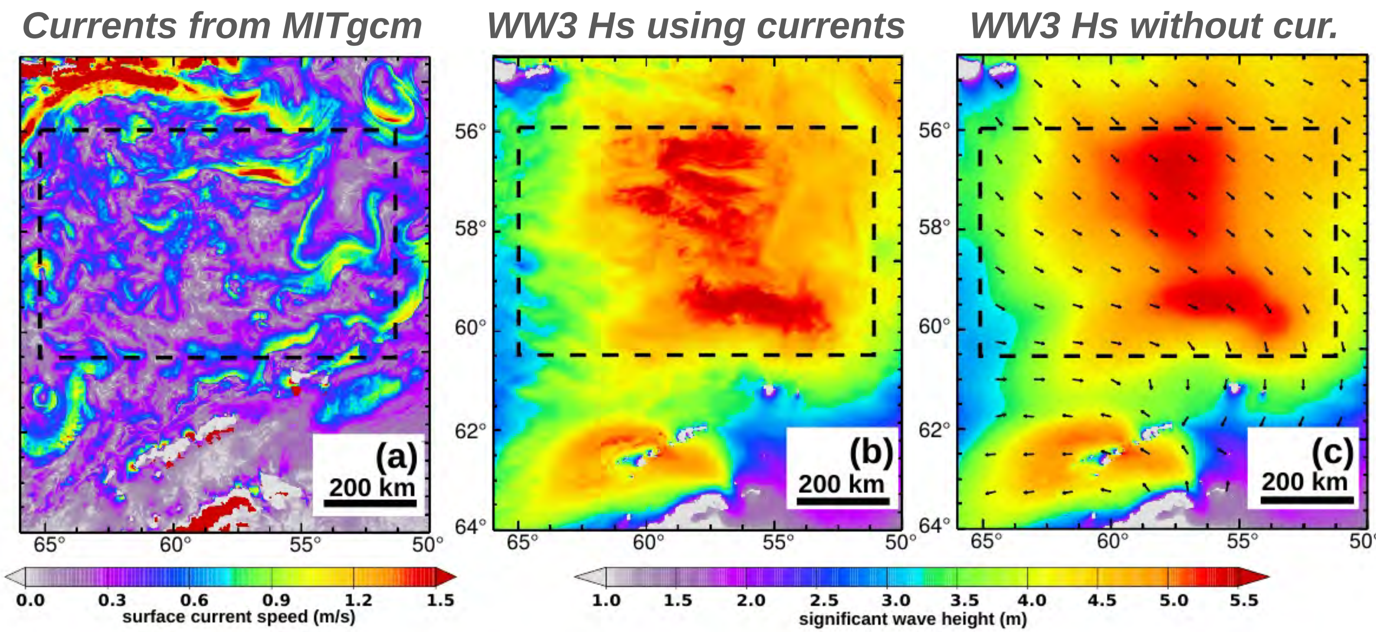
Wave height variations at scales under 100 km :

Small scale currents have large effects on ocean wave heights



Revised for JGR.

Available on ResearchGate

Fabrice Ardhuin[1], Sarah T. Gille[2], Dimitris Menemenlis[3], Cesar B. Rocha[2], Nicolas Rascle[1], Bertrand Chapron[1], Jonathan Gula[1], Jeroen Molemaker[1], *Pedro Guimaraes[1,4], Louis Marié[1]*

[1] LOPS (Univ. Brest, CNRS, Ifremer, IRD), [2] SIO, [3]JPL, [4] Ecole Centrale de Nantes

http://www.umr-lops.fr

ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST (/OTHER/SWOT)

Outline of this talk

1. **Waves & currents : scientific context**
2. **Quantifying, understanding, parametrizing SWH variability**
3. **Model validation : from nearshore to larger scales**
4. **Perspectives on joint waves & current studies : SKIM**
5. **Conclusion / advertisements …**

- **New « Halloween » version of WAVEWATCH III**
- **training in Brest, Cape Town, U. Maryland…**
- **Previmer → MARC** (hindcasts & forecasts)

ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST (/OTHER/SWOT)

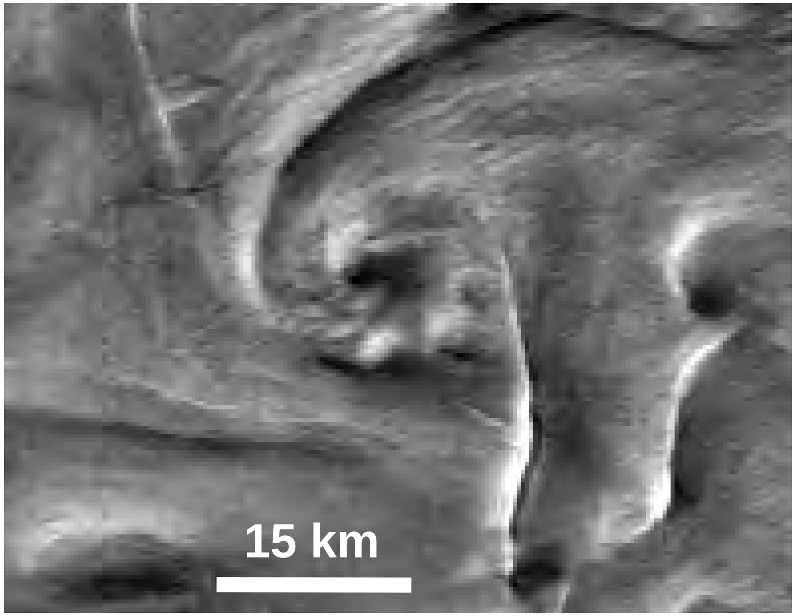
1

Waves and currents : scientific context

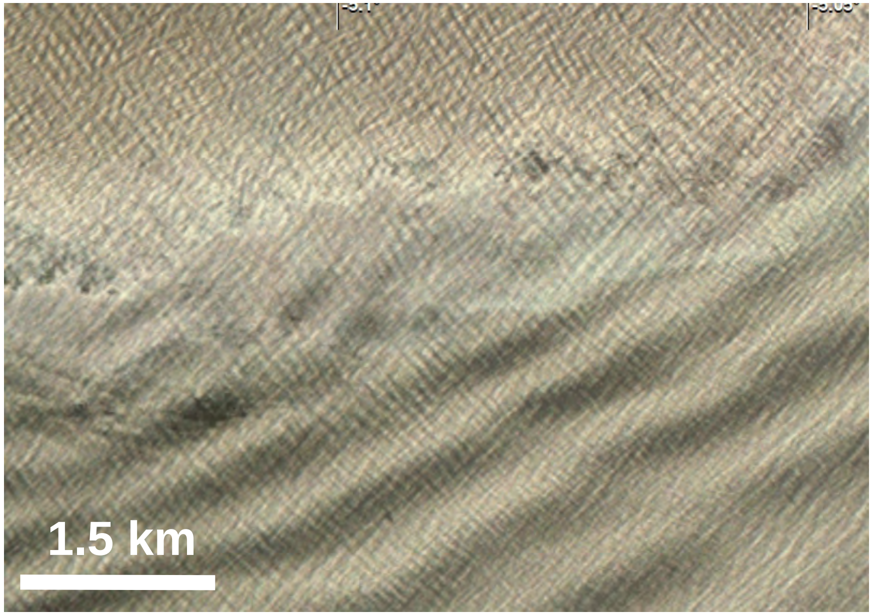
1. Waves and currents : scientific context

It is well known that currents have a strong impact on waves this is generally understood

→ Longuet-Higgins & Stuwart (1962)
→ Lavrenov (1986, 2003) → extreme waves in Agulhas current
→ Kudryavtsev et al. (2005, 2012) Rascle et al. (2014) : short waves & roughness



MERIS was pretty good for roughness



Now with Sentinel 2 we also resolve waves

1. Waves and currents : scientific context

It is well known that currents have a strong impact on waves this is generally understood

→ Longuet-Higgins & Stuwart (1962)

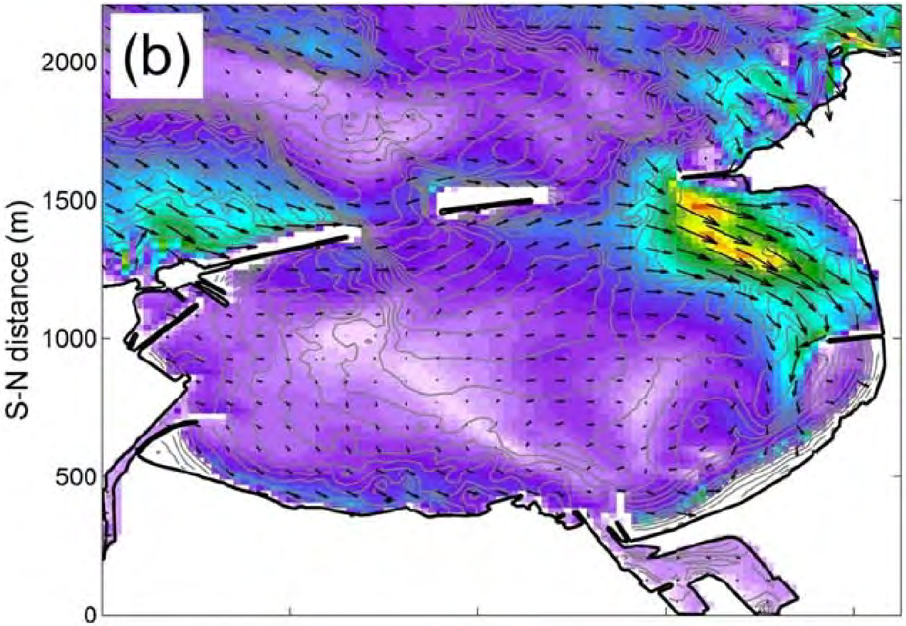
→ Lavrenov (1986, 2003) → extreme waves in Agulhas current

→ Kudryavtsev et al. (2005, 2012) Rascle et al. (2014) : short waves & roughness

By the way, waves also have a strong impact on currents & water level at small scale

→ nearshore currents (Longuet-Higgins 1970)

→ fronts and filaments (Suzuki et al. JGR 2016)



(Delpey et al. JGR 2014)

1. Waves and currents : scientific context

A still unresolved problem : wave dissipation

enhanced dissipation in current gradients
→ **new concept for dissipation by breaking**
Phillips (JPO 1984, JFM 1985), Banner et al. (JPO 2000)
→ **new parametrizations** (e.g. Ardhuin et al. JPO 2010)
→ **evaluation in current gradients** (Ardhuin et al. JPO 2012)
mostly OK… but missing data… → other work by Romero & Melville (ongoing)

Remote sensing applications :

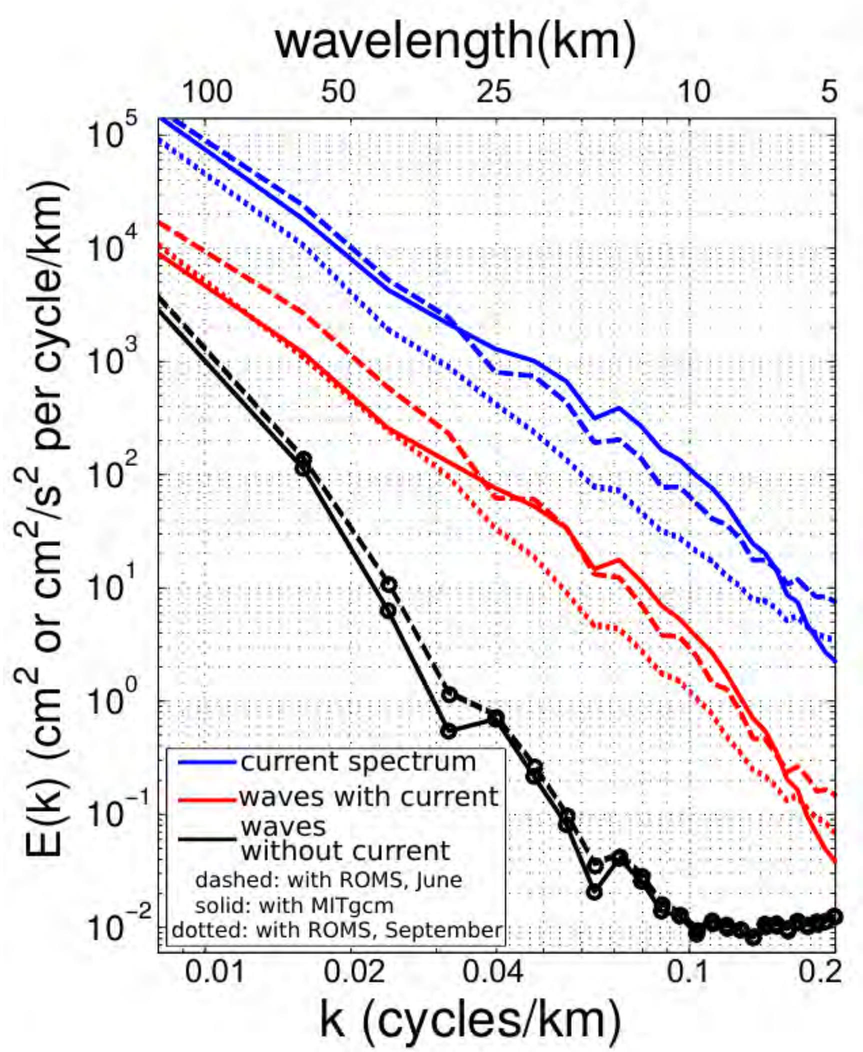
- **Measuring currents using wave properties (e.g. HF radars)**
- **Signature of currents on surface mean square slope or « mss »' (SAR, glitter …)**
- **Waves as sources of errors → SSB … in particular for SWOT.**

- **How much does SWH varies in the open ocean ?**

2

Quantifying & understanding SWH variability

2. Quantifying SWH variability

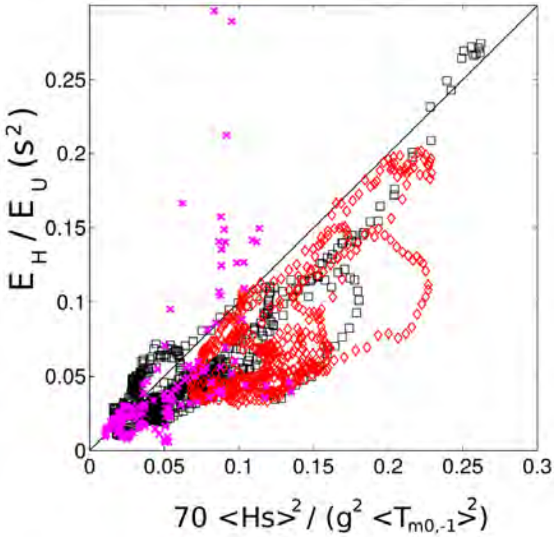


Plugging different currents in wave model (ROMS, Gula et al. 2015 ; MITgcm, Menemenlis)
→ generally same result :

shape of SWH spectrum follows surface current (KE) spectrum

@20 km wavelength : x 1000

2. Quantifying SWH variability

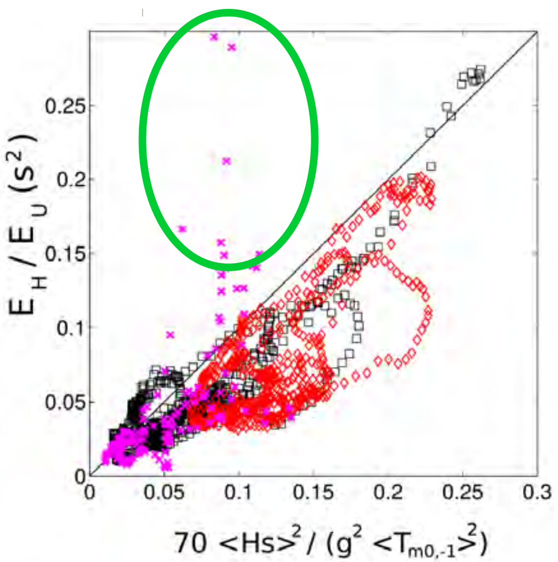


$$E_H \simeq 70 \frac{\langle H_s \rangle^2}{g^2 \langle T_{m0,-1} \rangle^2} E_U$$

SWH spectrum @ 10 km

current spectrum @ 10 km

2. Quantifying SWH variability



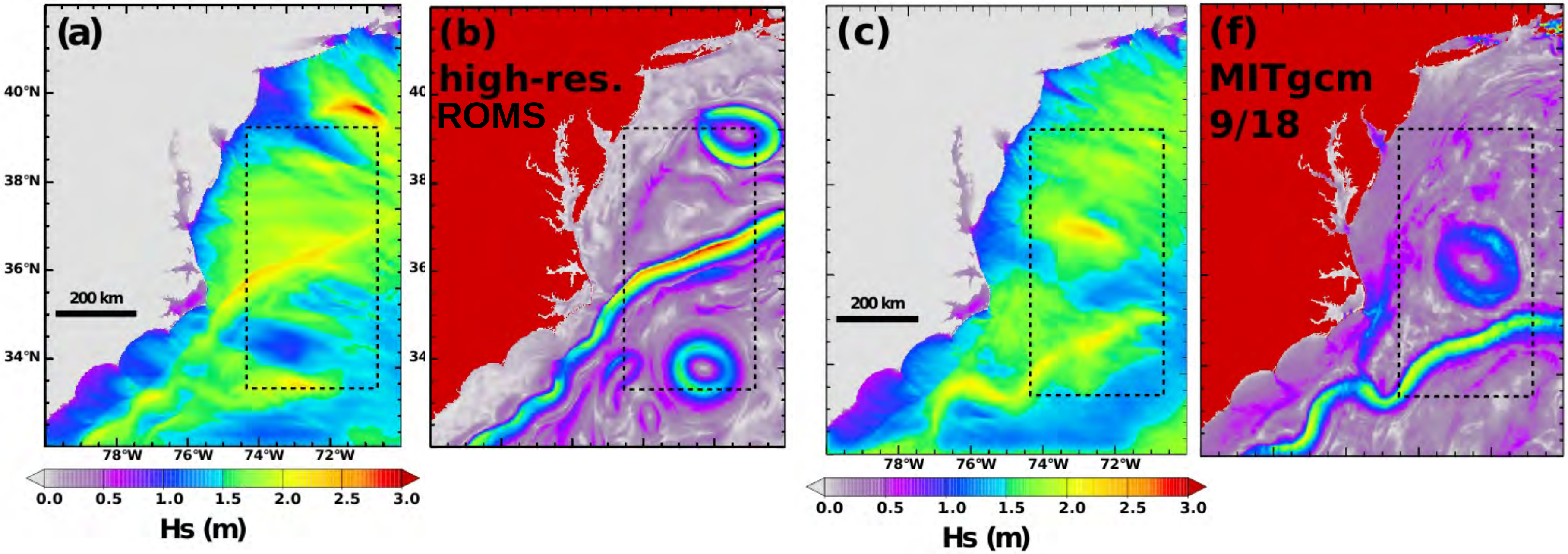
$$E_H \simeq 70 \frac{\langle H_s \rangle^2}{g^2 \langle T_{m0,-1} \rangle^2} E_U$$

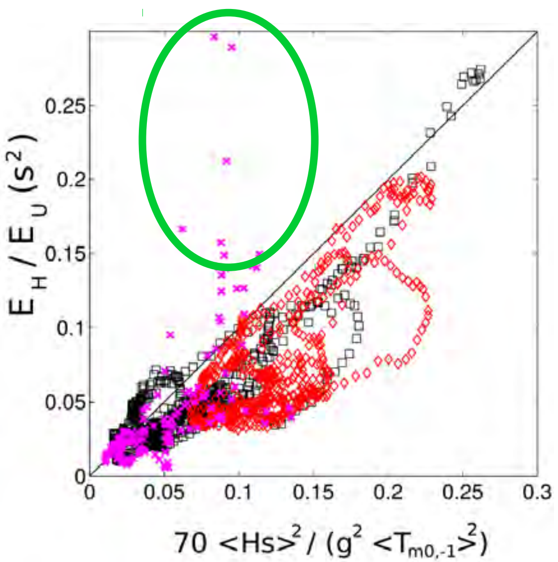
current spectrum @ 10 km

SWH spectrum @ 10 km

Spectra do not tell the whole story :
with same spectrum ROMS can give outliers
→ coherence scale (White and Fornberg JFM 1998)

2. Quantifying SWH variability





$$E_H \simeq 70 \frac{\langle H_s \rangle^2}{g^2 \langle T_{m0,-1} \rangle^2} E_U$$

SWH spectrum @ 10 km

current spectrum @ 10 km

Spectra do not tell the whole story :
with same spectrum ROMS can give outliers
→ coherence scale (White and Fornberg JFM 1998)

2. Understanding variability

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \lambda}\left(\dot{\lambda} N\right) + \frac{\partial}{\partial \phi}\left(\dot{\phi} N\right) + \frac{\partial}{\partial k}\left(\dot{k} N\right) + \frac{\partial}{\partial \theta}\left(\dot{\theta} N\right) = \frac{S}{\sigma}$$

Refraction

$$\dot{\theta} = \dot{\theta}_{DG} + \frac{\sin^2\theta}{R\cos\phi}\frac{\partial v_E}{\partial \lambda} - \frac{\cos^2\theta}{R}\frac{\partial u_E}{\partial \phi} + \frac{\cos\theta\sin\theta}{R}\left(\frac{1}{\cos\phi}\frac{\partial u_E}{\partial \lambda} - \frac{\partial v_E}{\partial \phi}\right)$$

Advection

$$\dot{\lambda} = \left(C_g \sin\theta + a\, u_E\right) / \left(R\cos\phi\right),$$

$$\dot{\phi} = \left(C_g \cos\theta + a\, v_E\right) / R,$$

« bunching »

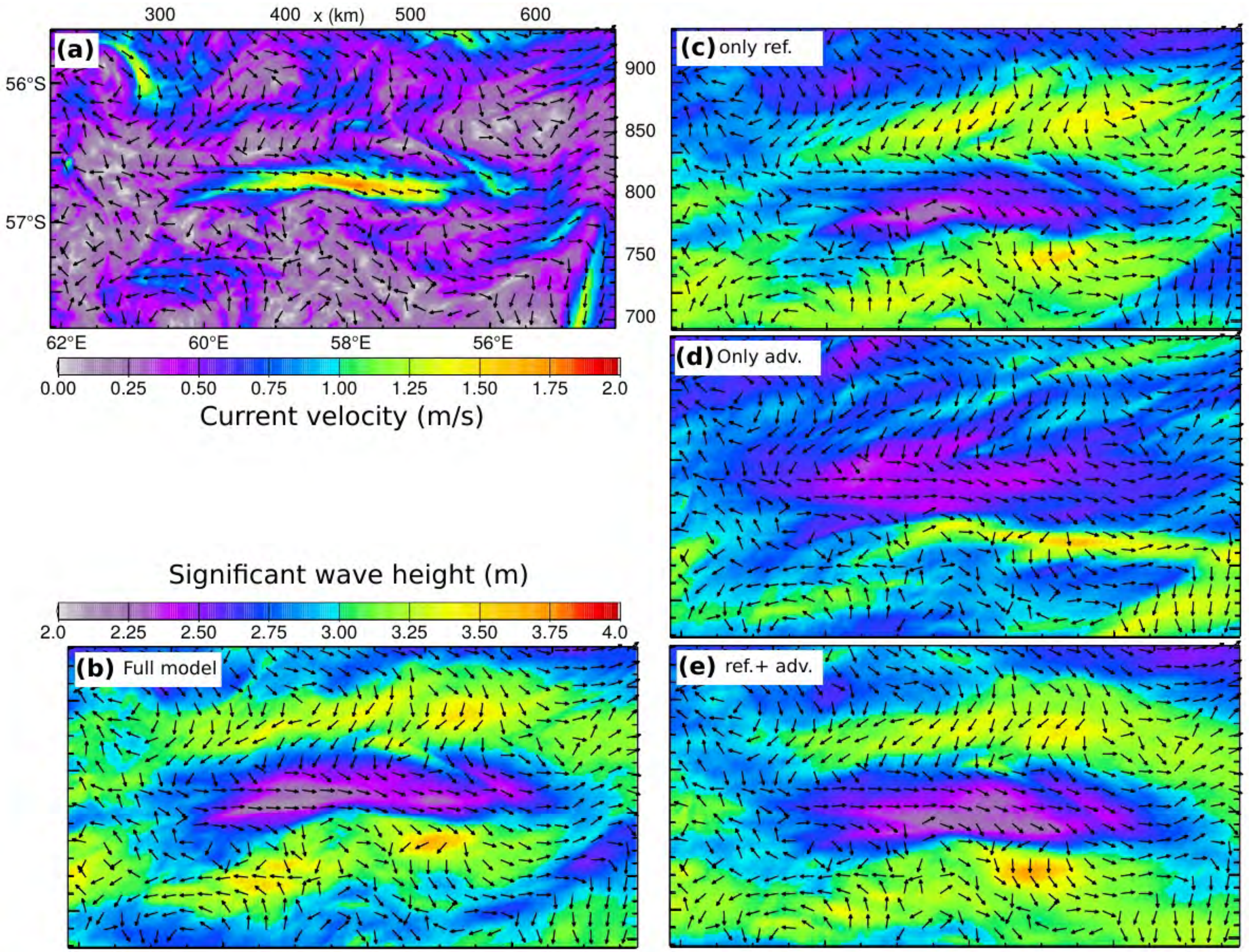
$$\dot{k} = -\frac{\partial \sigma}{\partial D}\frac{\mathbf{k}}{k}\cdot\nabla D - \mathbf{k}\cdot\nabla\, \boldsymbol{u}_E.$$

+ relative wind + effect of dissipation (steepness dependent)

2. Understanding variability

Scales > 20 km :
Refraction dominates

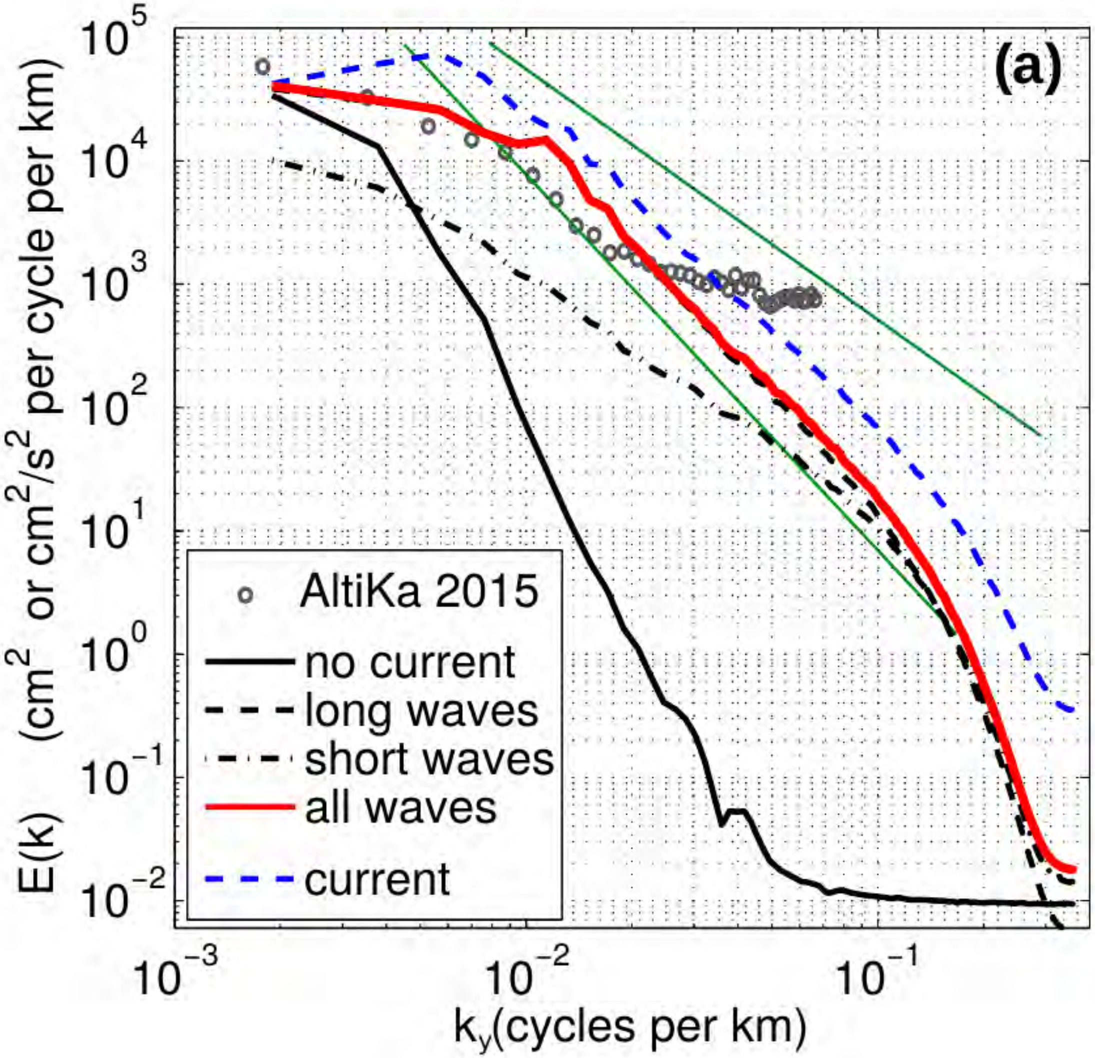
Scales < 20 km :
Advection dominates



3

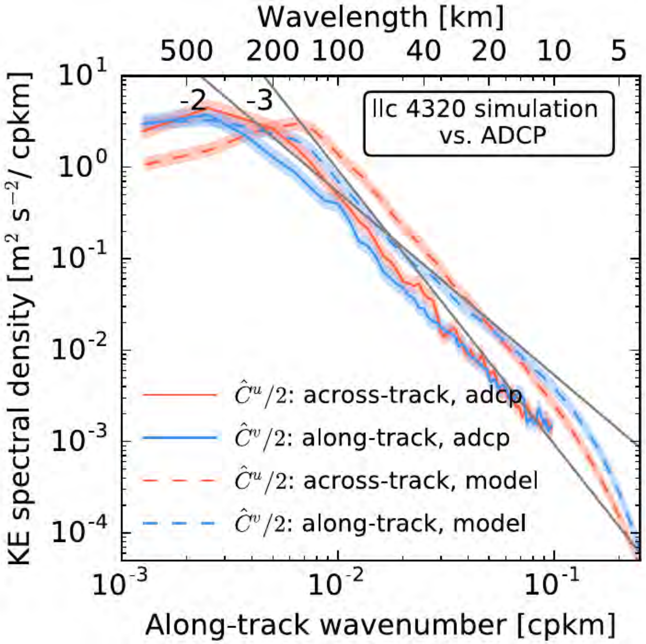
Model validation : from nearshore to large scales

3. Model validation : from nearshore to large scales



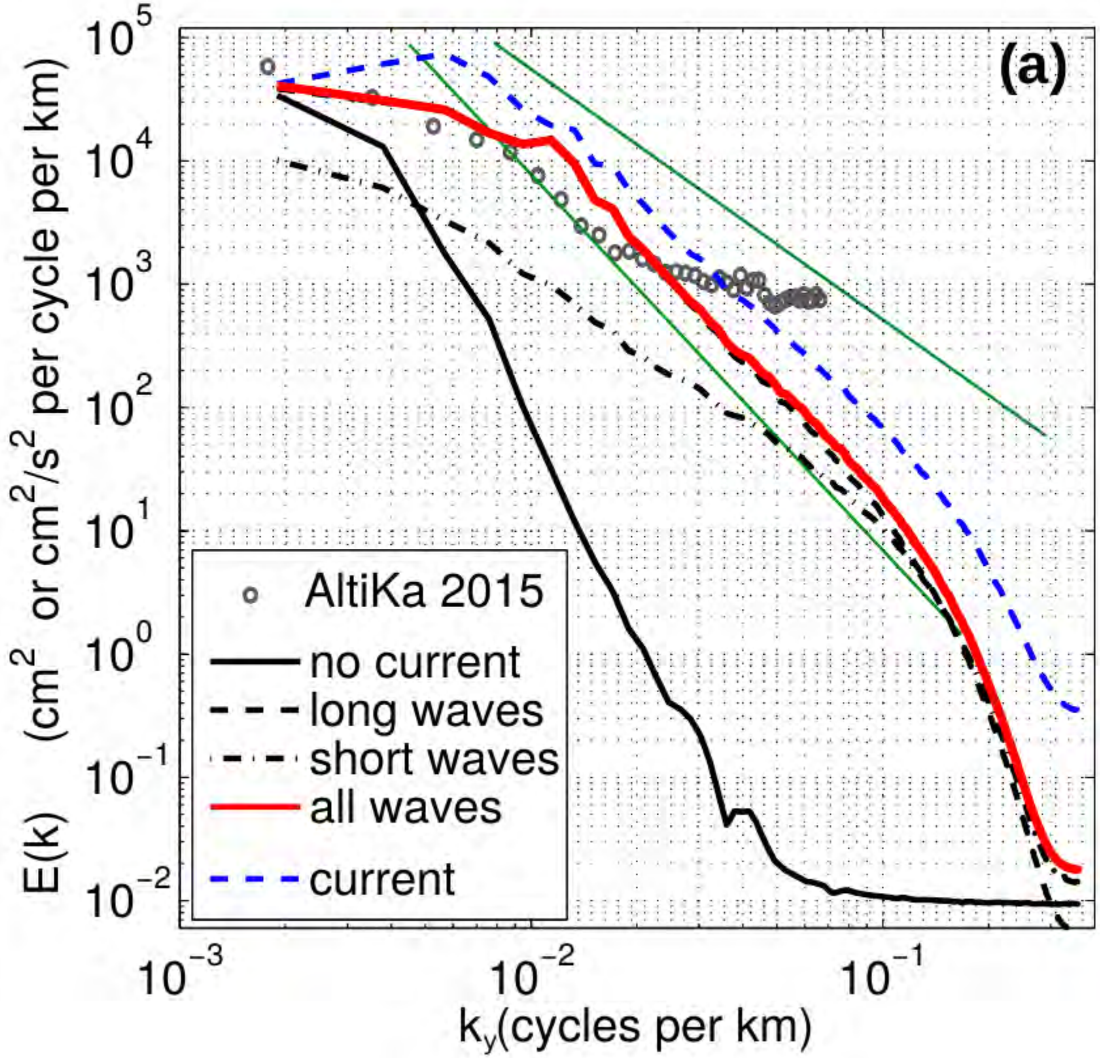
So how good are these modelled SWH spectra ?

Taking 1 year of AltiKa data in Drake passage
(« validated » by Rocha et al. 2016) **:**
k^{-3} from 120 to 80 km



From Rocha et al. (JPO 2016)

3. Model validation :
from nearshore to large scales



So how good are these modelled SWH spectra ?

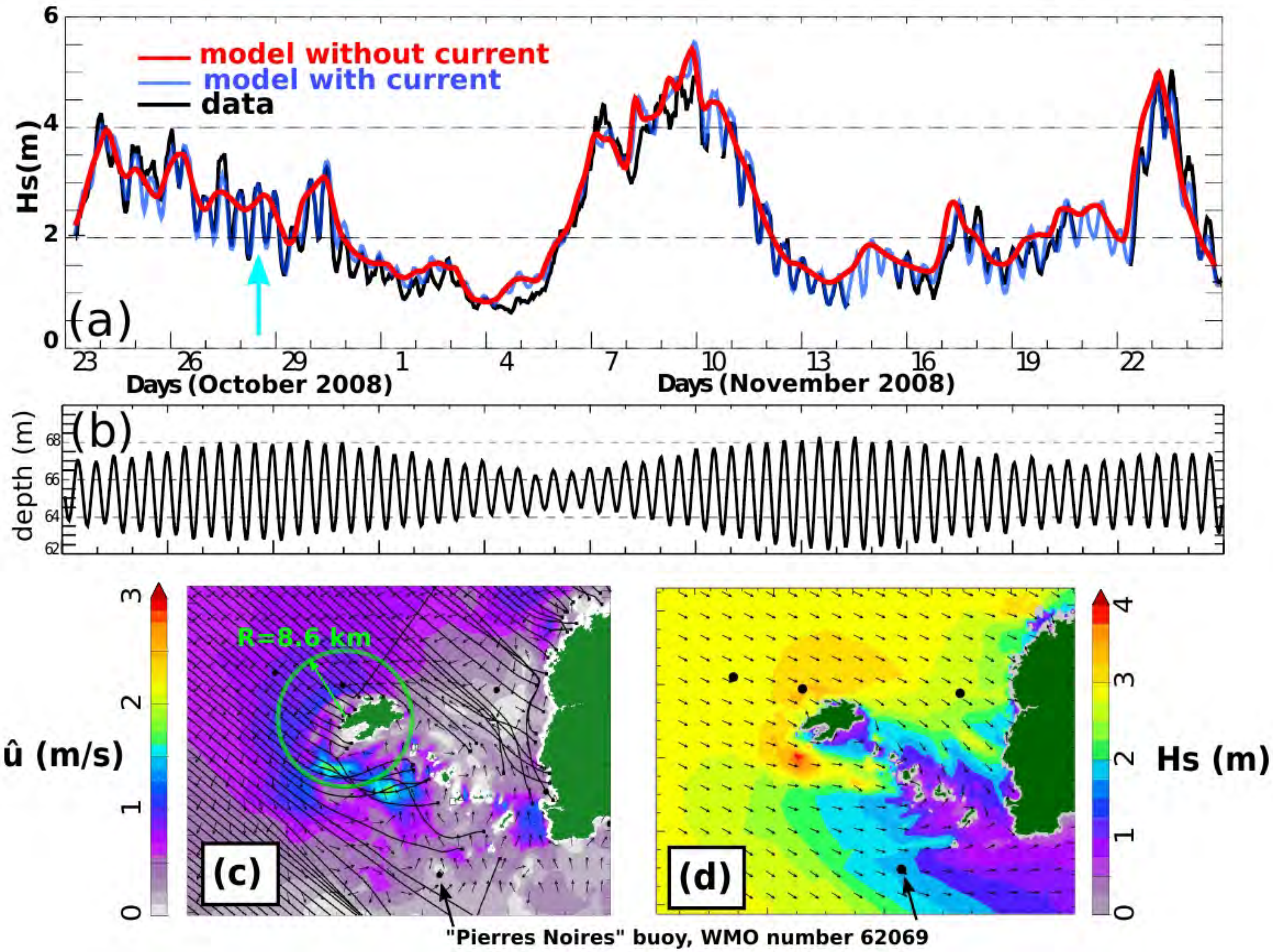
Taking 1 year of AltiKa data in Drake passage
(« validated » by Rocha et al. 2016) **:**
k^{-3} from 120 to 80 km

Can we go to shorter scales ?
- **Work in progress (Jason 3 PEACHI…)**

… still on the learning curve on MLE3 or 4 and other things…

3. Model validation :
from nearshore to large scales

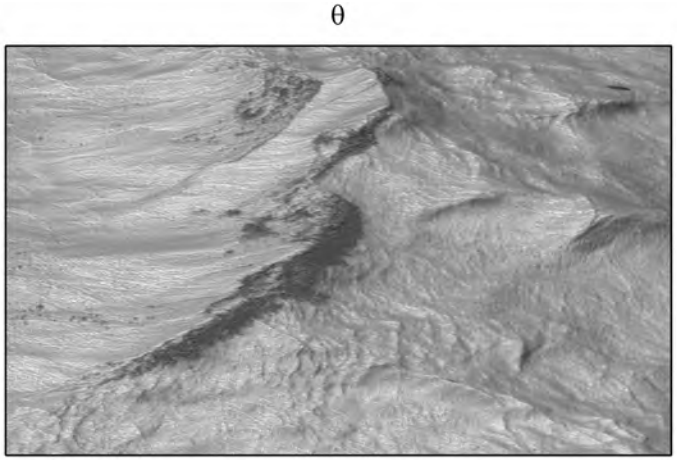
Wave model forced by tidal currents (validated with HF radar) is pretty good for refraction (Ardhuin et al. JPO 2012)

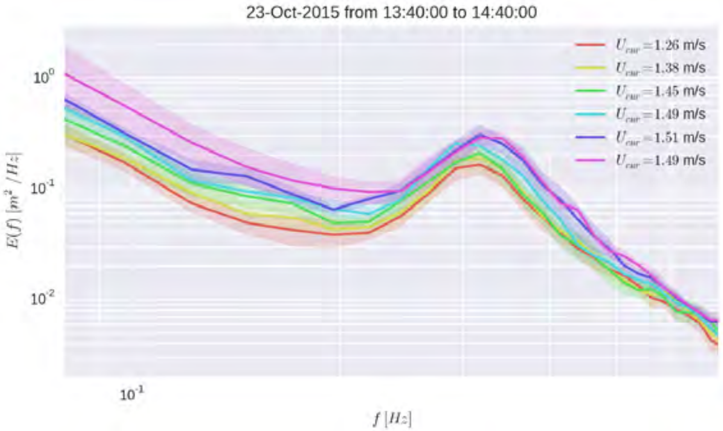


3. Model validation :
from nearshore to large scales

Uncertainties with current-induced wave breaking :
Target of « broadband waves » experiments (2015, 2016 …)

- drifting buoys   (Guimaraes et al., in preparation)
- polarimetric + stereo cameras
- wind & flux measurements





4

Perspectives on waves and current studies : The SKIM proposal

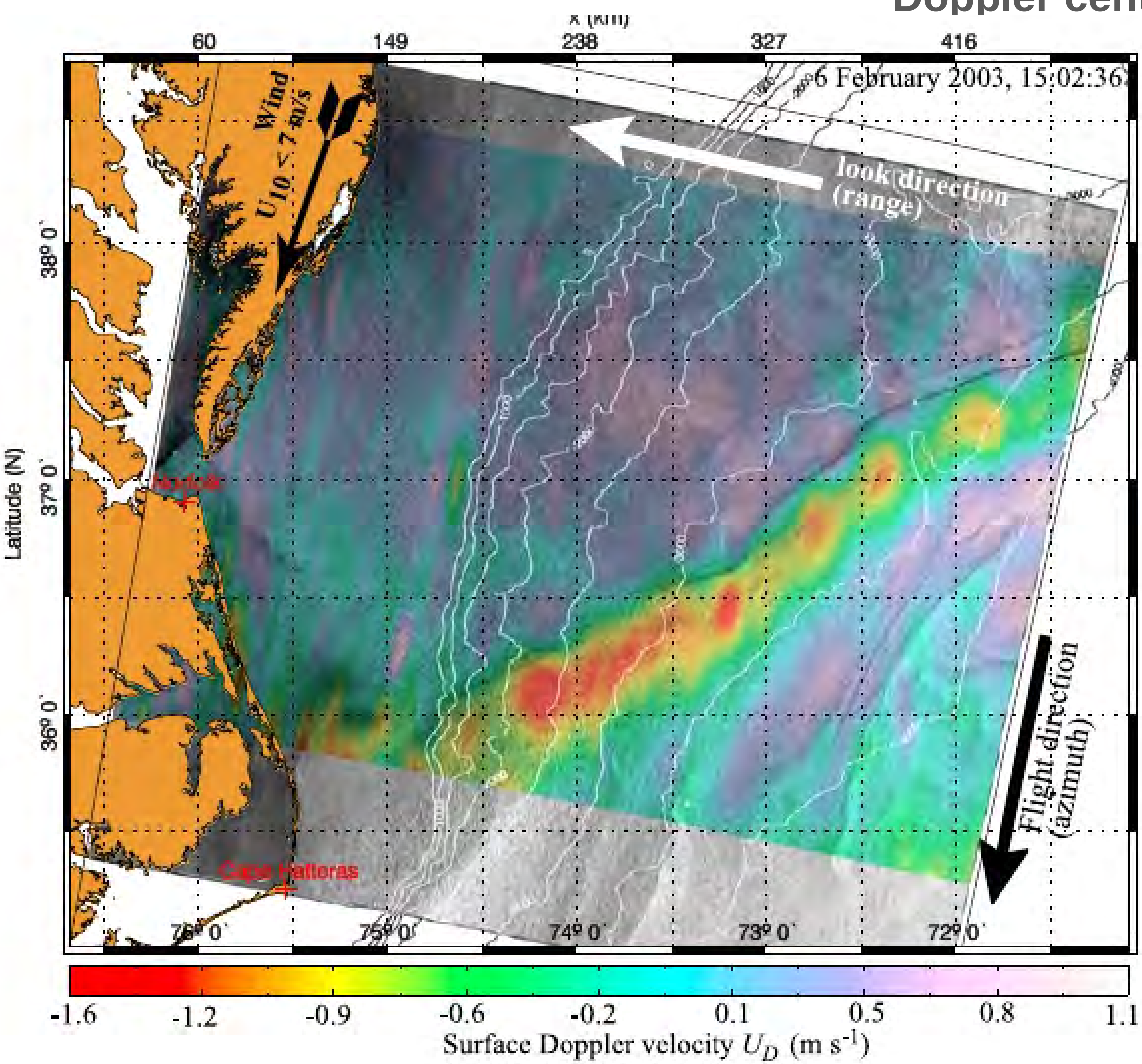
(see poster in far corner of hall)

Best data we have so far for small scale currents : HF radars

Doppler centroïd from Envisat ASAR

→ waiting for good data from S1

..

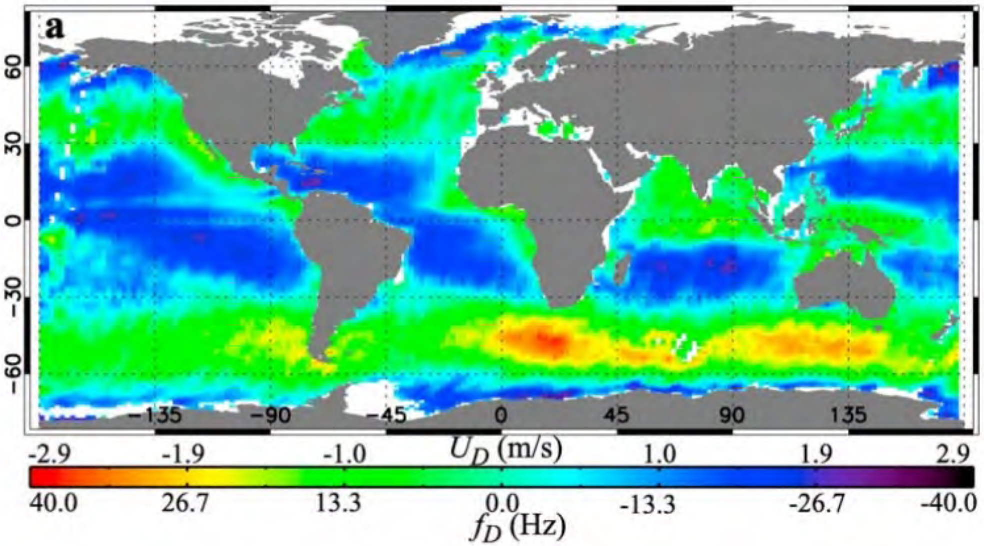


scales < 100 km :

Doppler is current in range

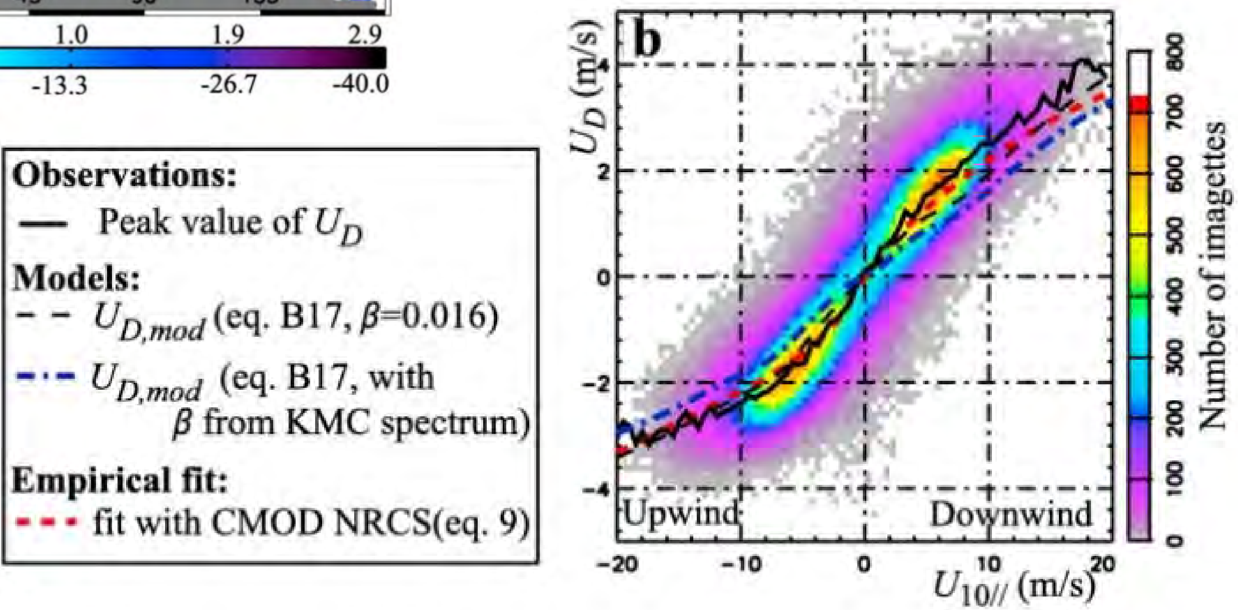
(van Der Kooij & Hughes 1997)

(Chapron et al. JGR 2005)



large scales :
Doppler is wind (through waves)

And we understand this at order 0
(Chapron et al. 2005, Mouche et al. 2012, Martin et al. JGR 2016)



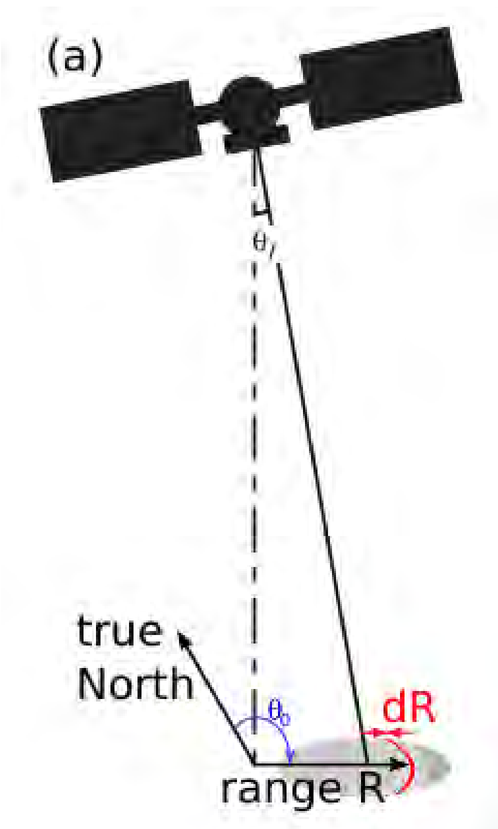
Current measurement from Doppler requires wind/wave correction : DopScat, Wavemill, SKIM...

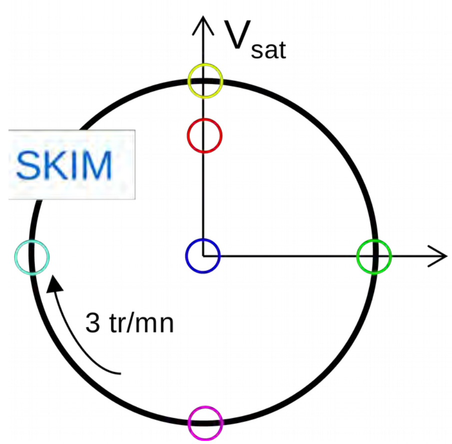
4. Perspectives on waves & currents
SKIM

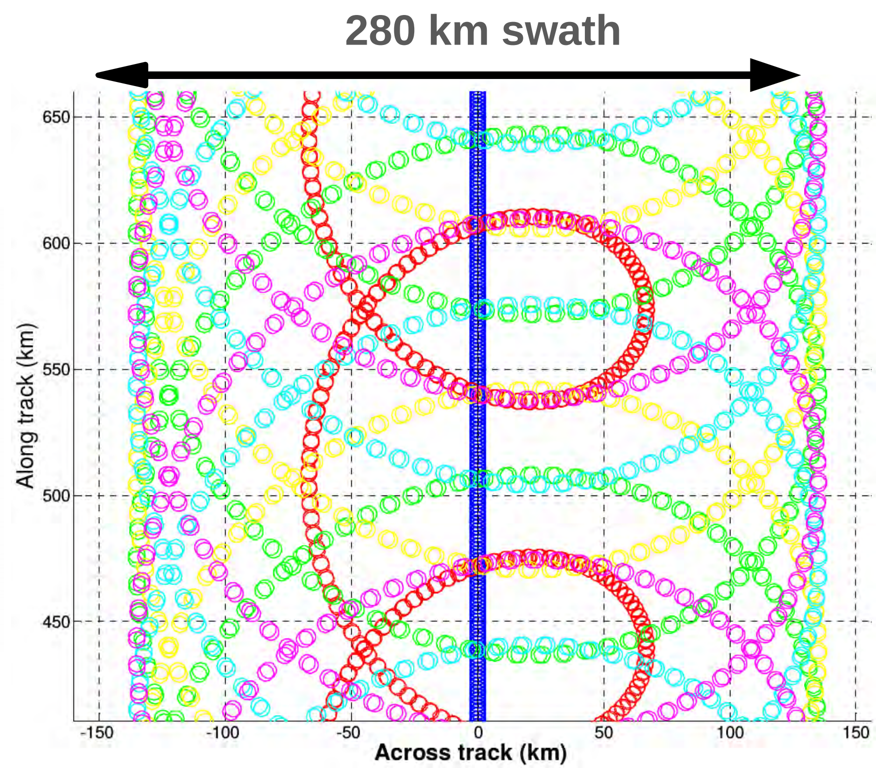
Th **S**urface **KI**nematics **M**ultiscale proposal (**SKIM**): going beyond CFOSAT & SWOT

SWIM instrument on CFOSAT →
- Ku-band → 20 km footprint
- No Doppler → **no current**
- Incidence 0 to 10°

SKIM (proposed to EE9)
- Ka-band → 6 km footprint
- Doppler bandwidth 15 kHz → **waves and currents**
- Incidence 0, 6, 12°
- Bandwidth 200 MHz (at least)
- **32 kHz PRF** → **0.1 m/s accuracy** over one footprint

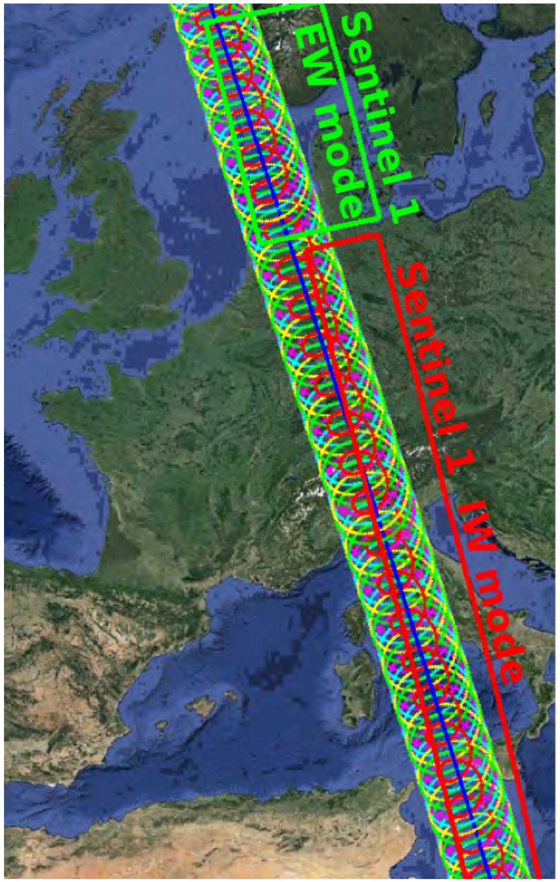


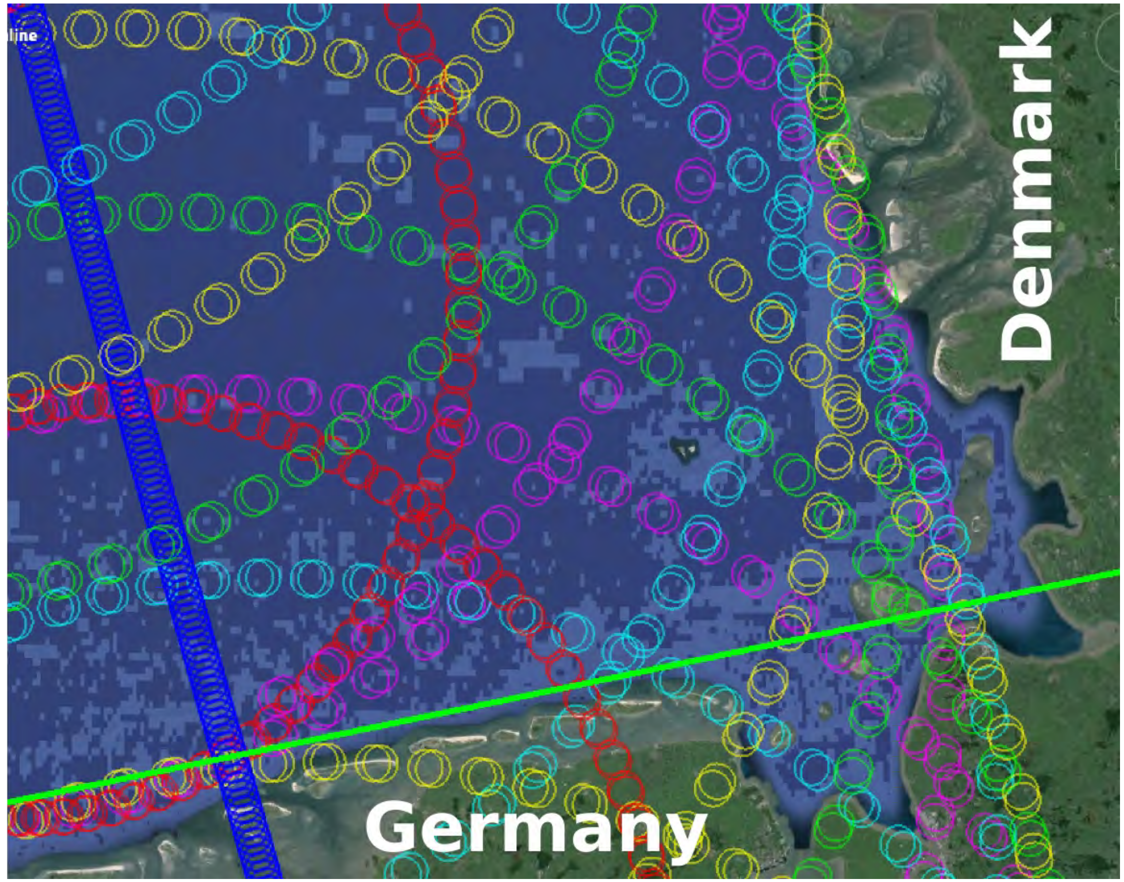




4. Perspectives on waves & currents
SKIM

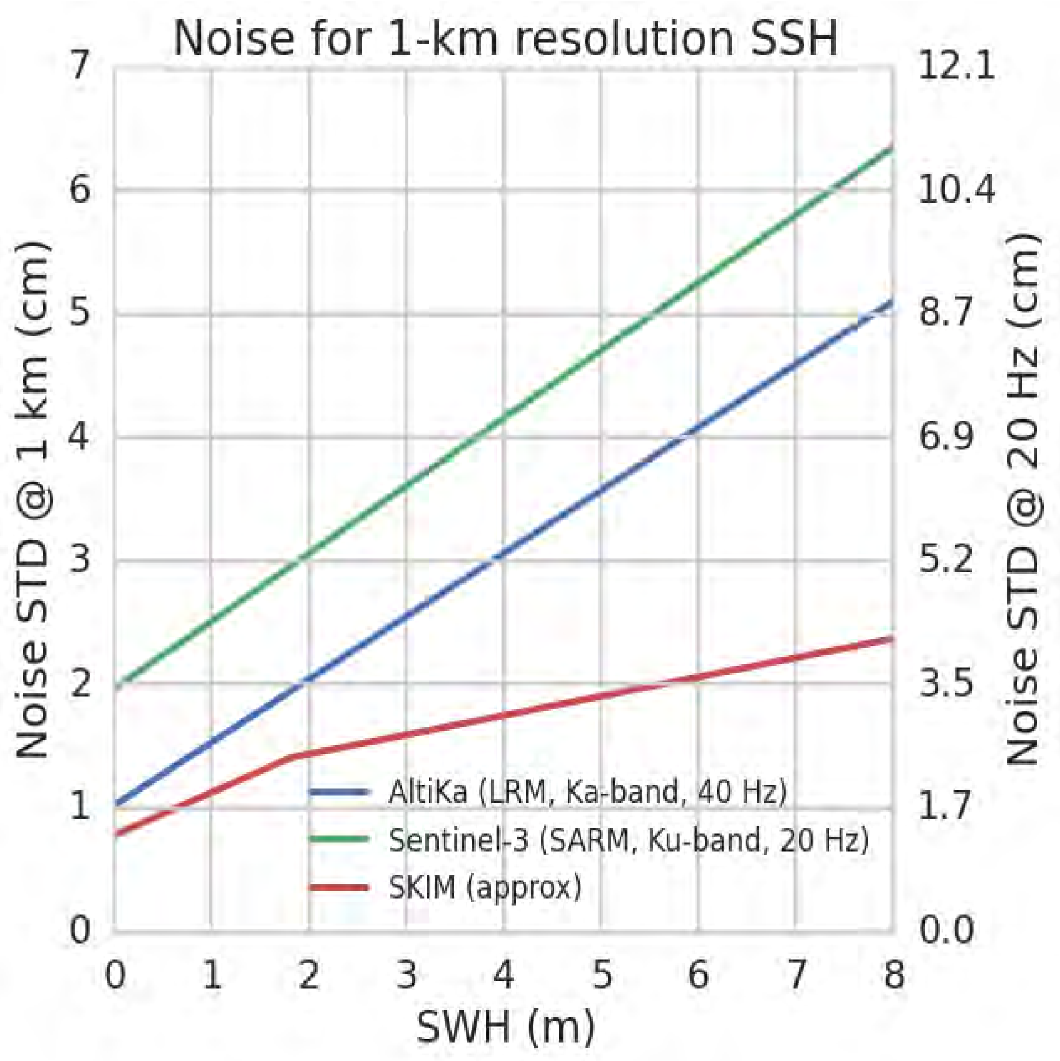
A companion to Sentinel 1 : providing wave bias corrections for Doppler centroid





4. The best-ever altimeter

Even without a radiometer on board… thanks to high bandwidth and PRF



5

Conclusions

5. Conclusions

1. At scales shorter than **100 km**, surface **currents** are the main source of **SWH variability**

   We need to rethink our view of the ocean wave field : extremes, applications ...

2. How can we futher verify this modelling result : we need **waves and current data**

   → focus in regions of well known (e.g. tidal) currents

   → in situ experiments

   → reprocessed altimeter data

   → analysis of SAR data (waves is swell + cut-off information… → SWH proxy)

   → soon CFOSAT (L2b products)

3. Consequences for SSB… later

   but warning : SSB probably varies on even shorter scales than SWH .

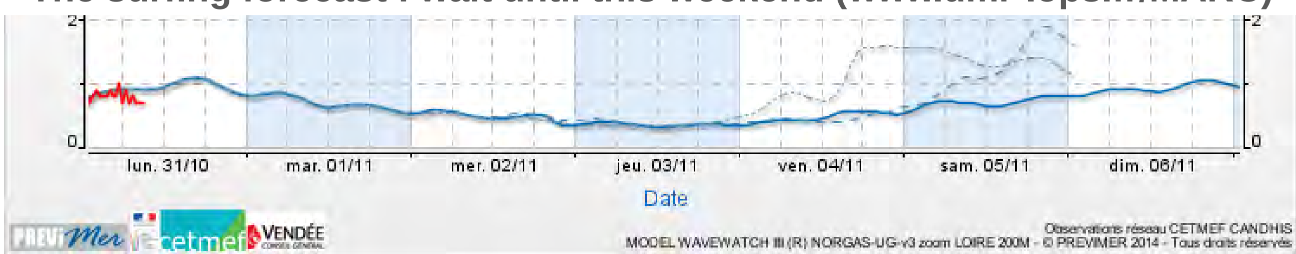
4. At some point we will need joint waves & current measurements : SKIM proposal

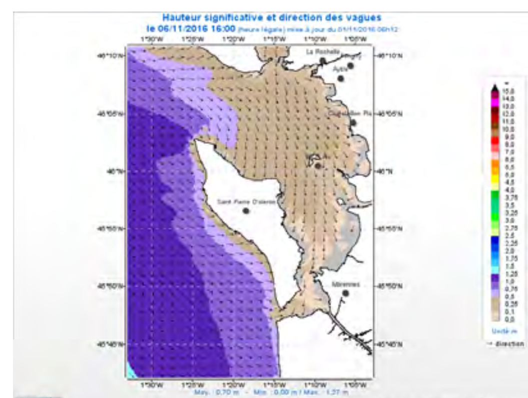
   we need your help to **get SKIM off the ground**

   https://www.facebook.com/SKIM4EE9/

   See also SKIM Project on ResearchGate

The surfing forecast : wait until this weekend (www.umr-lops.fr/MARC)





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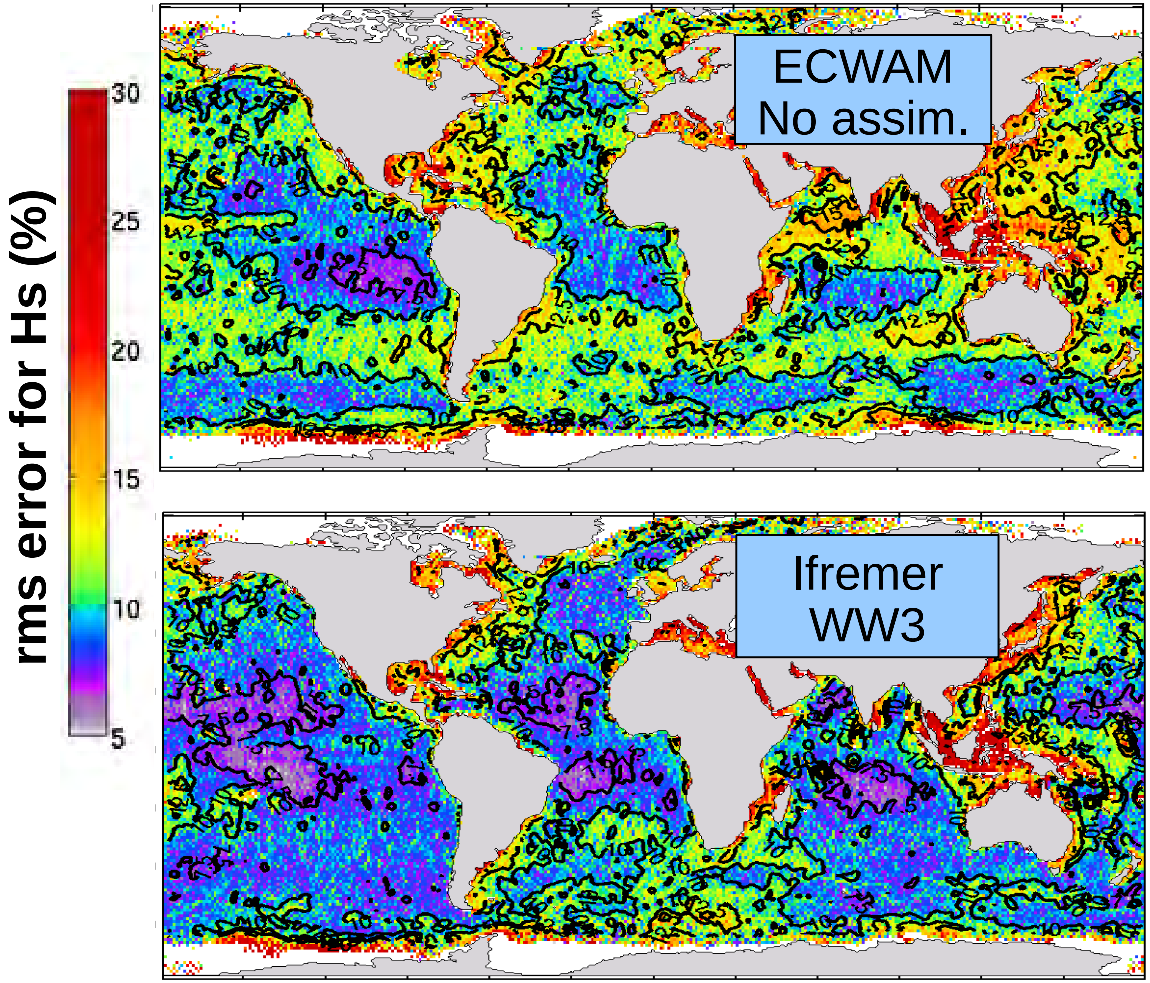
X

Bonus slides

1. Some reasons to measure waves & currents

Models are not perfect : coastal & polar regions

$$H_s \equiv H_{m0} \equiv 4\sqrt{E} = 4\sqrt{\int_0^{\infty}\int_0^{2\pi} E(f,\theta)\,d\theta\,df}$$



Errors in free model runs using ECWAM (top) and WW3 (bottom) for ***free runs, Year 2009***

→ ***large errors*** *at short fetch possibly due to weak wave-age dependence in wind stress*

→ ***wave-currents***

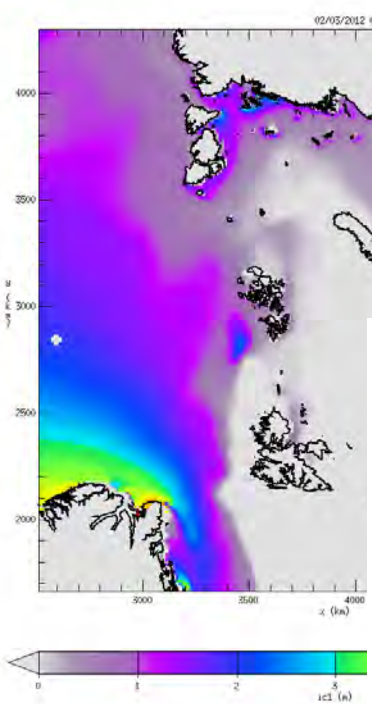
→ ***wave -ice …***

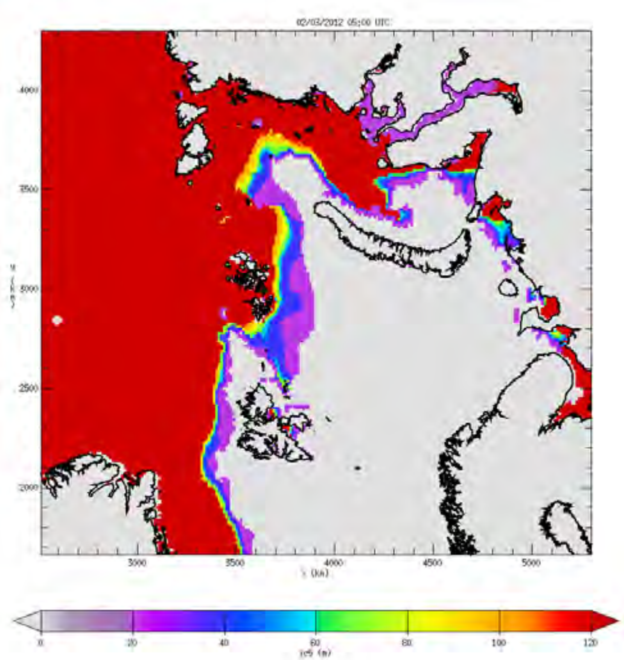
THIS IS ONLY HS !!!

Getting into sea ice:

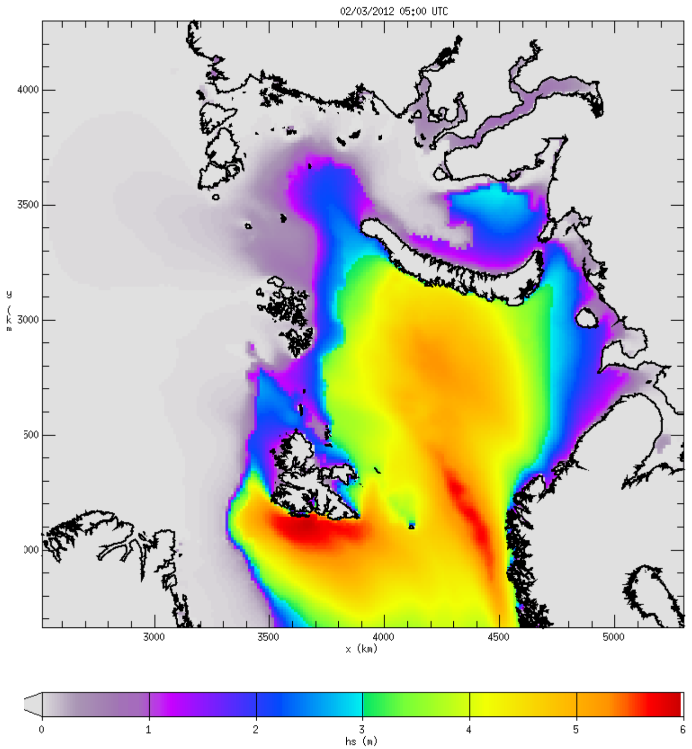
Hindcasts & forecasts for FP7 project « SWARP »

Ice thickness from TOPAZ





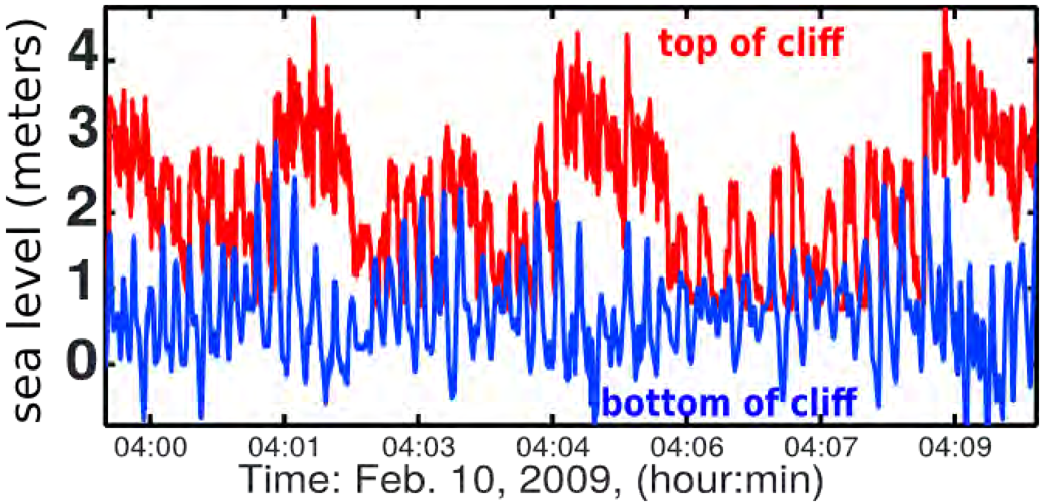
Maximum floe diameter (WW3)



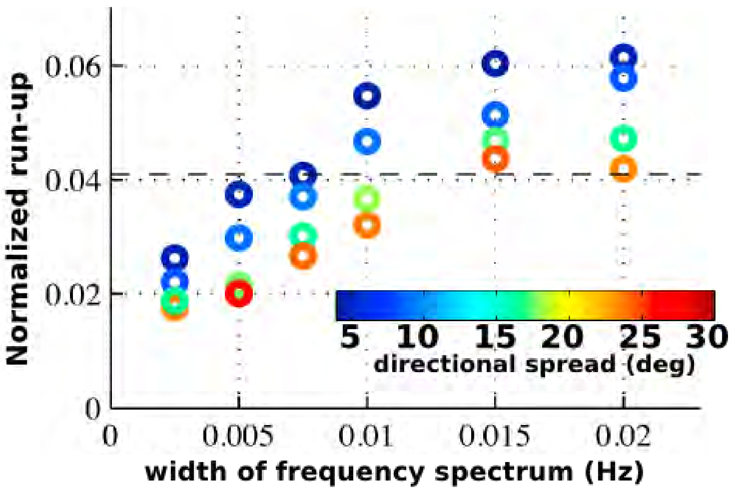
Hs (1 to 6 m)

Models are not perfect : coastal & polar regions

Shape of offshore wave spectrum → maximum water level



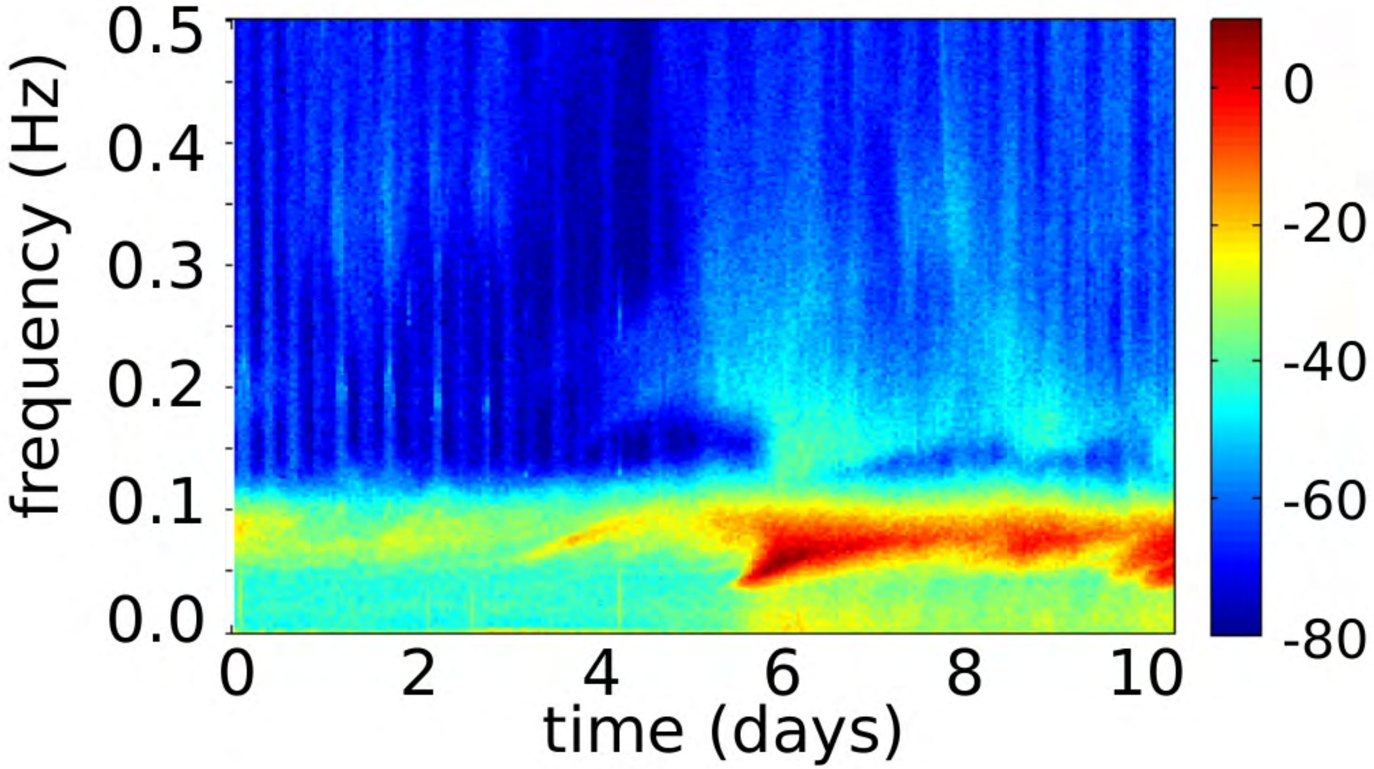
Sheremet et al. (GRL 2014)



Guza & Feddersen (2012)

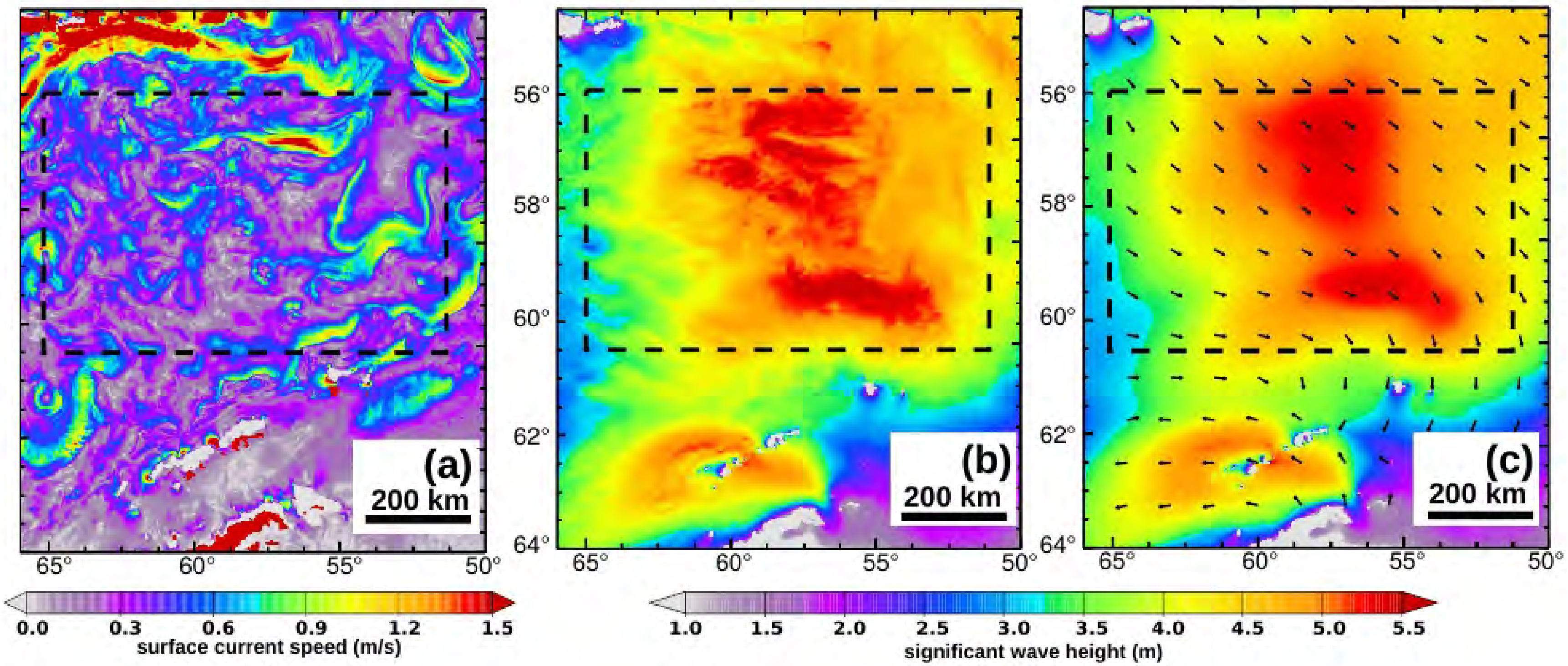
1. Some reasons to measure waves & currents
Sources of microseisms & microbaroms

Example BPR record from BBWAVES 2015



1. Some reasons to measure waves & currents
High-res variation in waves comes from currents

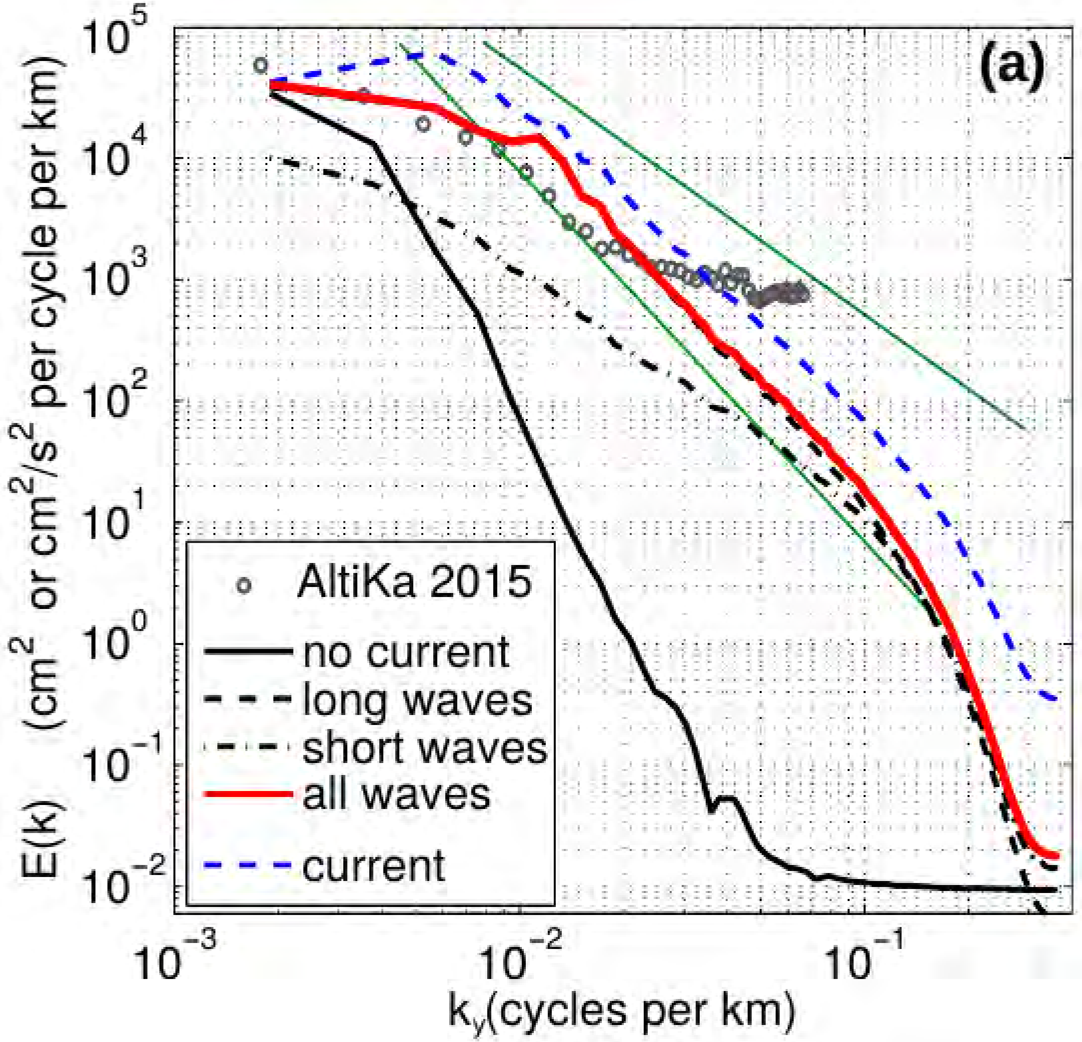
Unknown variations of waves at small scales



Ardhuin et al. (Submitted)

High-res variation in waves comes from currents

Unknown variations of waves at small scales

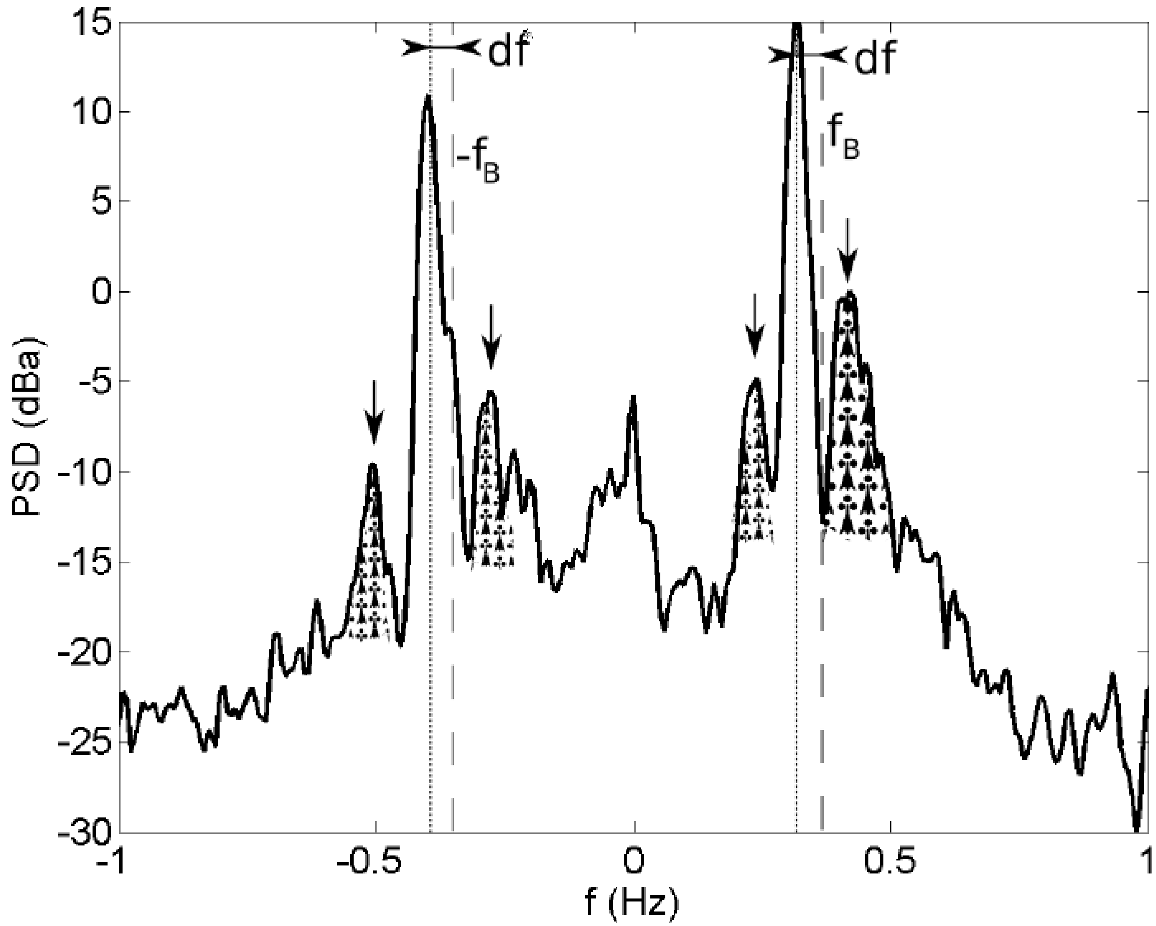


Ardhuin et al. (Submitted)

2. Doppler measurements : Wave directions and currents

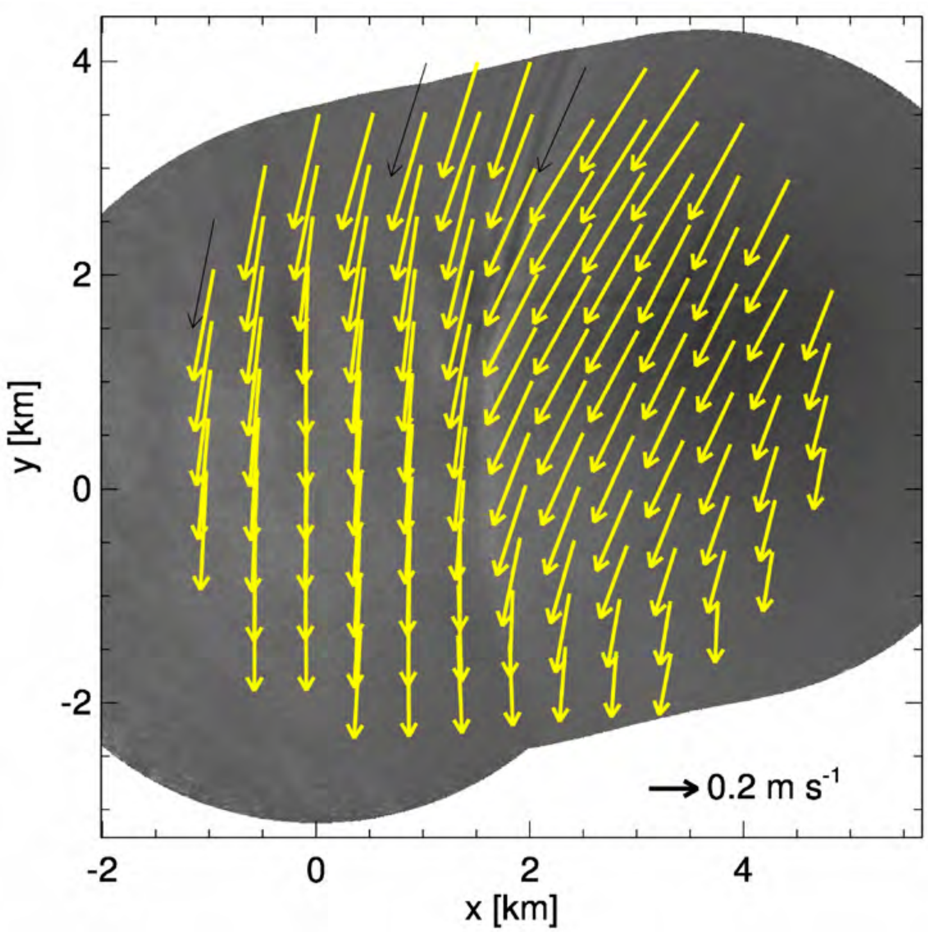
HF (coastal) radars : radio waves are scattered by the random wave field

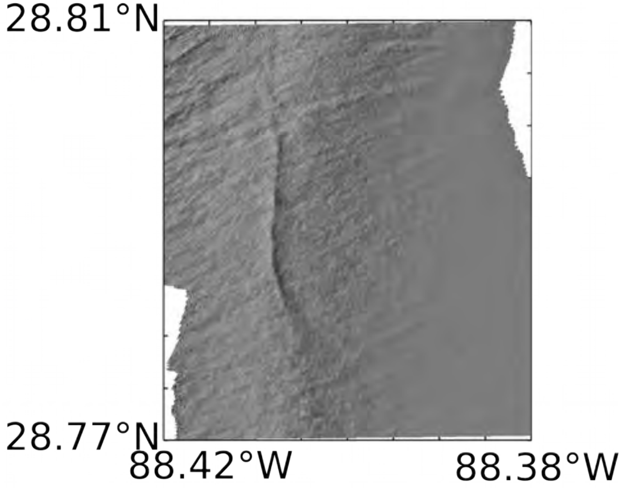
Example Doppler spectrum : measurement of wave phase speed → current component



2. Doppler measurements :
Wave directions and currents

Without doppler, other possibilites
X-band radar : current vector   (courtesy of B. Lund and N. Rascle)

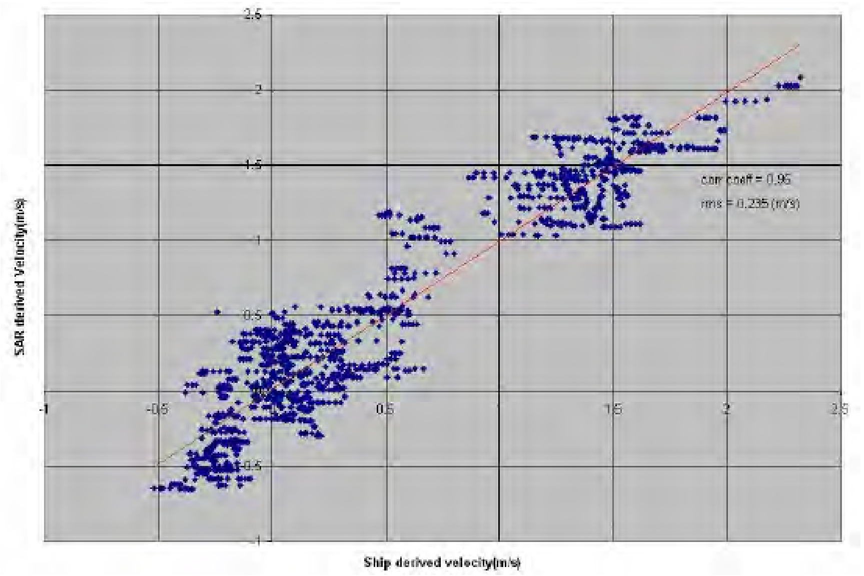


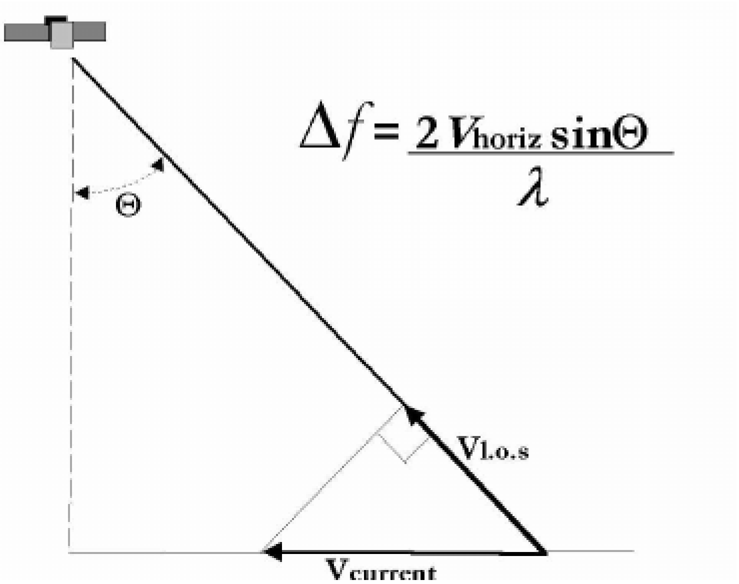


2. Doppler measurements : Wave directions and currents

Doppler from space … many experiments (interferometry ATI)… needs 2 SAR antennas…

But with only 1 antenna… there is also the Doppler centroïd ! (van der Kooij et al. 1997, 2001)



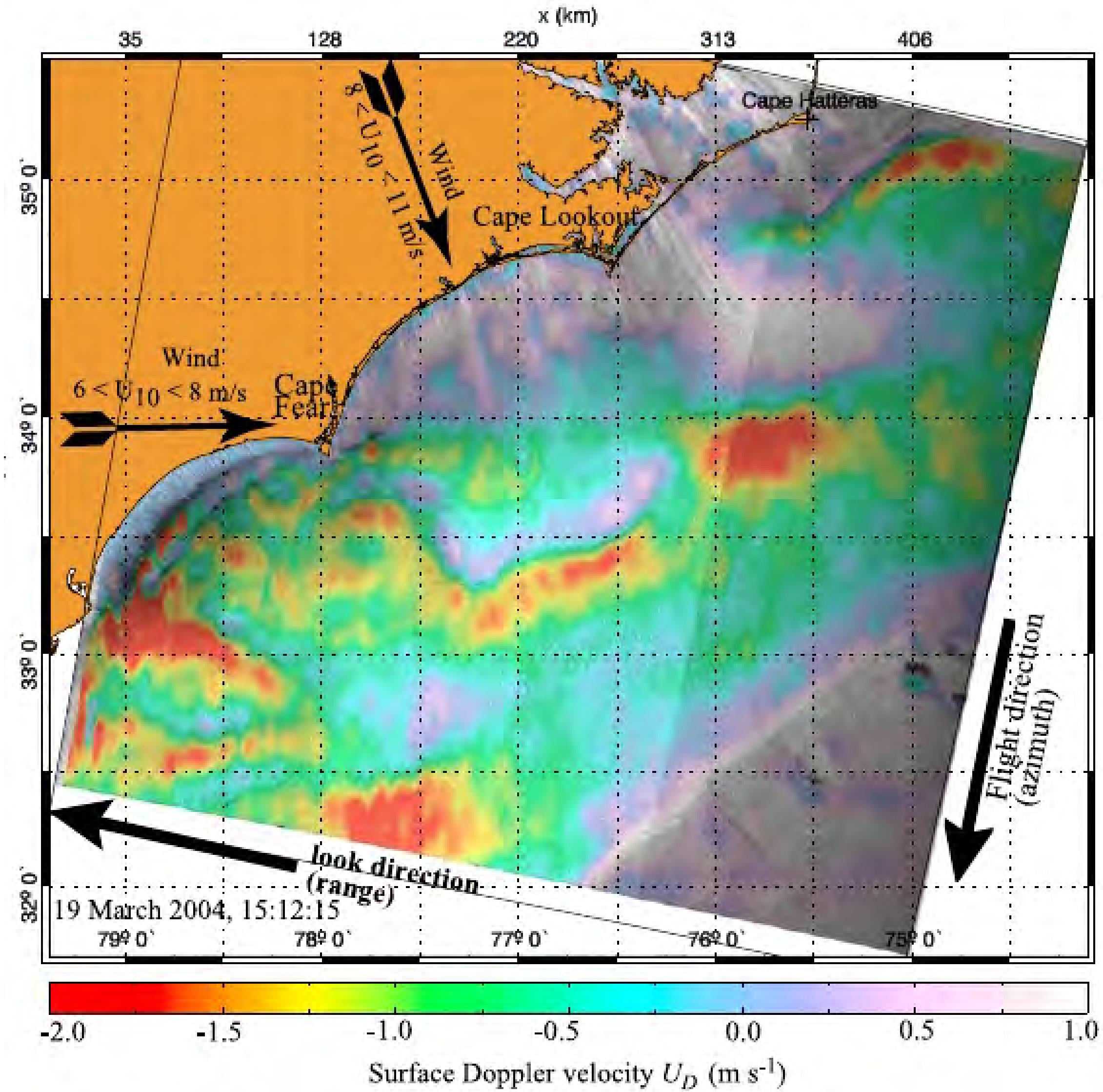


« It is recommended that the use of a wave model is evaluated to take into account the frequency shifts caused by wind-driven capillary and gravity waves. It is also recommended to consider the creation of a more refined frequency shift model for non-moving surface. »
(van der Kooij et al., 2001)

2. Doppler measurements :
Wave directions and currents

Pretty pictures and number crunching : Envisat images with different modes

Chapron et al. (2005)



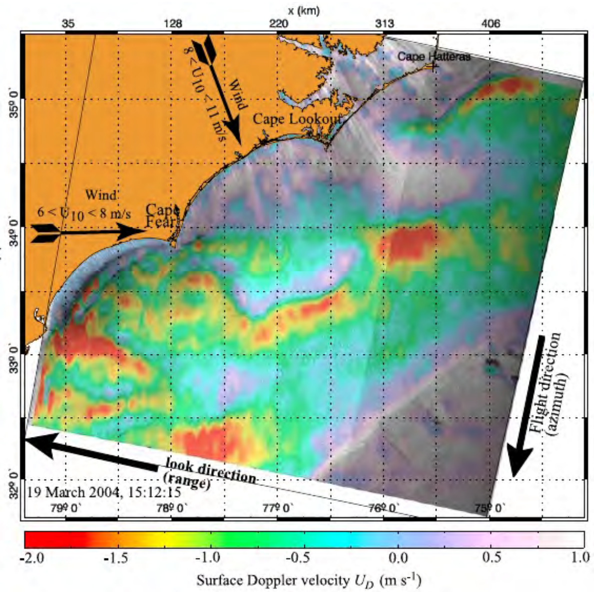
Doppler is current

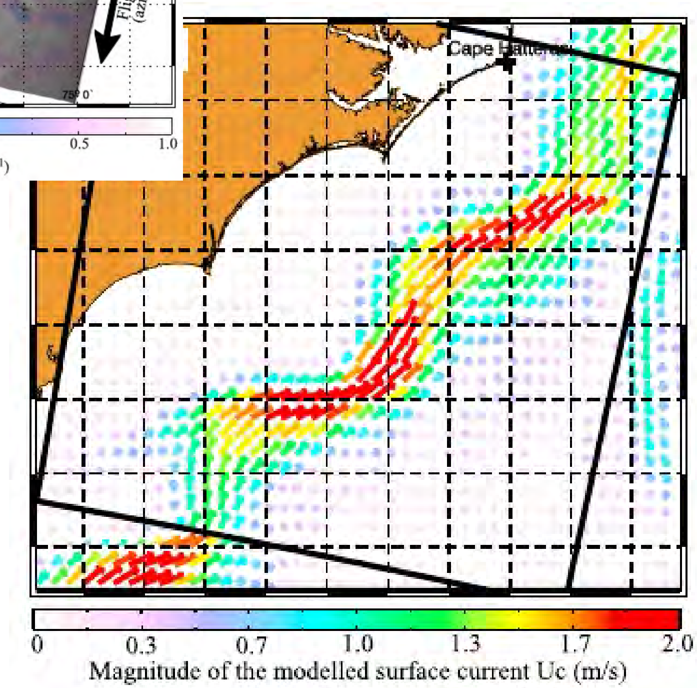
2. Doppler measurements :
Wave directions and currents

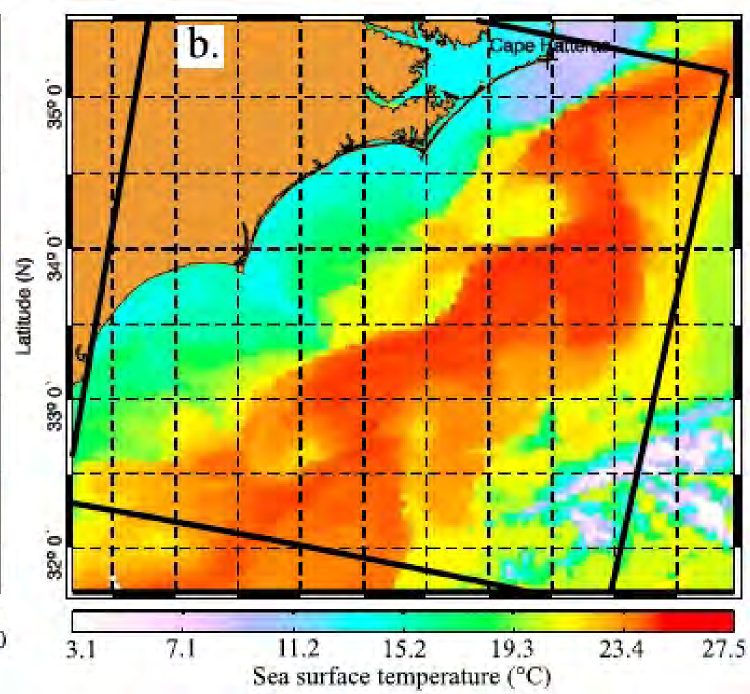
Pretty pictures and number crunching : Envisat images with different modes

Chapron et al. (2005)

Doppler is current

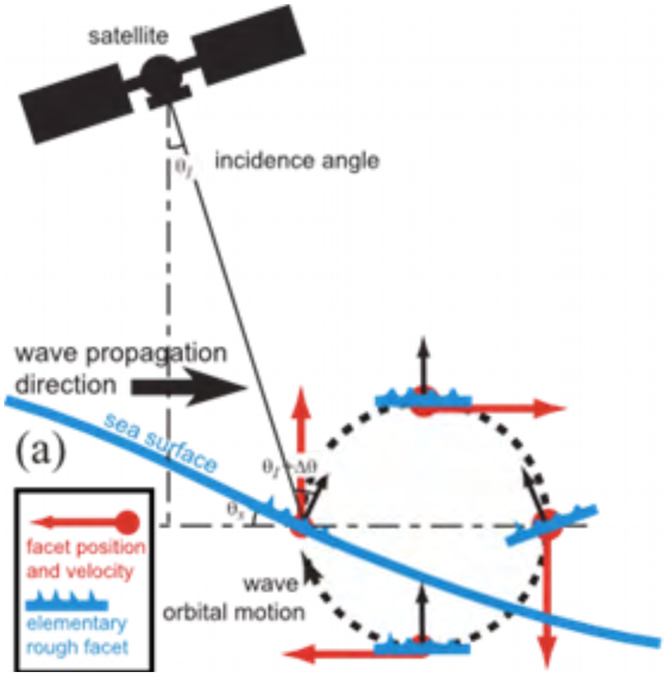


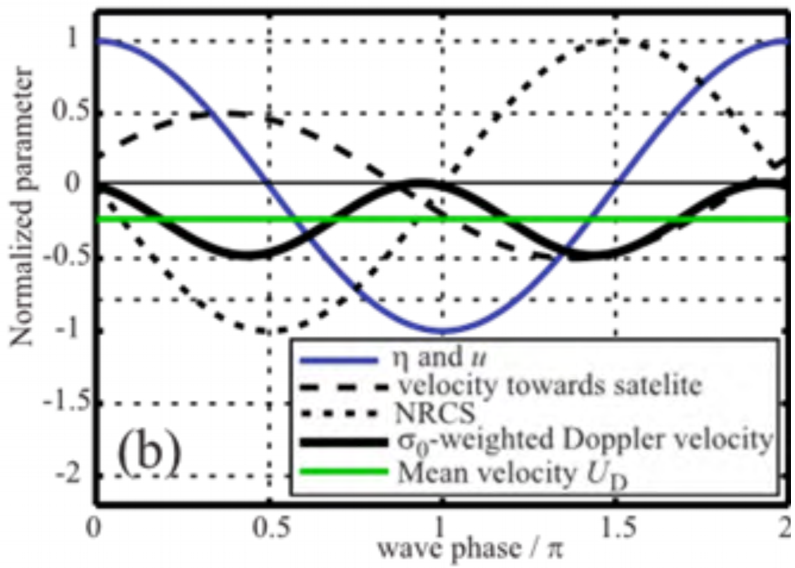




2. Doppler measurements : Wave directions and currents

… and a conceptual model …





OK, this was 12 years ago.

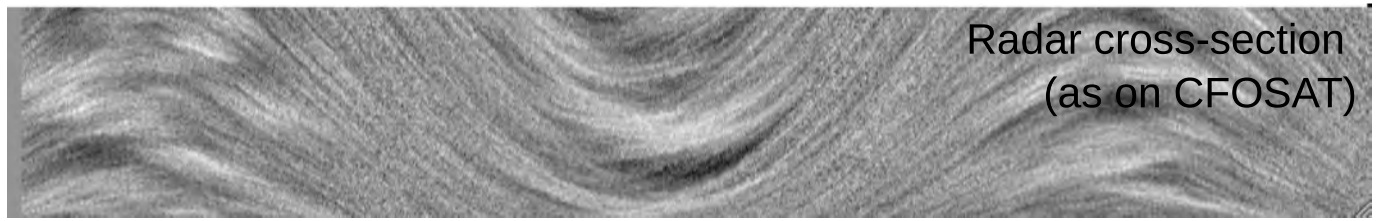
→ refinements by Mouche et al. (C-DOP...)
- → new scatterometer designs
- → mission proposals for new satellites
- → Earth Explorer 9

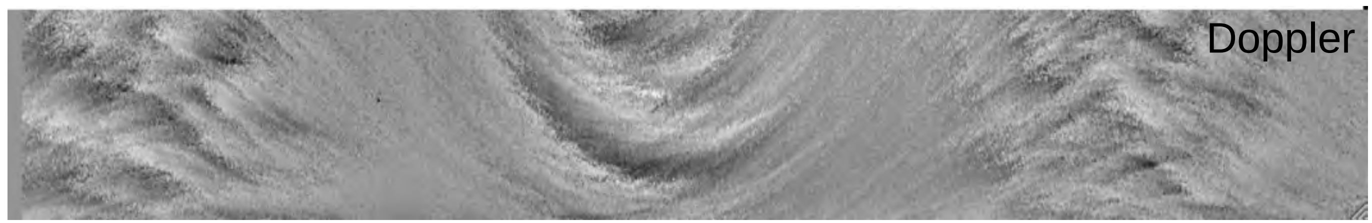
2. Doppler measurements :
Wave directions and currents

Recent data from KuROS : Doppler gives wind + waves + currents

Azimuth (look direciton) →

Range





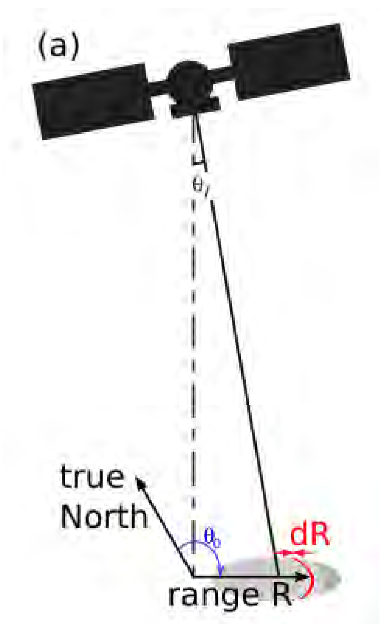
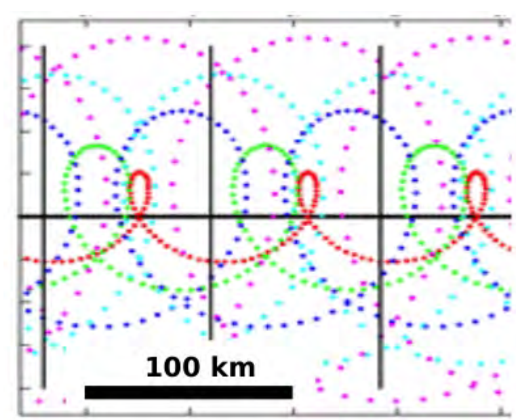


Figure by D. Hauser and G. Caudal

Geometry on CFOSAT :

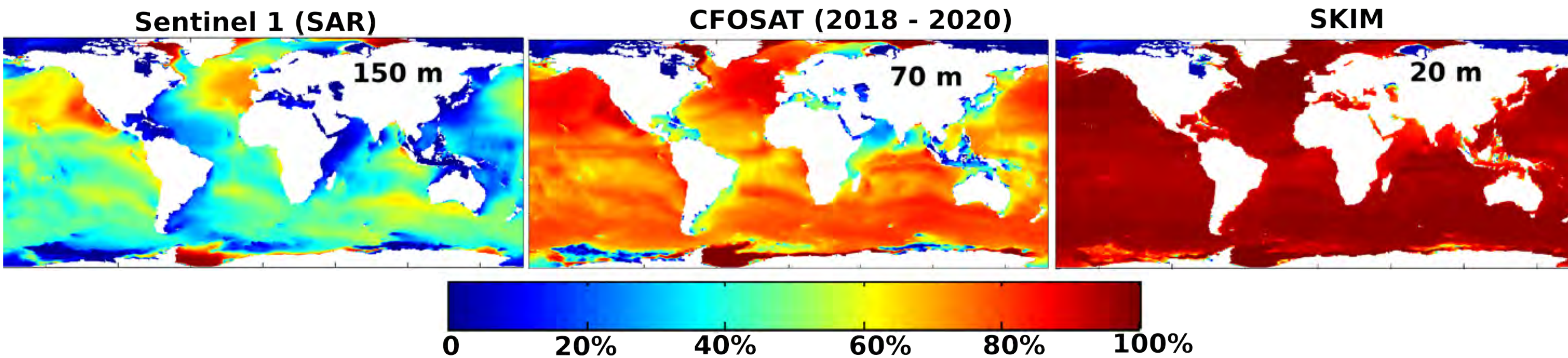


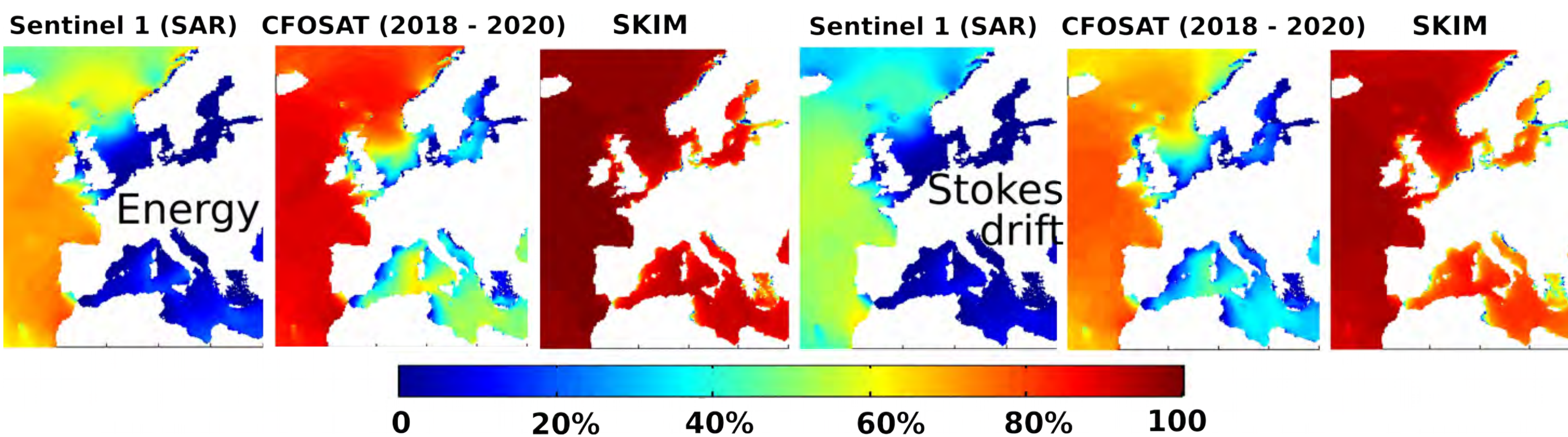
3

We can do better : SKIM
A speed gun in orbit

3. We can do better : SKIM

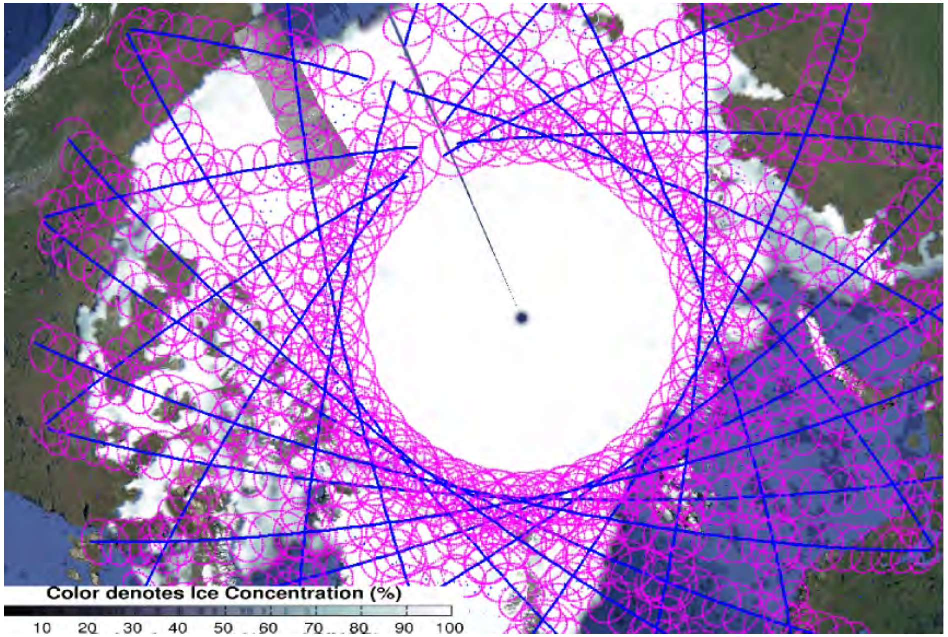
Measuring shorter waves than CFOSAT : fraction of resolved wave energy

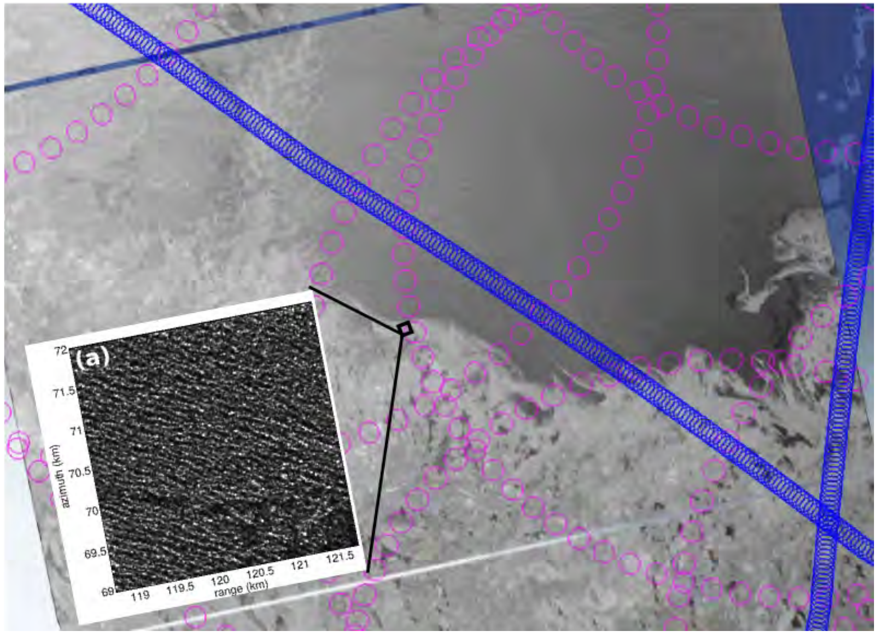




3. We can do better : SKIM

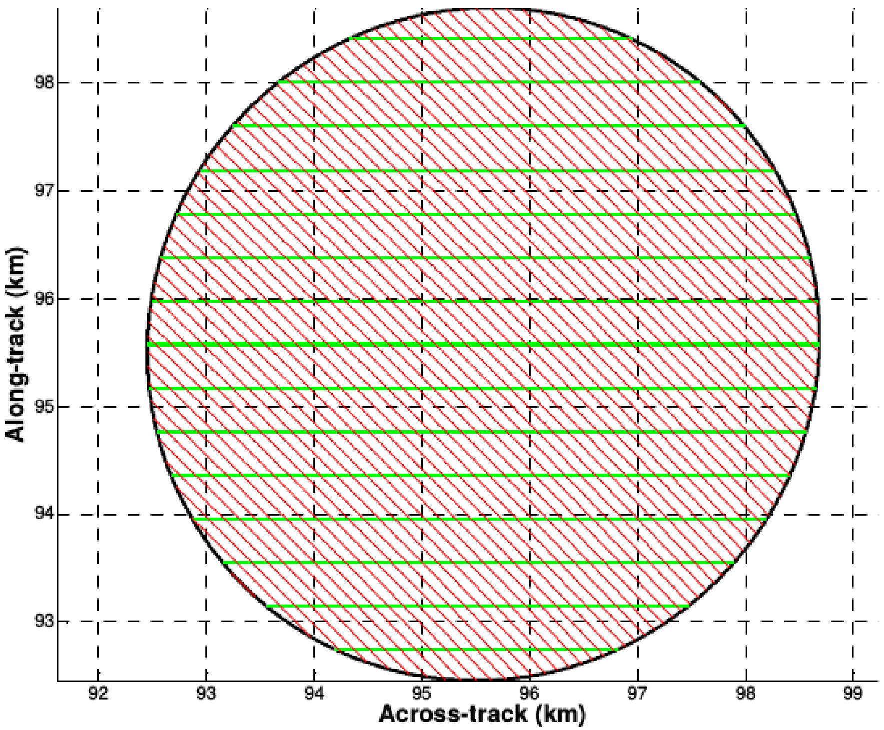
Choice of orbit : A companion to Sentinel 1 (1C and 1D)

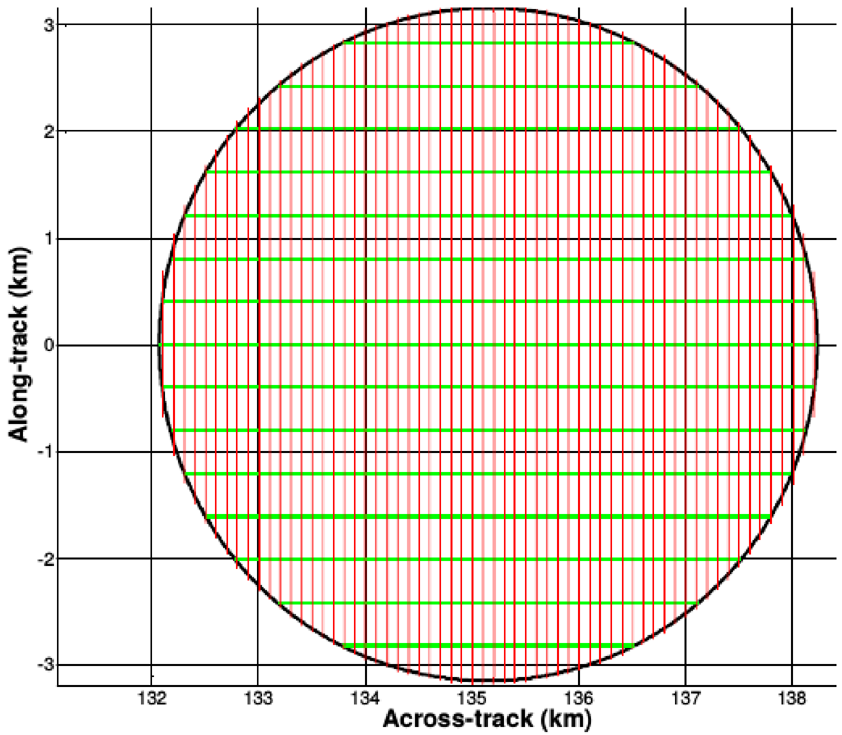




3. We can do better : SKIM

Sub-footprint resolution : unfocused SAR



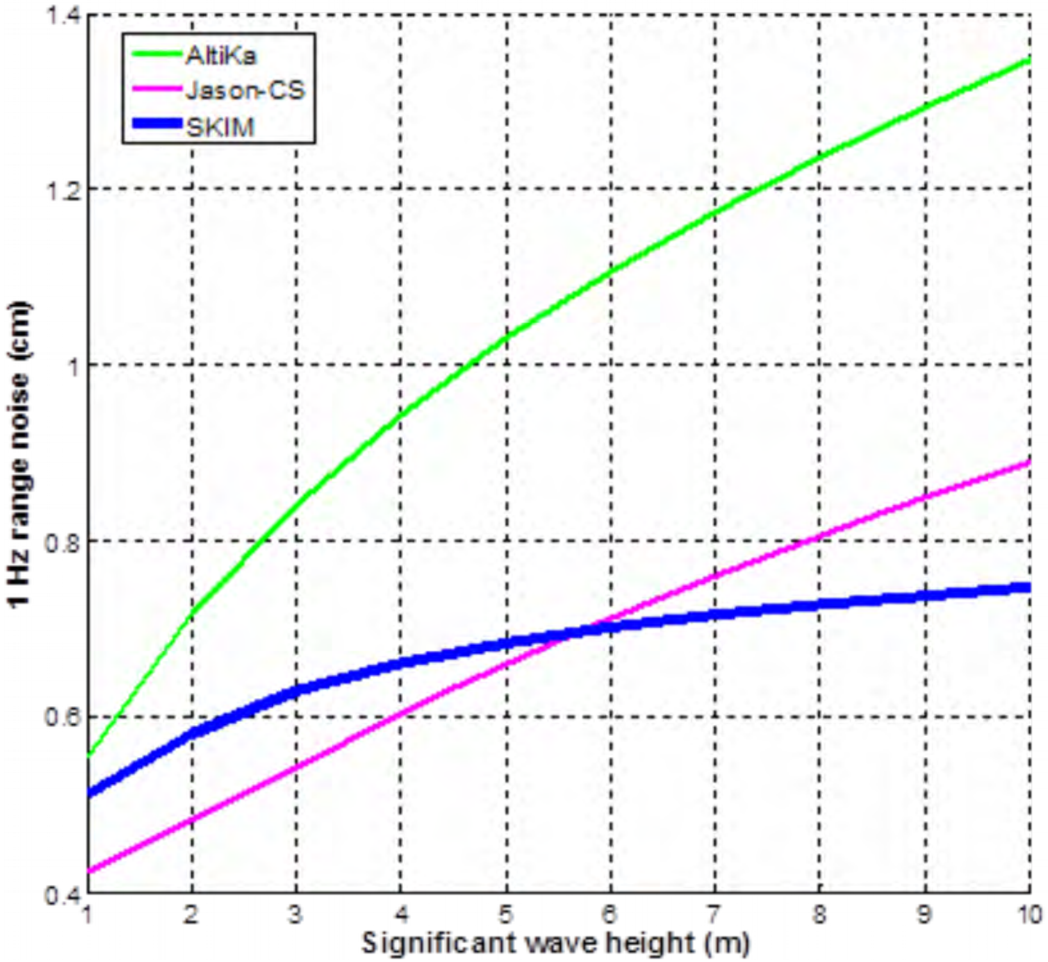


4

The best-ever altimeter Combined with an HF radar in space

4. The best-ever altimeter

It's all about PRFs …



4. The best-ever altimeter

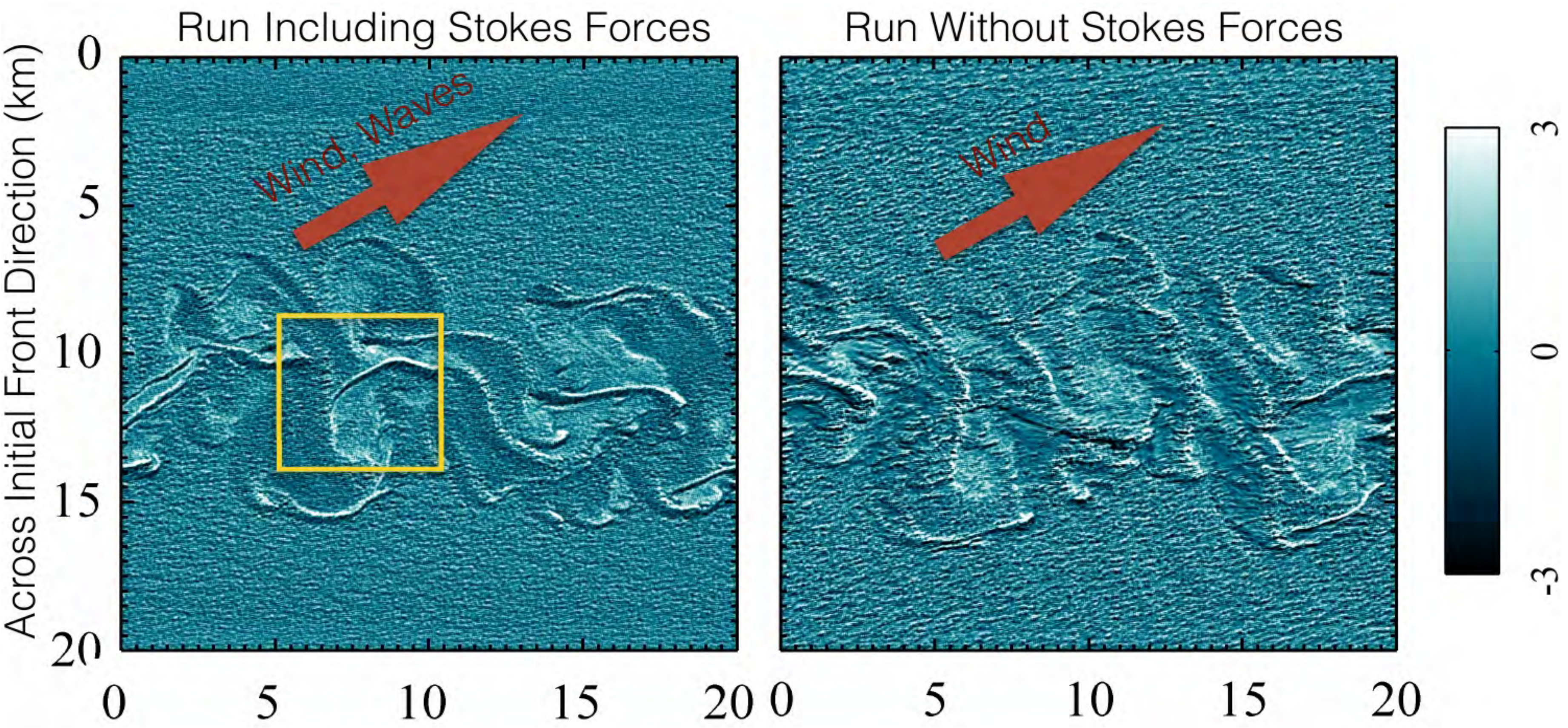
And SKIM is the ideal occation to measure the sea state bias…

… and it will really measure currents
(including wave corrections, which are small at 12°)

So it is the right time to build and launch SKIM.

… OK, now we need to find the 120 M€ …

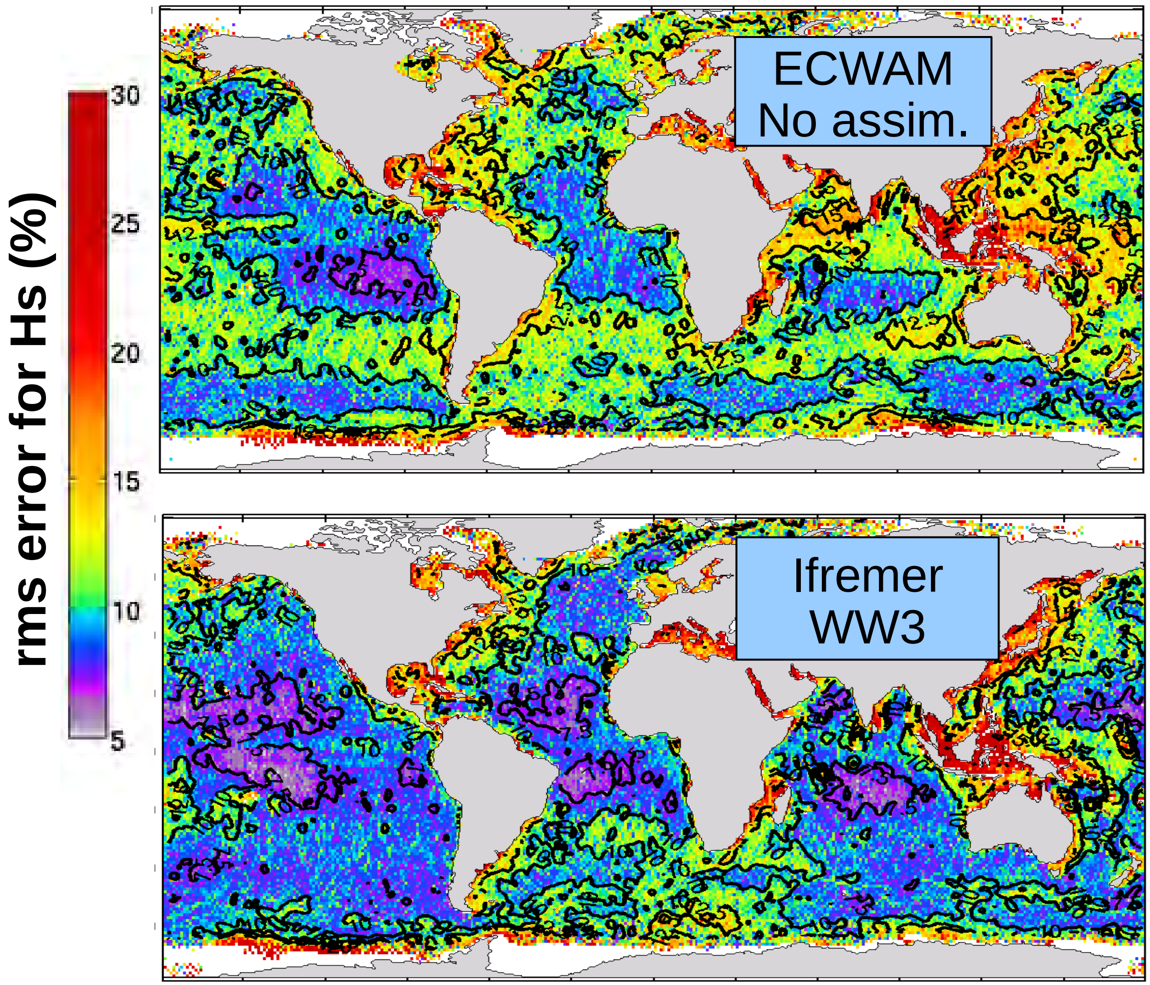
Mixing structures around fronts (Suzuki et al. JGR 2016) : waves are important



5

Let's get SKIM off the ground … various challenges …

Where we are today:
Wave heights



Errors in free model runs using ECWAM (top) and WW3 (bottom) for ***free runs, Year 2009***

→ ***large errors*** *at short fetch possibly due to weak wave-age dependence in wind stress*

→***wave-currents***

→ ***wave -ice …***

THIS IS ONLY HS !!!

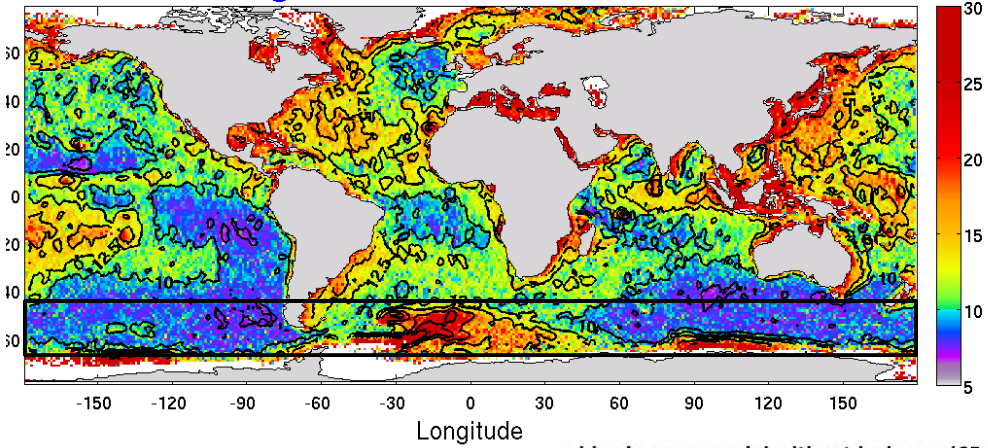
Recent steps:
Ice cubes

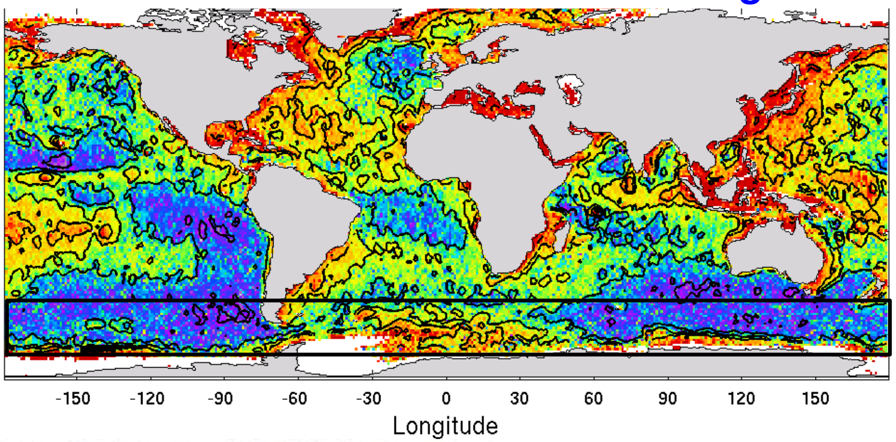
Icebergs needed in Southern Ocean wave models

(Ardhuin et al. Ocean Modelling, 2011)

Using iceberg data from altimeter (Tournadre & al. JGR 2009)

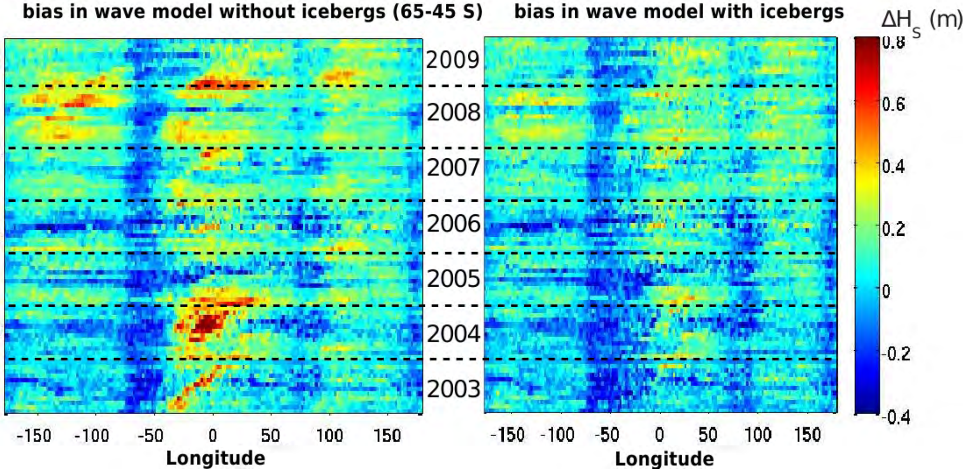
No icebergs **with icebergs**





bias in latitude band

65 to 45 °S

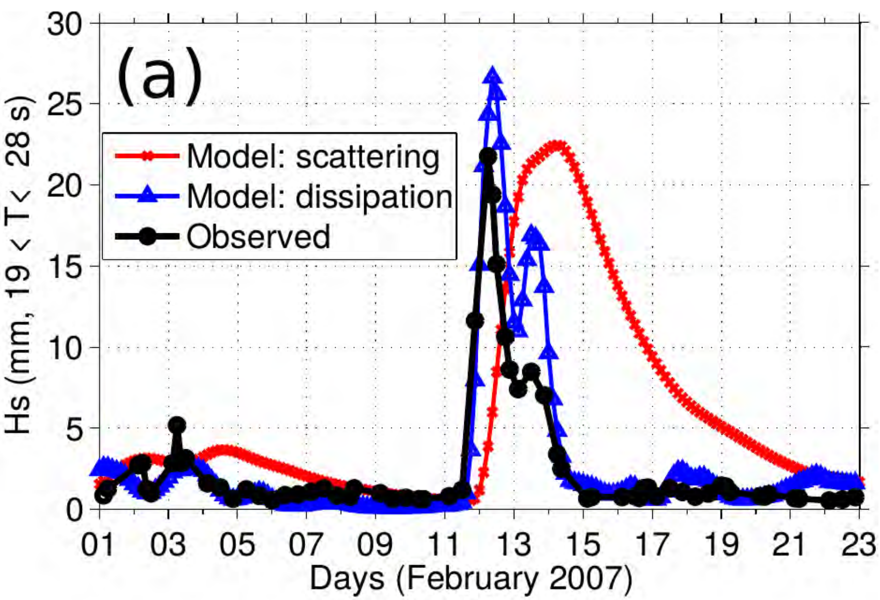


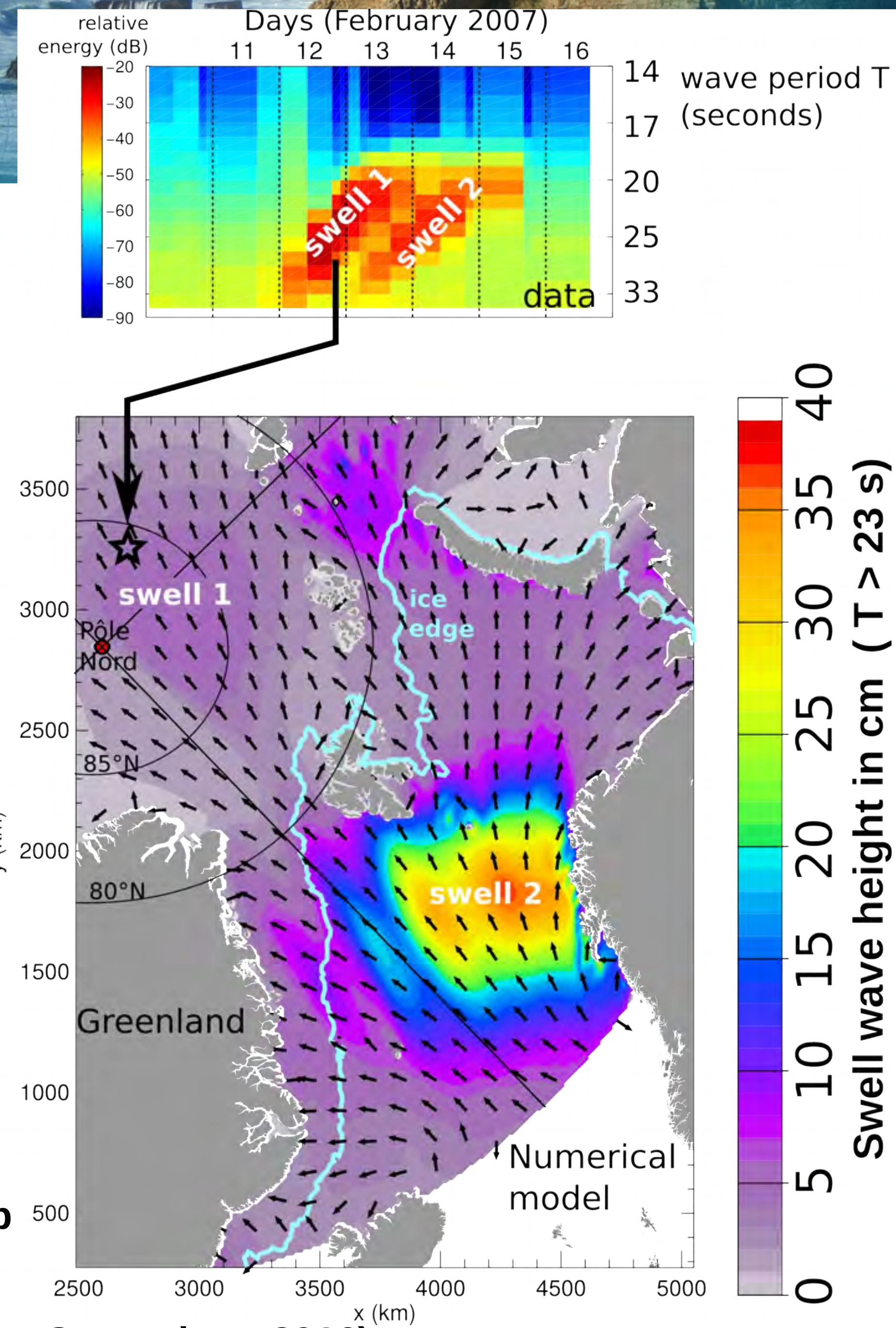
Getting into sea ice

Ardhuin, Sutherland, Doble, Wadhams

Ocean waves across the Arctic:
Attenuation due to dissipation dominates over scattering for periods longer than 19 s

GRL (2016)





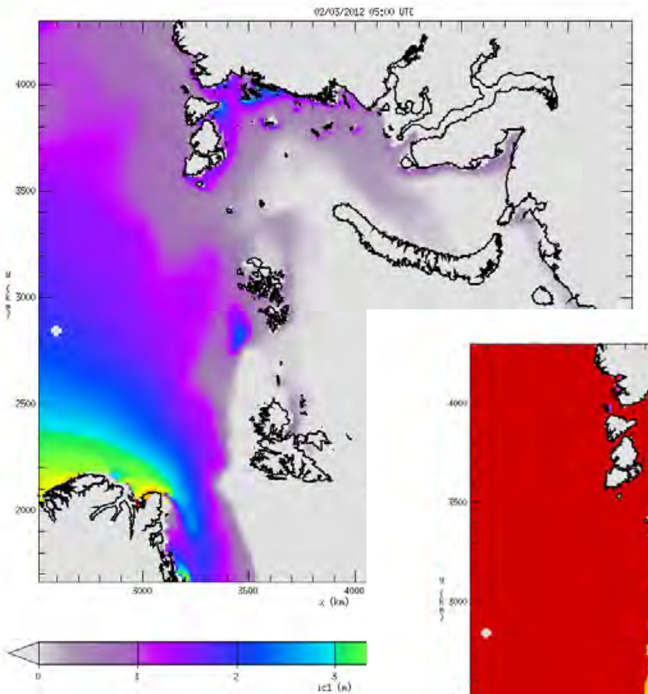
→ new parameterization : ice break-up and creep
Validation :S1 data in the Southern Ocean

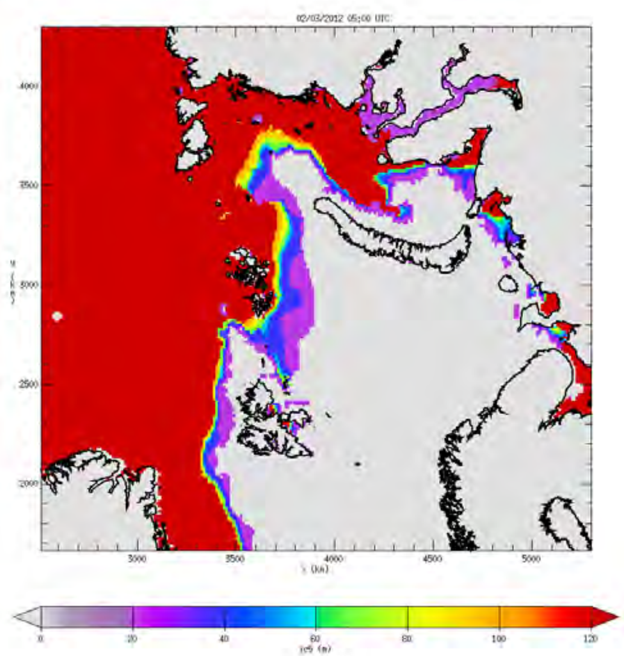
See also Stopa et al. (The Cryosphere 2016).

Getting into sea ice:

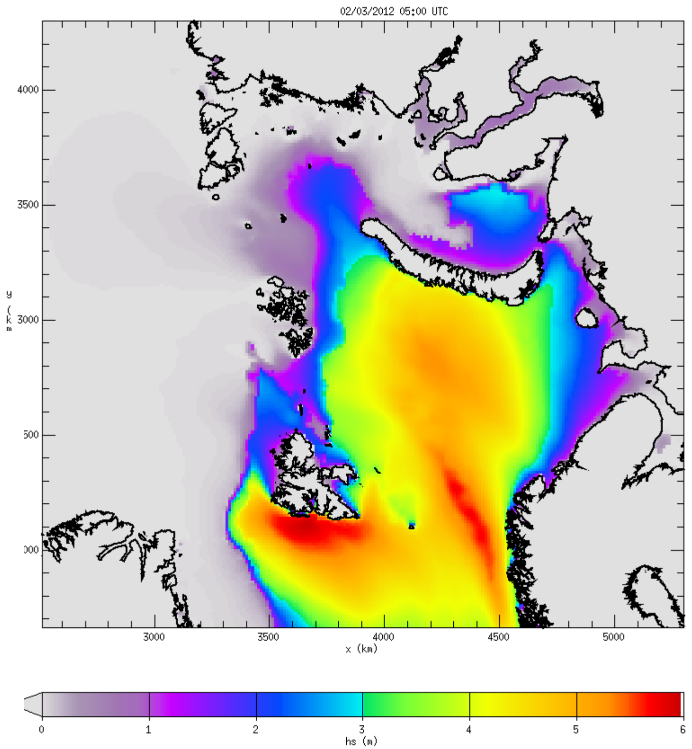
Hindcasts & forecasts for FP7 project « SWARP »

Ice thickness from TOPAZ





Maximum floe diameter (WW3)



Hs (1 to 6 m)

6

Available wave model results and tools

6. Available modeled sources & tools

it all starts here for model output:

ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST

Tools (for reading & using the model output):

ftp://ftp.ifremer.fr/ifremer/ww3/TOOLS

Tutorials (including synthetic double-frequency microseisms):

.../ww3/COURS/WAVES_SHORT_COURSE/TUTORIALS/

The 3 different « products » in HINDCAST folder :

- standard model runs (multi-grid, different zooms …) : GLOBAL, ATNE, ATNW, ARCTIC …

- special global runs with infragravity waves : GLOBAL_IG (now 2013 to 2015… more coming)
- special runs to play with shoreline reflection : SISMO folter
    – NOREF : Without coastal / iceberg reflection
    – REF102040 : « constant » (10 %, 20 %, 40%) reflection
    – REFSLOPE : reflection defined from bottom slope

Warning : as we improve on the wave model, we will update these model output…

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Warning : as we improve on the wave model, we will update these model output…

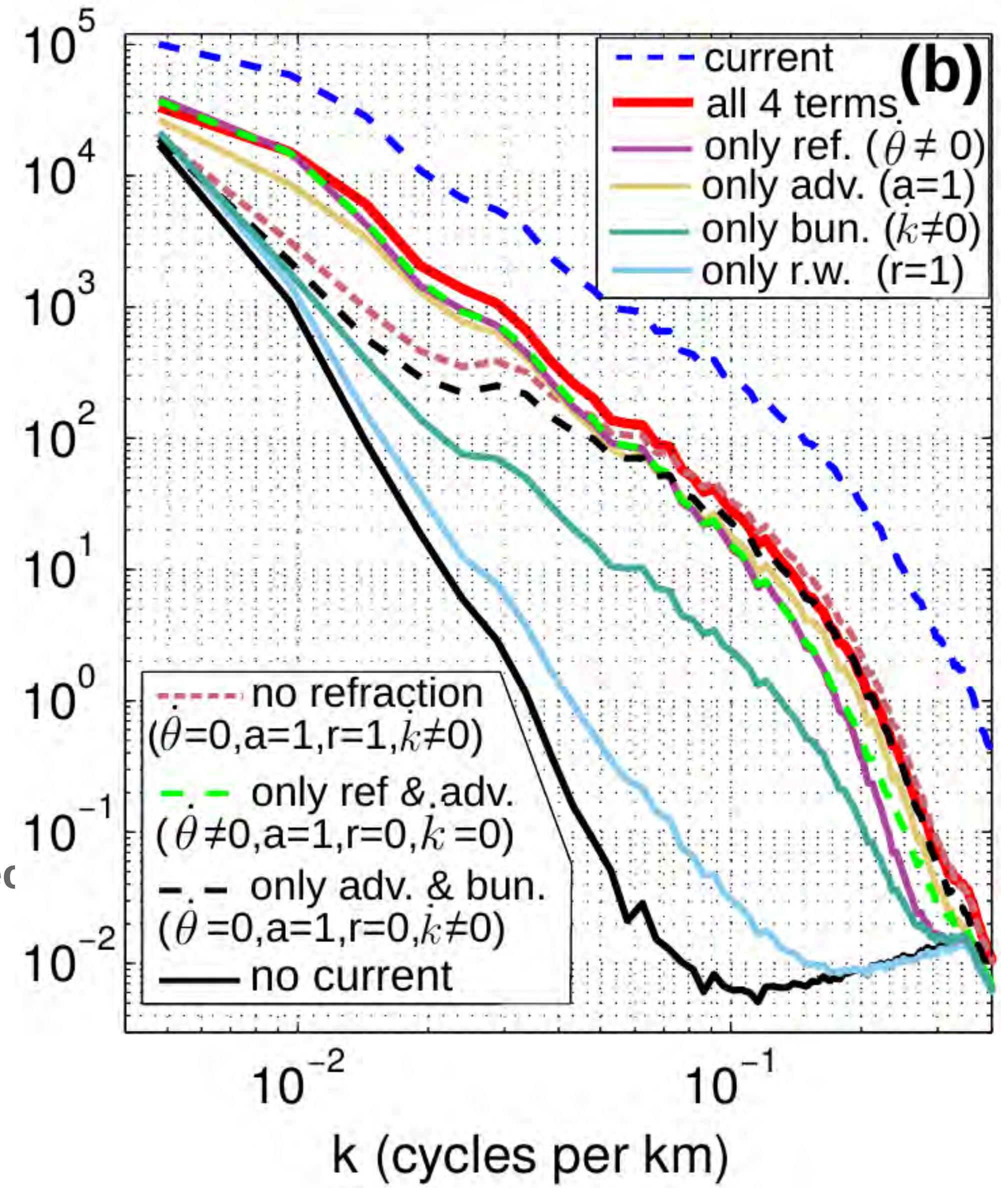
2 Understanding variability

Refraction

Advection

« bunching »

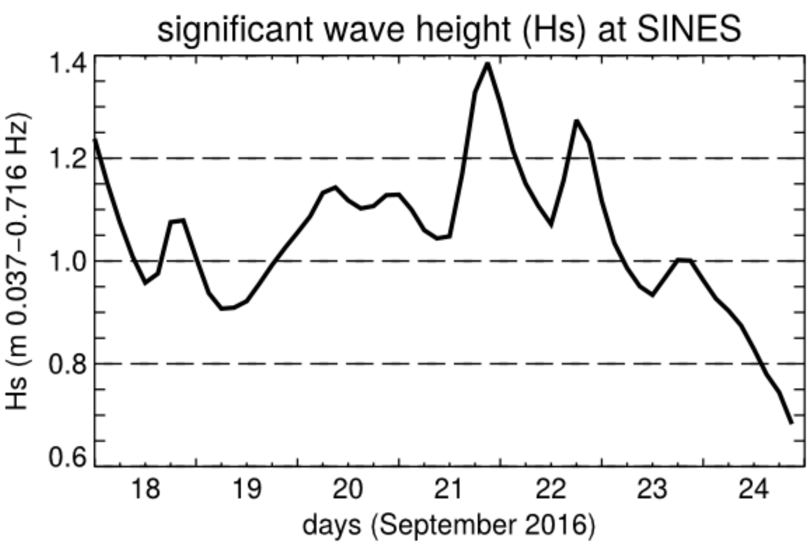
+ relative wind + effec

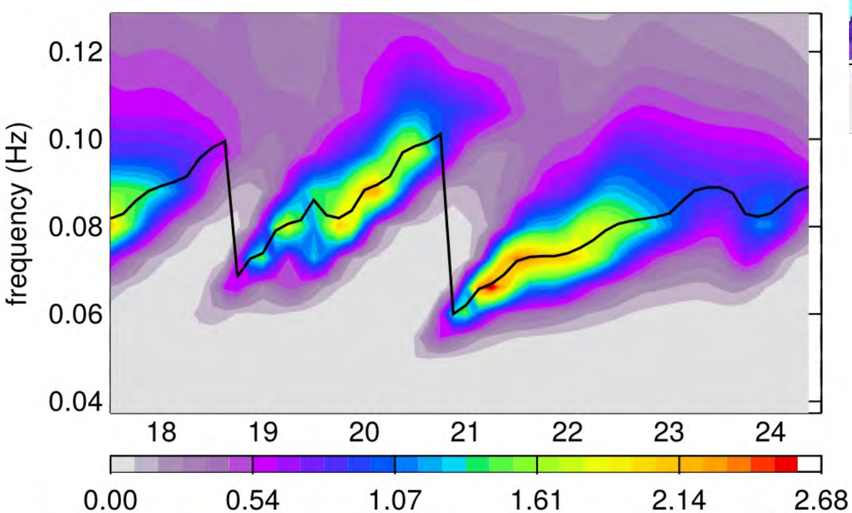


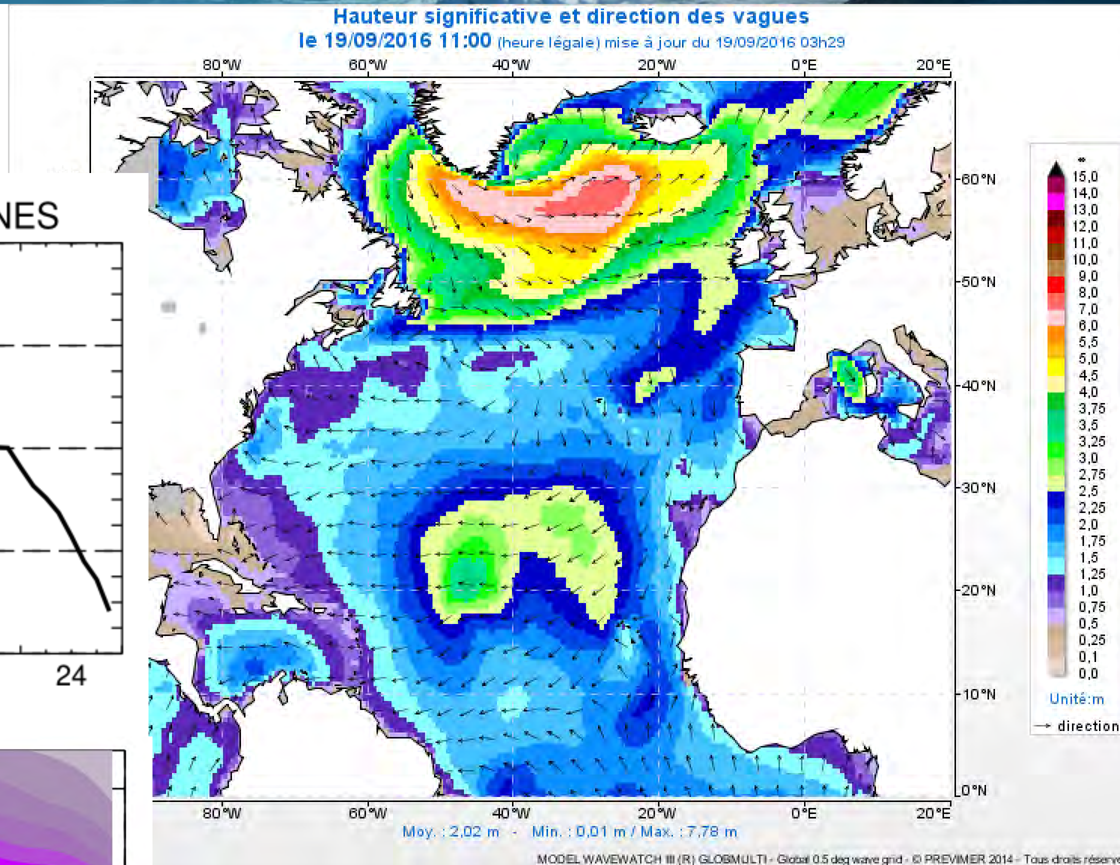
6. Available modeled sources & tools

And even forecasts

http://www.previmer.org







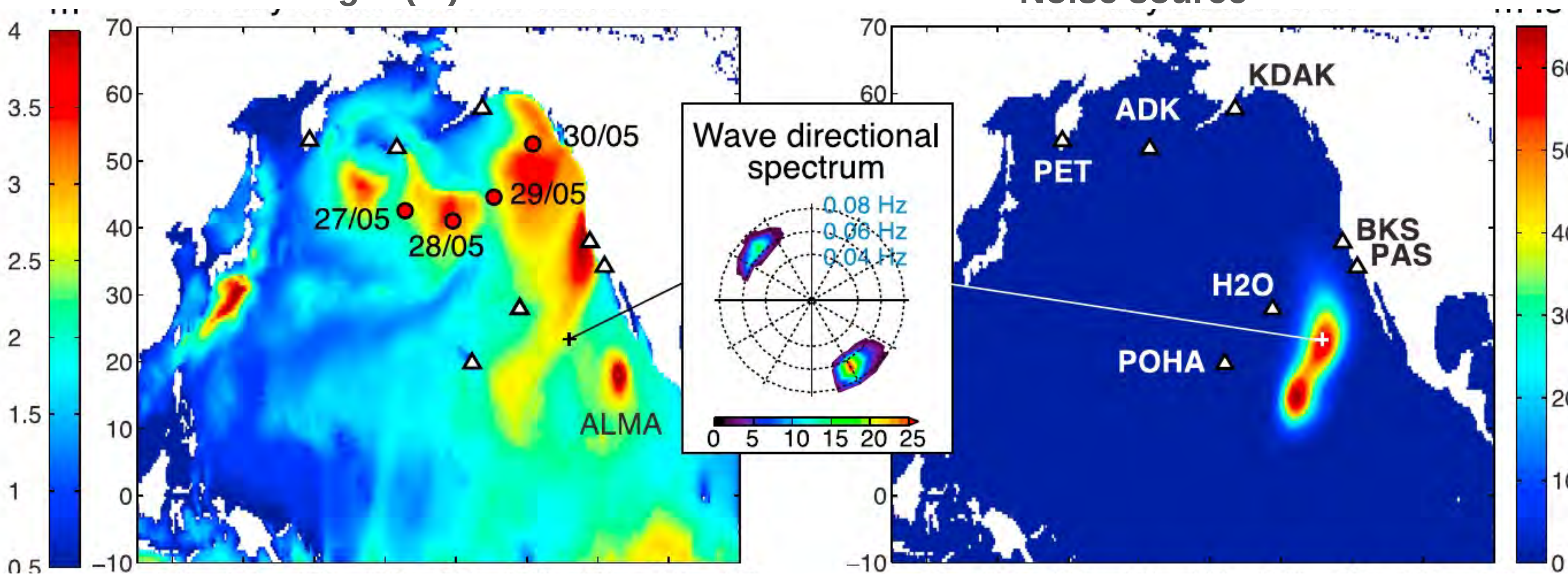
7

Time to stop : a summary

1. Some reasons to measure waves & currents
Sources of microseisms & microbaroms

Noise source is proportional to product of wave energy in opposite directions.
Here waves from Hurricane Alma meet waves from a North Pacific storm
(Obrebski & al. GRL 2012)

Wave height (m) | **Noise source**



This is our model…
It is used by everybody (e.g. Nishida et al. Science 2016)
how good is it ? → ANR MIMOSA

7. Summary

Ocean waves generate microseisms through 2 types of interactions :

- **Wave-wave interactions → $K=k+k'$ $f_s=f+f'$ → double frequency**
- **Wave-topography interactions → $K = k+k_b$ $f_s = f$ → same frequency**

(this is for vertical components… to get SH or Love waves you can imagine $K=k+k_b$ (wave interaction on sloping bottom), $K=k+k'+k_b$ (double-frequency interaction on sloping bottom …)

For double frequency, the directional spectrum defines the overlap integral, I(f) and the seismic source is proportional to E^2(f/2) I(f/2) … but I(f) is very poorly known

For wave-topography : it is the topography PSD at kb ~ k that is important… not so well known for fs ~ 10 s, probably OK for hum.

We can use near-surface pressure records (dominated by AG modes) to determine I(f)

Numerical wave models are probably OK up to f ~ 0.5 Hz … (directional spectrum not very good above, see Peureux & Ardhuin JGR 2016)

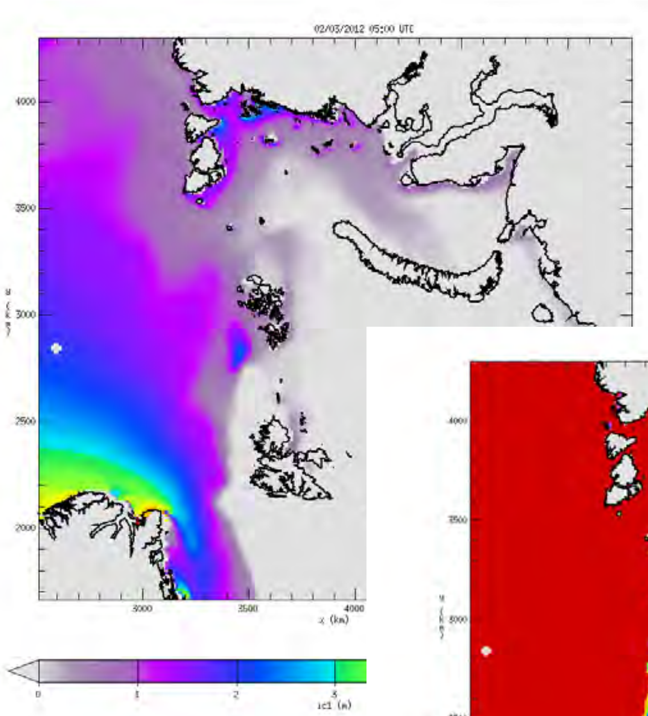
Strong wave modeling errors : regions of strong current and in and around sea ice

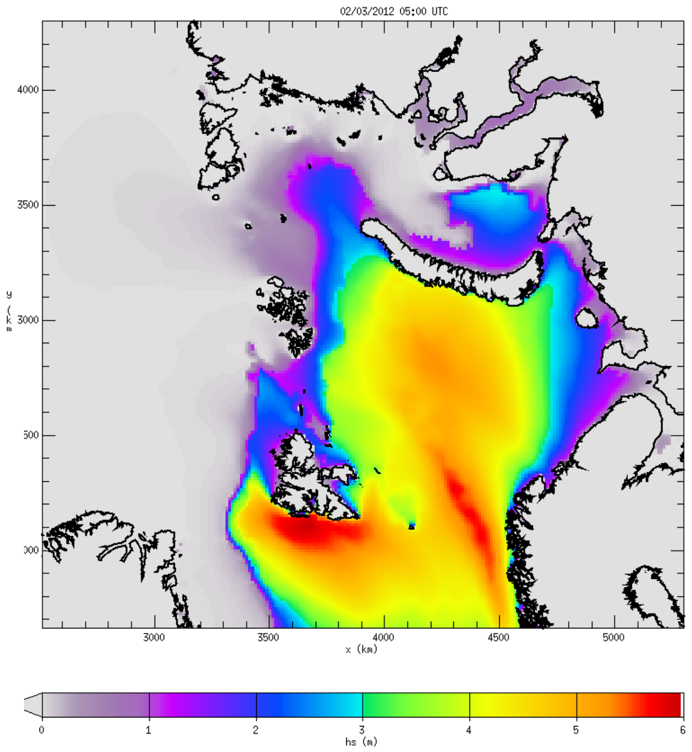
Old seismic records can be used to calibrate wave model for times before 1993…
I'm looking for such older data sets...

1. Some reasons to measure waves & currents

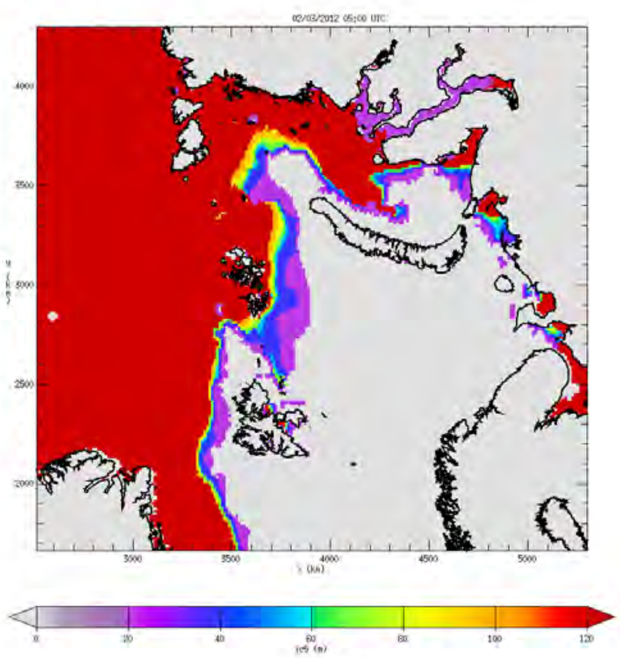
Models are not perfect : coastal & polar regions

Ice thickness from TOPAZ





Hs (1 to 6 m)



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