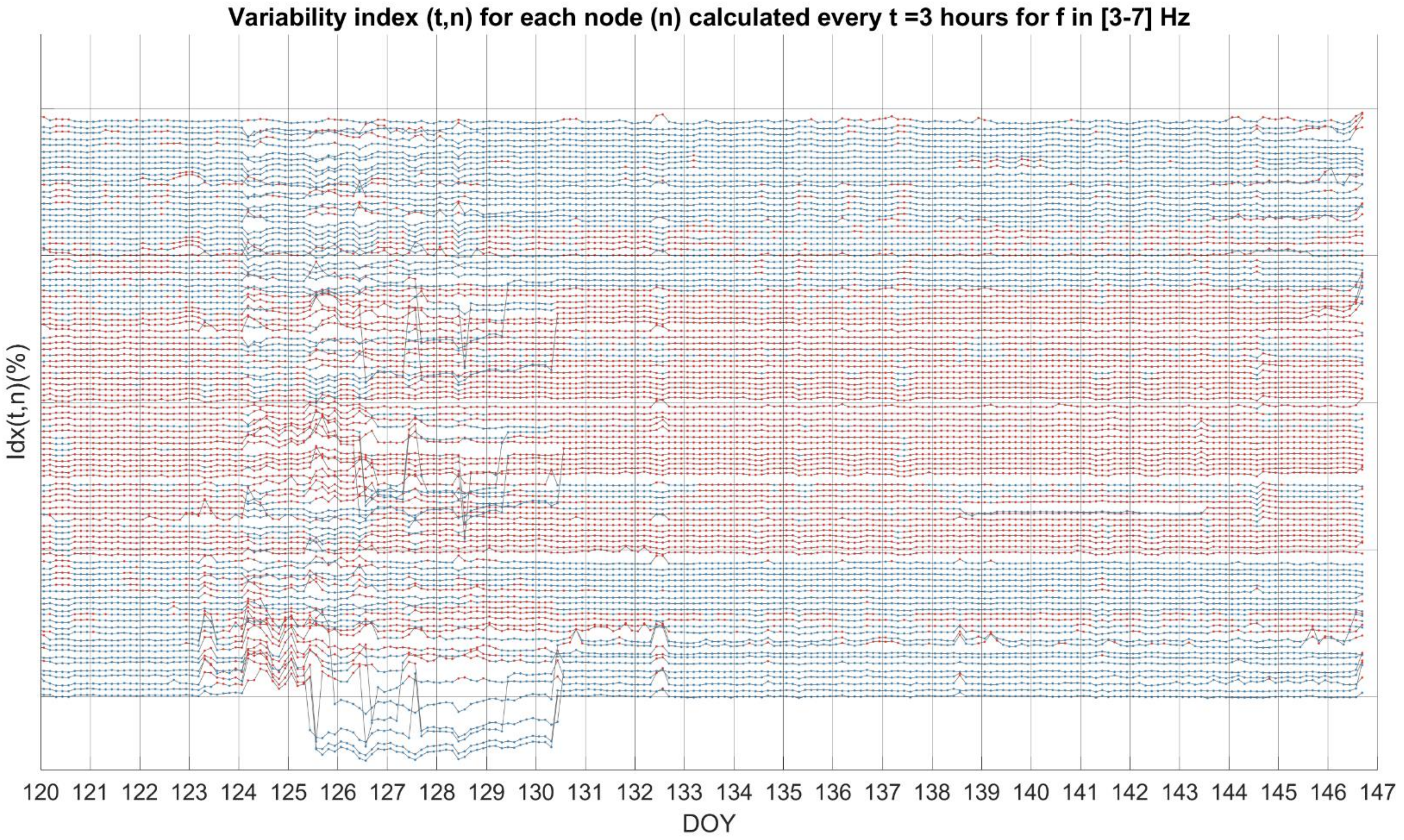
(a) [4-8.5] Hz
(b) [9-13.5] Hz
(c) [14-18.5] Hz
(d) [19-23.5] Hz
(e) [24-28.5] Hz
(f) [29-33.5] Hz
(g) [34-38.5] Hz
(h) [39-43.5] Hz
(i) [44-48.5] Hz
(j) [49-53.5] Hz
(k) [54-58.5] Hz
(l)
PDF
Axes ratio
Freq. (Hz)

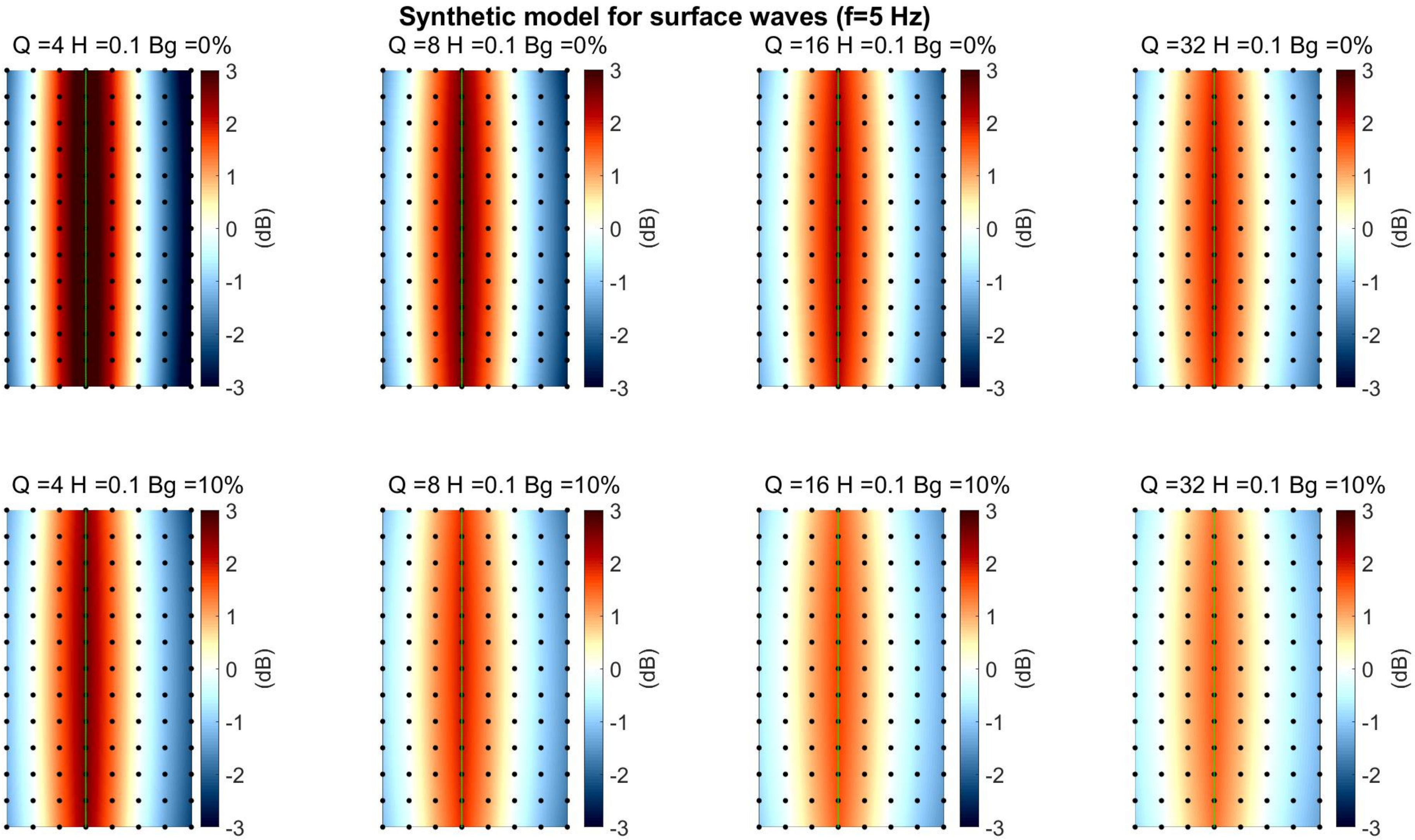

Pwelch window 300 sec
Pwelch window 30 sec
Pwelch window 5 sec
Seismic Power (dB)
-170
-180
-190
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
1 to 10
1 to 15
1 to 20
5 to 10
5 to 15
5 to 20
10 to 20

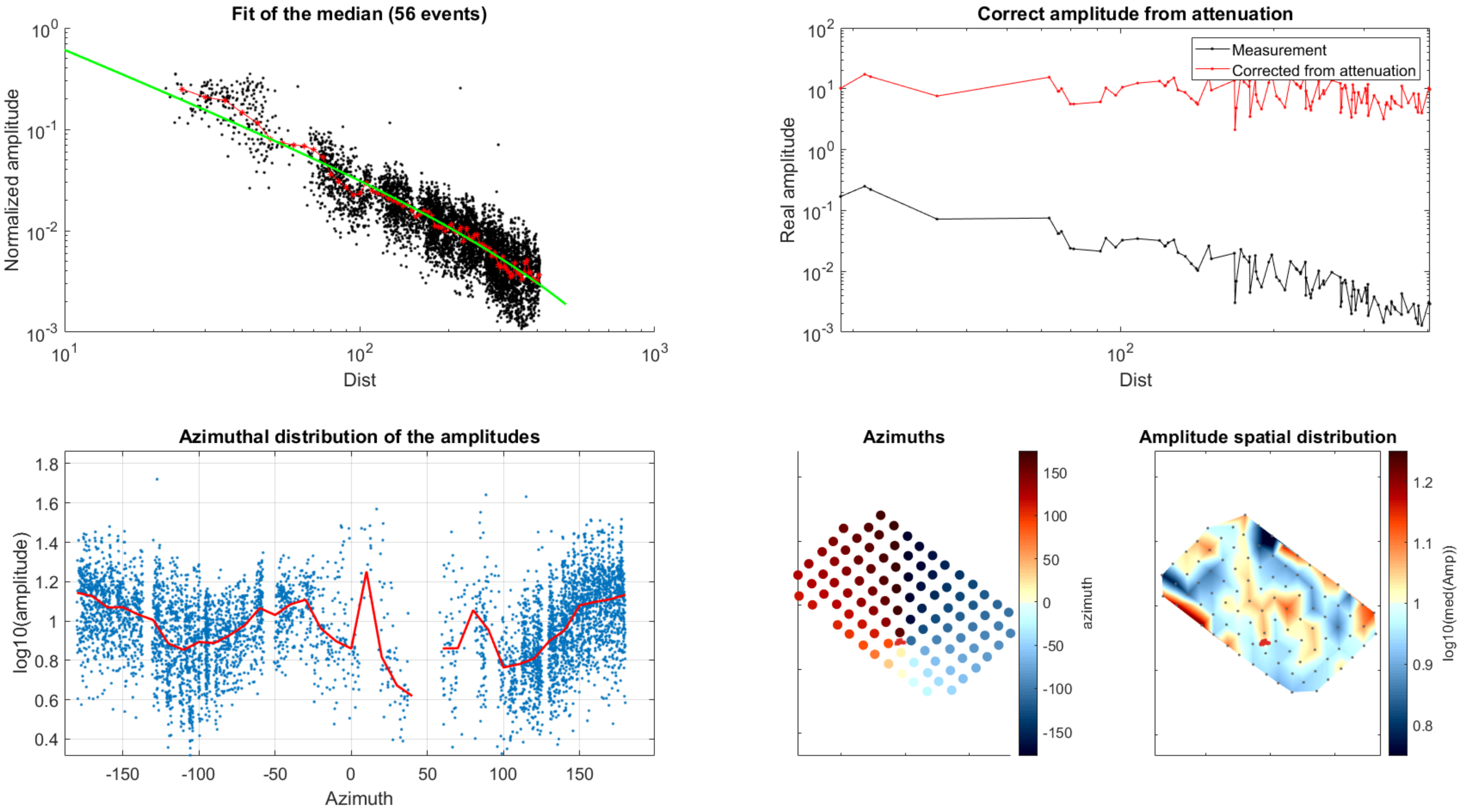


Q = 5, R_{ini}= 1
Q = 20, R_{ini}= 1
Q = 60, R_{ini}= 1
Q = 100, R_{ini}= 1
Q = 5, R_{ini}= 200
Q = 20, R_{ini}= 200
Q = 60, R_{ini}= 200
Q = 100, R_{ini}= 200
P (dB)
R(m)
Frequencies
2 Hz
5 Hz
10 Hz
20 Hz
50 Hz
100 Hz
R_{ini}= 1
R_{ini}= 200
R (m)
Frequency (Hz)
Quality factor
5
20
60
100


Energy distribution over the 97 NODES for different time periods
A) Days 110.25 to 117.25
B) Days 117.75 to 124.75
C) Days 125.25 to 132.25
D) Days 132.75 to 139.75
E) Days 140.25 to 147.25
F) Days 147.75 to 154.75
P (dB)
-60
-80
-100
1
3
7
10
20
30
50
100
Frequency (Hz)
Probability (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

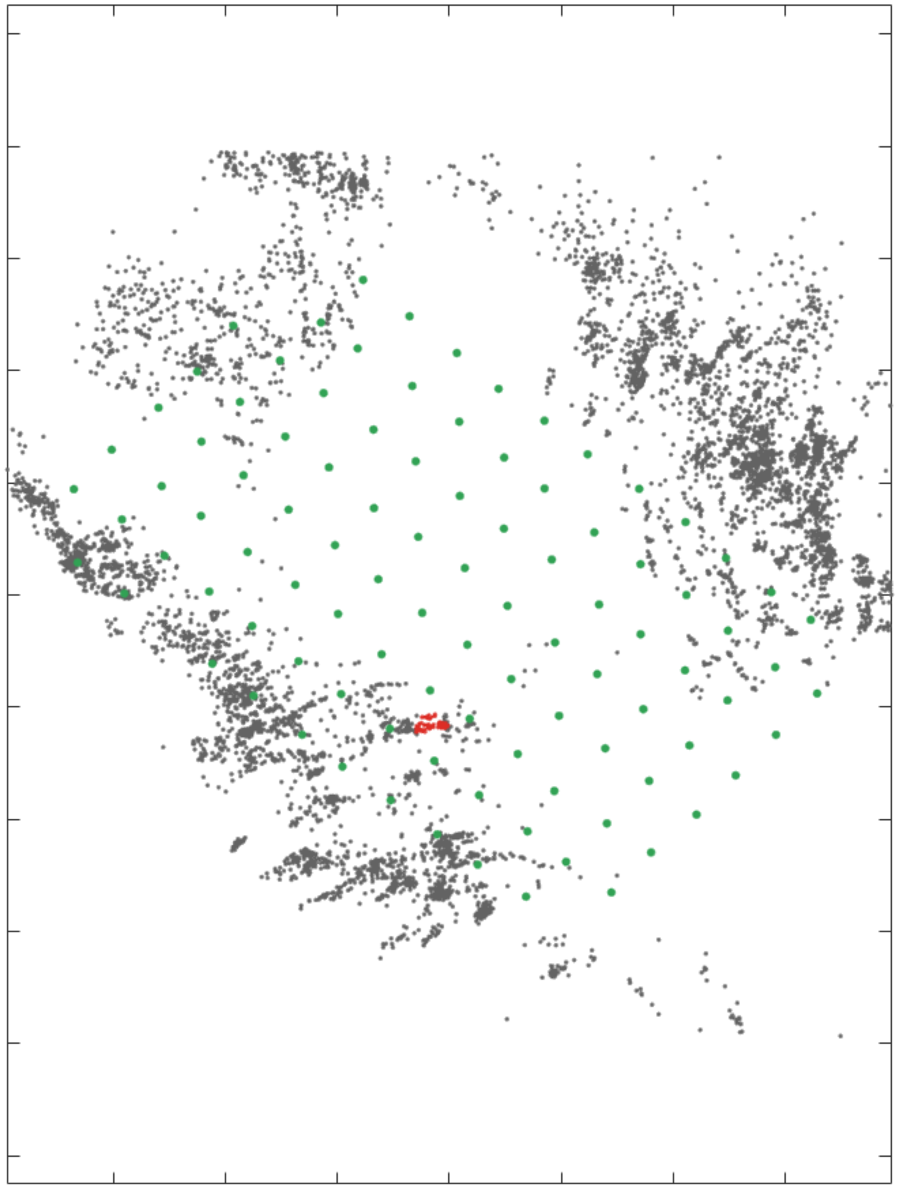

Variability index (t,n) for each node (n) calculated every t =3 hours for f in [3-7] Hz
Idx(t,n)(%)
120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147
DOY


Synthetic model for surface waves (f=5 Hz)
Q =4 H =0.1 Bg =0%
Q =8 H =0.1 Bg =0%
Q =16 H =0.1 Bg =0%
Q =32 H =0.1 Bg =0%
Q =4 H =0.1 Bg =10%
Q =8 H =0.1 Bg =10%
Q =16 H =0.1 Bg =10%
Q =32 H =0.1 Bg =10%
(dB)
3
2
1
0
-1
-2
-3

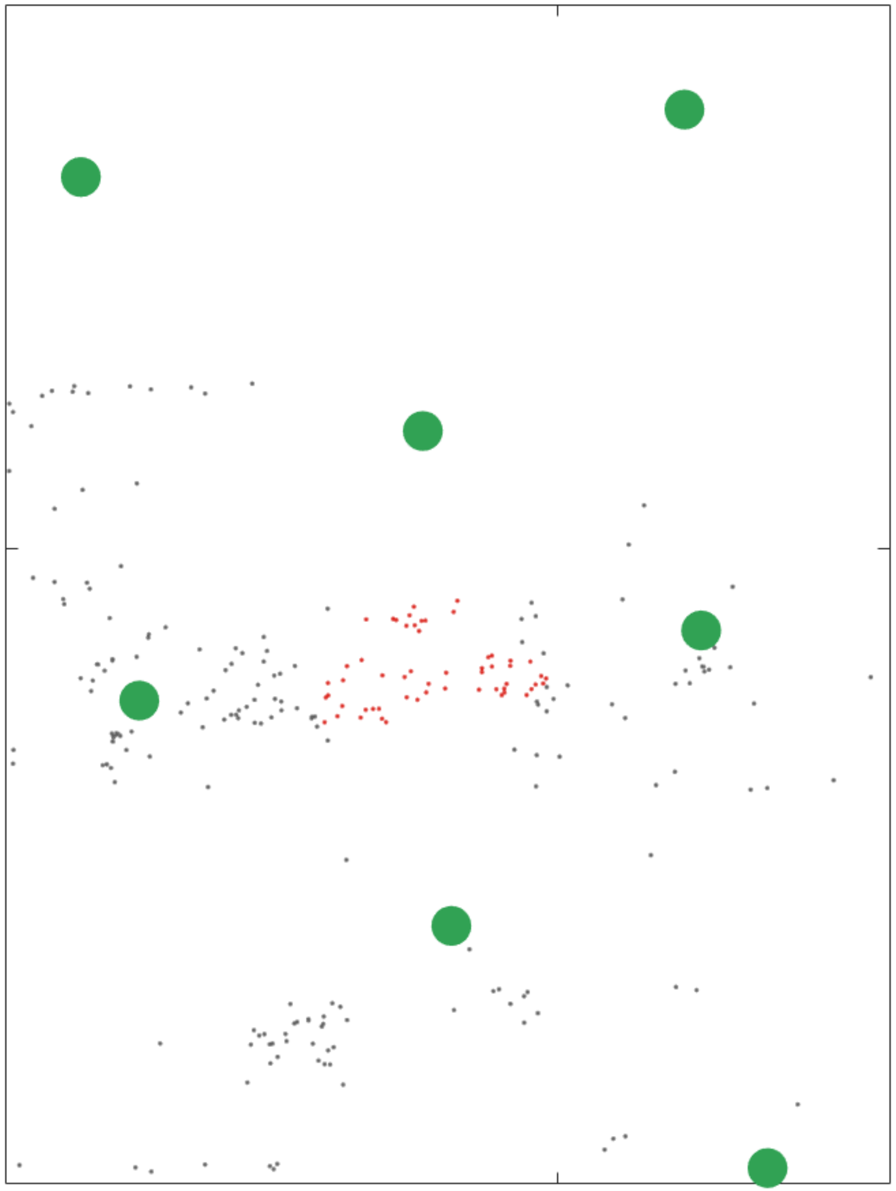


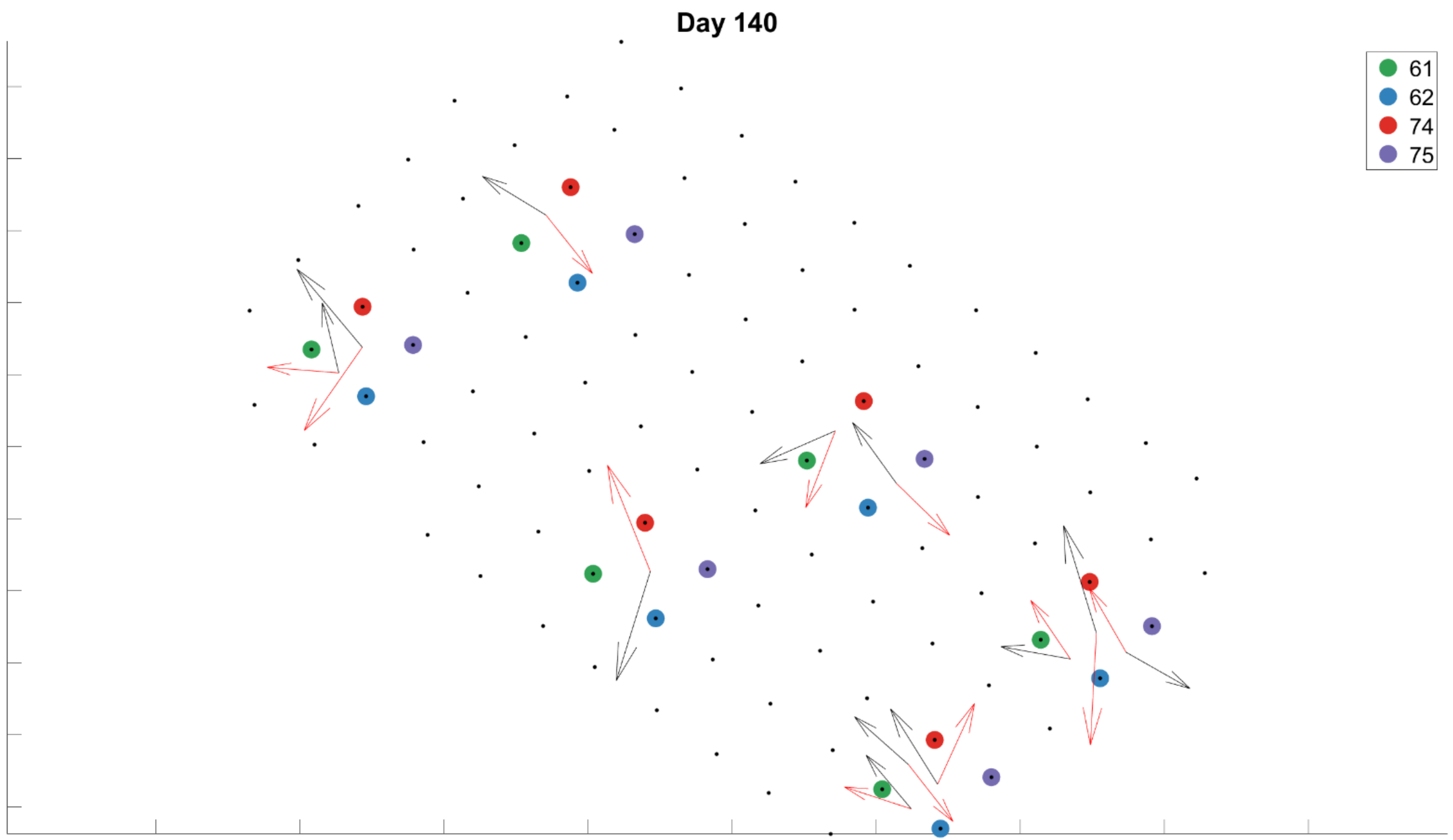
Fit of the median (56 events)
Normalized amplitude
Dist
Correct amplitude from attenuation
Measurement
Corrected from attenuation
Real amplitude
Dist
Azimuthal distribution of the amplitudes
log10(amplitude)
Azimuth
Azimuths
azimuth
Amplitude spatial distribution
log10(med(Amp))

Events with p > 0.8 location over the complete period



Zoom on the studied crevasse




Day 140
61
62
74
75