Bedford Institute of Oceanography

Wave-ice interactions in wave models like WW3

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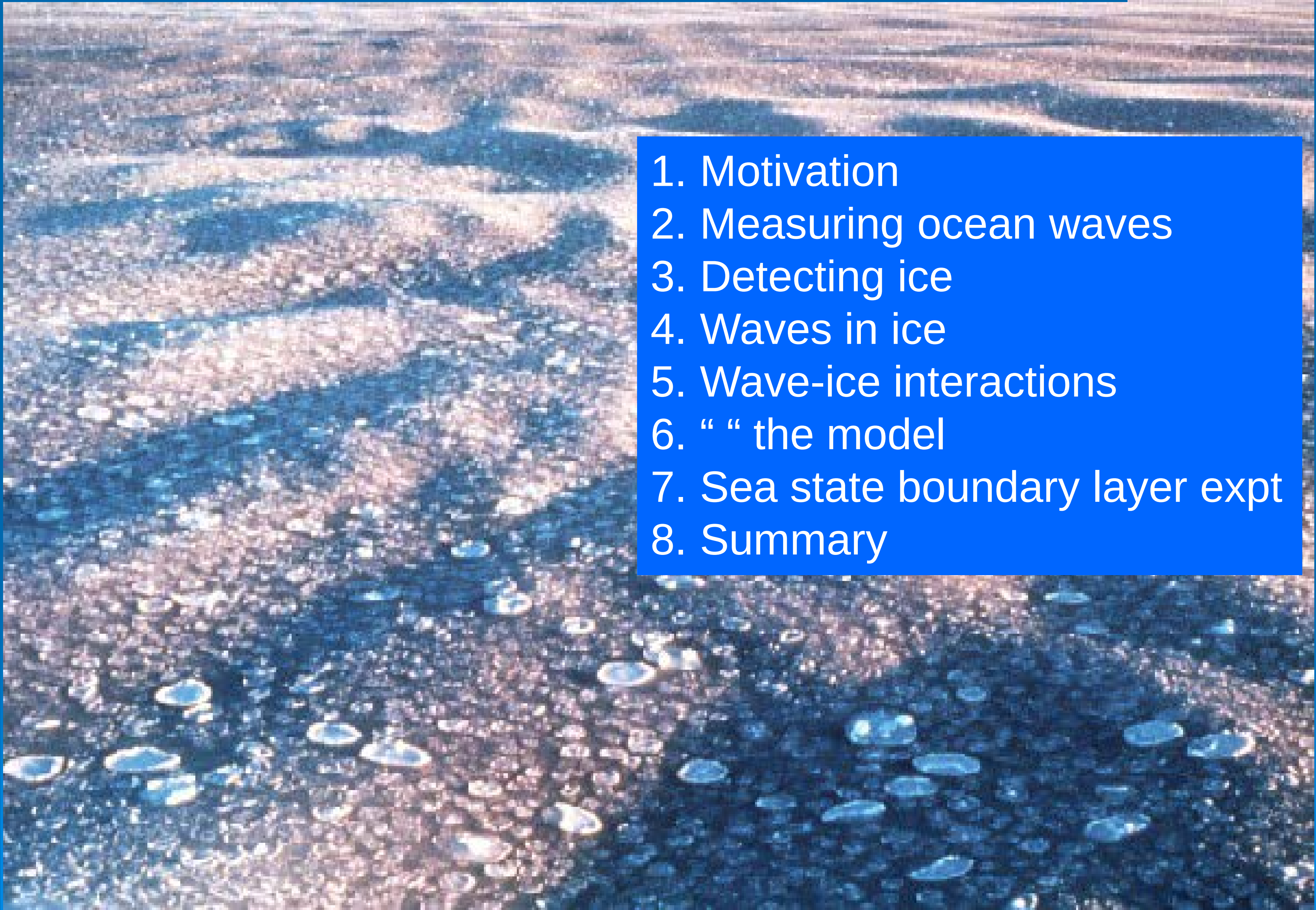
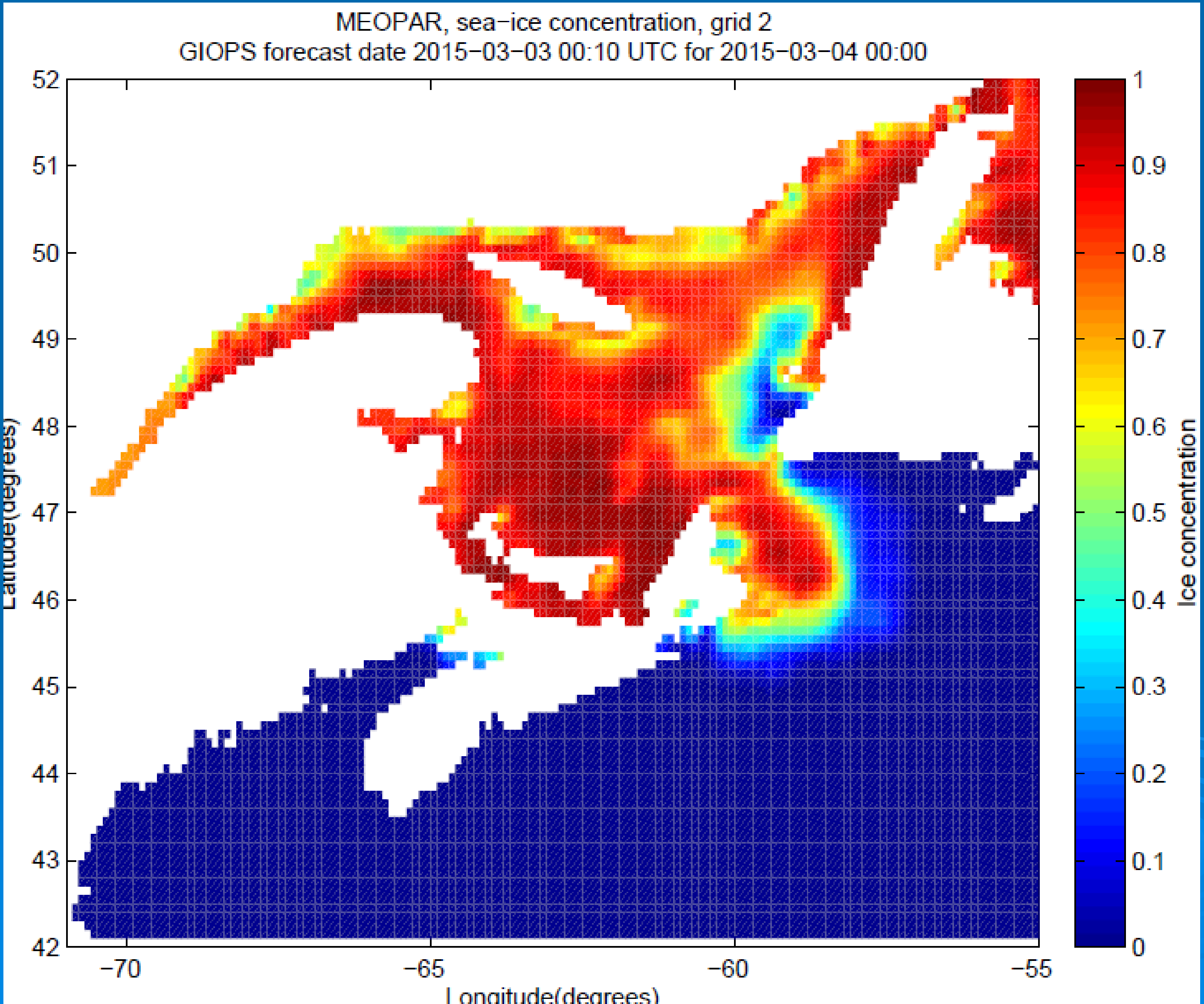
1. Motivation Waves in the marginal ice zone

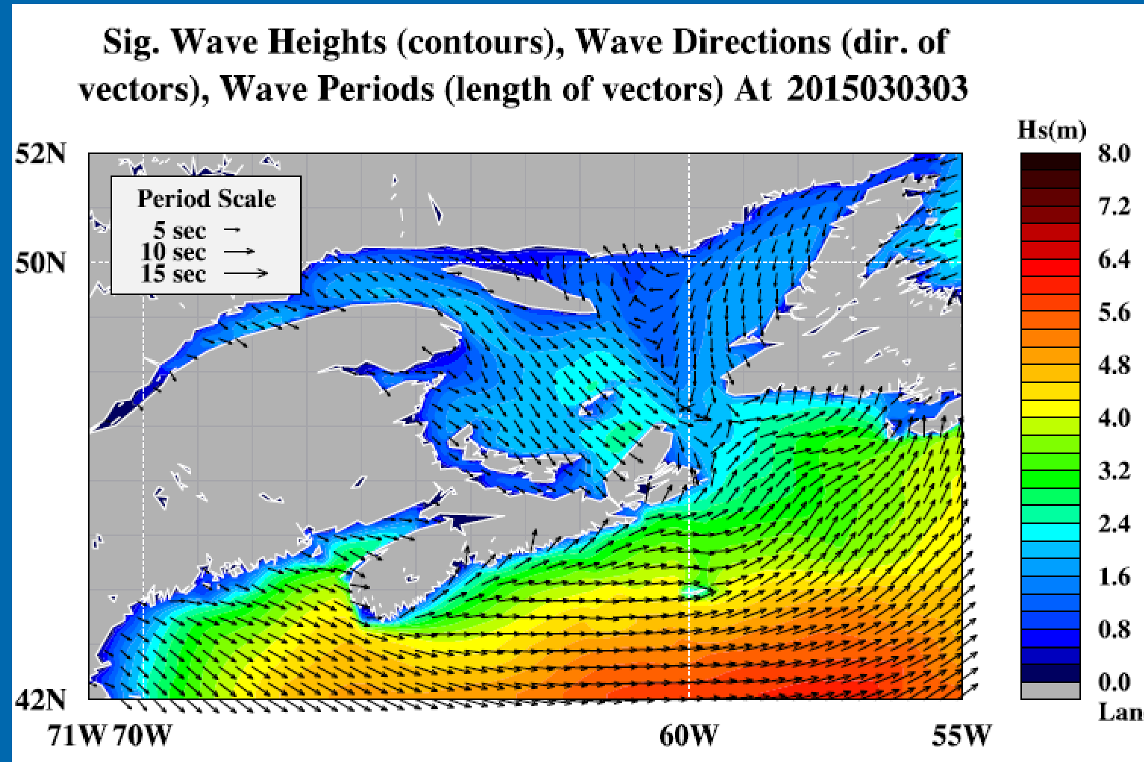


1. Motivation
2. Measuring ocean waves
3. Detecting ice
4. Waves in ice
5. Wave-ice interactions
6. “ “ the model
7. Sea state boundary layer expt
8. Summary

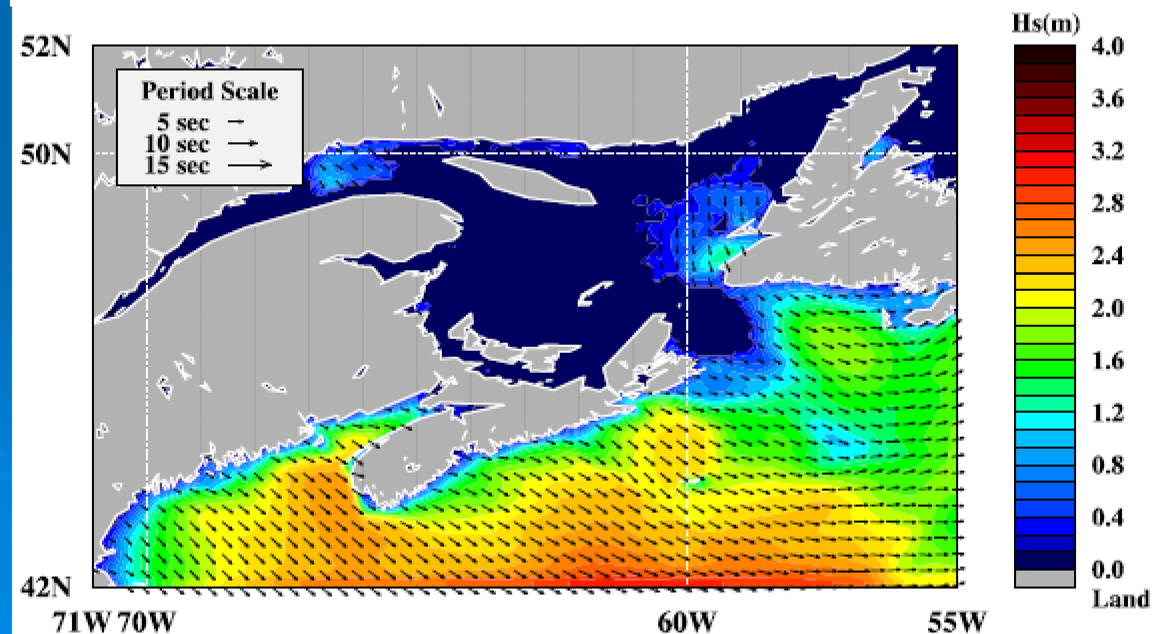
Waves in the operational Halifax Harbour wave forecasts



Wave forecast assuming **no** ice at 00 UTC on Mar 3 2015



Wave forecast **assuming** ice at 00 UTC on Mar 3 2015



→ Note the change in scale!

2. Ocean waves by fully polarimetric SAR

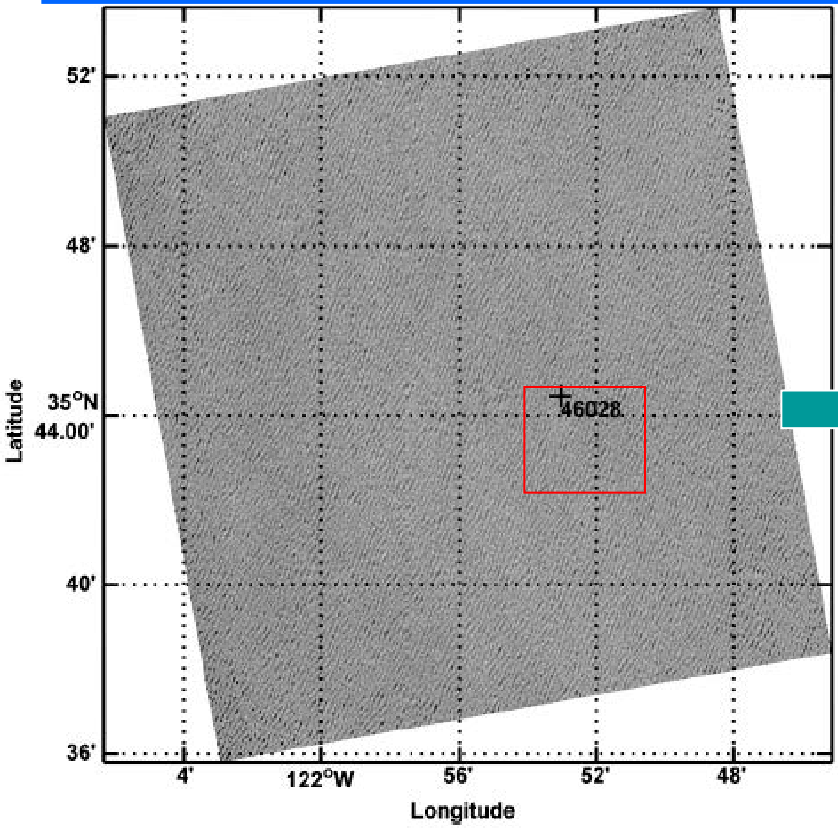


Figure 1. A C band, vertically (VV) polarized, image of area northwest of Morro Bay, CA acquired by RADARSAT-2 at 02:09 UTC on 25 February 2009. Further details are given in Tables 1 and 2. RADARSAT-2 Data and Products© MacDonald, Dettwiler and Associates Ltd. (2008–2009) – All Rights Reserved.

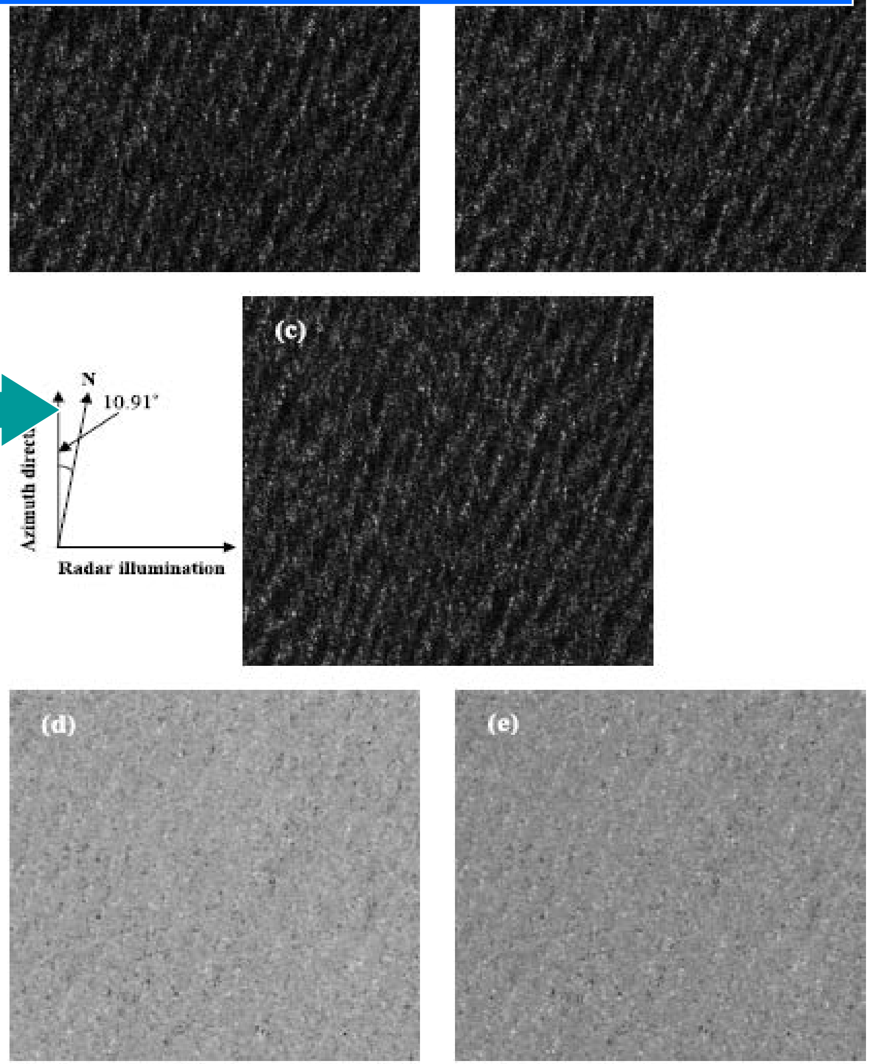


Figure 3. Corresponding 512 × 512 pixel size images of area northwest of Morro Bay, CA selected from SAR image in Figure 1, at 02:09 UTC on 25 February 2009, showing (a) horizontal (HH) polarization, (b) vertical polarization, (c) linear polarization, (d) wave slope image in the azimuth direction, and (e) wave slope image in the range direction. NDBC directional wave buoy (46028) is colocated to these images.

Wave retrievals from fully polarimetric SAR

Linear modulation transfer function -

$$\frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} - \frac{\Delta\sigma_{hh}}{\bar{\sigma}_{hh}} = -\frac{8\tan\theta}{1+\tan^2\theta}\frac{\partial\xi}{\partial x}$$

$$\frac{\Delta\sigma_{\psi\psi}}{\bar{\sigma}_{\psi\psi}} - \frac{\Delta\sigma_{vv}}{\bar{\sigma}_{vv}} = A\frac{\partial\xi}{\partial x} + B\frac{\partial\xi}{\partial y}$$

$$\sigma(0,\psi) = \frac{1}{4}(\sigma_{hh}+\sigma_{vv})\cdot\left[1+\cos^2(2\psi)\right] + \frac{1}{2}(\sigma_{hh}-\sigma_{vv})\cos(2\psi) + \sigma_{hv} + \frac{1}{2}\Re(\sigma_{hhvv})\sin^2(2\psi)$$

$\partial\xi/\partial x$ wave slope in range direction

$\partial\xi/\partial y$ wave slope in azimuth direction

σ_{hh} σ_{vv} σ_{hv} radar observed backscatter cross section in co- and cross-polarizations

Zhang, B., W. Perrie, and Y. He (2010), Validation of RADARSAT-2 fully polarimetric SAR measurements of Ocean surface waves, *J. Geophys. Res.*, 115, C06031, doi:10.1029/2009JC005887.

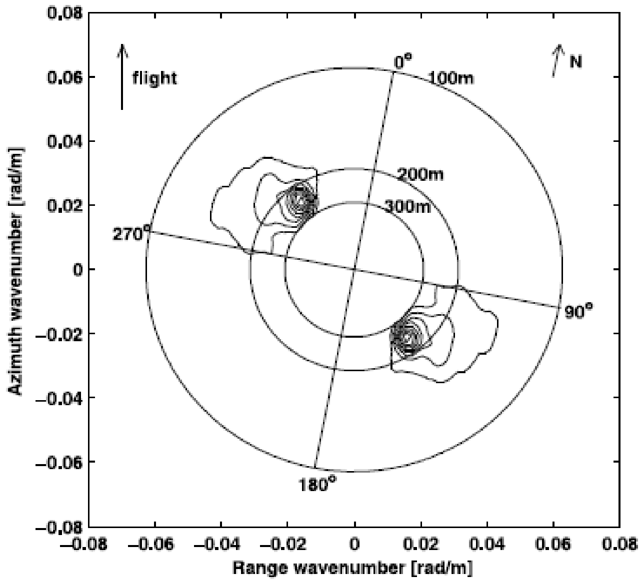


Figure 5. Wave slope spectrum from C band fully polarimetric SAR image of area northwest of Morro Bay, CA (Figure 1) acquired at 02:09 UTC on 25 February 2009.

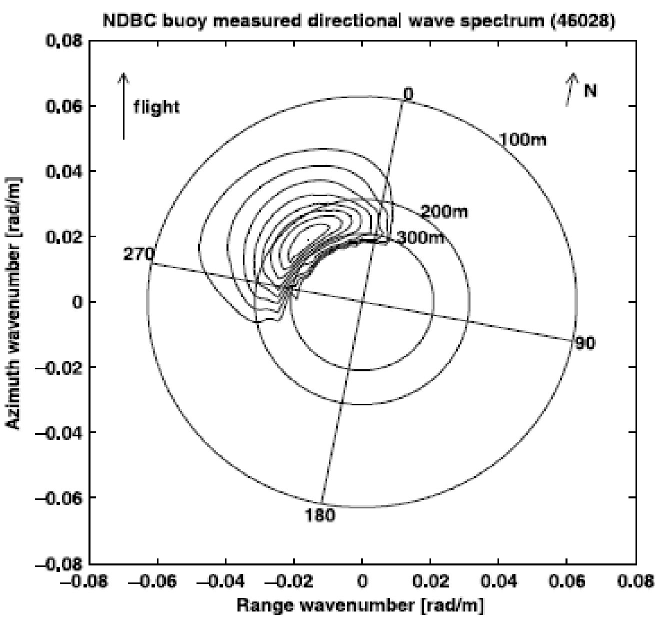
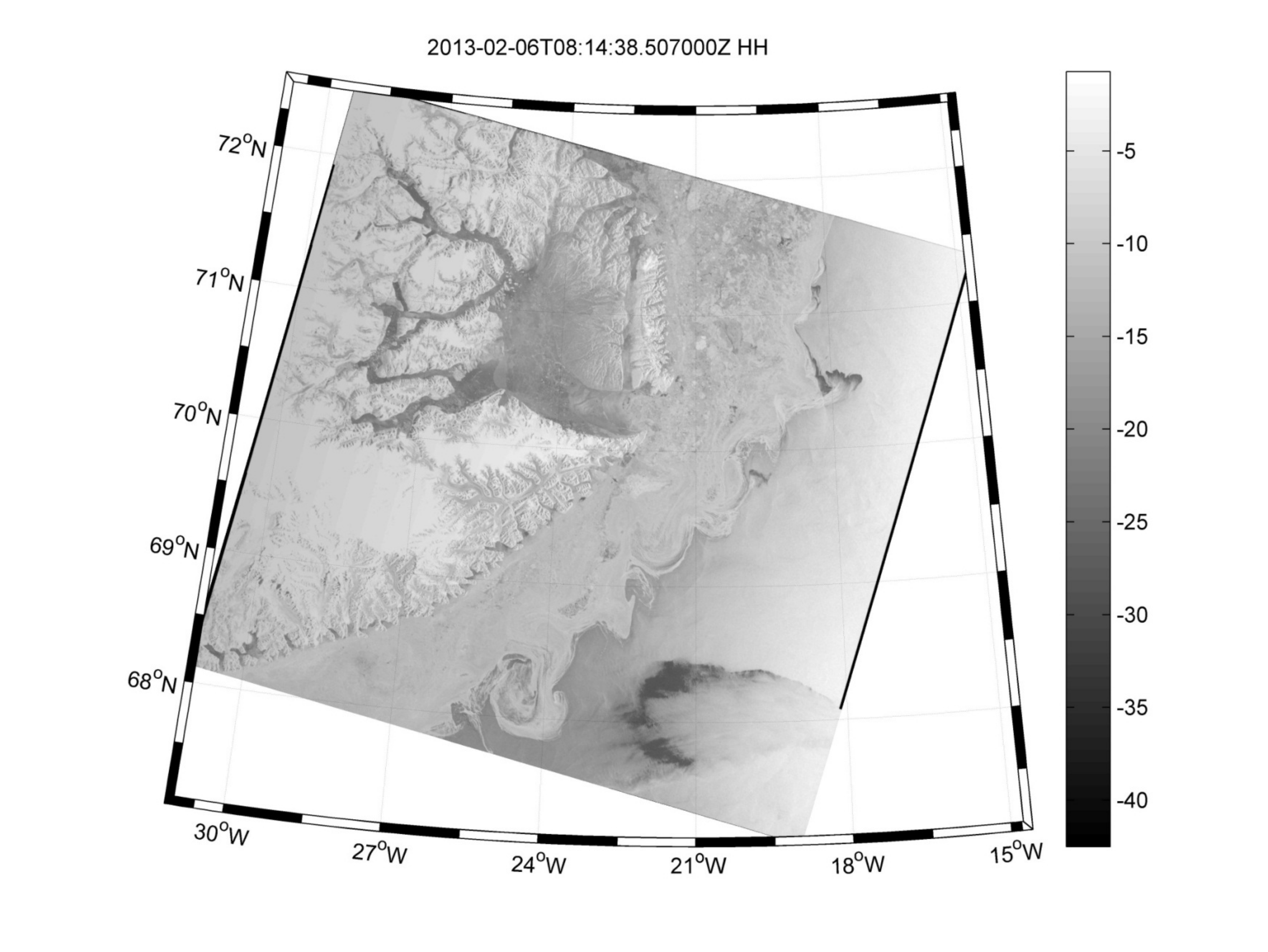


Figure 7. Directional wave spectrum measured by NDBC buoy (46028) colocating with the SAR image in Figure 1, at 01:50 UTC on 25 February 2009.

Table 3. Wave Parameters Extracted From the Six RADARSAT-2 Fully Polarimetric SAR (Fine Quad-Polarization Mode) Images in Table 2 Compared to Corresponding Wave Parameters Provided by NDBC Buoy Measurements

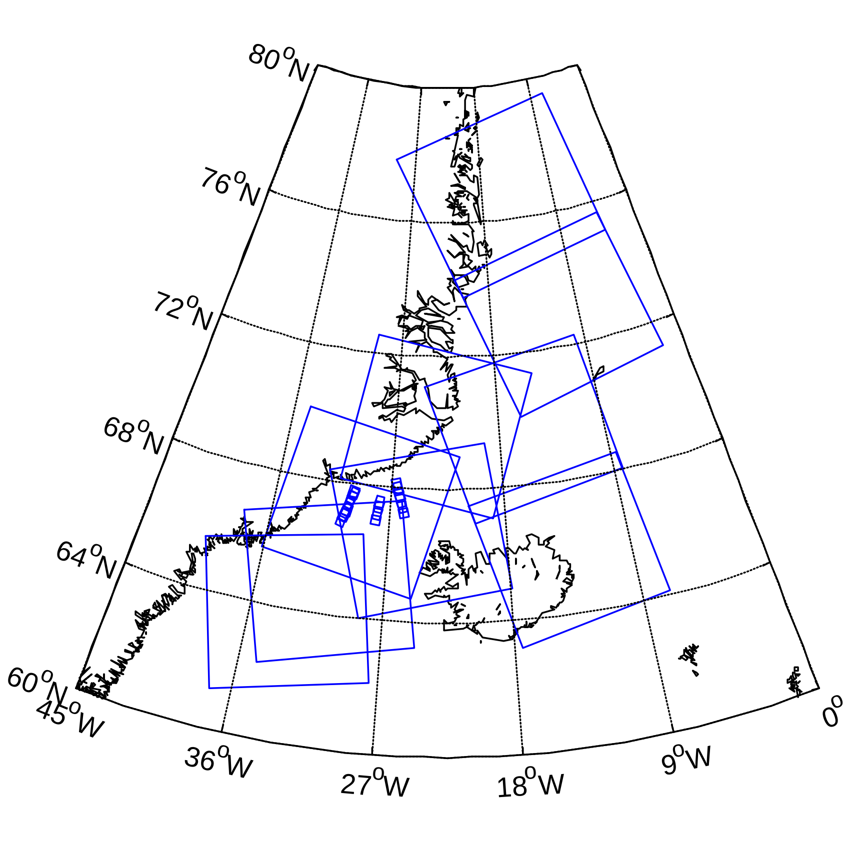
Parameter	Image ID	Buoy ID	SAR	Buoy	
Wave period	1	46005	15.57	16.00	seconds
	2	46089	12.54	12.90	
	3	46028	12.48	12.12	
	4	46071	11.51	11.00	
	5	46029	12.89	12.90	
	6	46029	11.15	11.00	
Wave length	1	46005	378.3	399.5	meters
	2	46089	245.2	259.7	
	3	46028	242.9	229.2	
	4	46071	206.7	188.8	
	5	46029	259.2	258.8	
	6	46029	193.9	188.8	
Wave direction	1	46005	261.1	240.0	degrees
	2	46089	251.0	268.0	
	3	46028	311.5	310.0	
	4	46071	253.3	270.0	
	5	46029	282.4	285.0	
	6	46029	299.0	307.0	
Significant wave Hs		46005	2.91	3.10	meters
		46089	2.67	2.51	
		46028	2.74	2.88	
	4	46071	4.08	4.10	
	5	46029	2.98	3.44	
	6	46029	2.08	2.50	
RMS slope	1	46005	0.88	0.89	
	2	46089	1.25	1.11	
	3	46028	1.29	1.44	
	4	46071	2.26	2.49	
	5	46029	1.32	1.52	
	6	46029	1.23	1.52	

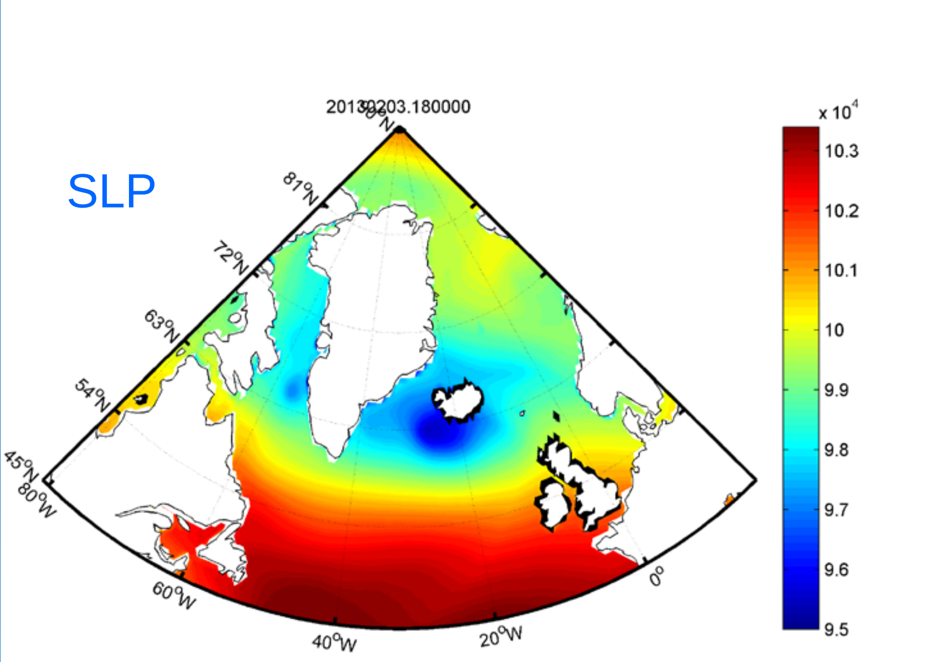
3. Arctic ice
Ice patterns in 2013-02-06 in east coast of Greenland



What about the marginal ice zone ?

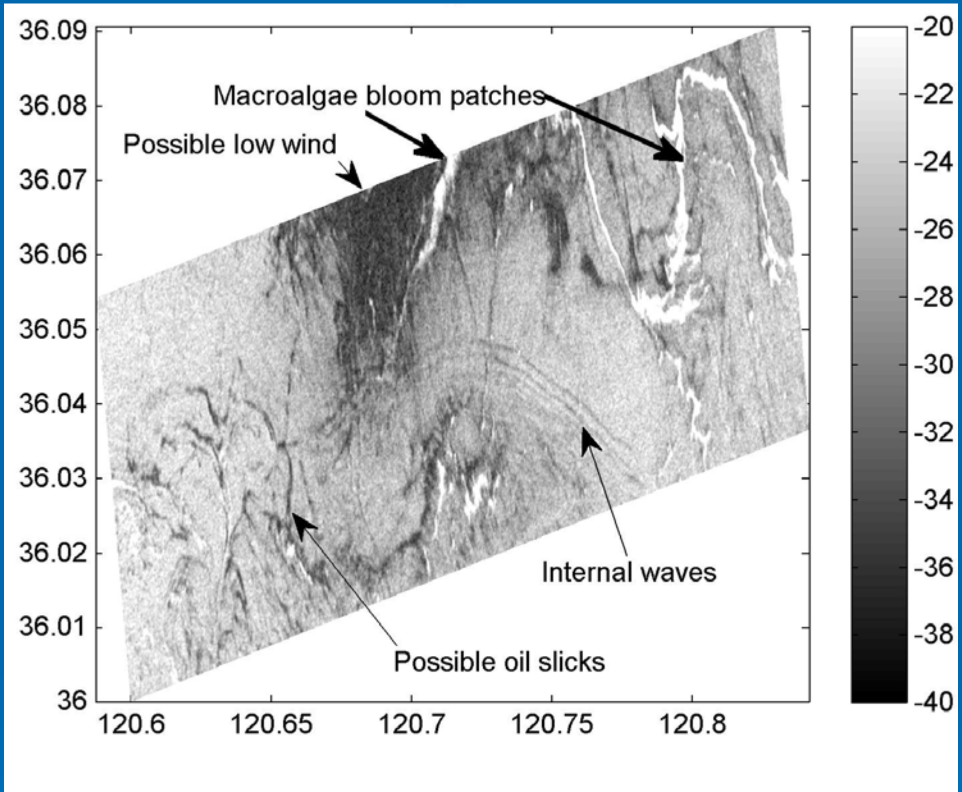
Winds and waves off Greenland in 2013

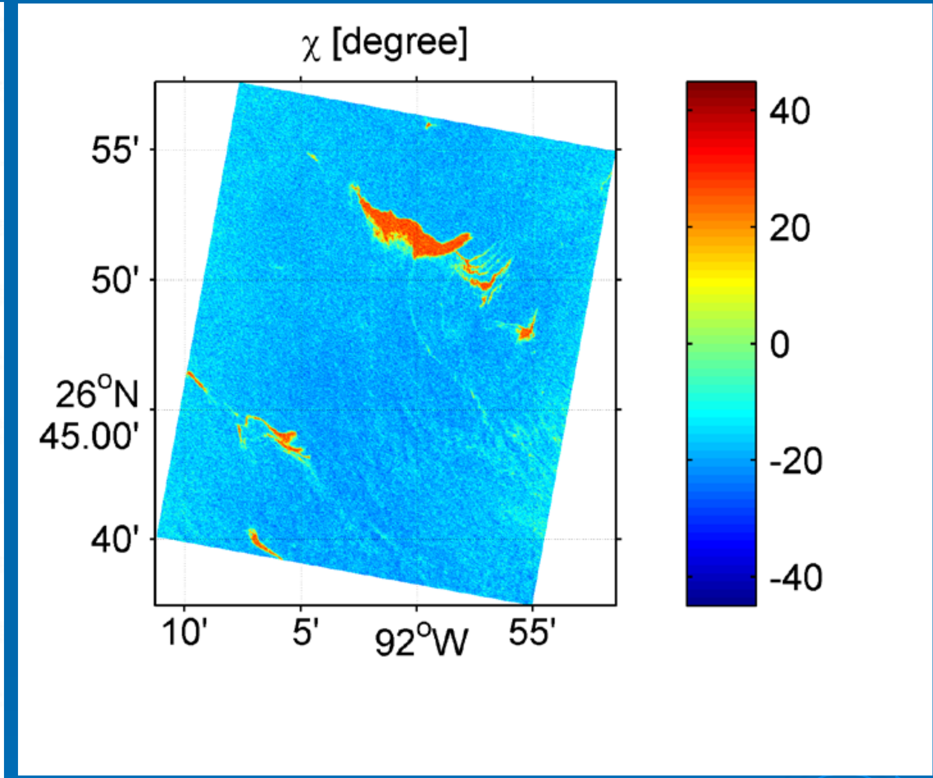




Feb 3 2013 18UTC

Competing ocean surface features





Subset images from the VV mode quad-pol SAR captured on July 24, 2011

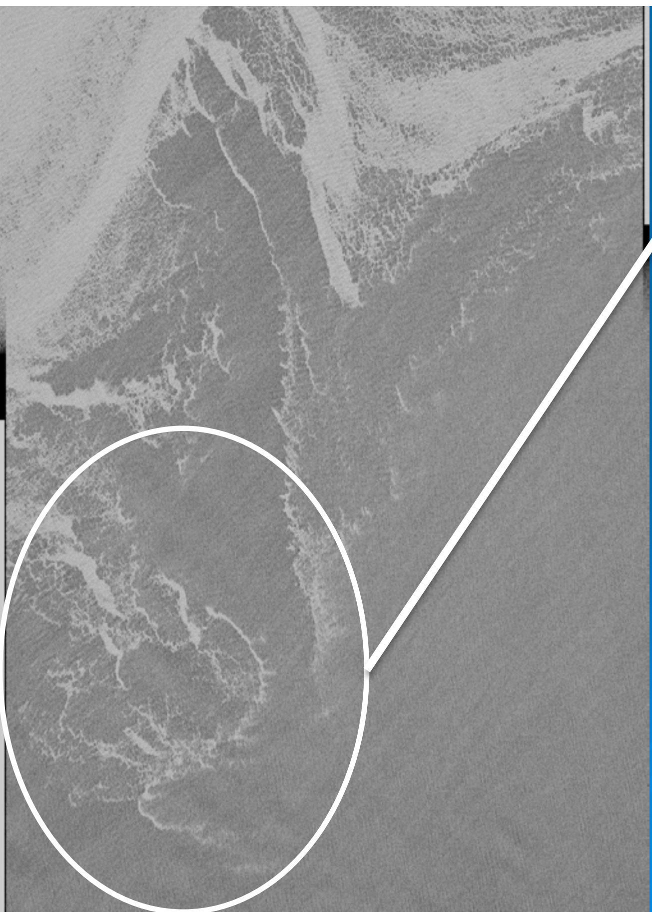
Shen et al. 2013

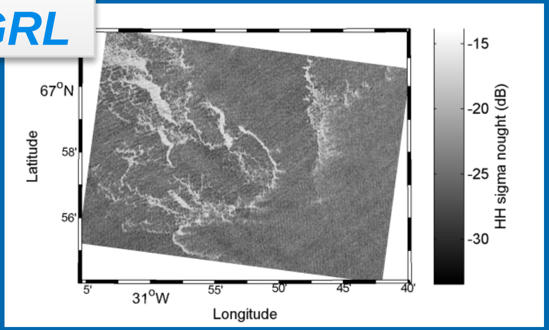
Oil spill detection:
Li et al., 2015 JSTARS
Zhang et al., 2011: GRL

A new ice detection scheme from SAR

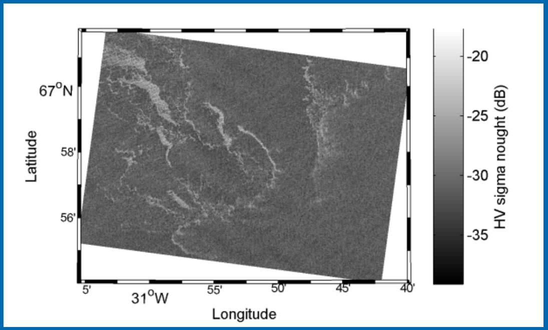
Shen and Perrie, submitted GRL

$$IF_{cross} = \mathrm{Re}\left(\left(2S_{HV} - S_{VH}\right) / S_{VH} \right)$$

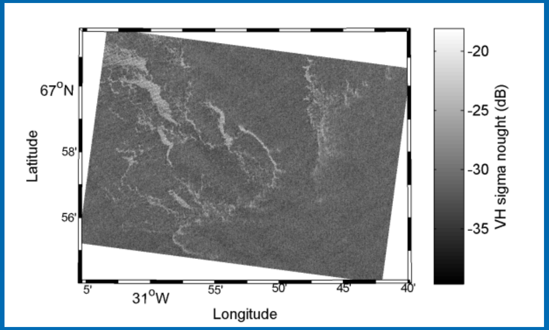




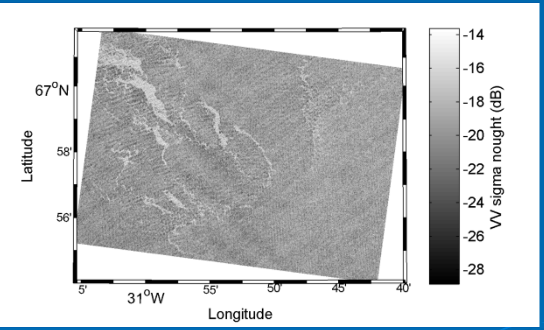
R2 HH



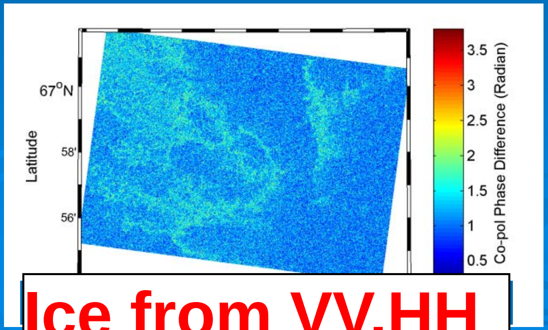
R2 HV



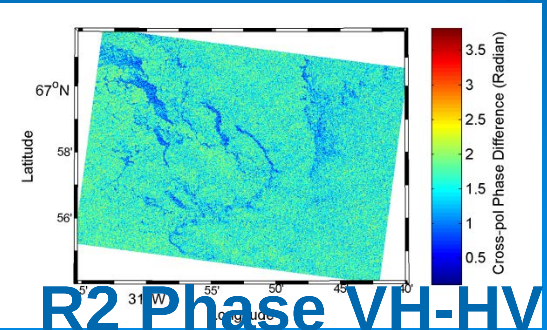
R2 VH



R2 VV

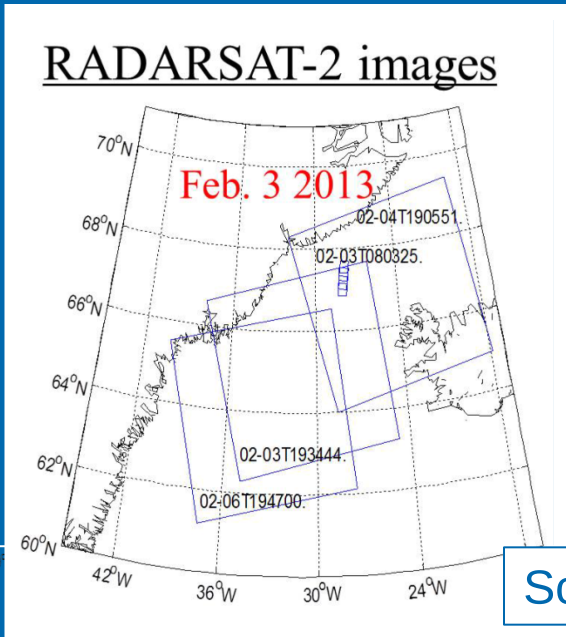


Ice from VV,HH

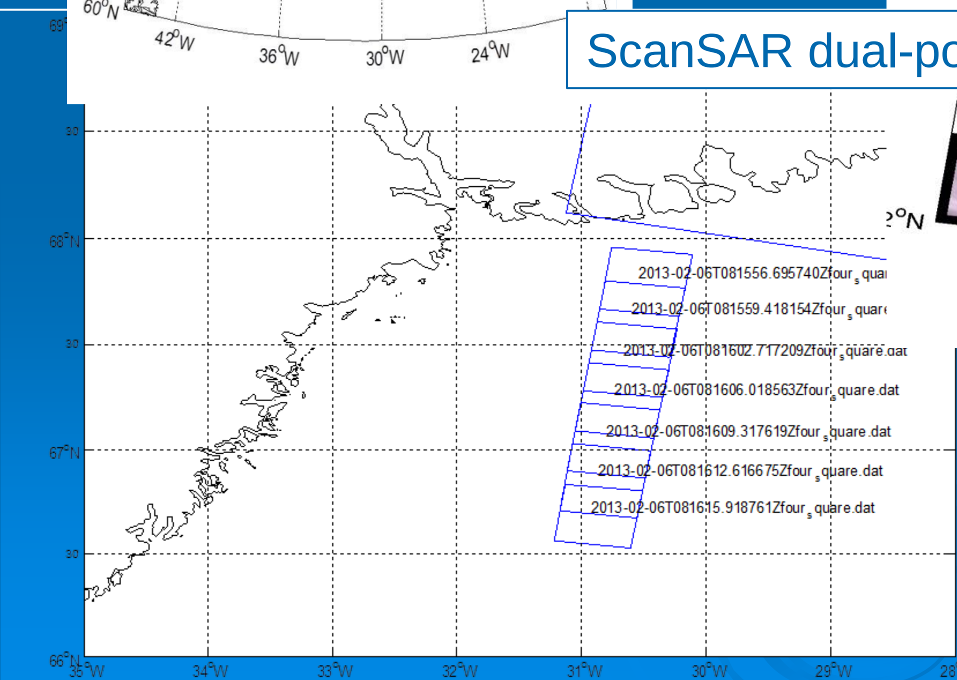


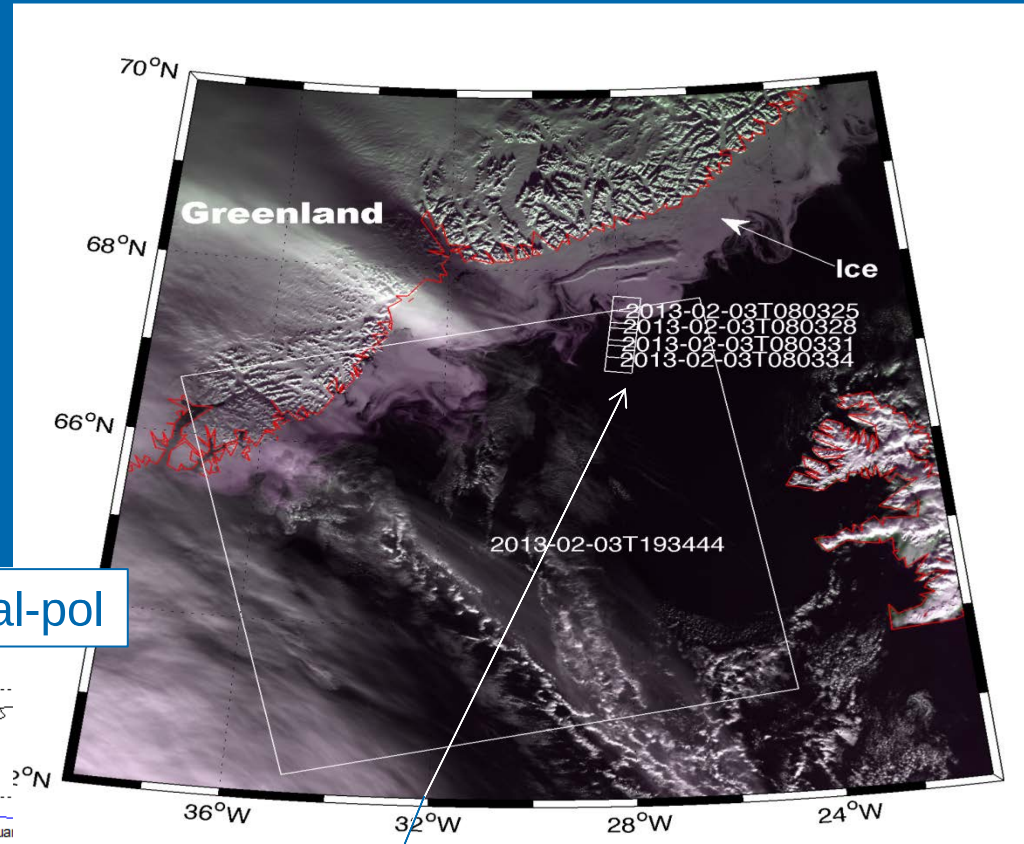
R2 Phase VH-HV

4. Waves in ice and open water



ScanSAR dual-pol





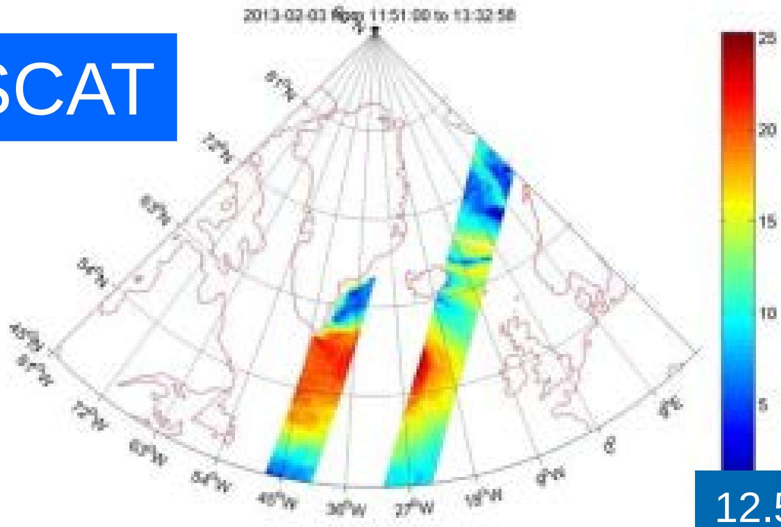
Quad-polarization SAR images on Feb. 3

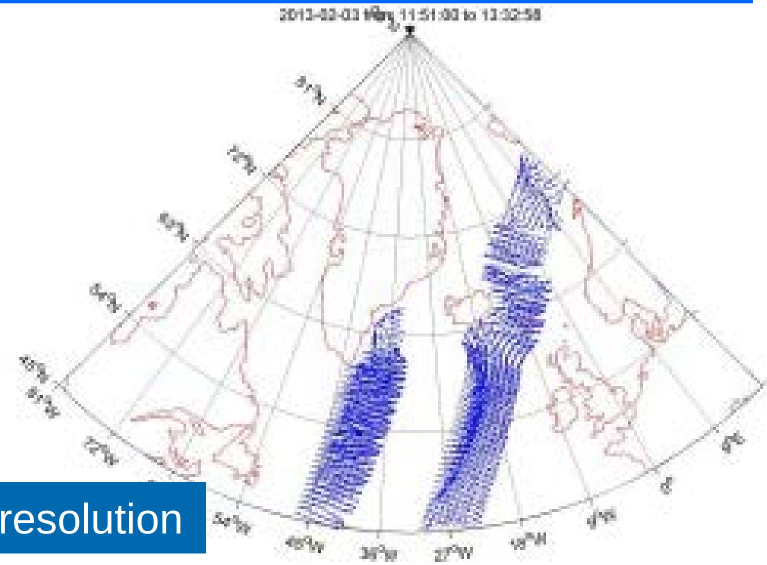
MODIS image of ice conditions
Feb.5, 2013 16:24:03UTC

A case study

Winds

ASCAT



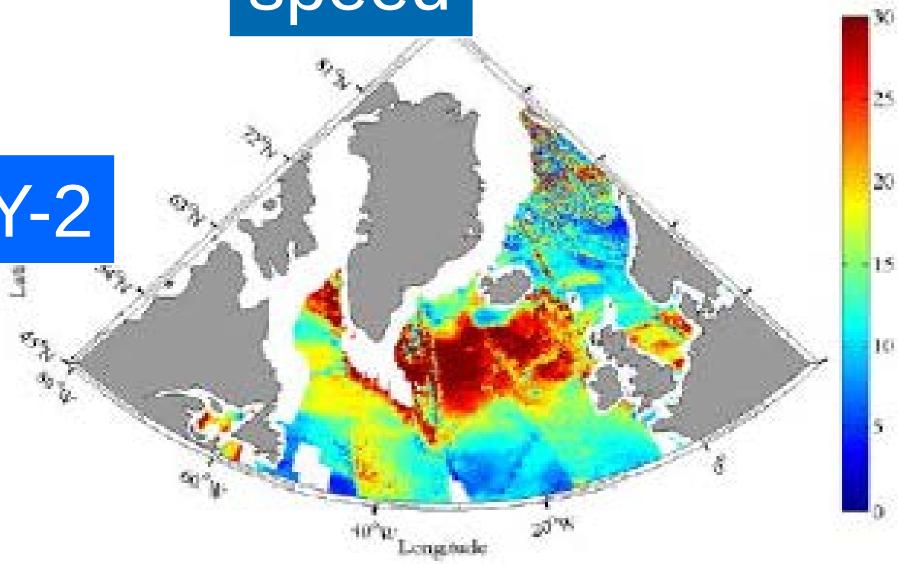


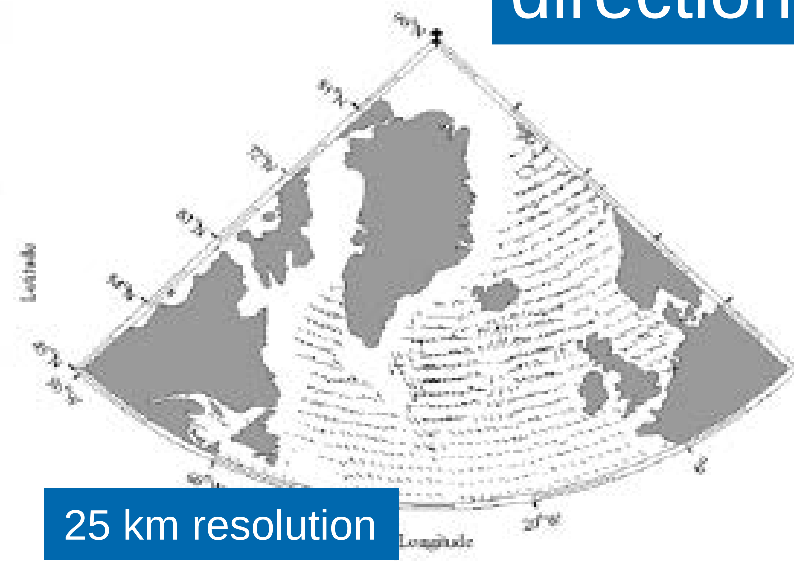
12.5 km resolution

speed

direction

HY-2

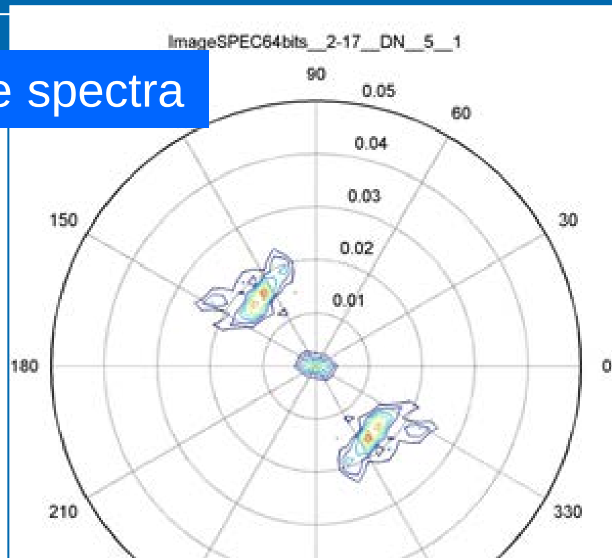


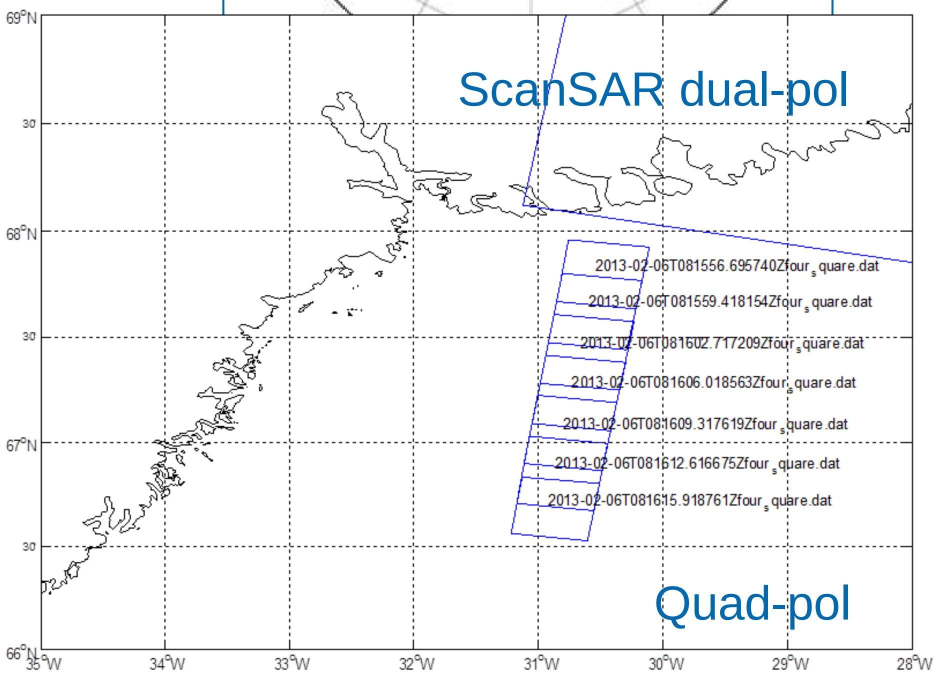


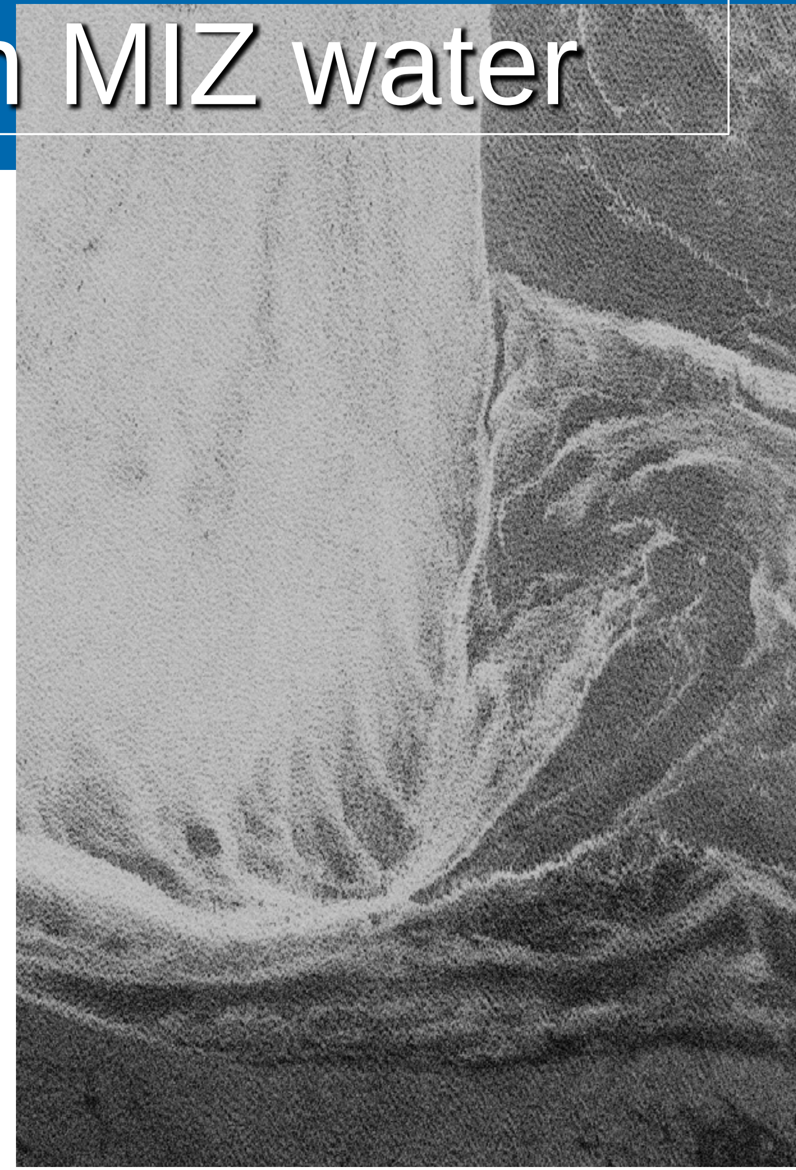
25 km resolution

Wave retrieval in MIZ water

Retrieved wave spectra

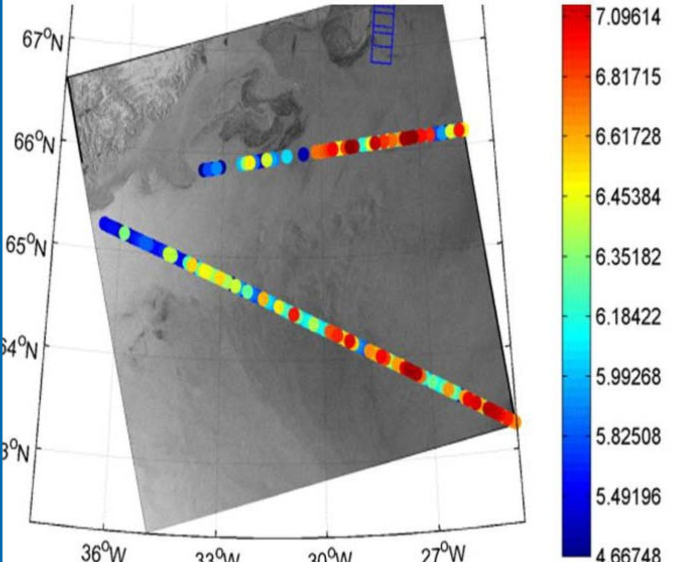




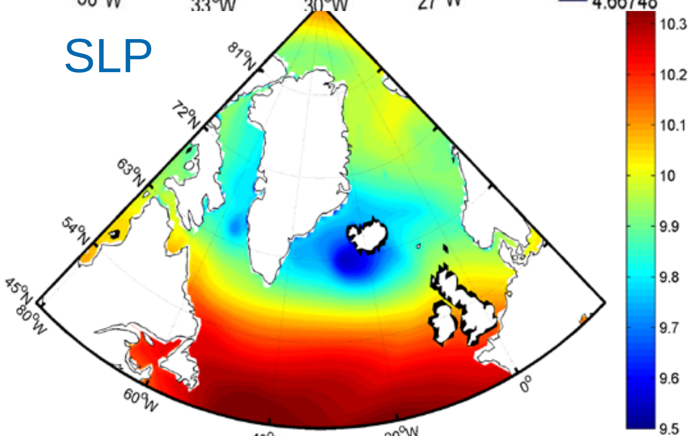


Wave analysis from SAR

Jason-2 altimeter Hs wave heights on SAR

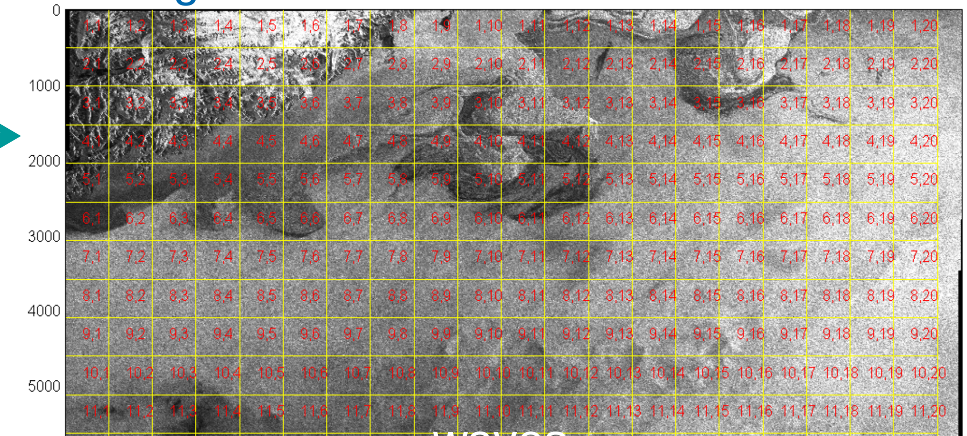


SLP

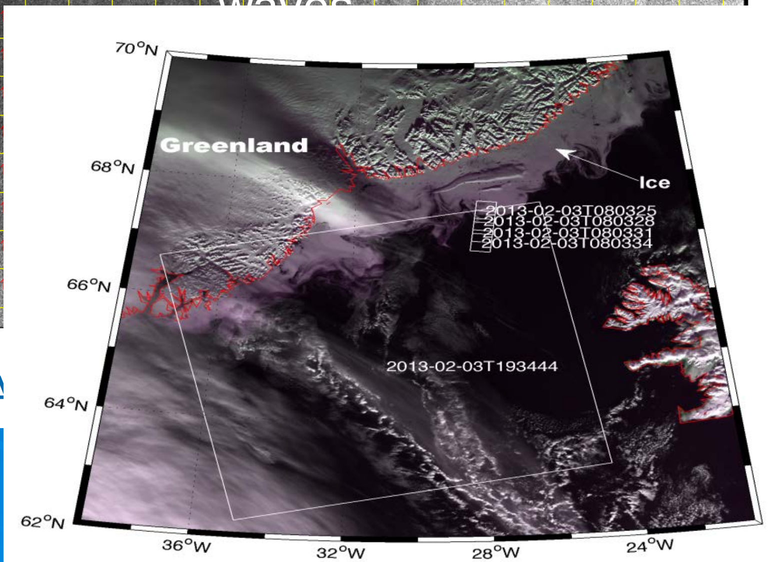


~30m/s winds → swell +waves

Sub-images

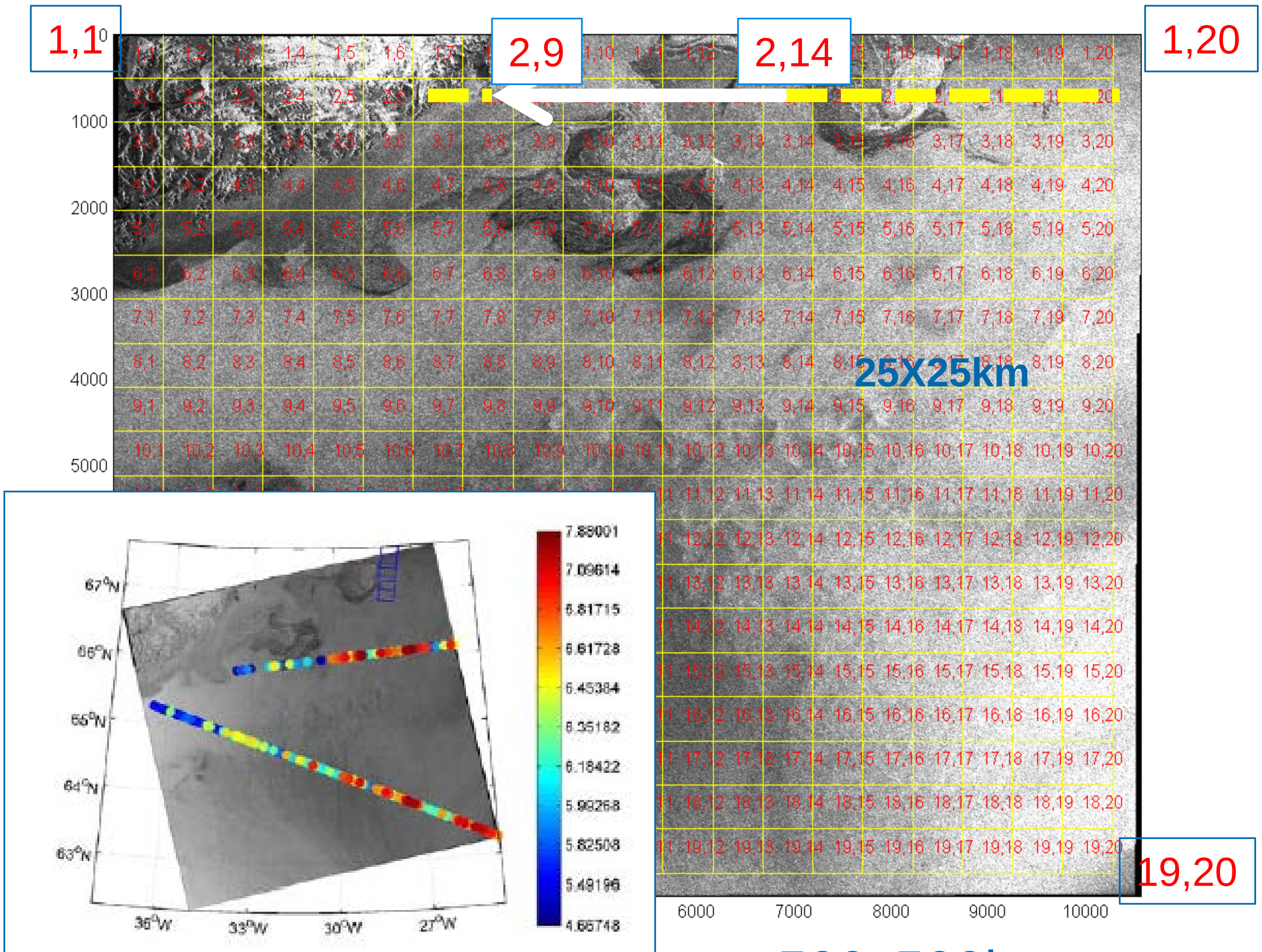


ScanSA



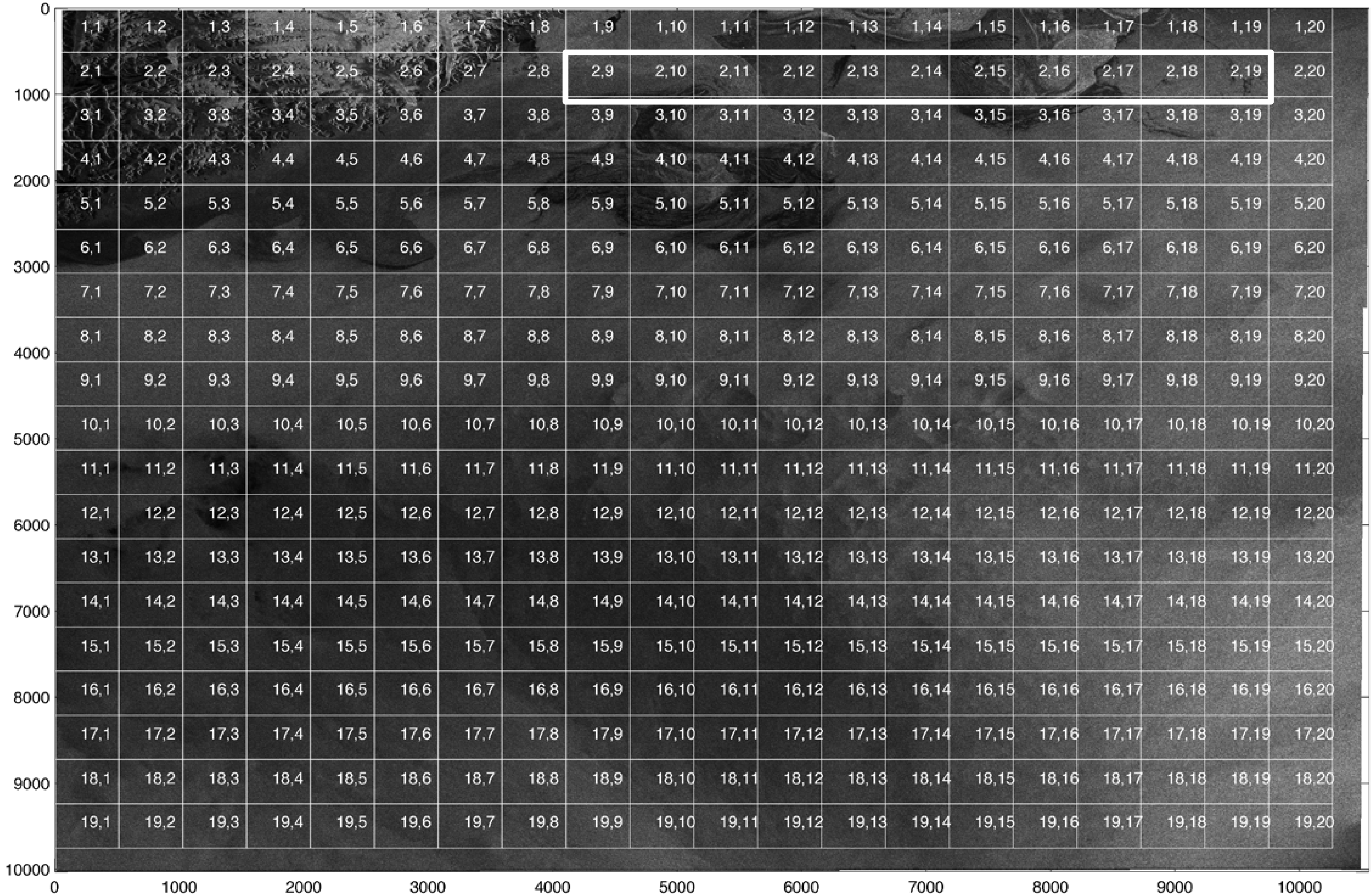
Feb 3 2013 1

SAR image segmentation

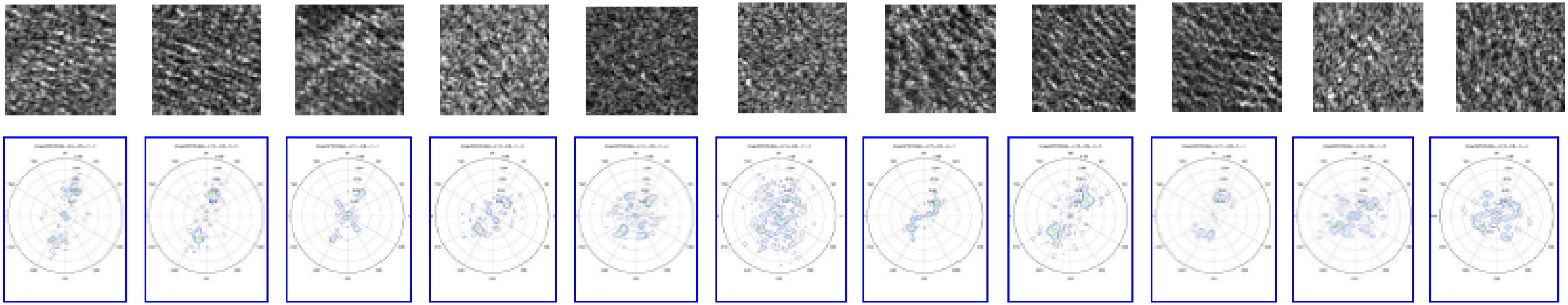


500x500km

Partition scheme of the ScanSAR image; each sub-image box is 512 by 512 pixels.



Snapshots and spectra of sub-images



(2,9) (2,10) (2,11) (2,12) (2,13) (2,14) (2,15) (2,16) (2,17) (2,18) (2,19)

Image spectra from SAR snapshoot

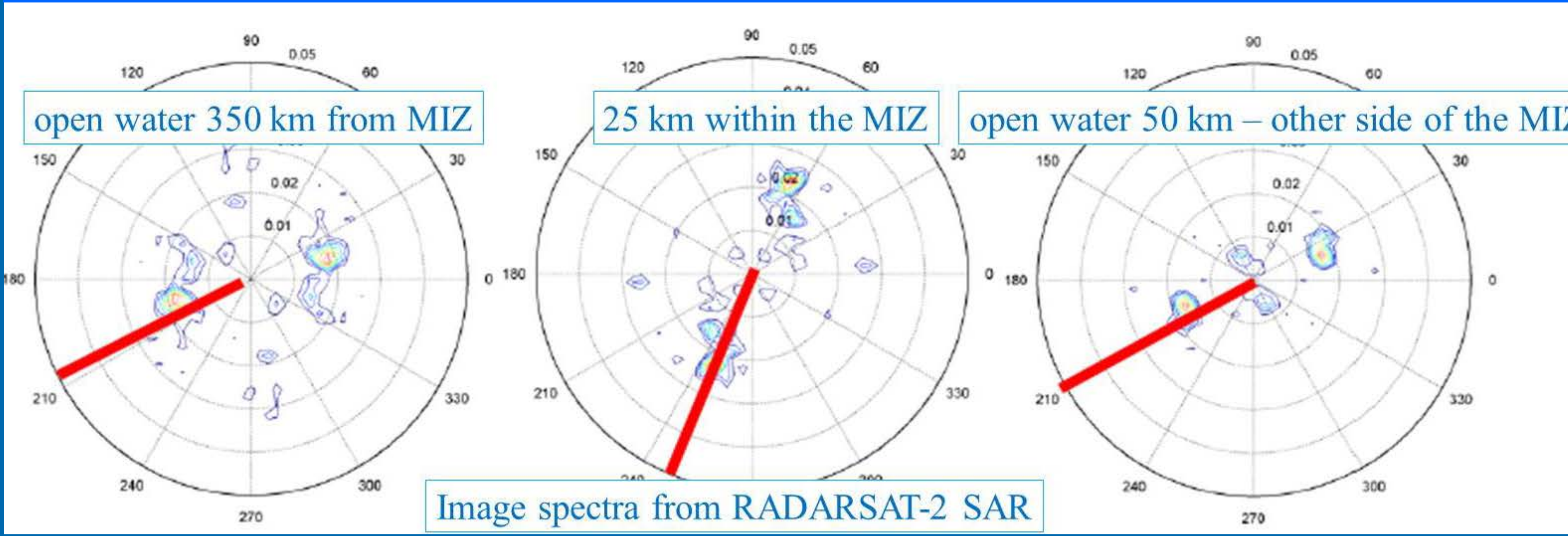
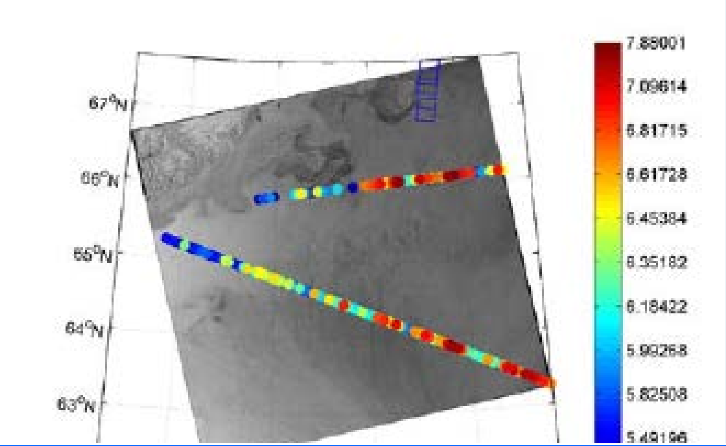


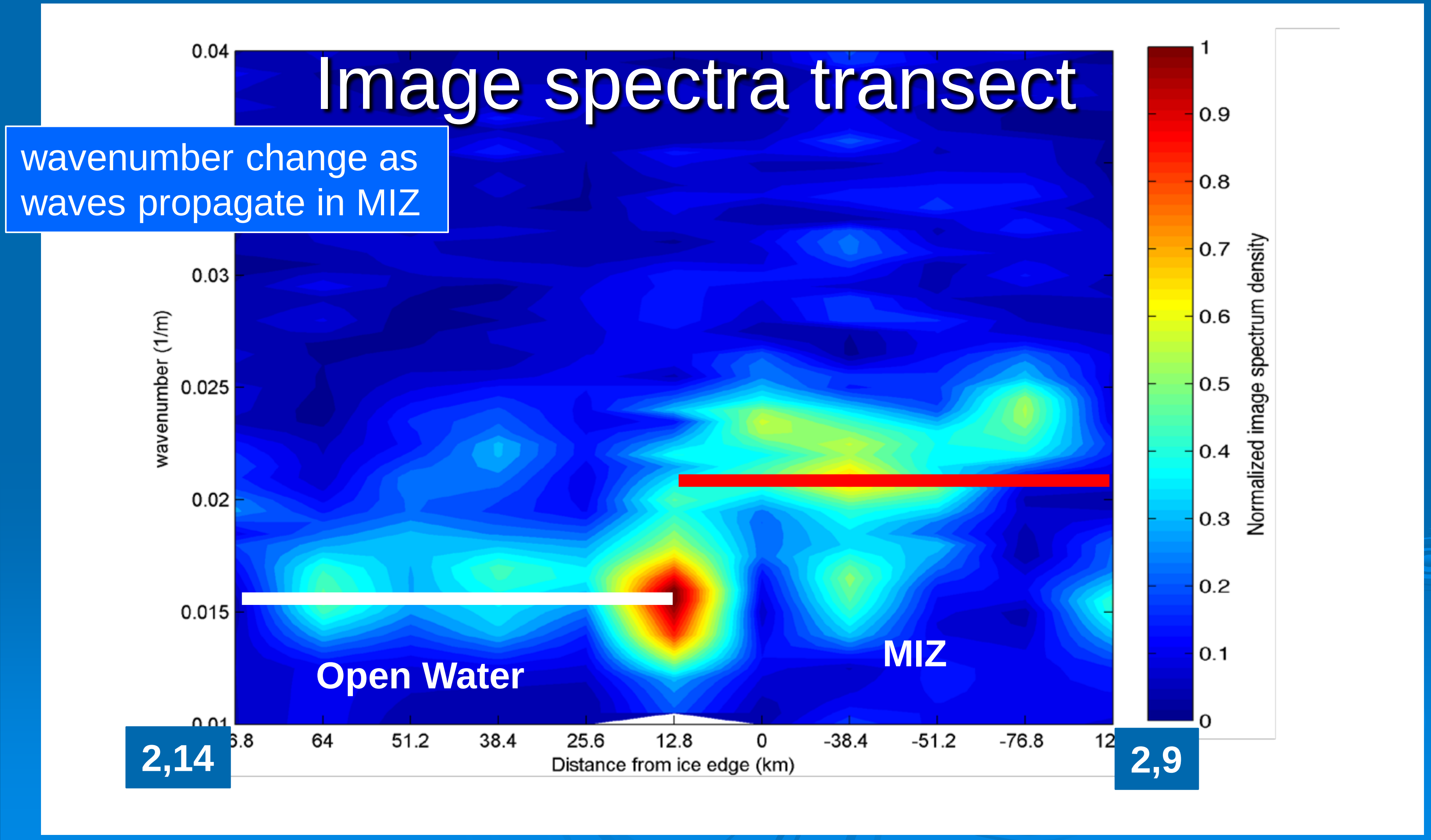
Image spectra from the ScanSAR for:
(a) open water 350 km from the MIZ
(b) 25 km within the MIZ
(c) open water 50 km from the MIZ.

→ Shortening of the waves in the MIZ

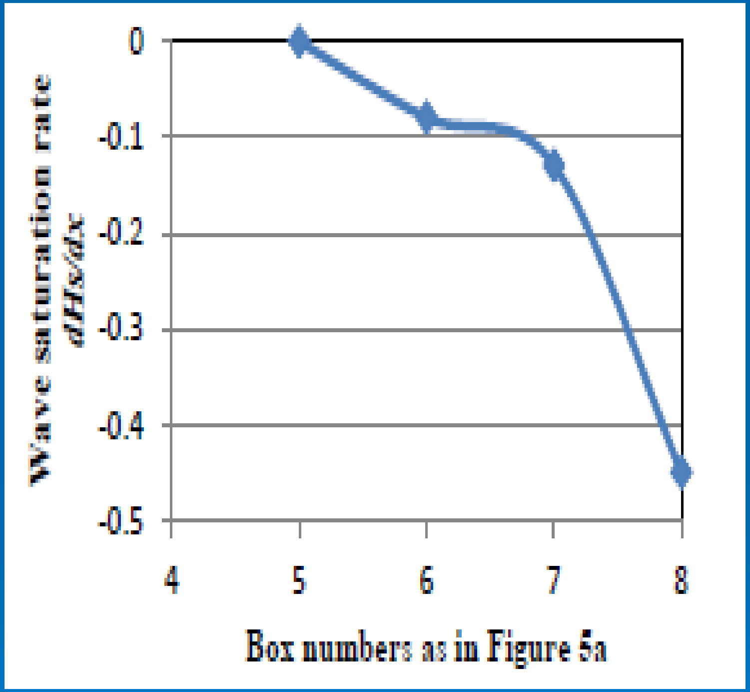


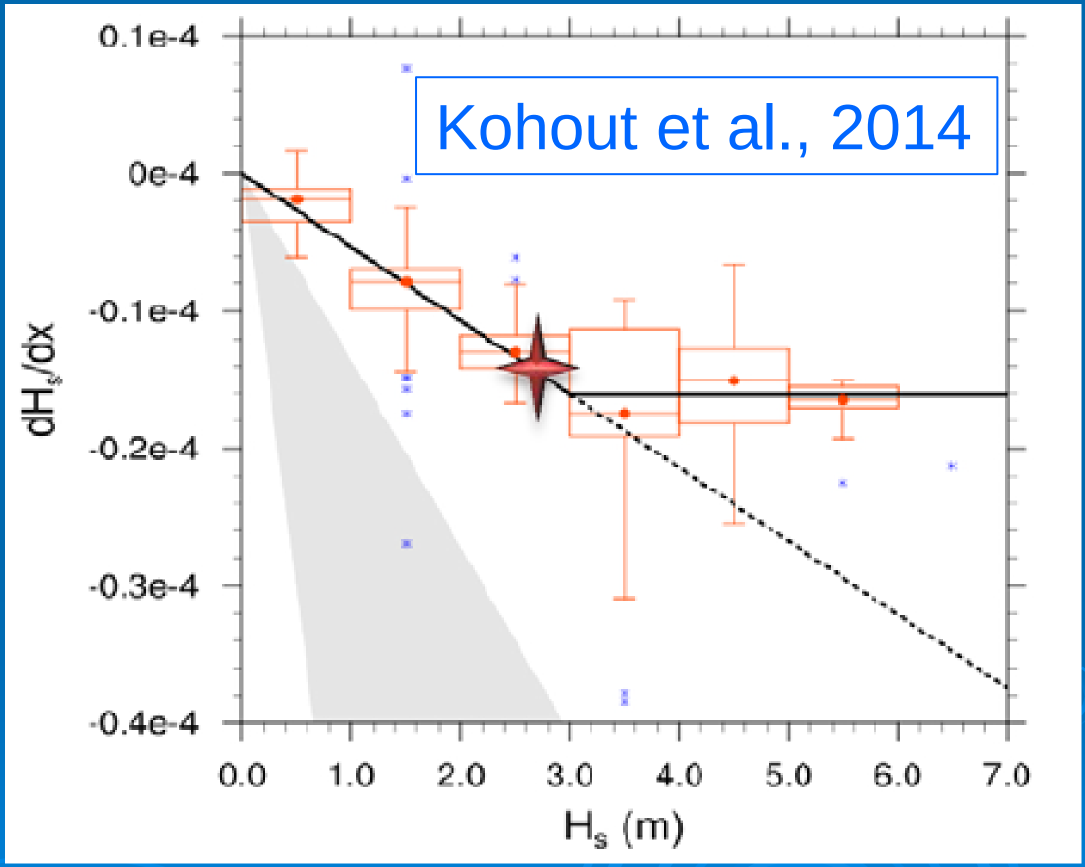
Jason-2 significant wave heights on SAR

a) Normalized image spectrum density on transect, reordered, with respect to x-axis,
b) based on distance to the ice edge; +x-axis = open water, - x-axis = in ice
c) last x-axis values corresponds to box number 7 where waves emerge from MIZ ice.



Observed wave attenuation





attenuation rate retrieved from SAR, indicated by symbol ✦

5. How do waves interact with sea ice?

$$\frac{\partial E(f,\vartheta)}{\partial t} + \vec{C}_g \cdot \nabla E(f,\vartheta) = (S_{in} + S_{ds})(1 - F_{ice}) + S_{nl} + S_{ice}$$

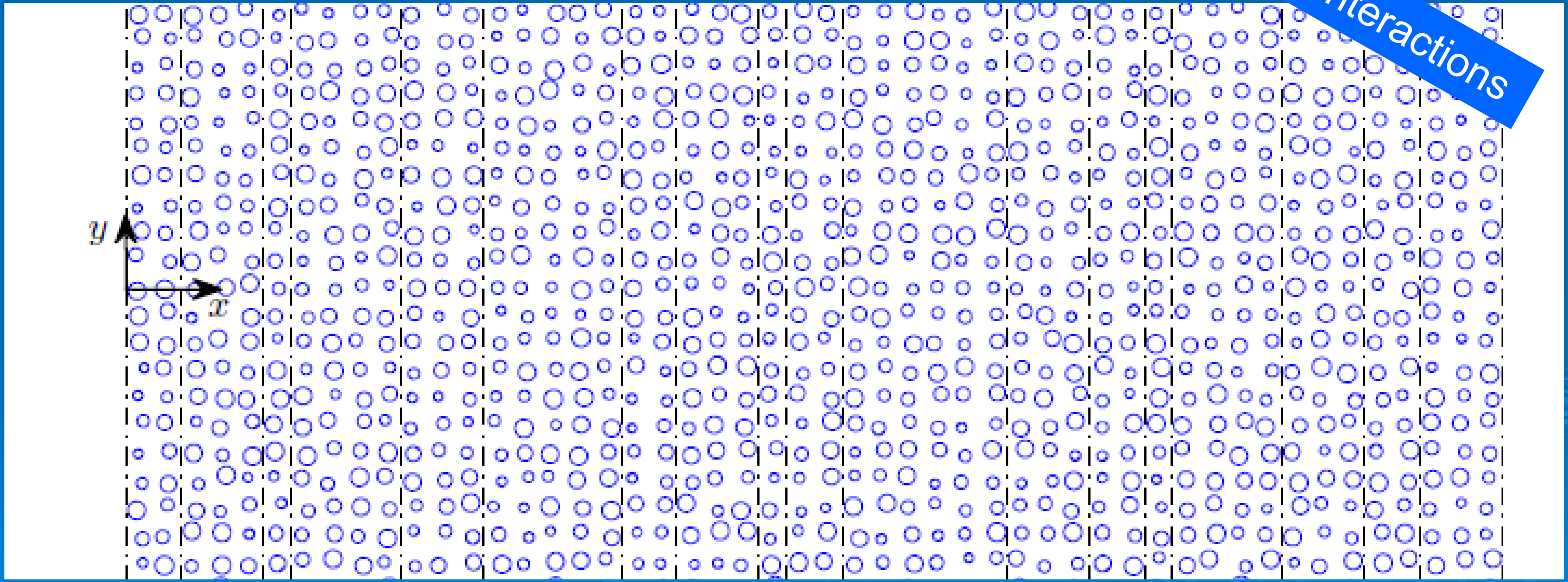
Ice fraction

Wwave-ice interactions

Dissipation

Wind input

Wave-wave interactions



What is the drag coefficient? Cd?

Dissipation due to ice:

$$S(f_m, \vartheta_n)_{ice} = E\left(f_m, \vartheta_j\right) T_{F_{ice}}^{nj}$$

And

1) transformation tensor, $T_{F_i}^{ij}$, is expressed
2) scattering tensor, $D\left(\vartheta_{ij}\right)$, for ice floe motions; heave, surge, and pitch

→ This can be re-formulated…
→ As a linear Boltzman equation for MIZ wave scattering (Meylan and Masson 2006)!

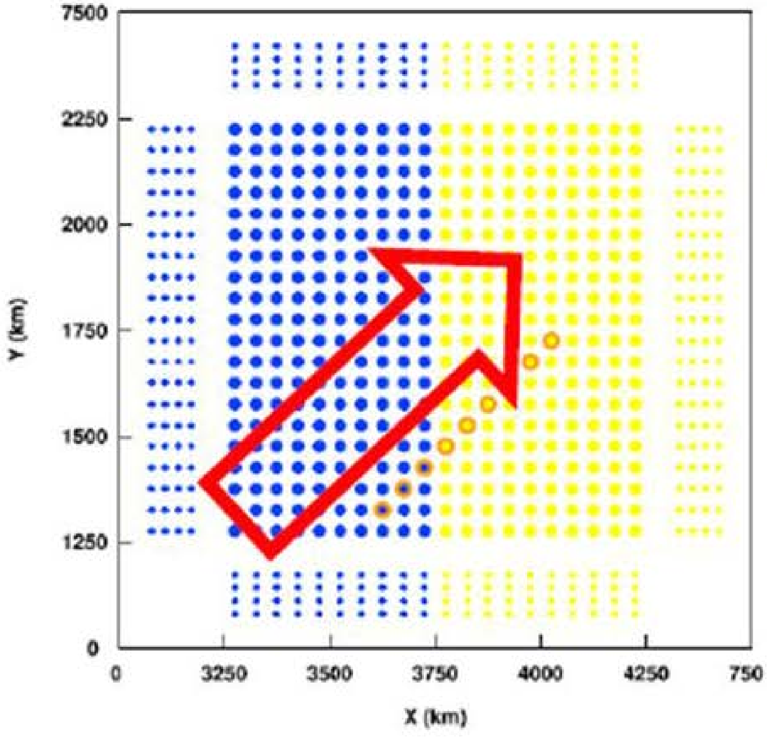
… as a Boltzmann scattering equation,

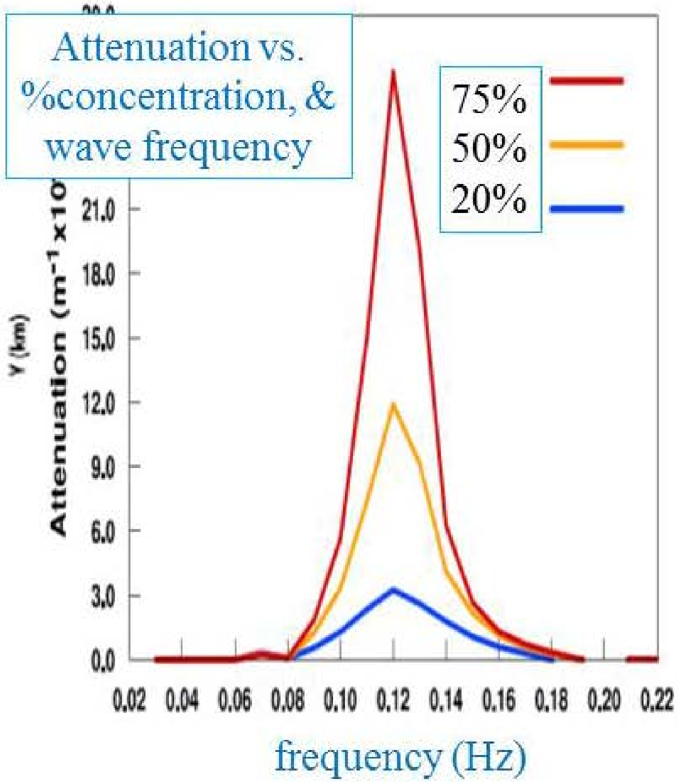
$$\frac{\partial E(f,\vartheta)}{\partial t} + \vec{C}_g \cdot \nabla E(f,\vartheta) = (S_{in} + S_{ds})(1 - F_{ice}) + S_{nl} + \int_0^{2\pi} \frac{F_{ice}}{A_f} |D(\vartheta - \vartheta'|^2 d\vartheta'$$

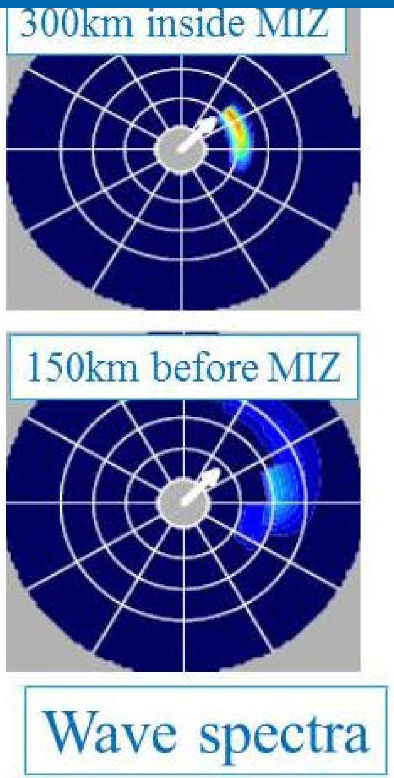
$$- \left(\int_0^{2\pi} \frac{F_{ice}}{A_f} |D(\vartheta - \vartheta')|^2 d\vartheta' + \sigma_a \frac{F_{ice}}{A_f} \right) E(f,\vartheta)$$

- S is scattering density for spectral energy $E(f,\vartheta)$, or the scattering kernel:
- AND S is written in terms of scattering tensor D,
- $S(\vartheta,\vartheta') = \frac{F_{ice}}{A_f} |D(\vartheta - \vartheta')|^2$
- where A_f is the average surface area of the ice floes
- σ_a is absorption cross-section,

6. Wave-ice interactions model







Computer test: winds 20m/s at 45° to northeast, 10m ice floes 1m thick

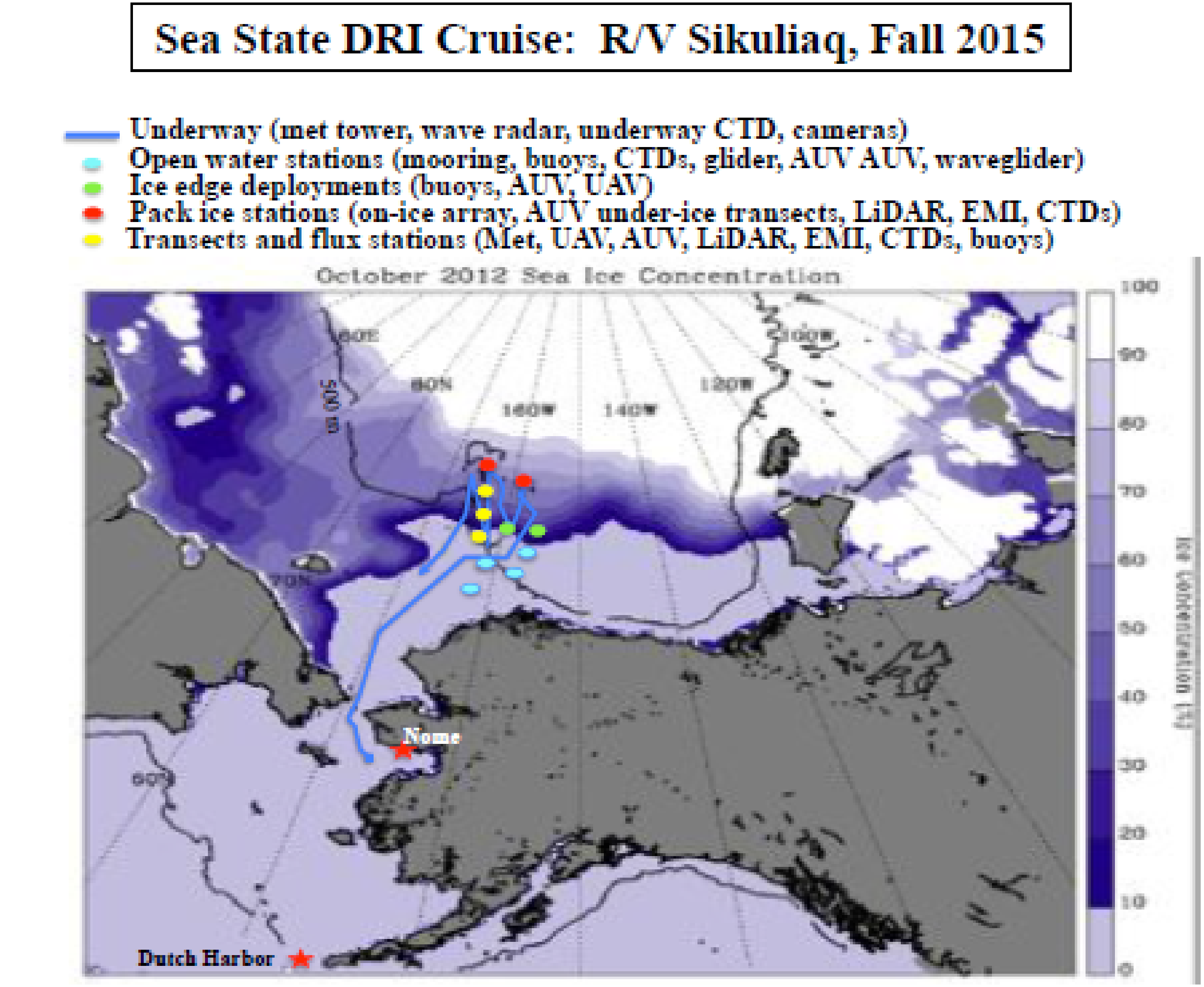
Wave-ice interactions model: Perrie and Hu, 1996 JPO
WHAT is the dispersion relation in the MIZ for waves?

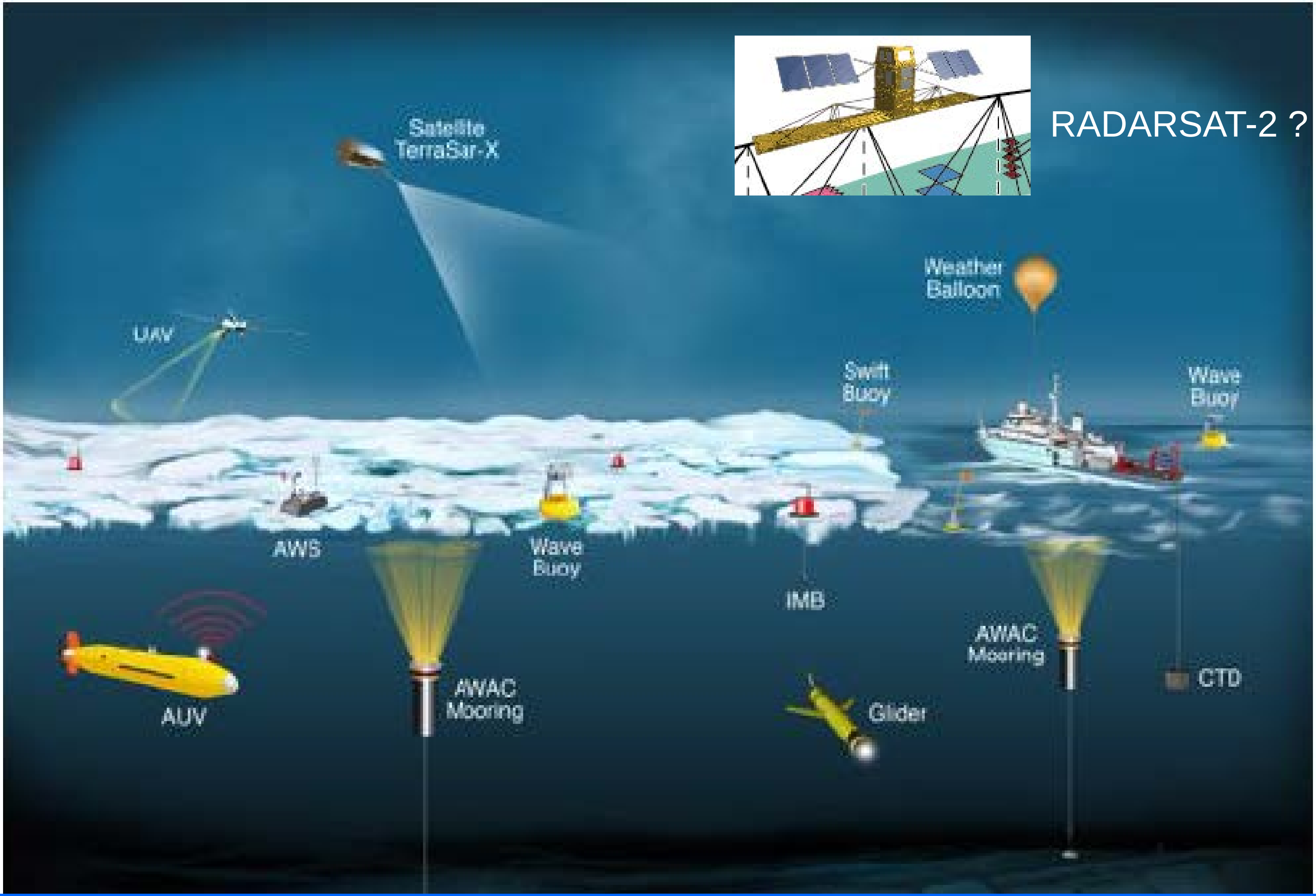
Fox + Squire '91

$$\kappa \tan \kappa H = -\frac{\rho\omega^2}{L\kappa^4 + \rho g - m\omega^2}$$

7. Sea State and Boundary Layer Physics of the Emerging Arctic Ocean

by J. Thomson[1], V. Squire[2], S. Ackley[3], E. Rogers[4], A. Babanin[5], P. Guest[6], T. Maksym **et al.**

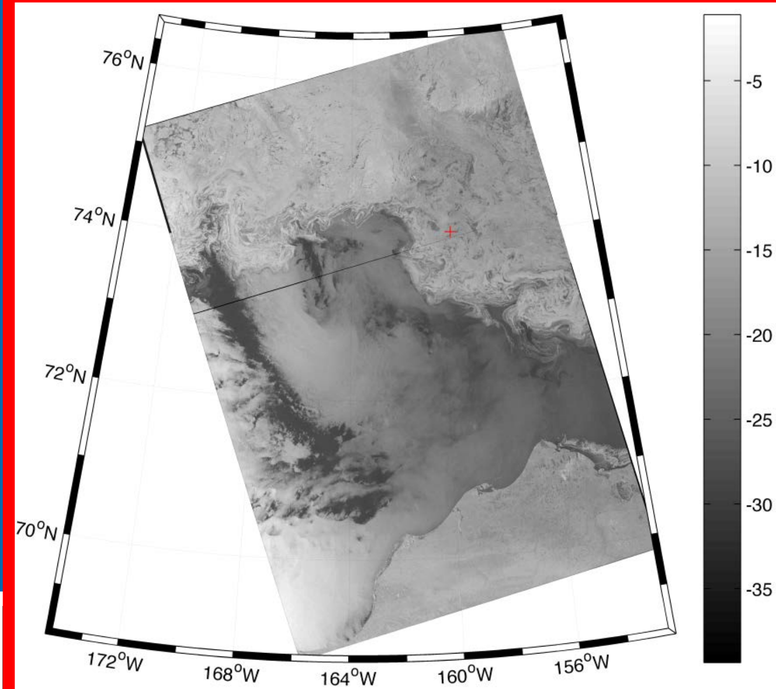




Radarsat-2 SAR: 1184 images were processed to guide the cruise in Arctic ice: August (tests, 18), Sept (349), Oct (780), Nov (37), with about 500 images sent to collocate with the cruise. Value ~ $5M.

J. Thomson et al. 2015, draft cruise report…

Cruise track and stations



WaveBuoy 02: an example of the heavy icing during the deployment

Big waves amongst the pancakes

8. Summary: to do list

1. Wave model: Transition the wave-ice interactions methodology to wave forecast model, WW3: pre-calculate the ice scattering kernel.

2. Elastic ice floes: Use the "elastic ice plate model" for ice floes + elastic scattering kernel formulation of Meylan and Masson (2006).

3. Multiple scattering: Model effect of multiple scattering and relatively dense floe packing, incorporating approach of Squire et al.

4. Floe breaking: Setting a floe breaking criteria based on significant wave height and modify the scattering kernel as part of the time-stepping.

5. Academic tests: Do academic tests with wind forcing and simple geometry ocean topography, to get basic model behavior.

6. Validation: Check with *in situ* attenuation rates, and collocated satellite data collected from the field experiments: BLSS, MIZ, R/V Oden cruise

Summary

- RADARSAT-2 SAR can measure long waves ~200m
- Also good ability for wind fields
- Ice information on open water, vs. MIZ
- Still need to map SAR image backscatter to ice types, via classification scheme
- Plan and complete the implementation in WW3