# Using SAR for Ocean Applications


**Waves**
**Near Surface Wind**

**Internal Waves**

**Surface Current**

**Ship detection**
**Oil spill**

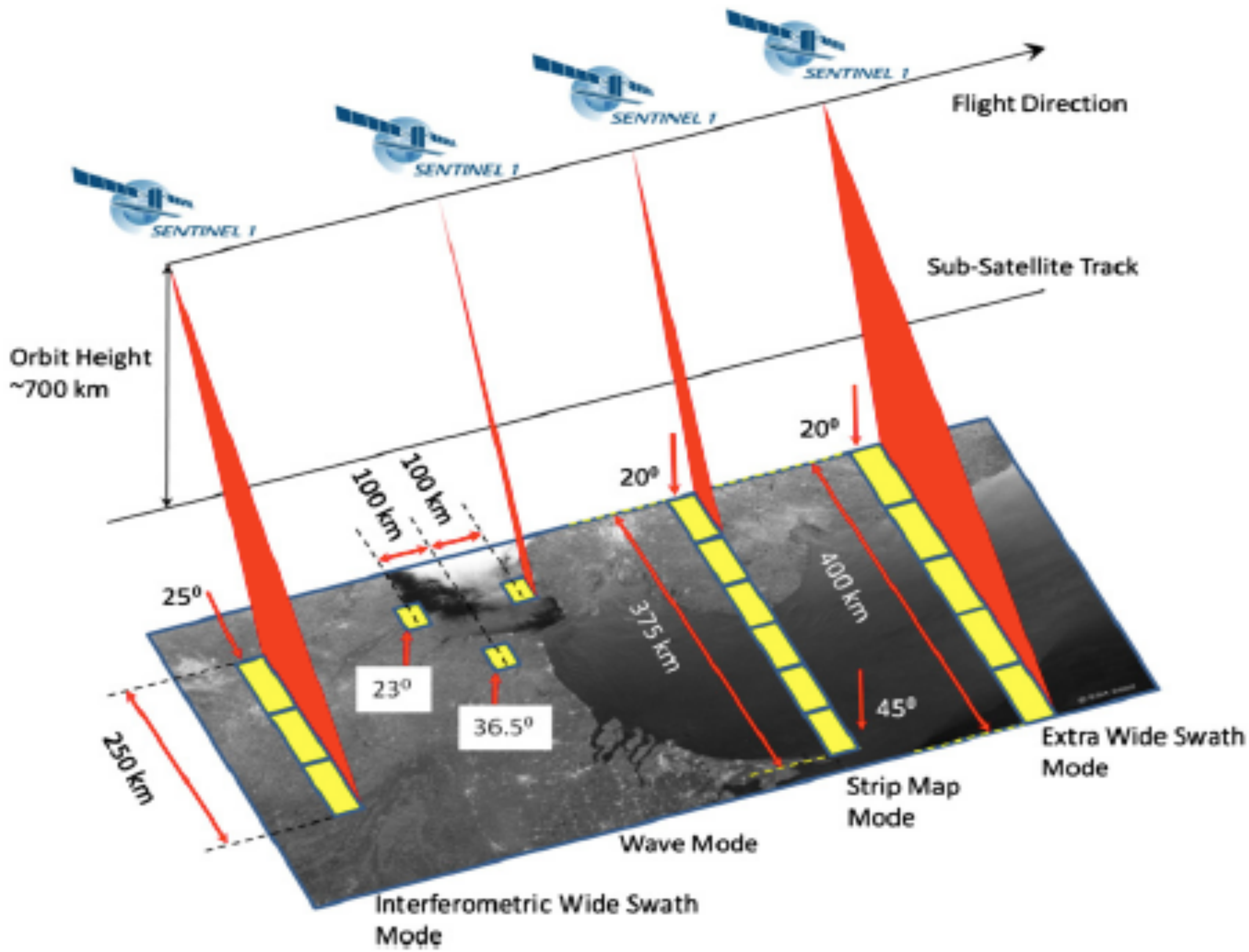
**Sea ice**

# Research Needs and SAR imaging

- Air-sea interaction, thermodynamcs and mixing in the atmospheric boundary layer – upper ocean mixed layer;
- Wind field interaction and coupling to surface waves, current, Stokes drift, Ekman current and mixing – momentum exchange between the air-upper ocean;
- Physical based explanation for the surface roughness at all scales from cm to 100 of km.

- SAR imaging by Bragg scattering, specular and wave breaking in response to cm waves, coupled with modulation by longer waves, wind field variations and surface current variations and damping material. SAR is unique for this!!!

# Sentinel-1 Operating Modes for Wind-Wave-Current detection



| Parameter | Interferometric Wide-swath mode (IW) | Wave mode (WV) |
|---|---|---|
| Polarisation | Dual (HH + HV, VV + VH) | Single (HH, VV) |
| Access (incidence angles) | 31°–46° | 23°–37° (mid incidence angle) |
| Azimuth resolution | <20 m | <5 m |
| Ground range resolution | <5 m | <5 m |
| Azimuth and range looks | Single | Single |
| Swath | >250 km | Vignette 20×20 km |
| Maximum NESZ | −22 dB | −22 dB |
| Radiometric stability | 0.5 dB ($3\sigma$) | 0.5 dB ($3\sigma$) |
| Radiometric accuracy | 1 dB ($3\sigma$) | 1 dB ($3\sigma$) |
| Phase error | 5° | 5° |

| Parameter | Strip Map mode (SM) | Extra Wide-swath mode (EW) |
|---|---|---|
| Polarisation | Dual (HH + HV, VV + VH) | Dual (HH + HV, VV + VH) |
| Access (incidence angles) | 20°–47° | 20°–47° |
| Azimuth resolution | <5 m | <40 m |
| Ground range resolution | <5 m | <20 m |
| Azimuth and range looks | Single | Single |
| Swath | >80 km | >410 km |
| Maximum NESZ | −22 dB | −22 dB |
| Radiometric stability | 0.5 dB ($3\sigma$) | 0.5 dB ($3\sigma$) |
| Radiometric accuracy | 1 dB ($3\sigma$) | 1 dB ($3\sigma$) |
| Phase error | 5° | 5° |

# SAR CONTRIBUTION TO MARINE MONITORING

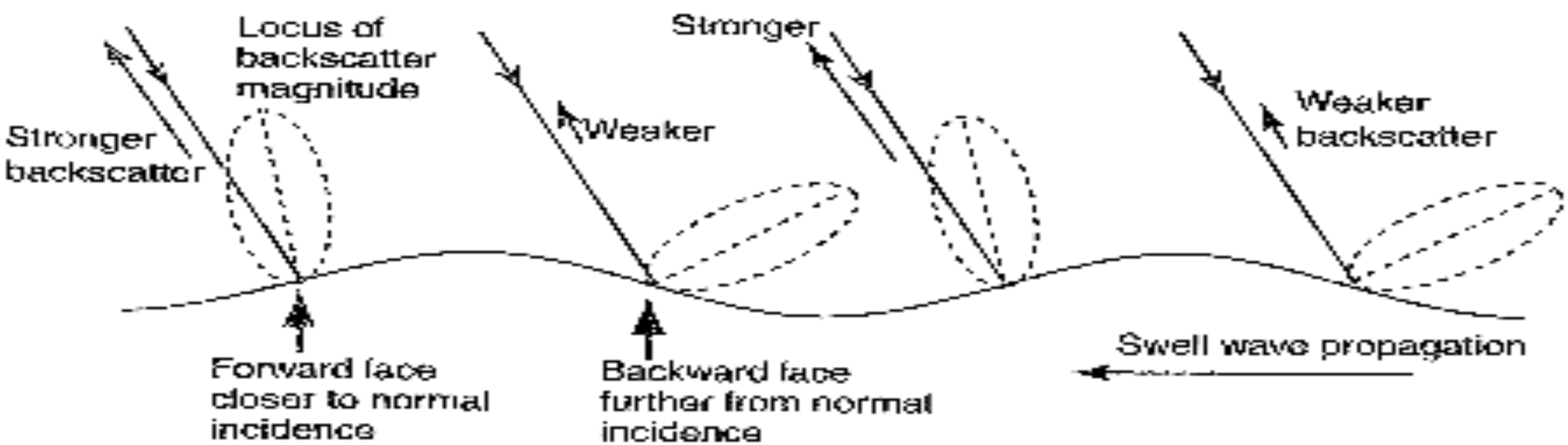
| Operational Surveillance | Emerging new Operational application | Routine Product and partly used in NWP | Research Dominated |
|---|---|---|---|
| **Ship detection**<br><br>**Oil spill detection**<br><br>**Sea Ice**<br><br>**Shallow water Bathymetry** | **Wind field retrievals** | **Ocean Waves and Ocean Spectra** | **Surface current fronts and eddies**<br><br>**Internal Waves**<br><br>**Atmospheric boundary layer Processes**<br><br>**Film damping** |

# SAR WAVE IMAGING MECHANISMS

- Longer waves locally modify the exact plan of incidence to produce a contrast corresponding to the local change in cross section

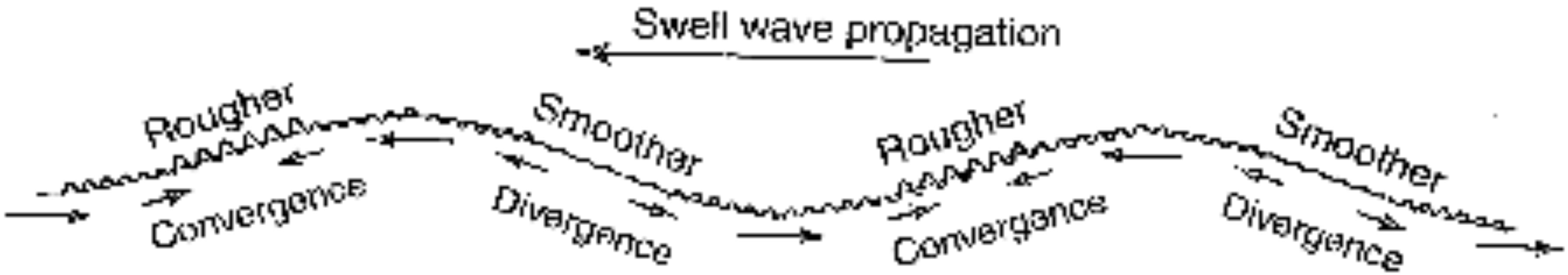
→ **Tilt Modulation** : a priori knowledge of the gradient of the relative cross section as a function of the small incidence angle deviation

$$T_t(k) = \left(\frac{1}{\sigma^o}\cdot\frac{\partial\sigma}{\partial\theta}\right)_{\theta = \theta_0}\cdot ik_r$$

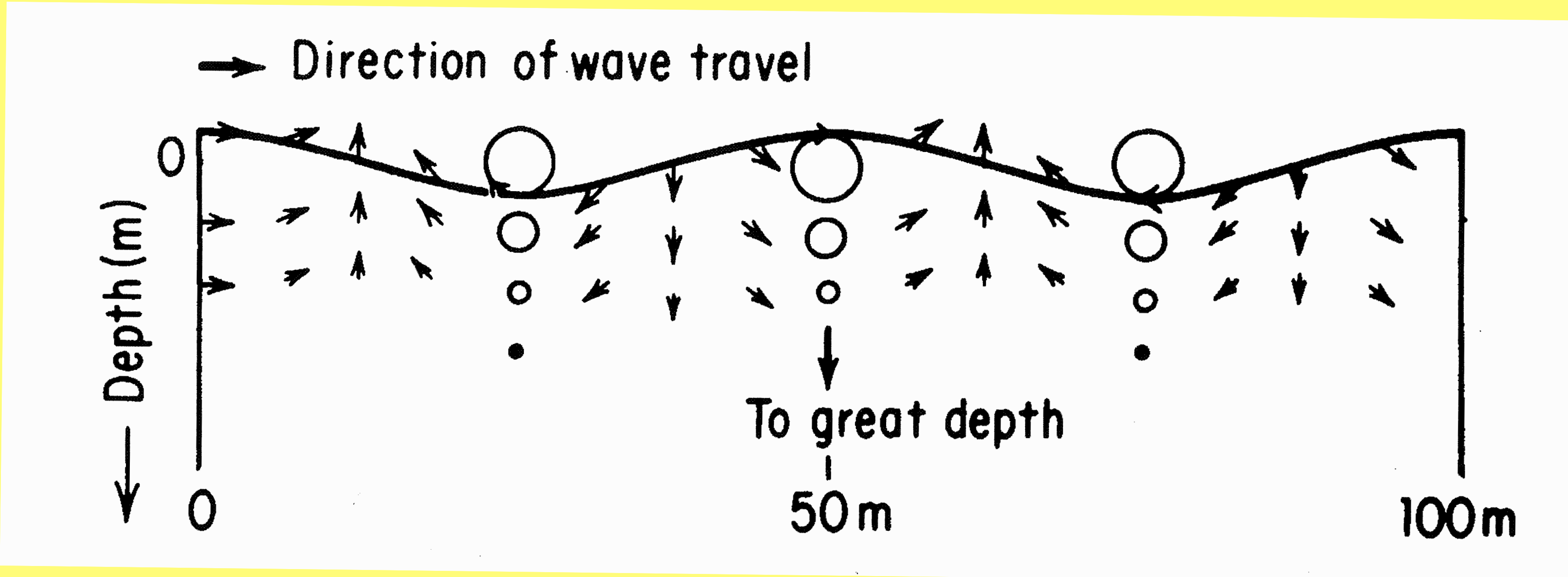


→ **Hydrodynamic Modulation** : a priori knowledge of the gradient of the relative cross as a function of the phase of the long wave

$$T_h(k) = \left(\frac{1}{\sigma^o} \cdot \frac{\partial \sigma}{\partial \varphi}\right) \cdot ik_r$$



# PARTICLE MOTION DUE TO TRAVELLING WAVES



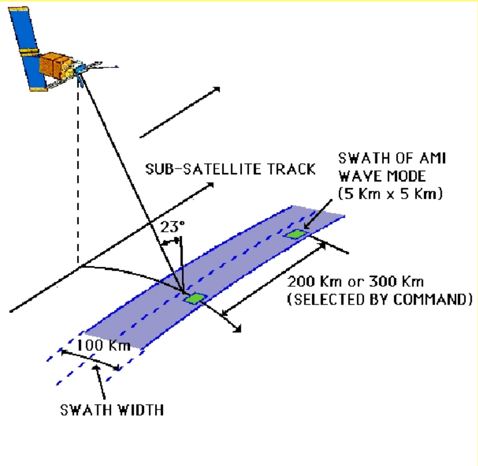

After Neumann and Pierson

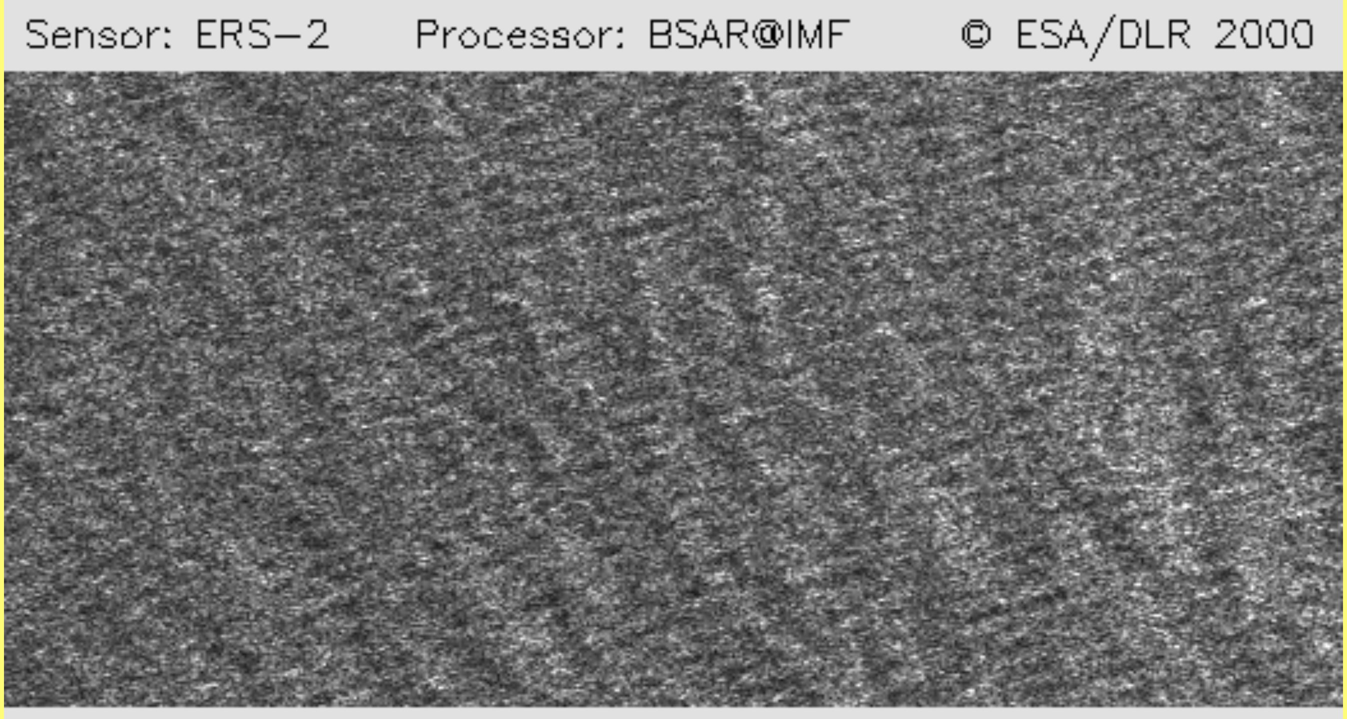
# SAR Signatures of Ocean Waves

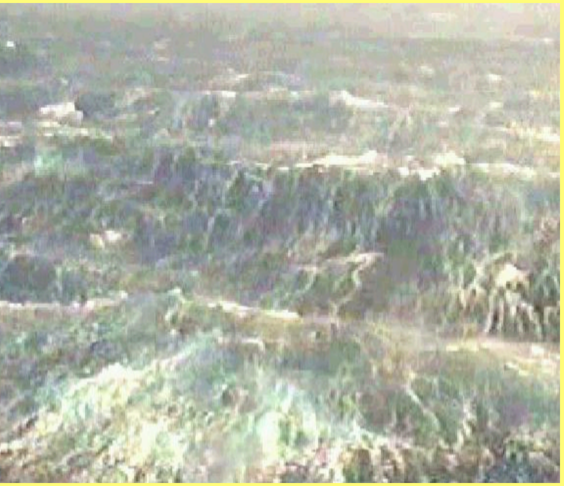
- Bragg scattering: NRCS $\propto$ Bragg wave intensity; relation depends on incidence angle
- Longer waves modulate the NRCS
  - Tilt modulation affects incidence angle
  - Hydrodynamic modulation affects Bragg wave energy

Courtesy Roland Romeiser

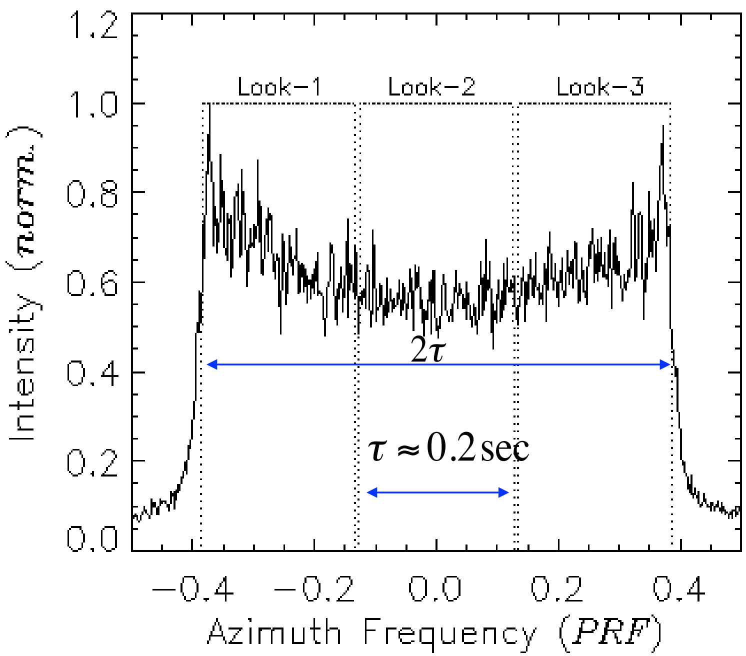
# SAR wave imaging: What is the travel direction

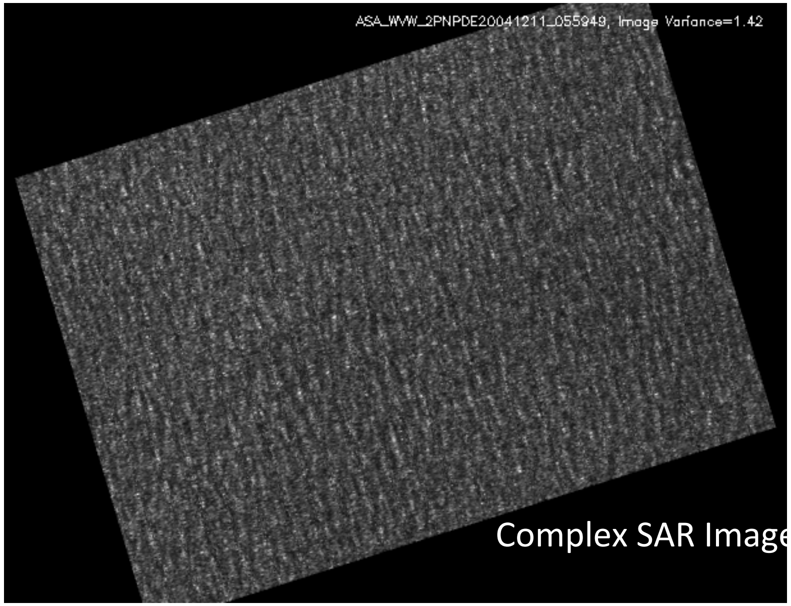


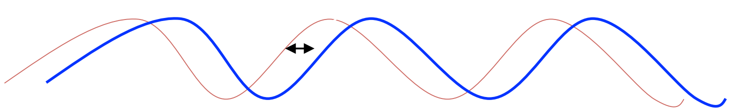
# From Co- to Cross-Spectra Estimation: Ambiguity Removal




-Look Extraction
-Intensity Detection

$$\Delta\varphi = \omega_k \cdot \tau \approx 10^o$$

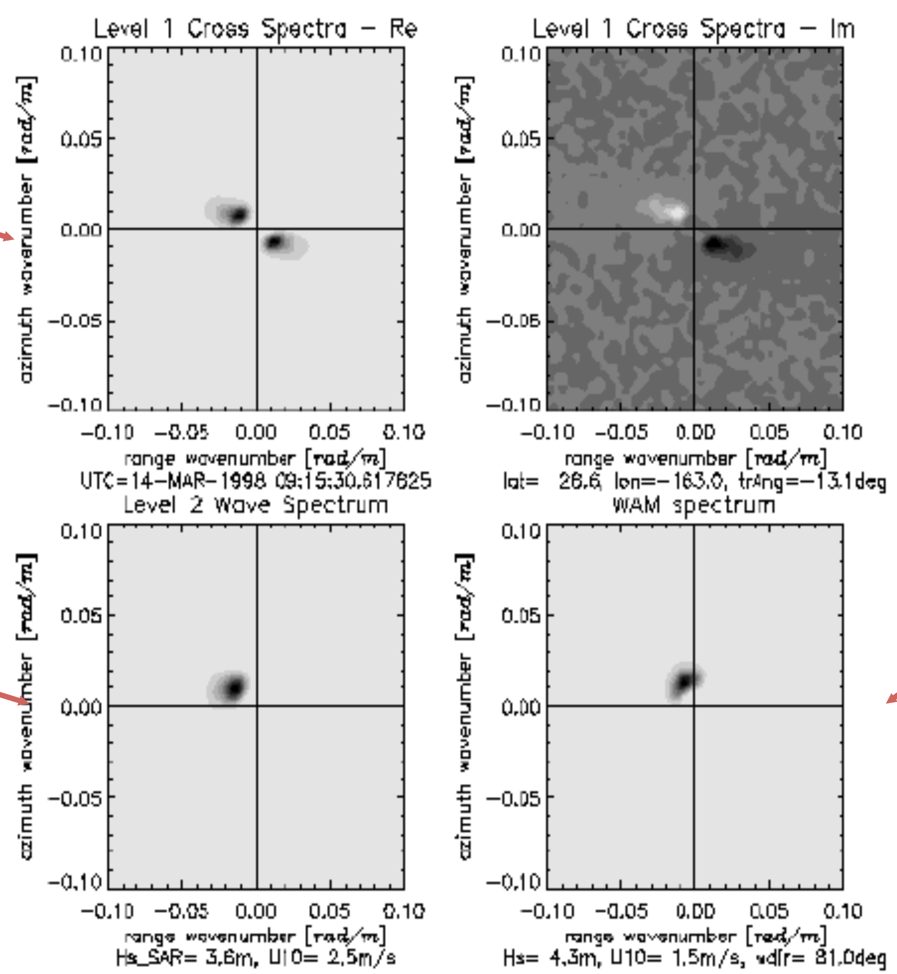


phase term resolves wave propagation direction

# Inversion to SAR Ocean Wave Spectra

SAR image cross-spectra

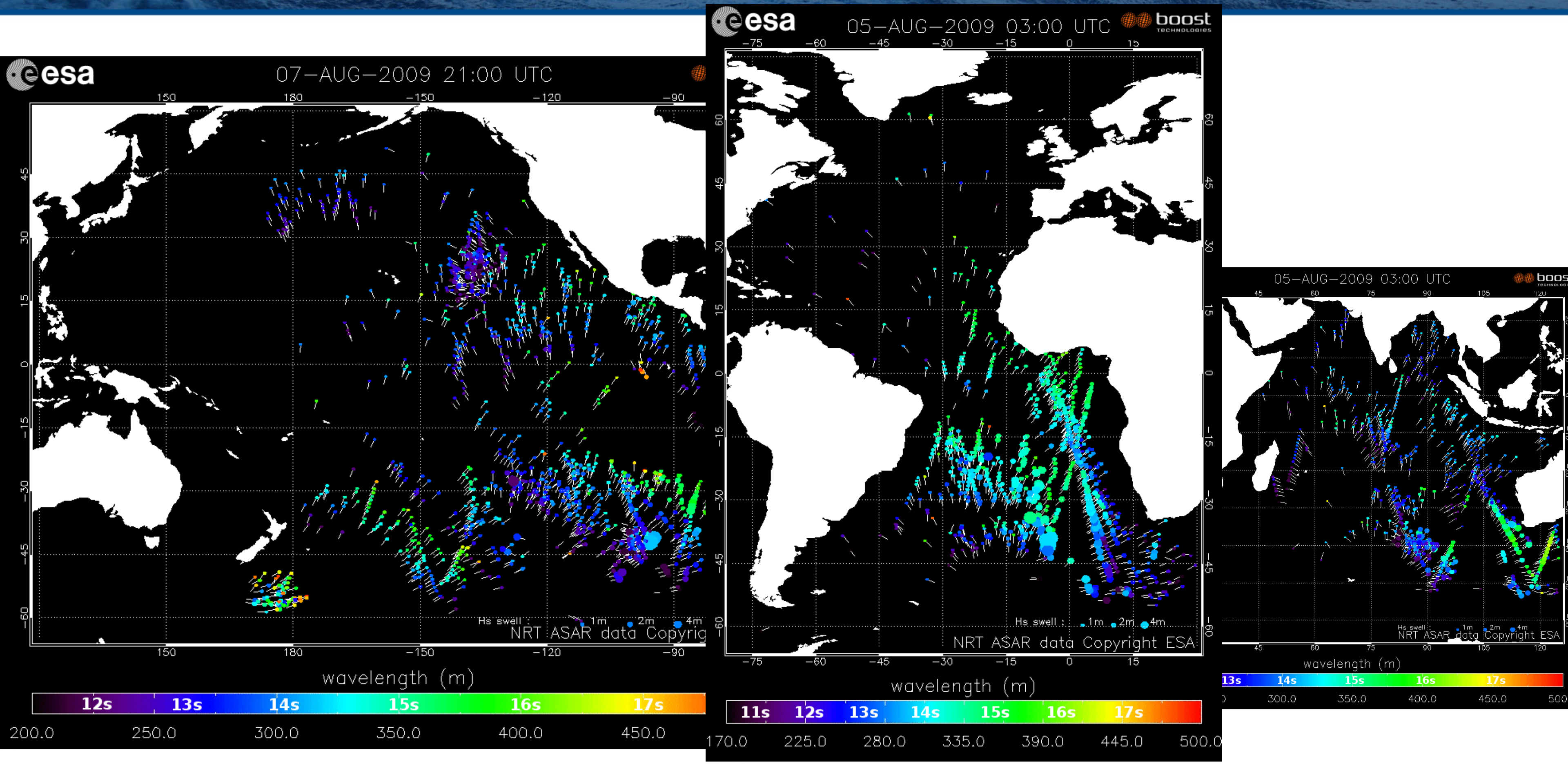
SAR ocean wave spectra




WAM (for comparison)

Courtesy NORUT

# Swell propagation

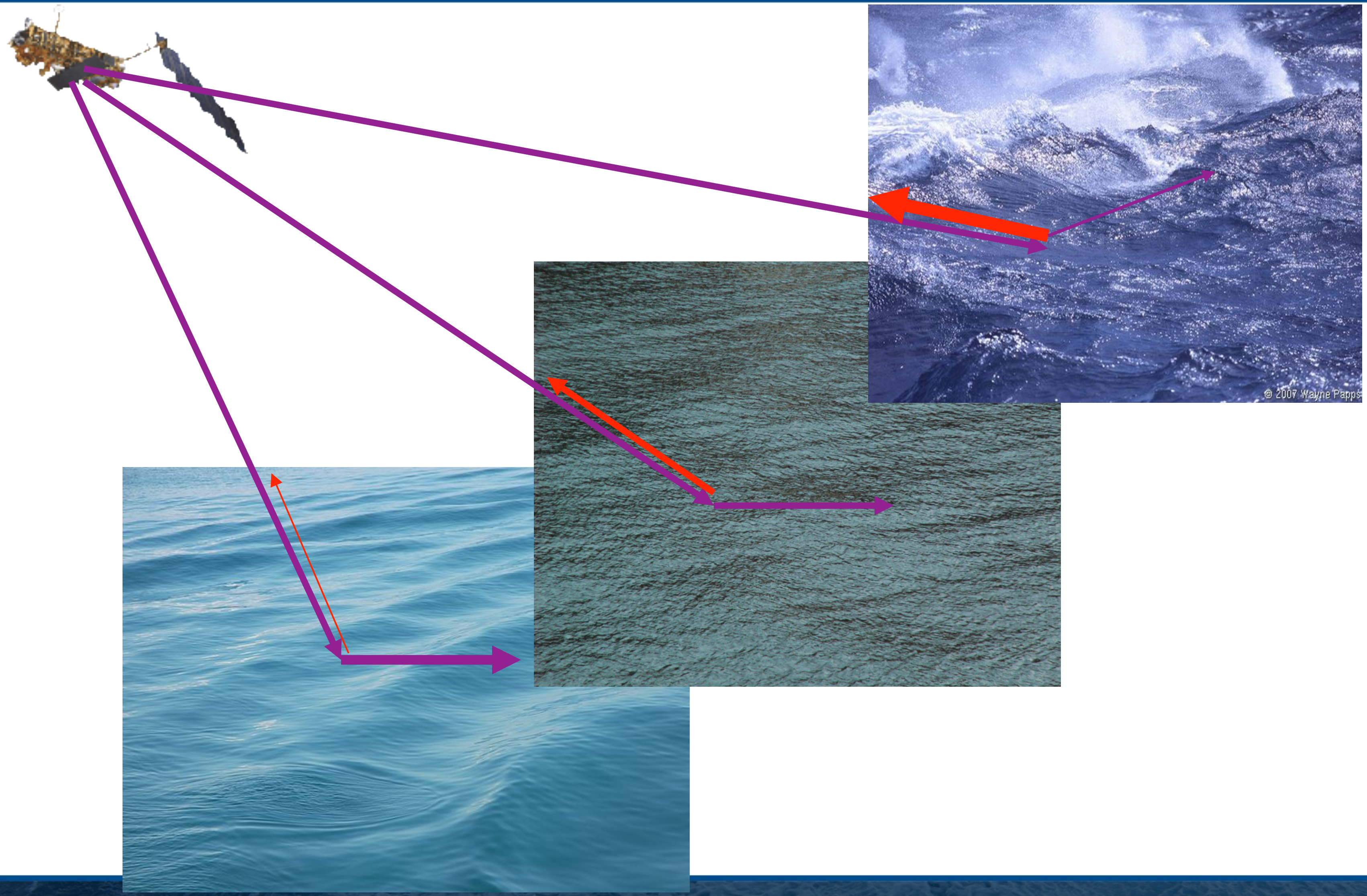



Courtesy Collard, Chapron (ESA WVC study) http://soprano.cls.fr

# SAR CONTRIBUTION TO MARINE MONITORING

| Operational Surveillance | Emerging new Operational application | Routine Product and partly used in NWP | Research Dominated |
| --- | --- | --- | --- |
| Ship detection<br><br>Oil spill detection<br><br>Sea Ice<br><br>Shallow water Bathymetry | Wind field retrievals | Ocean Waves and Ocean Spectra | Surface current fronts and eddies<br><br>Internal Waves<br><br>Atmospheric boundary layer Processes<br><br>Film damping |

# Radar backscatter increases with wind speed



# SAR sensing of wind speed

- Transmits a puls of  microwave radiation
- Measures the fraction that comes back

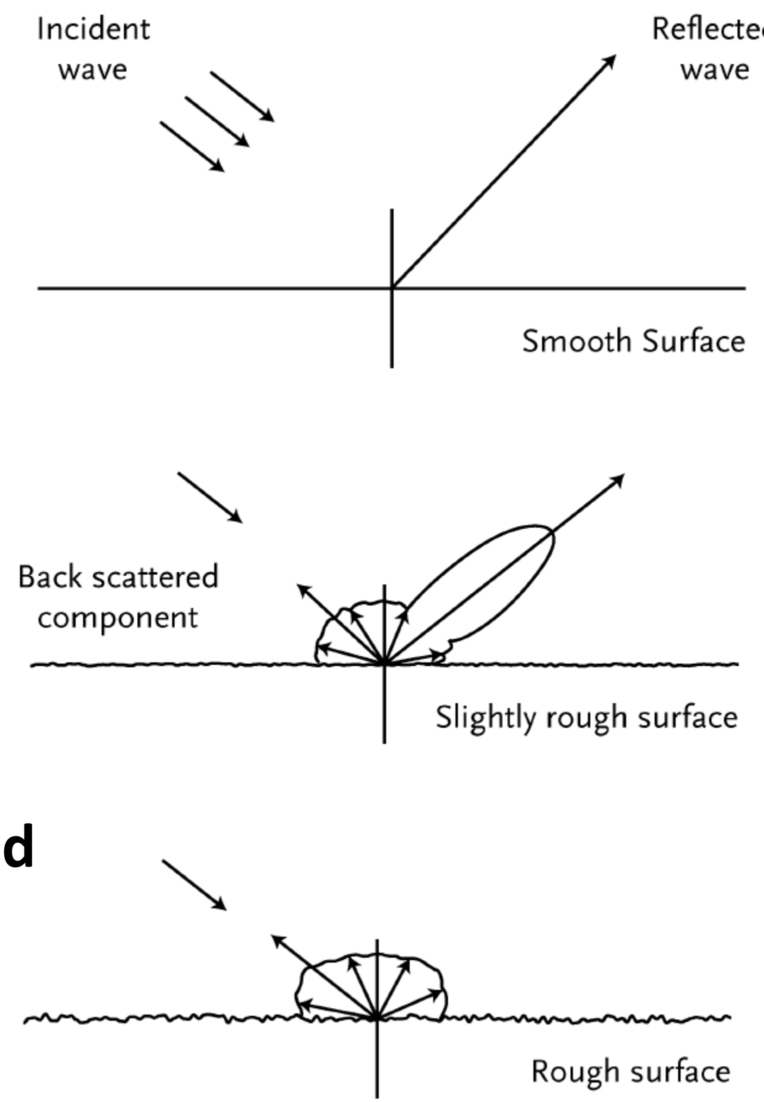
$$P_r \quad = \quad (P_t/4\pi R^2)\ G\ (\sigma/4\pi R^2)\ A$$

measured =    incident  x  reflected

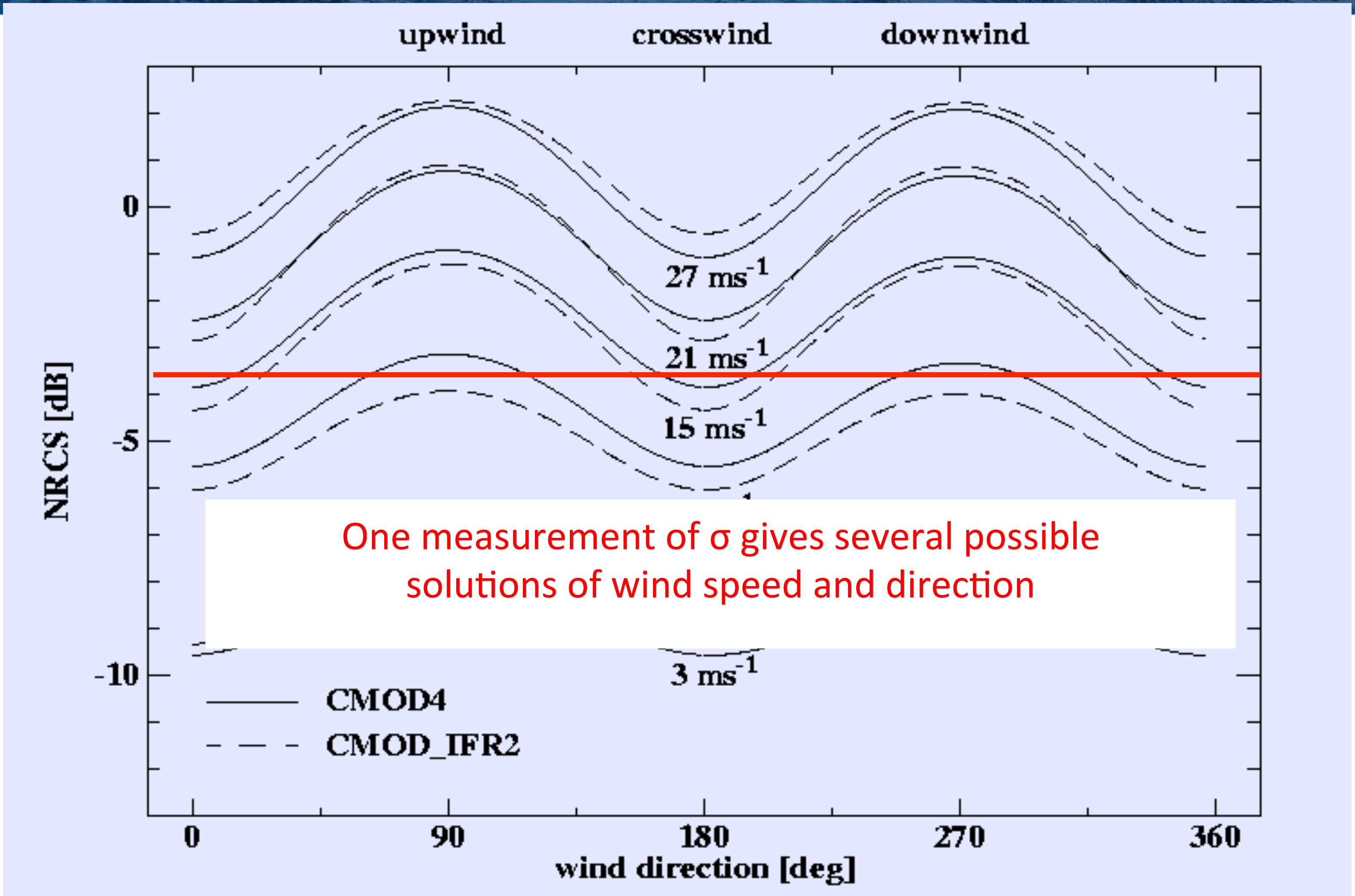
G = antenna gain, A = antenna area,
σ = radar cross section, R = range distance

σ is a measure of the surface roughness

**σ is well  correlated with wind speed**

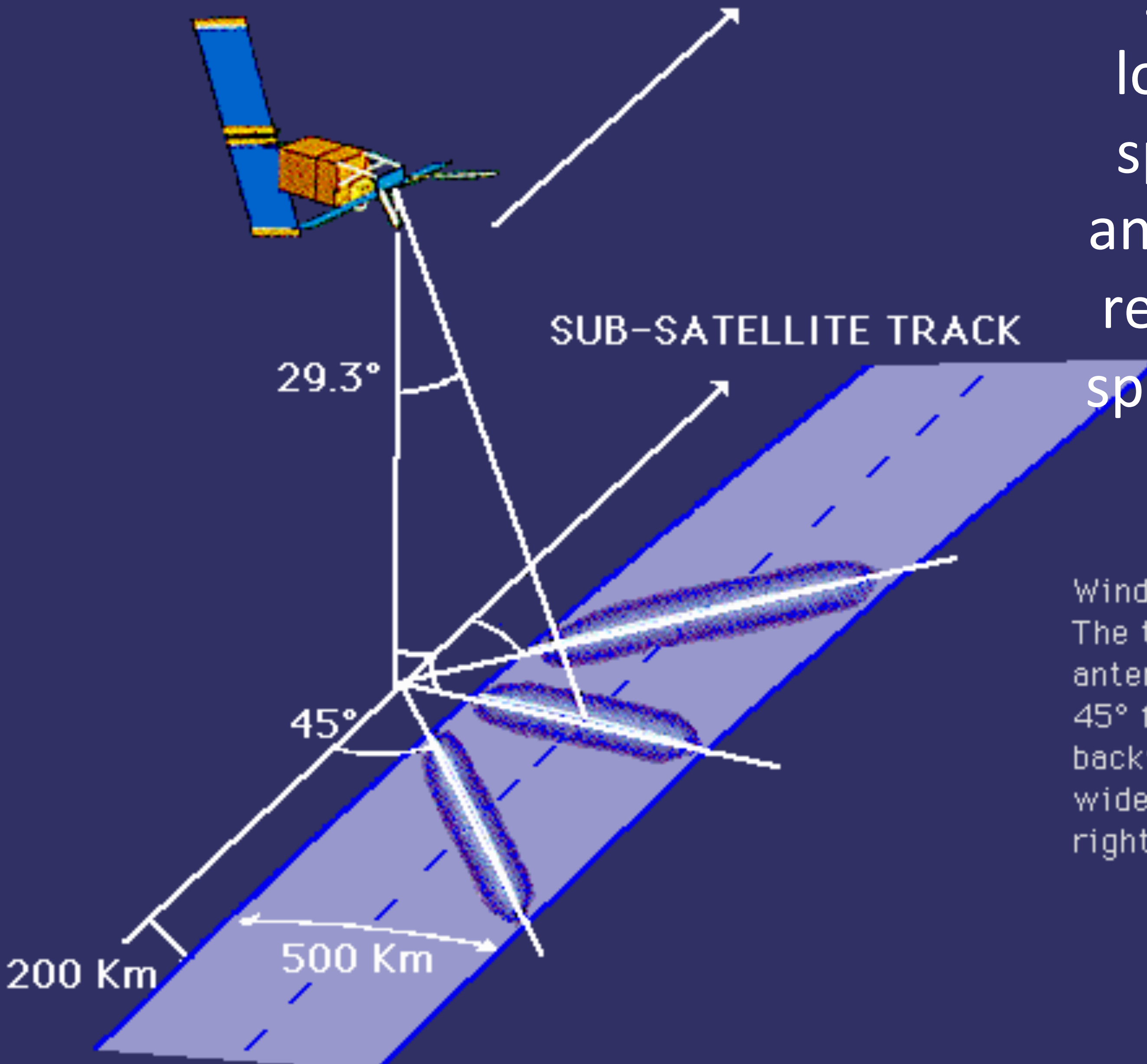


# σ as function of wind direction for various wind speeds




One measurement of σ gives several possible solutions of wind speed and direction

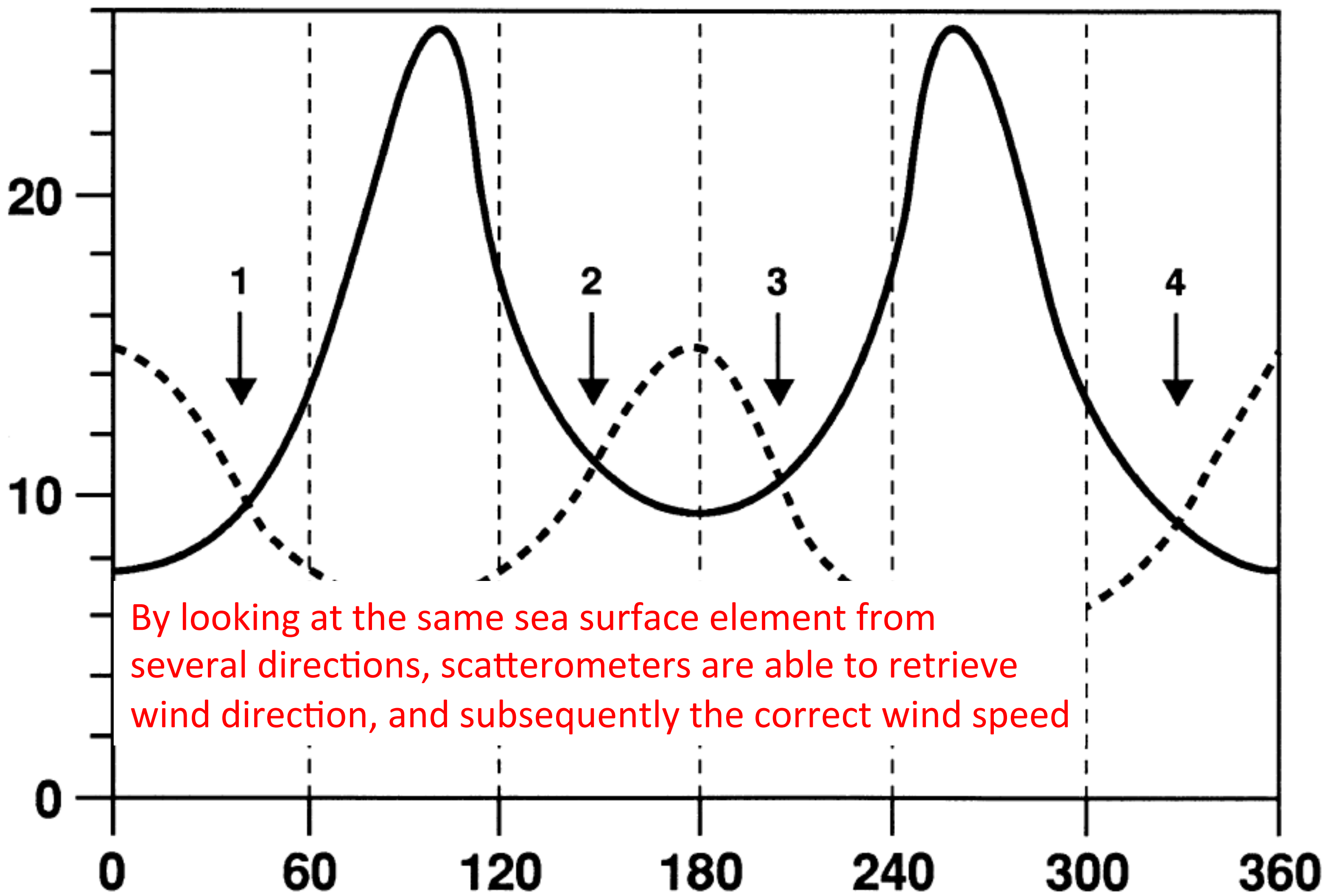
# Wind Scatterometer Geometry




Scatterometers looks at the same spot from several angles to be able to retrieve both wind speed and direction

Wind Scatterometer geometry. The three Wind Scatterometer antennae generate radar beams 45° forward, sideways and 45° backwards across a 500 Km wide swath, 200 Km to the right of the sub-satellite track.

# Multi-antenna solution




By looking at the same sea surface element from several directions, scatterometers are able to retrieve wind direction, and subsequently the correct wind speed

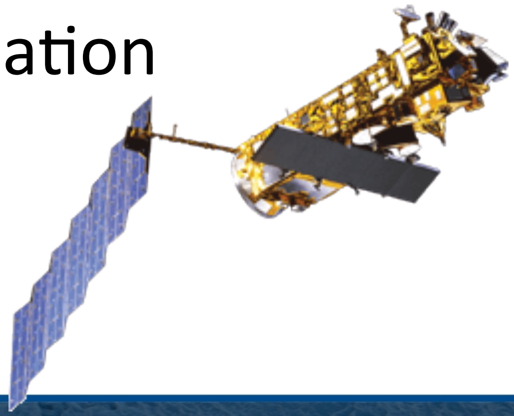
Wind speed

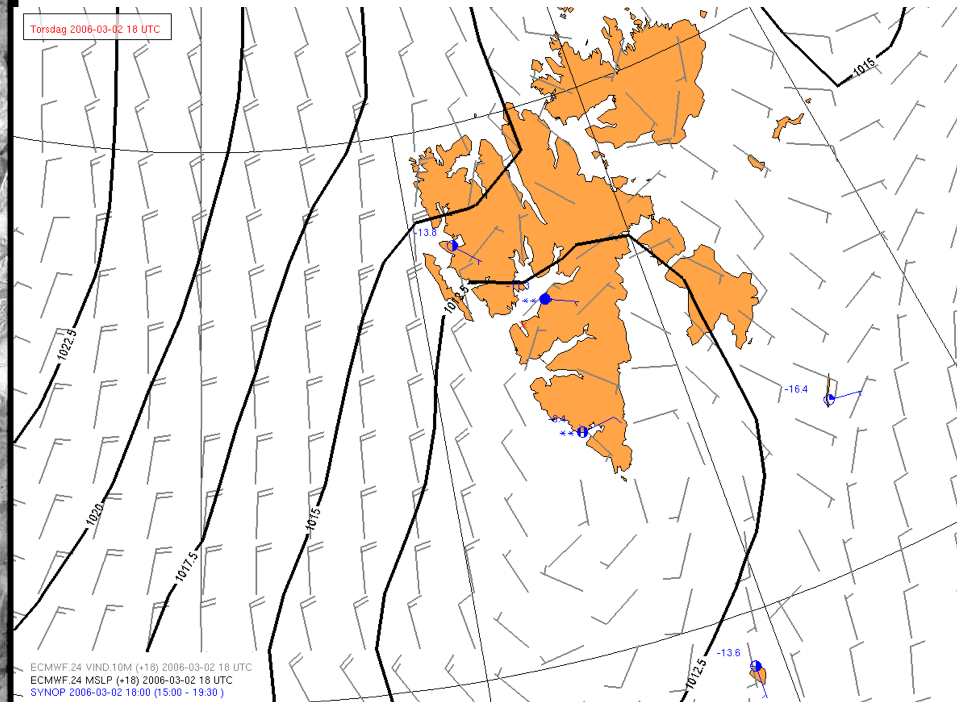
Wind direction

# SAR's have only one antenna

- Wind direction information must be taken from another source
  - Numerical model
  - Scatterometer (if colocated in time and space)
  - From wind streaks in the SAR-image

  - New resource: SAR Doppler information

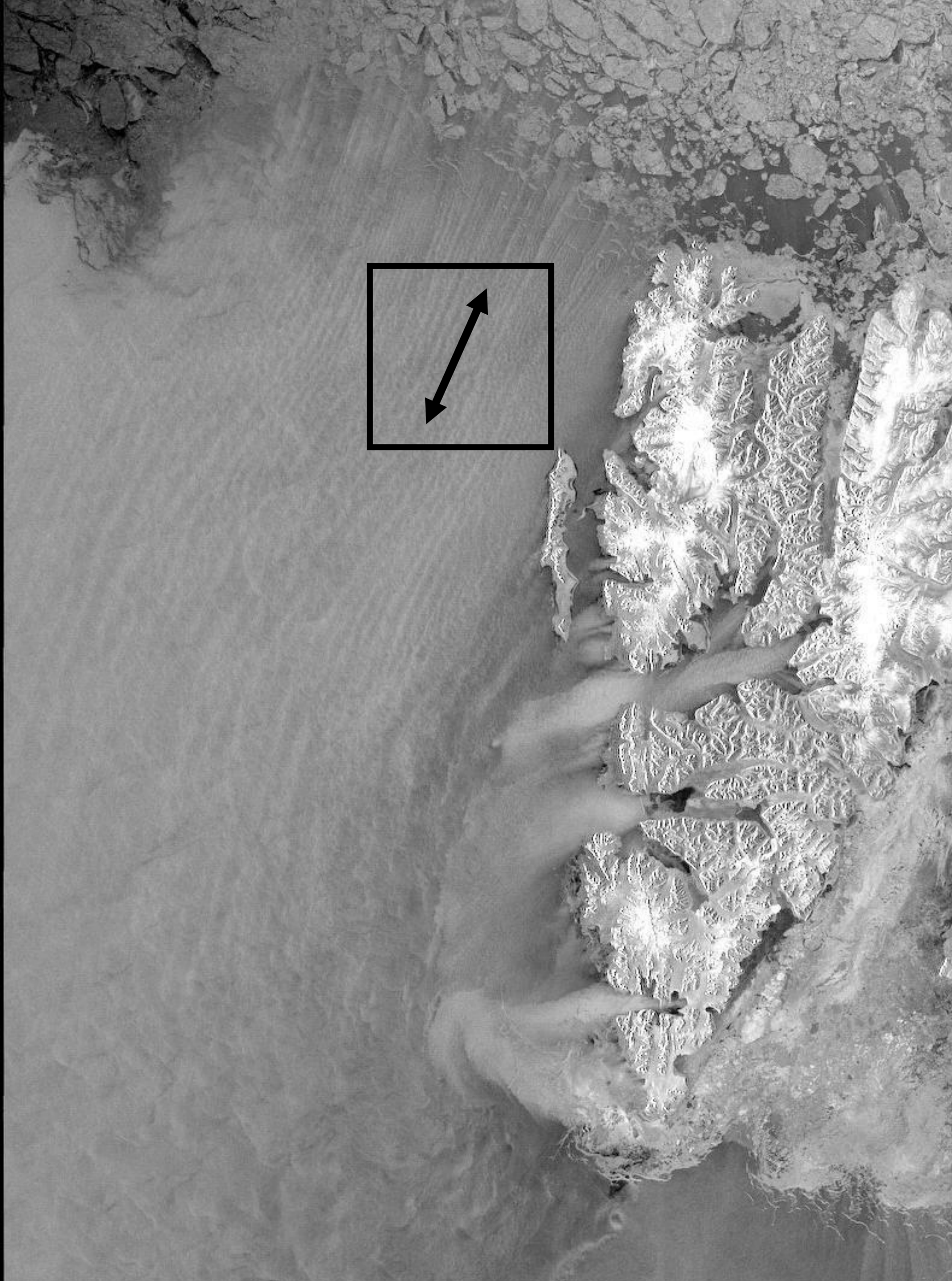


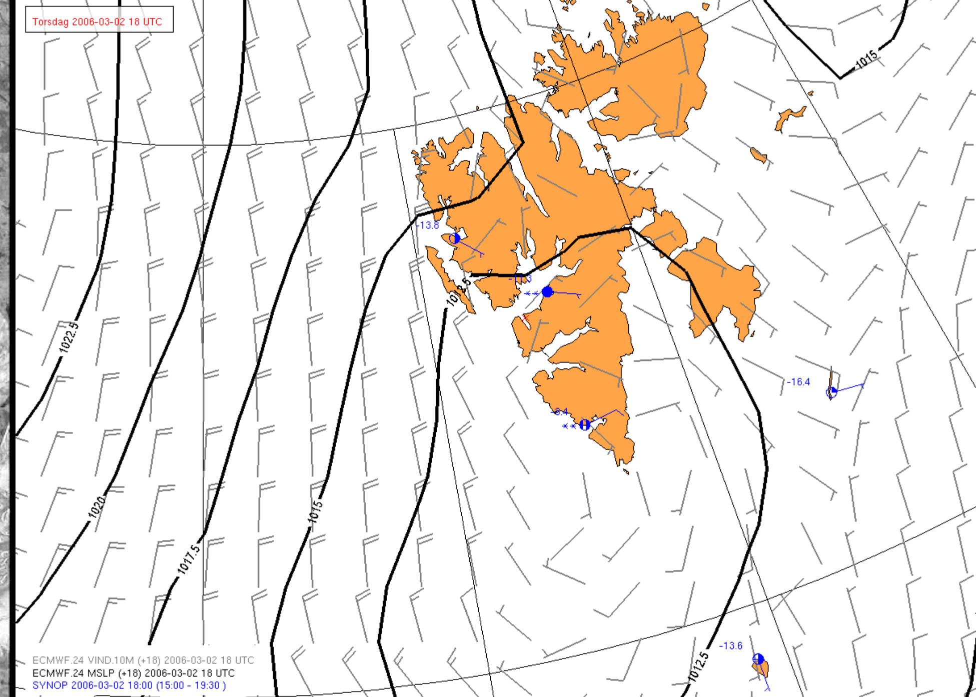


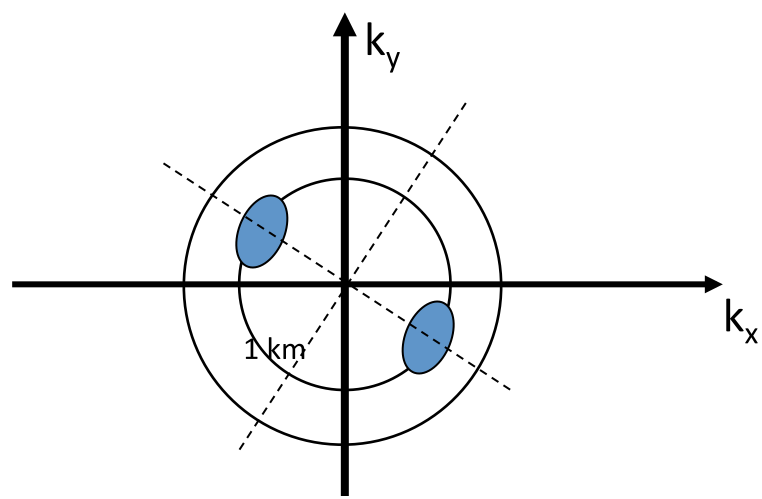

NERSC

Envisat ASAR V/V ASCENDING

02-MAR-2006 19:43:43





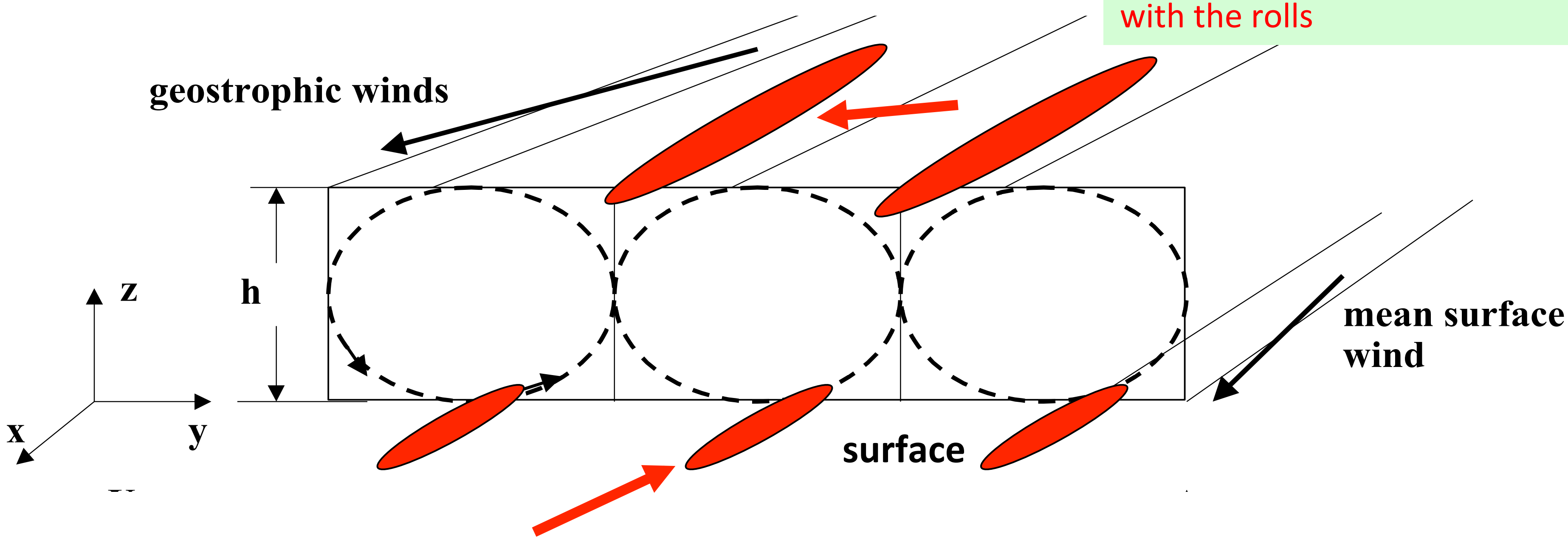



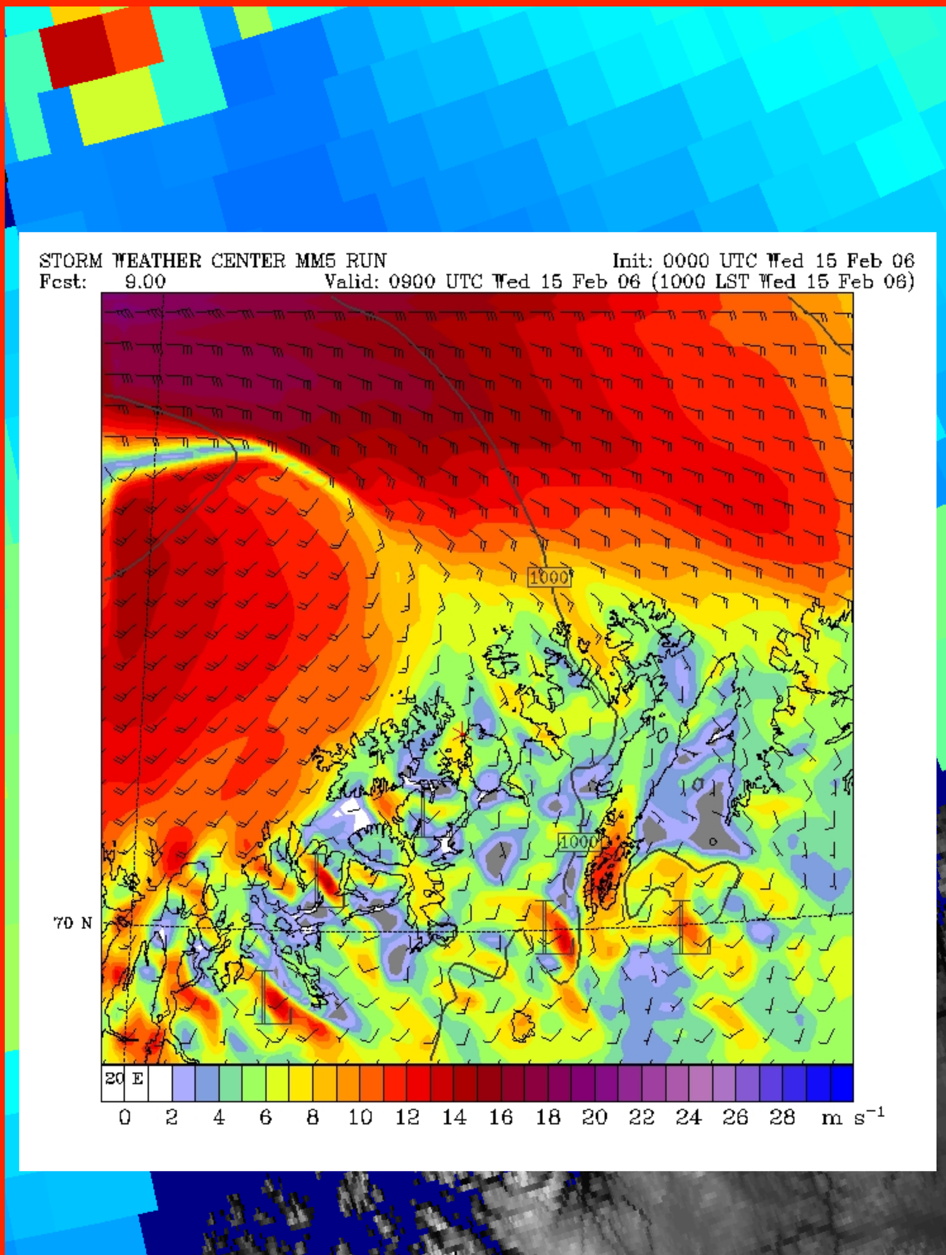

Envisat ASAR V/V ASCENDING

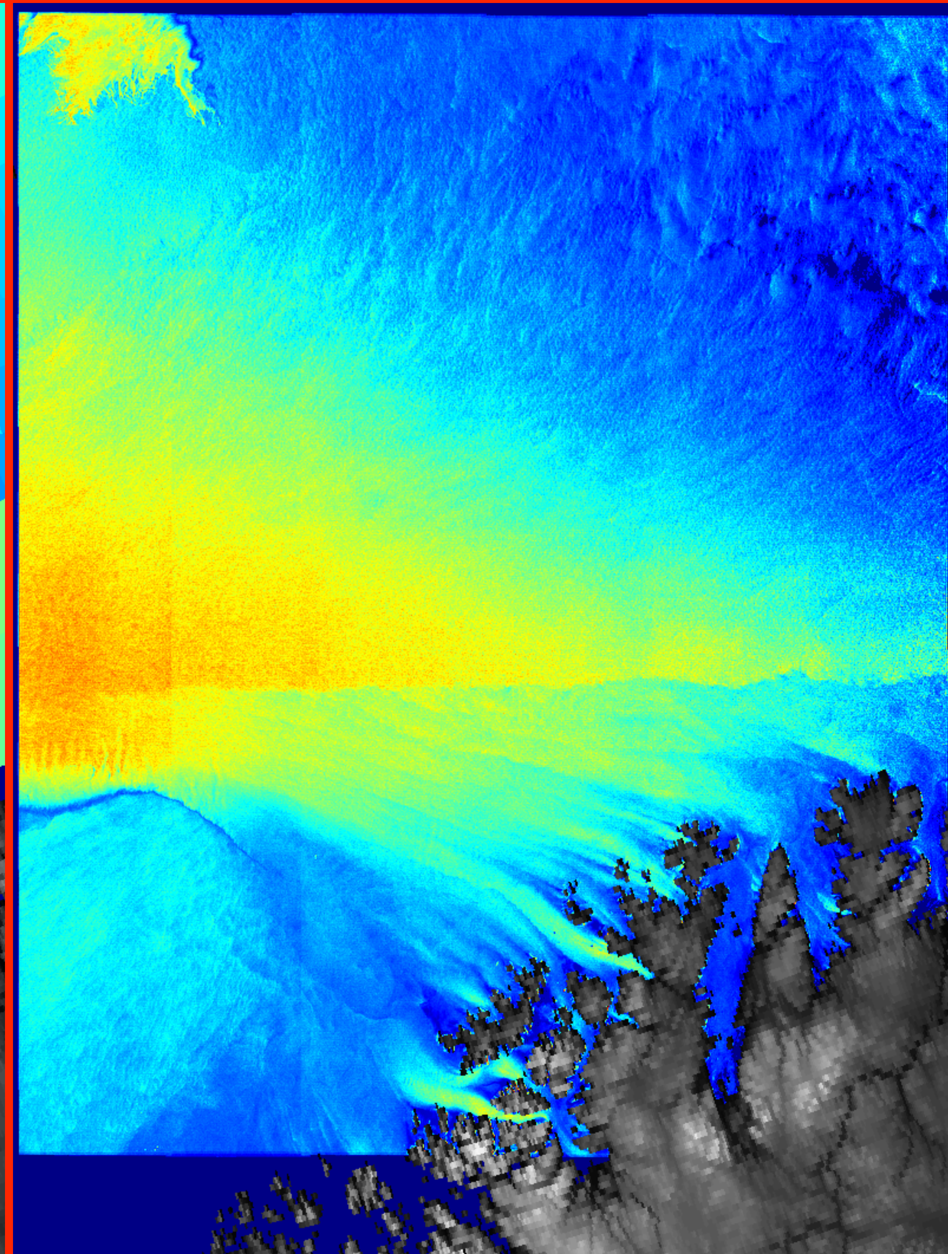
02-MAR-2006 19:43:49

# Atmospheric Boundary layer rolls

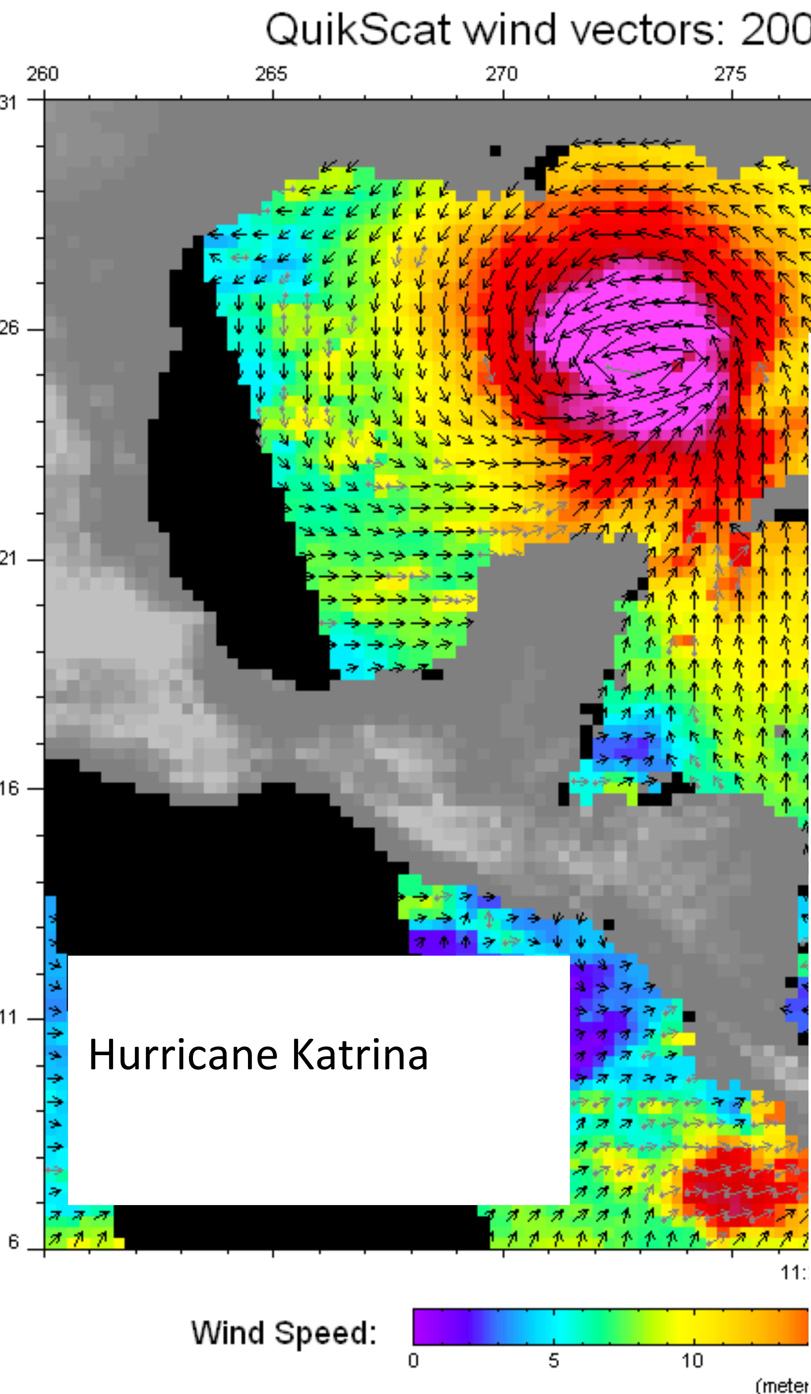
An optical instrument may observe cloud streets aligned with the rolls

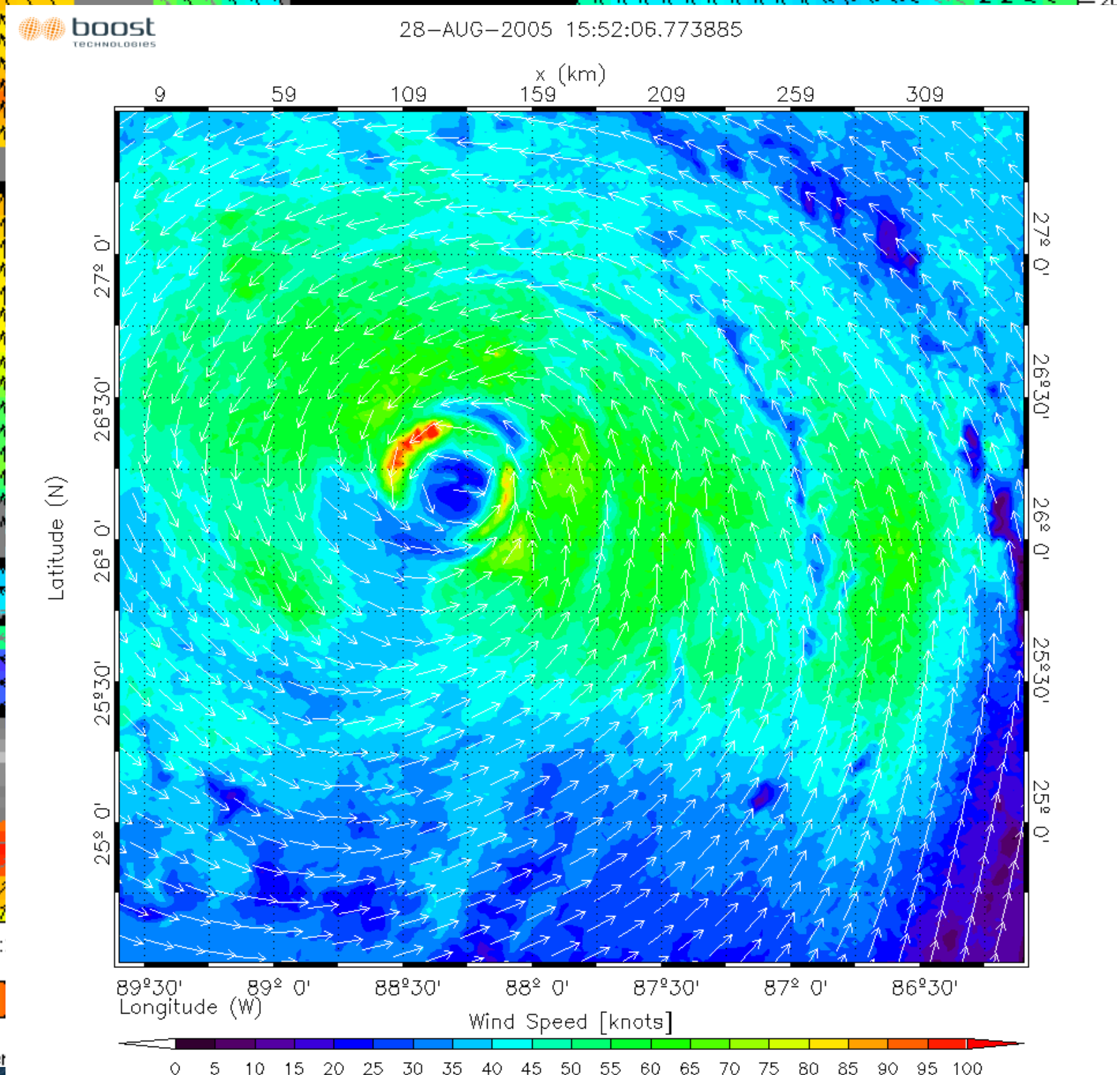



STORM WEATHER CENTER MM5 RUN
Init: 0000 UTC Wed 15 Feb 06
Fcst: 9.00
Valid: 0900 UTC Wed 15 Feb 06 (1000 LST Wed 15 Feb 06)
1000
1000
70 N
20 E
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 m s$^{-1}$



# Hurricane Katrina

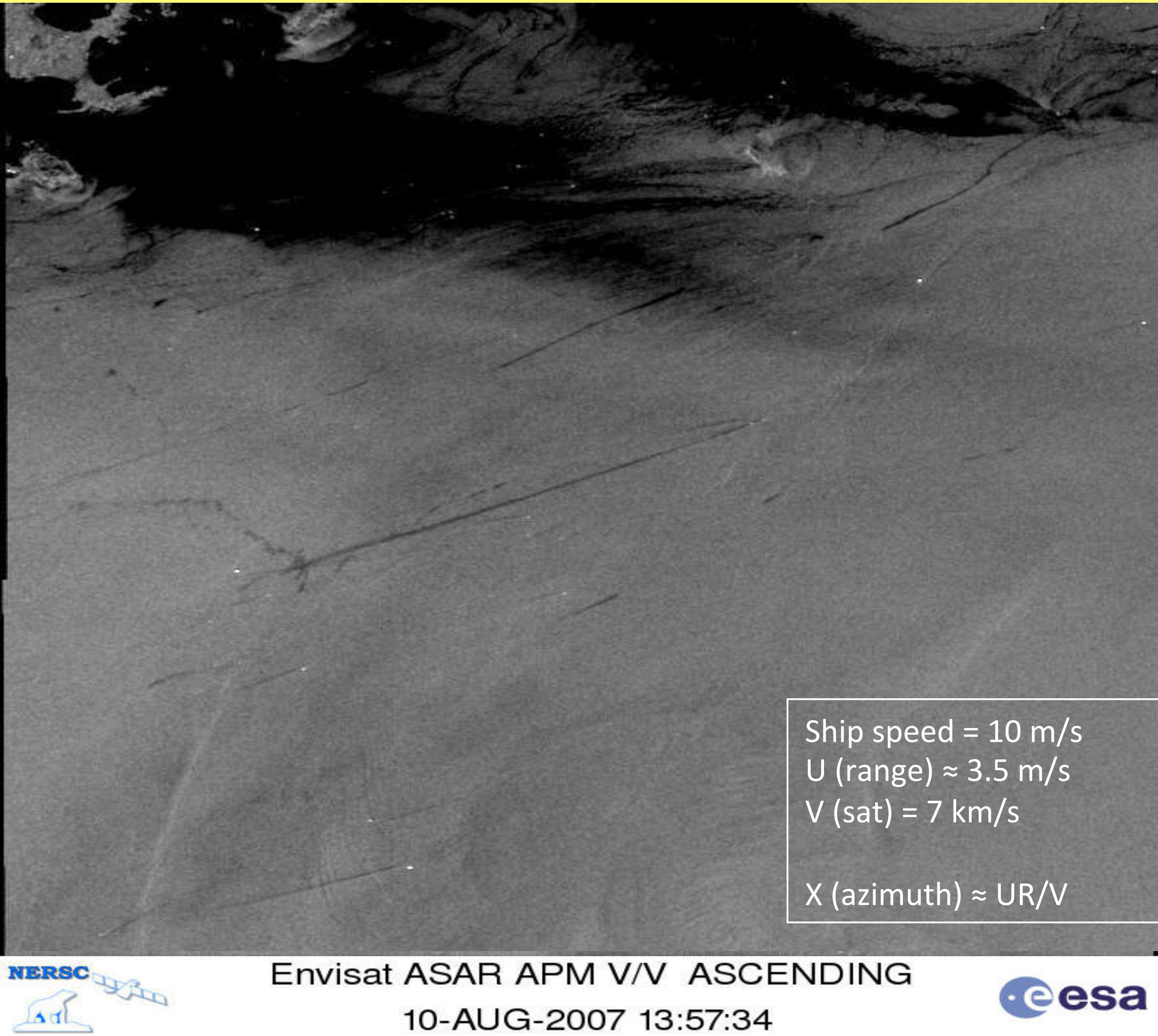


## SAR CONTRIBUTION TO MARINE MONITORING

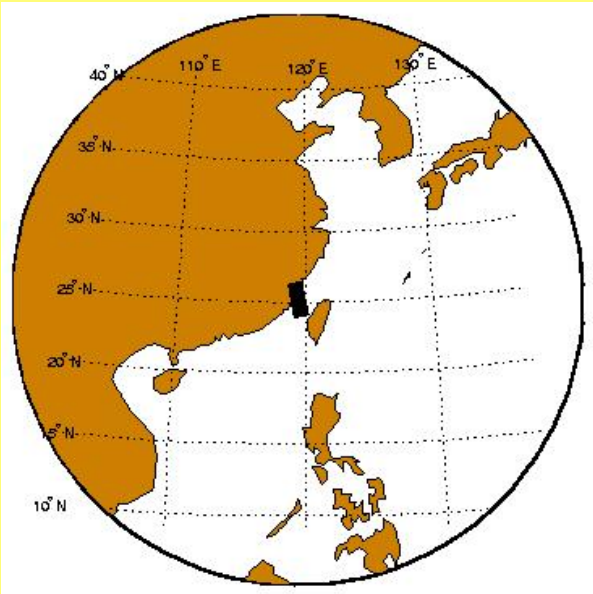
| Operational Surveillance | Emerging new Operational application | Routine Product and partly used in NWP | Research Dominated |
|---|---|---|---|
| **Ship detection**<br><br>**Oil spill detection**<br><br>**Sea Ice**<br><br>**Shallow water Bathymetry** | **Wind field retrievals** | **Ocean Waves and Ocean Spectra** | **Surface current fronts and eddies**<br><br>**Internal Waves**<br><br>**Atmospheric boundary layer Processes**<br><br>**Film damping** |

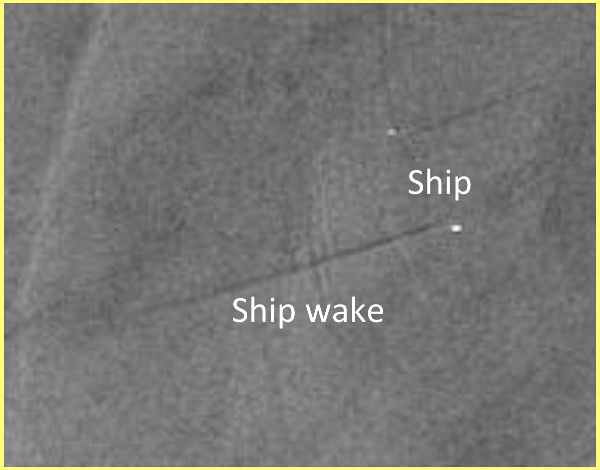
# Ships and Ship Wakes - Oil spill?



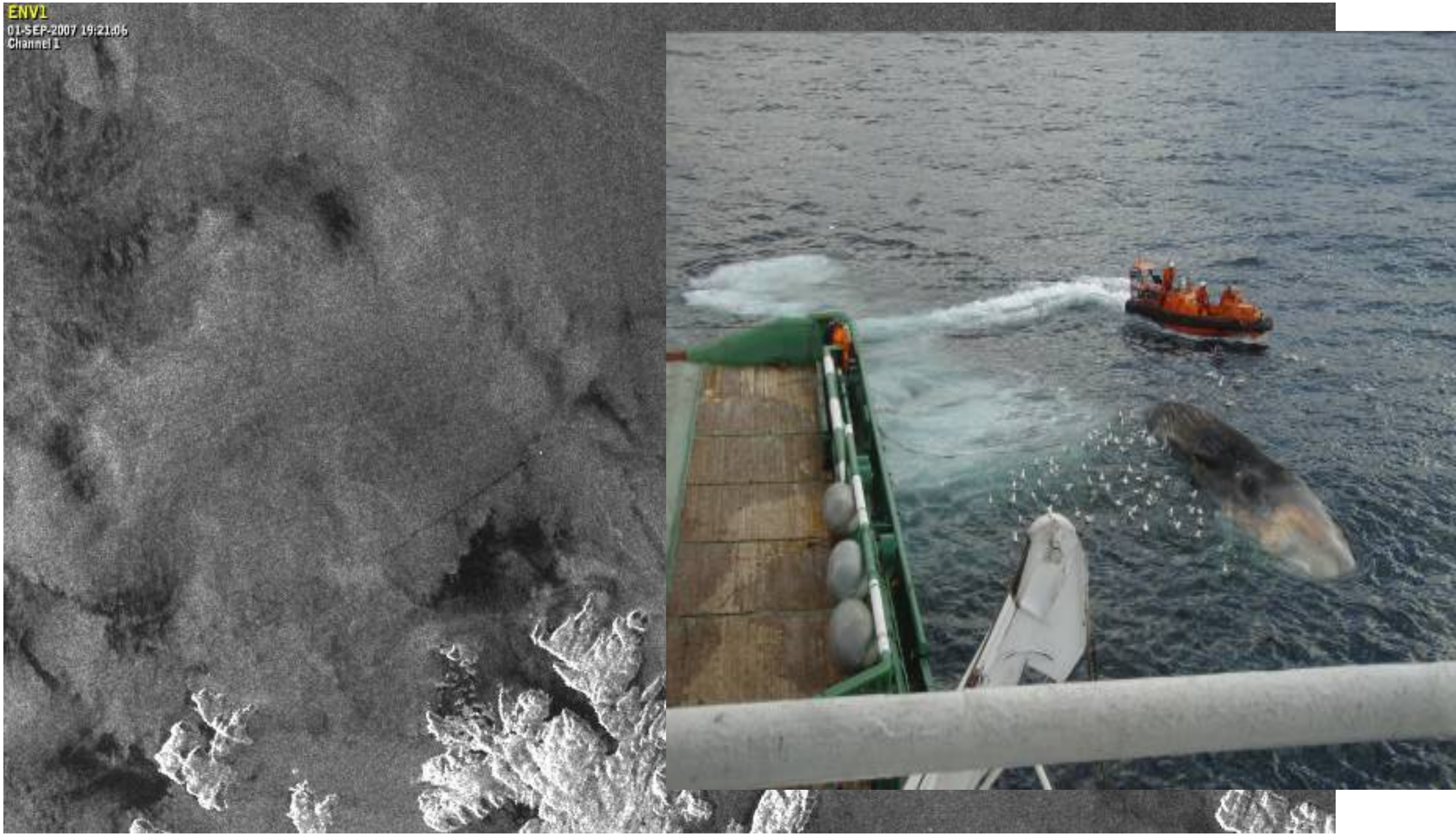

Ship speed = 10 m/s
U (range) ≈ 3.5 m/s
V (sat) = 7 km/s

X (azimuth) ≈ UR/V

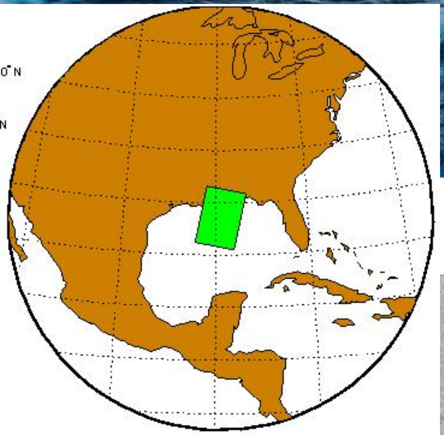


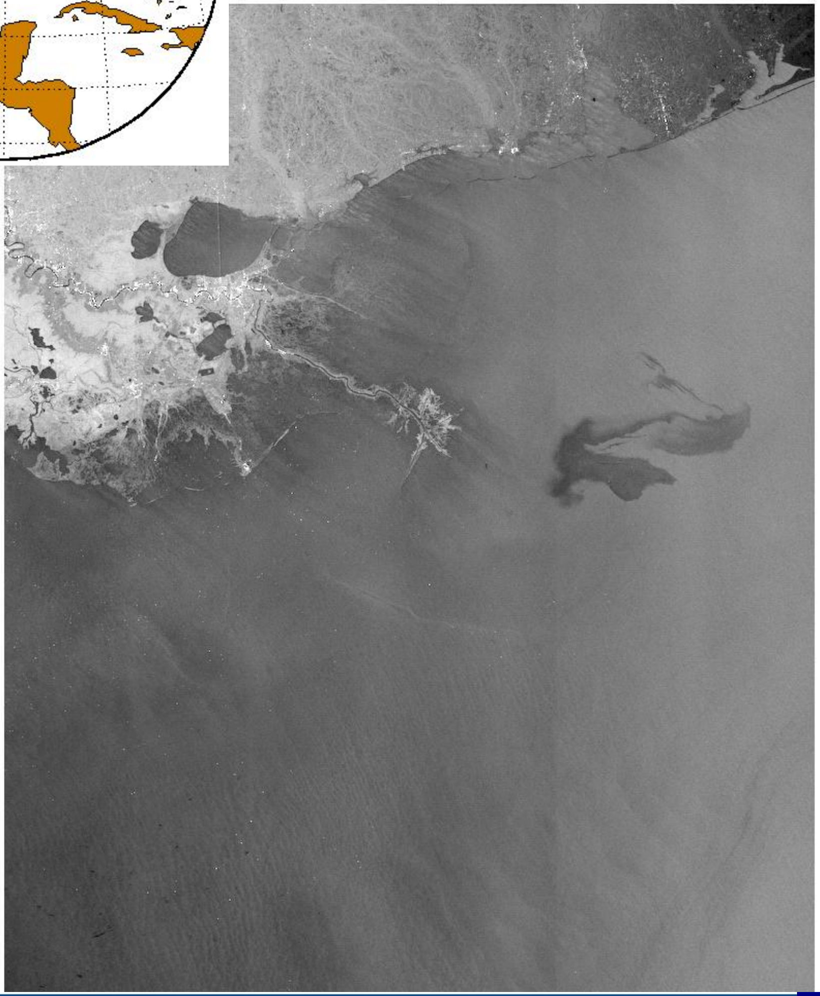



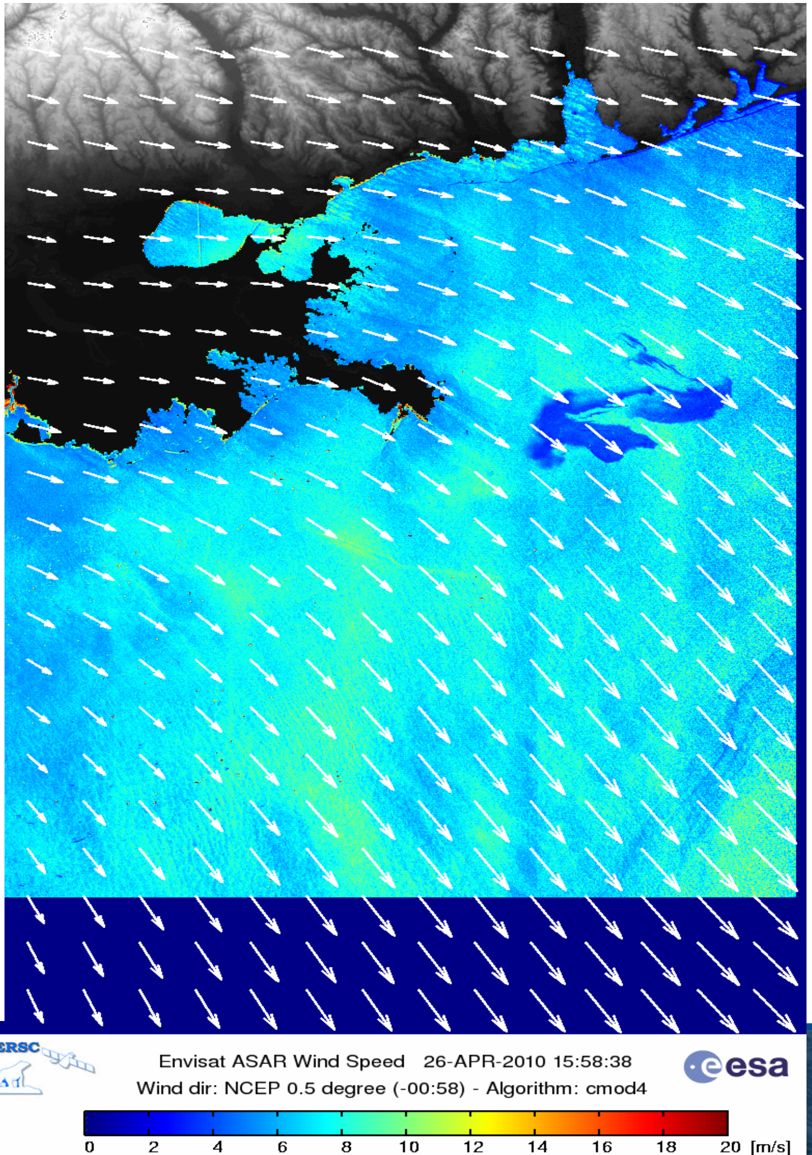
# Black tail – but not always a real pollution



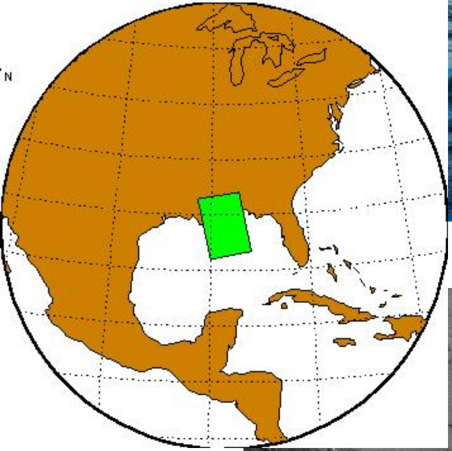
# Oil spill in the Gulf of Mexico

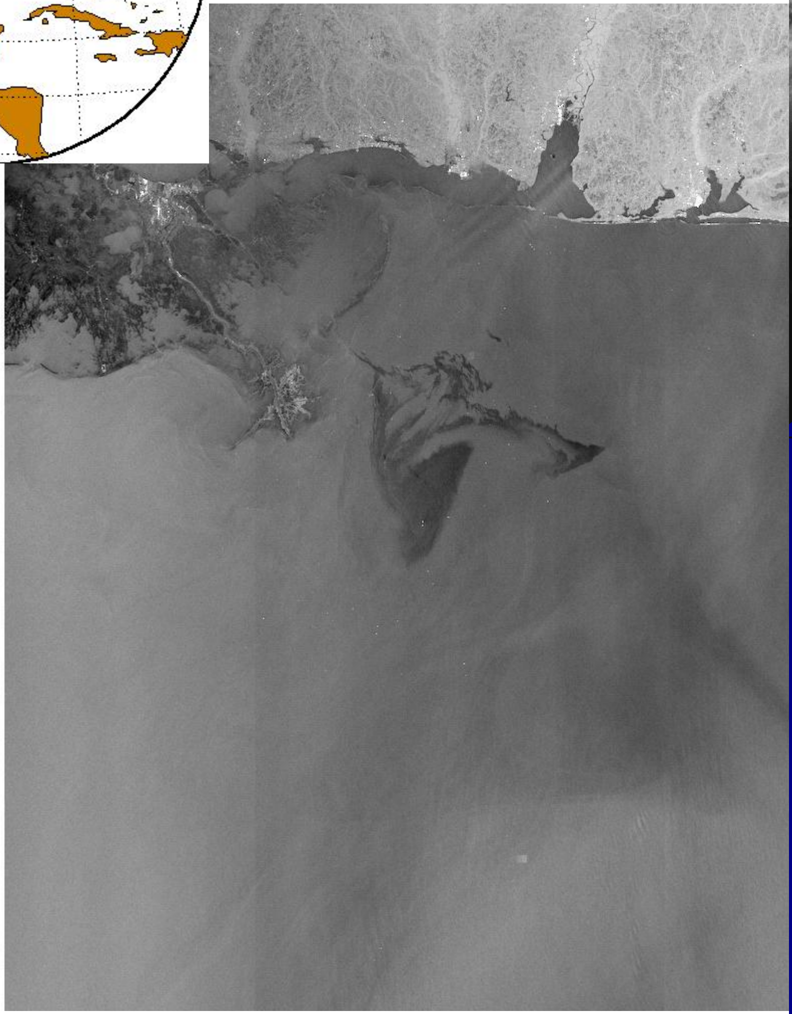


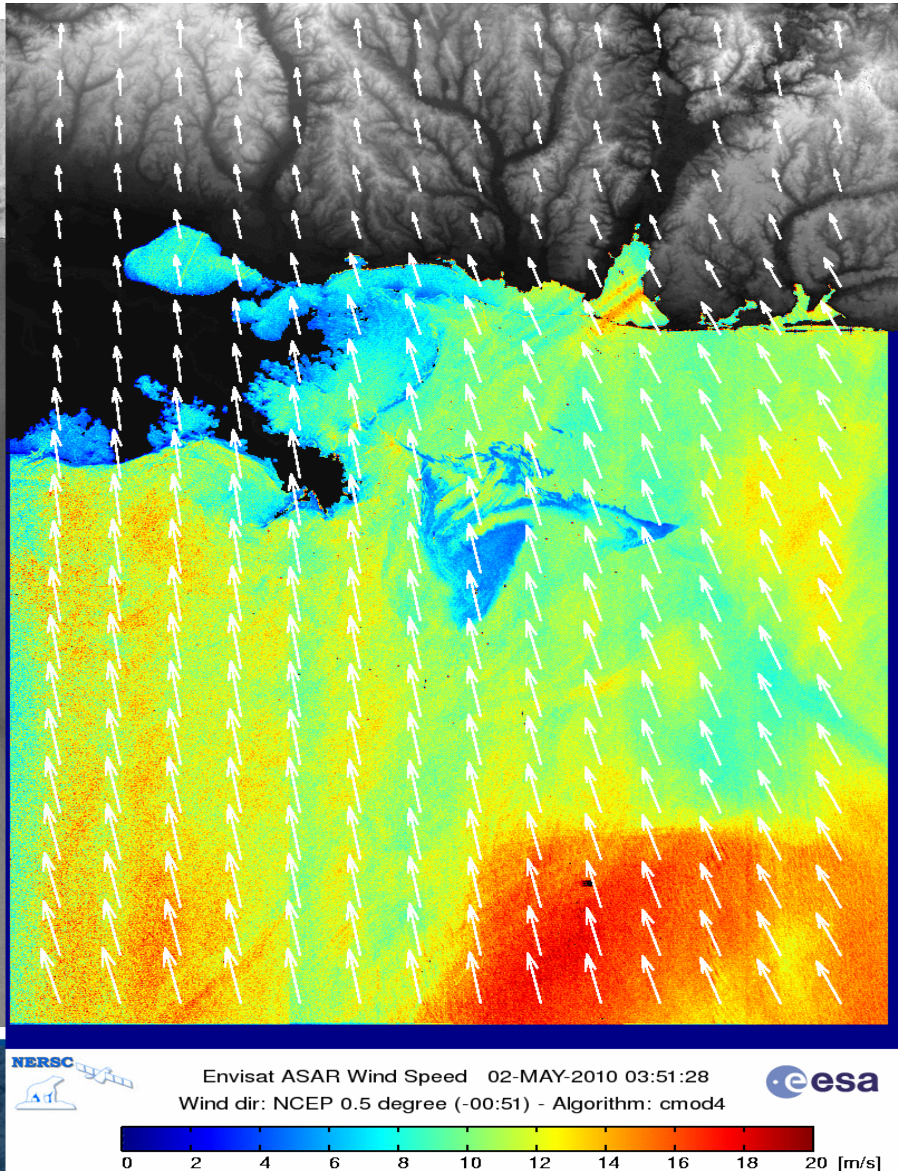




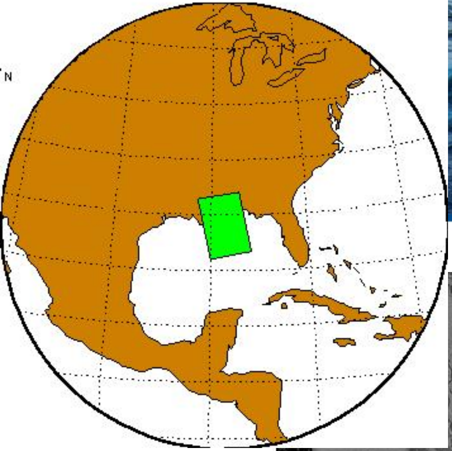
# Oil spill in the Gulf of Mexico

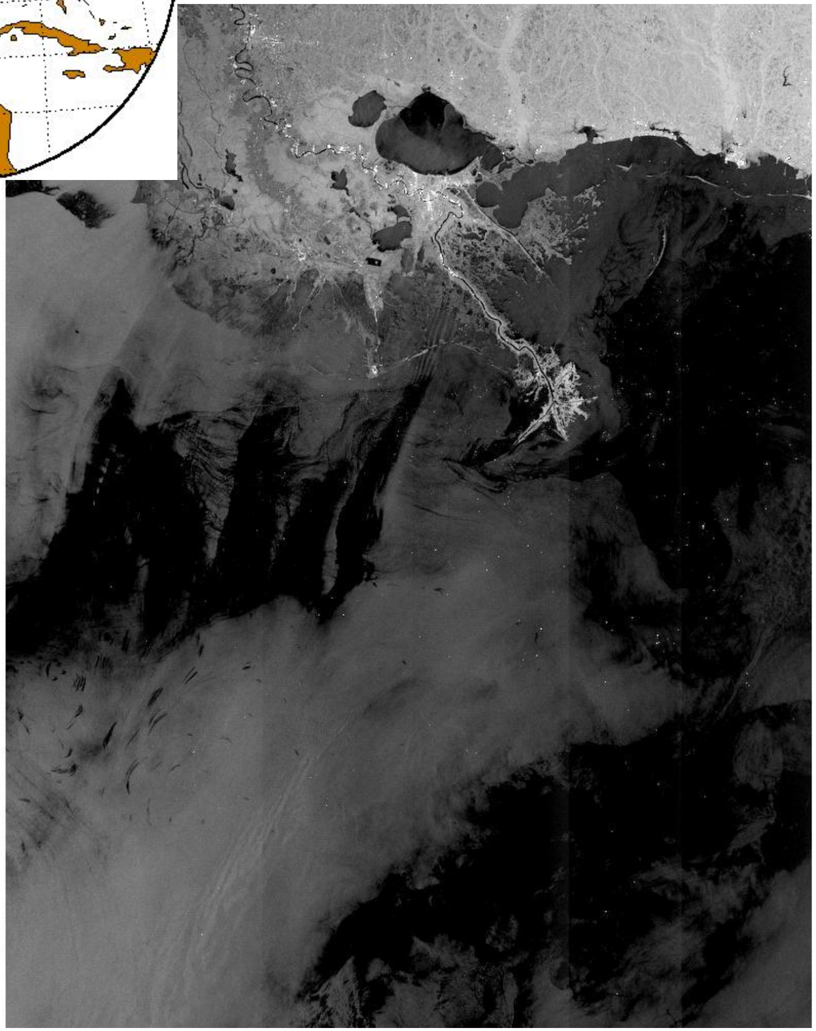


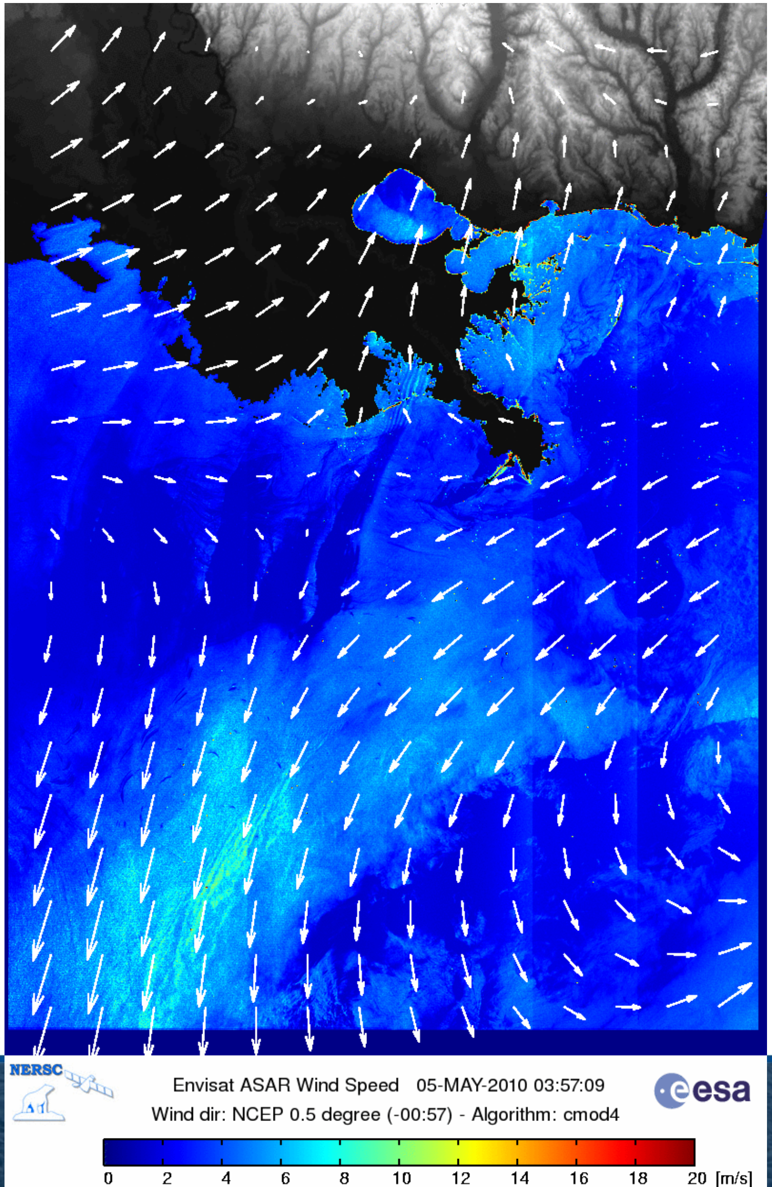





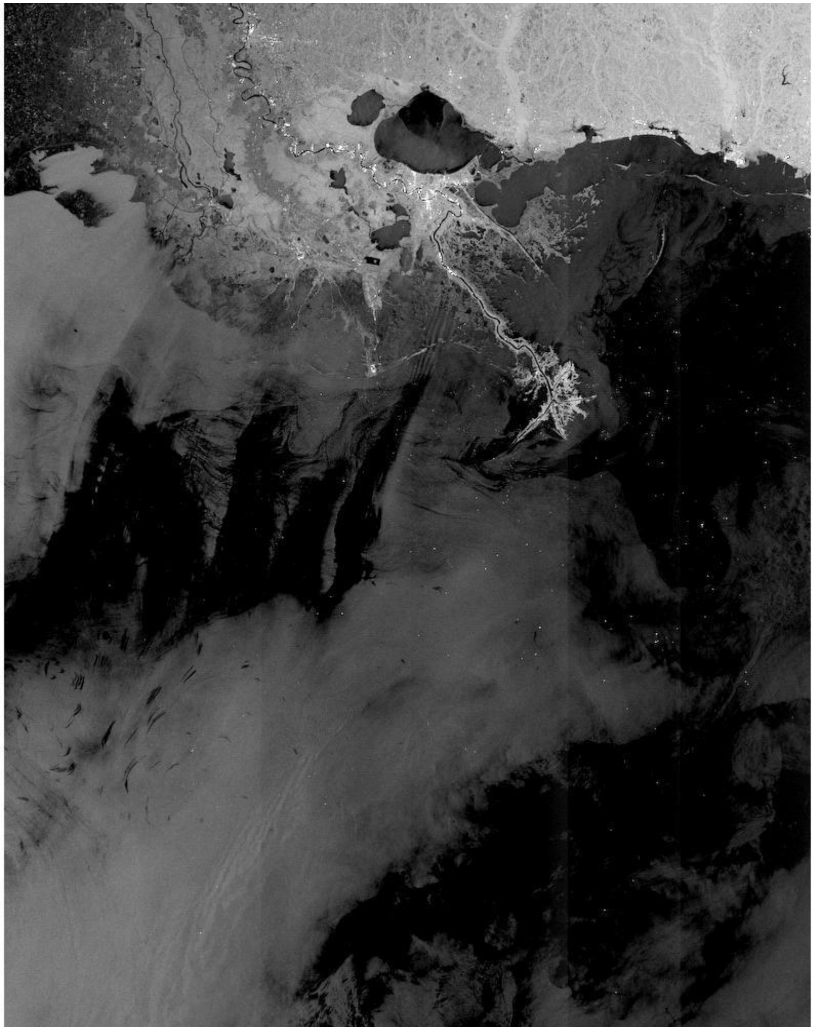
# Oil spill in the Gulf of Mexico







# Separation of Spill from like-alikes



Quad-polarization SAR for ocean feature classifications

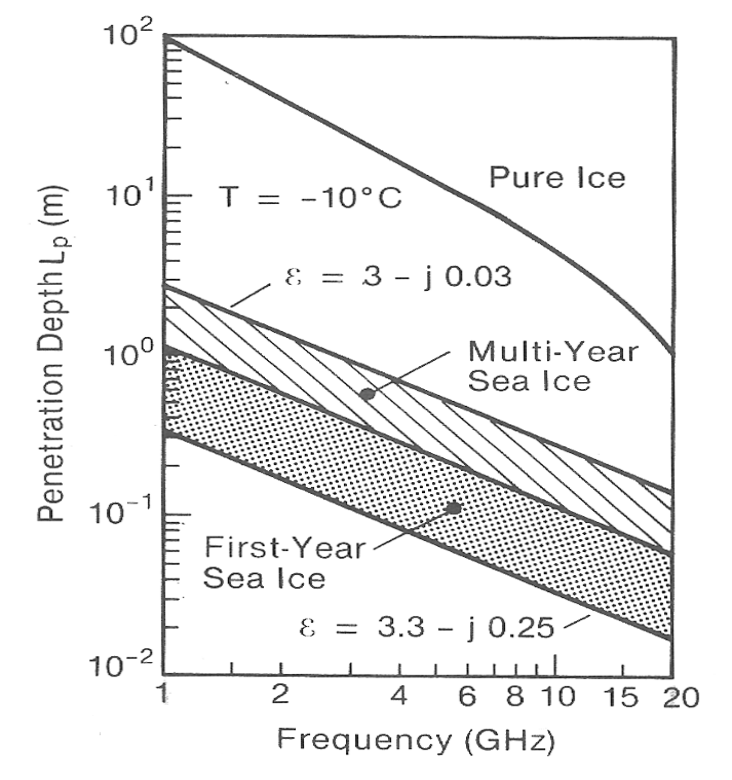
Decompose images in Pol diff., Pol ratio, non-polarized, Cross polarized

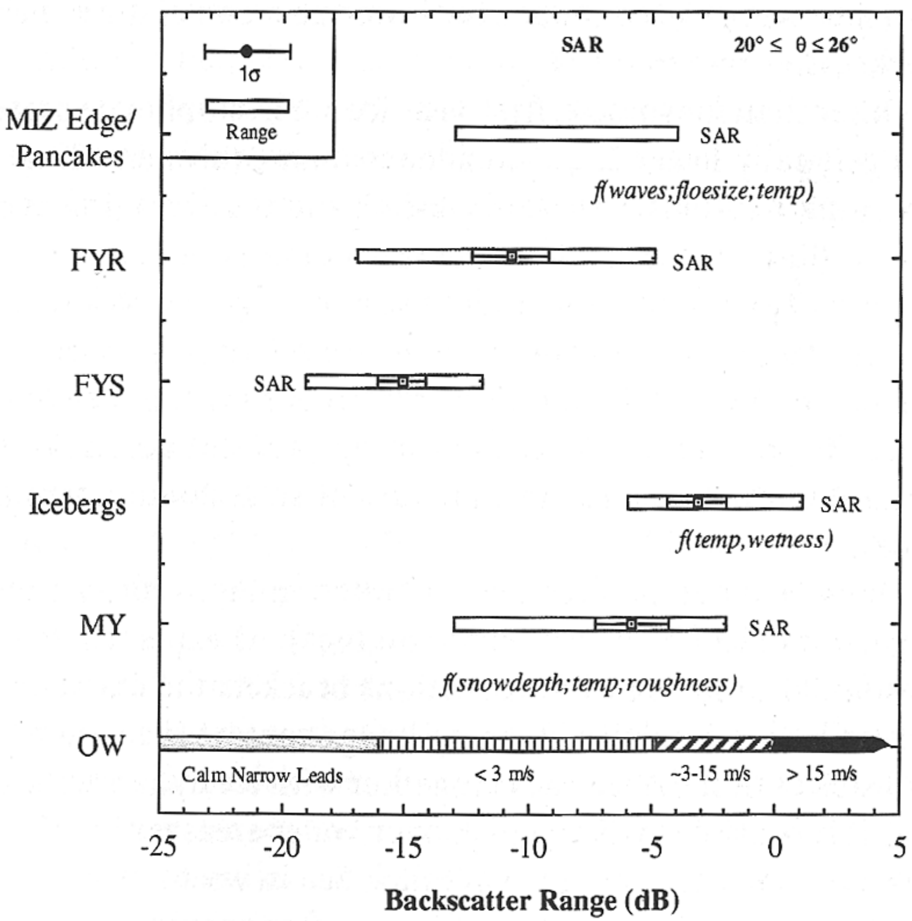
# SAR CONTRIBUTION TO MARINE MONITORING

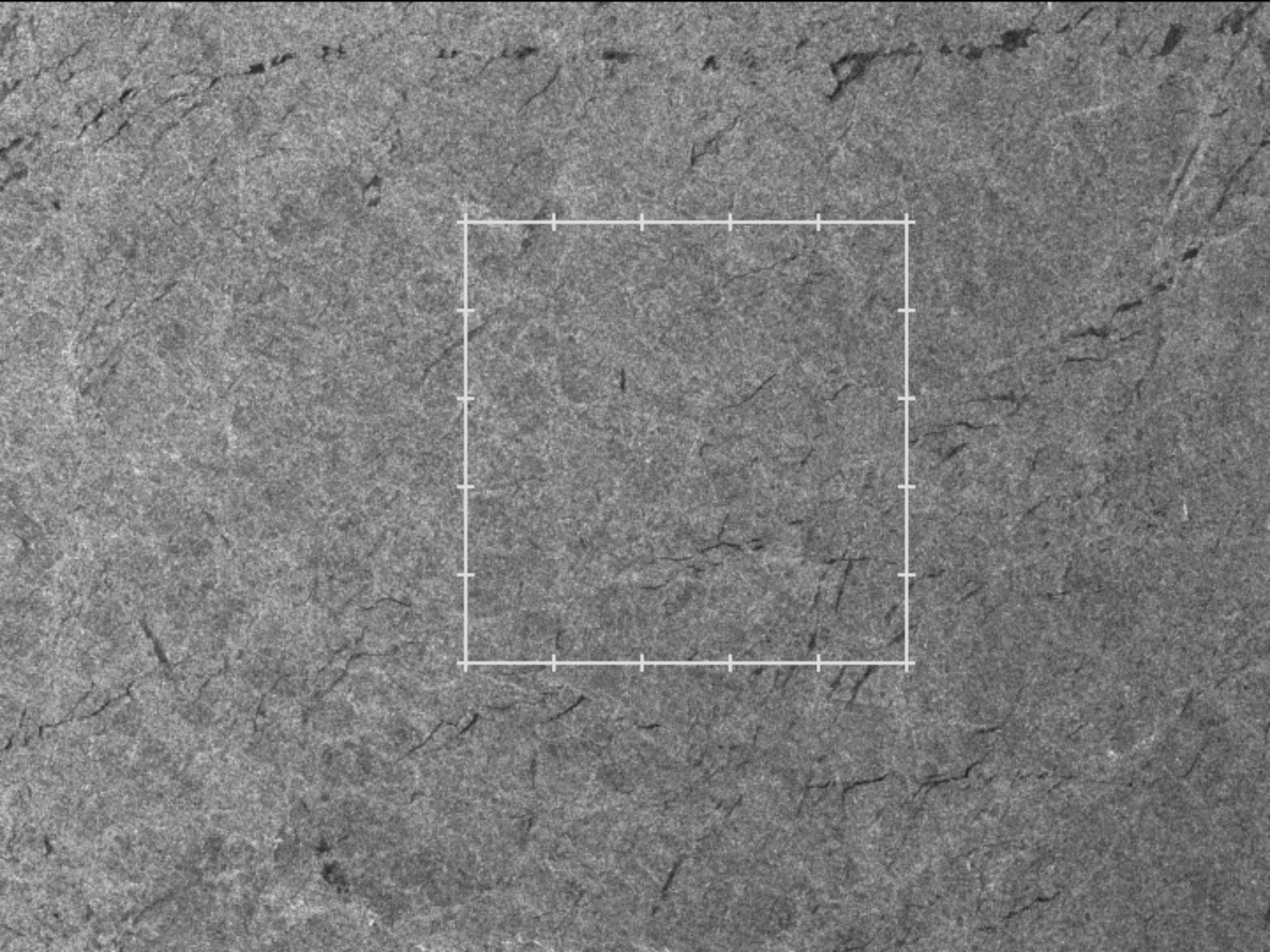
| Operational Surveillance | Emerging new Operational application | Routine Product and partly used in NWP | Research Dominated |
|---|---|---|---|
| Ship detection<br><br>Oil spill detection<br><br>Sea Ice<br><br>Shallow water Bathymetry | Wind field retrievals | Ocean Waves and Ocean Spectra | Surface current fronts and eddies<br><br>Internal Waves<br><br>Atmospheric boundary layer Processes<br><br>Film damping |

# Surface and volume scattering

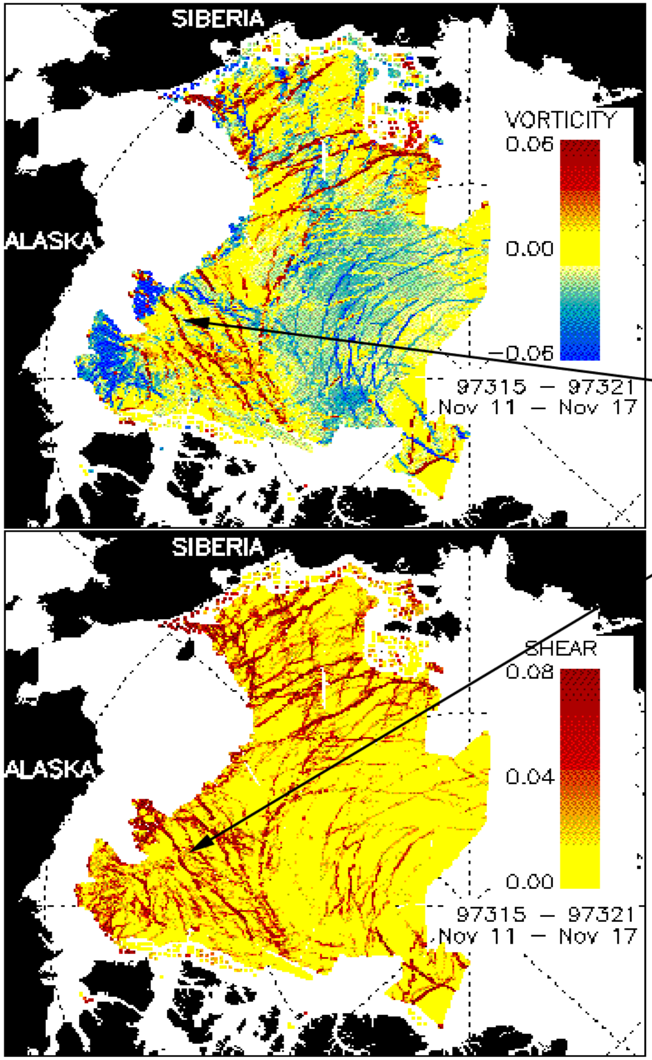
The importance of volume scattering is governed by the dielectric properties (dielectric constant) of the material:
High DE:  surface scattering dominates
Low DE:   volume scattering dominates

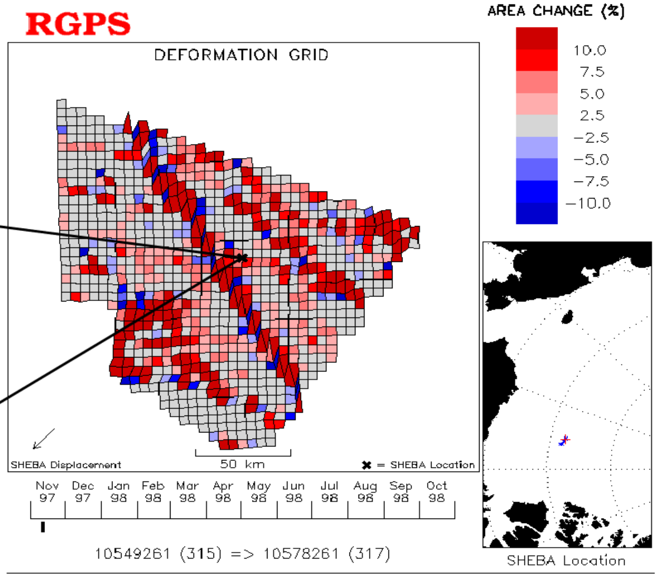




## Location of SHEBA, Nov 97



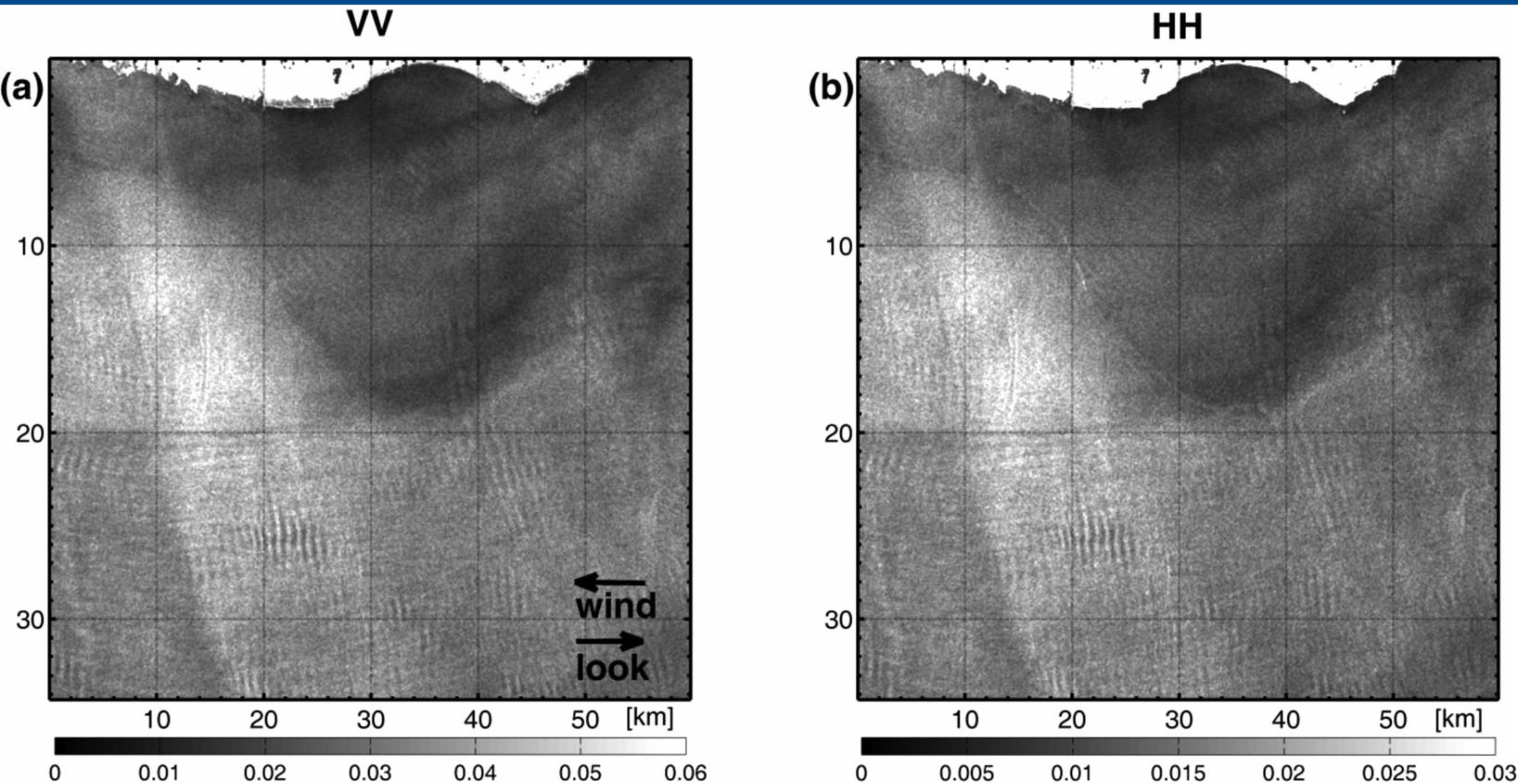




**Large-scale Visualization Of Cell Deformation**

Ifremer esa

# SAR CONTRIBUTION TO MARINE MONITORING

| Operational Surveillance | Emerging new Operational application | Routine Product and partly used in NWP | Research Dominated |
|---|---|---|---|
| Ship detection<br><br>Oil spill detection<br><br>Sea Ice<br><br>Shallow water Bathymetry | Wind field retrievals | Ocean Waves and Ocean Spectra | Surface current fronts and eddies<br><br>Internal Waves<br><br>Atmospheric boundary layer Processes<br><br>Film damping |




Kudryavtsev et al., 2014

# Radarsat 2 Image 1 August 2012 over the White Sea

# Quad-polarization SAR for ocean feature classifications

Decomposed NRCS in Polarized and non-polarized signals

$$\sigma_0^{pp} = \sigma_{0B}^{pp} + \sigma_{wb}.$$

Polarization difference (PD)

$$\Delta\sigma_0 \equiv \sigma_0^{vv} - \sigma_0^{hh} = \sigma_{0B}^{vv} - \sigma_{0B}^{hh}.$$

Polarization ratio (PR)

$$P = \frac{\sigma_{0B}^{hh} + \sigma_{wb}}{\sigma_{0B}^{vv} + \sigma_{wb}}.$$

Non-polarized signal (NP)

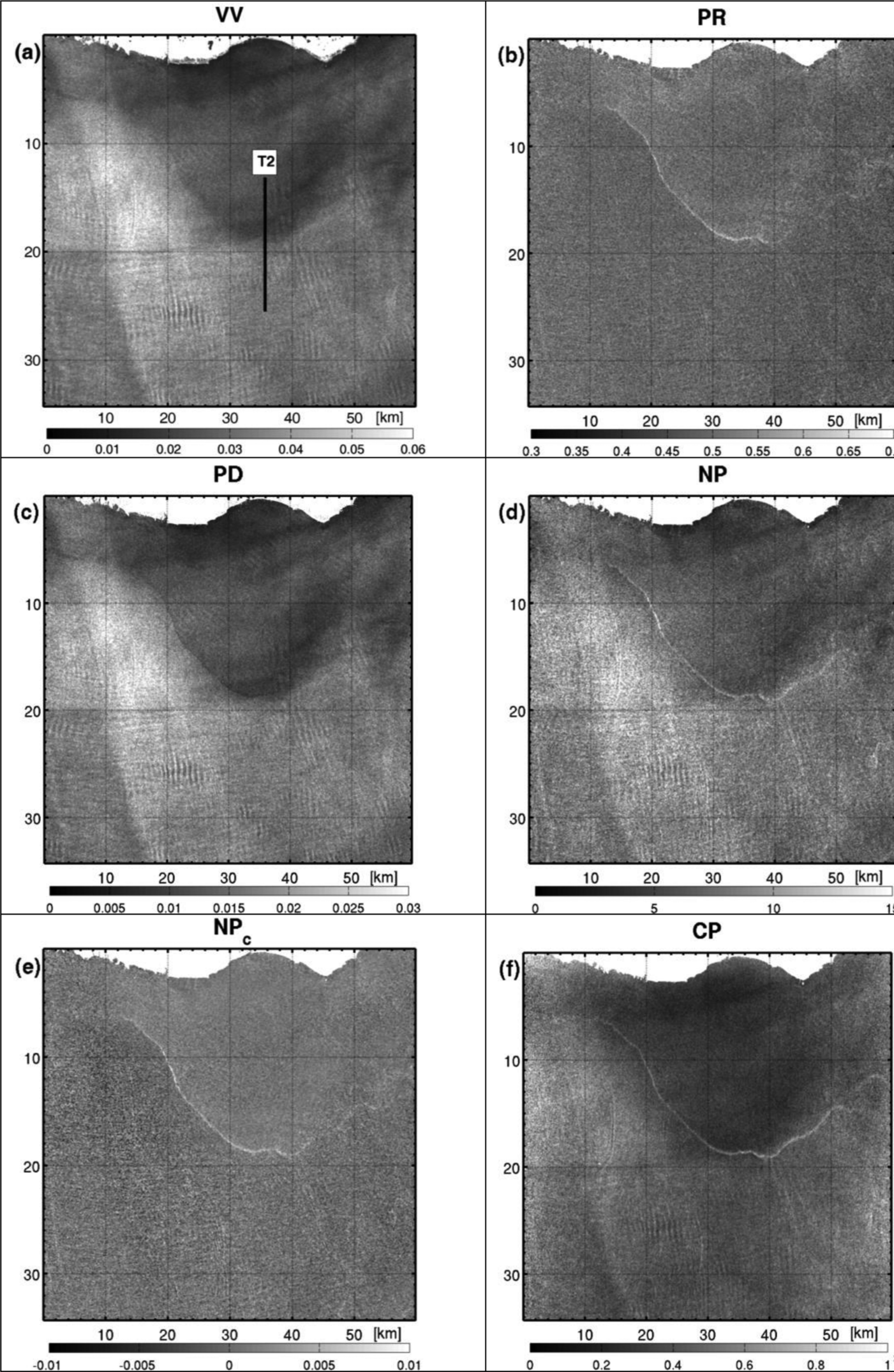
$$\sigma_{wb} = \sigma_0^{vv} - \Delta\sigma_0/(1 - p_B).$$

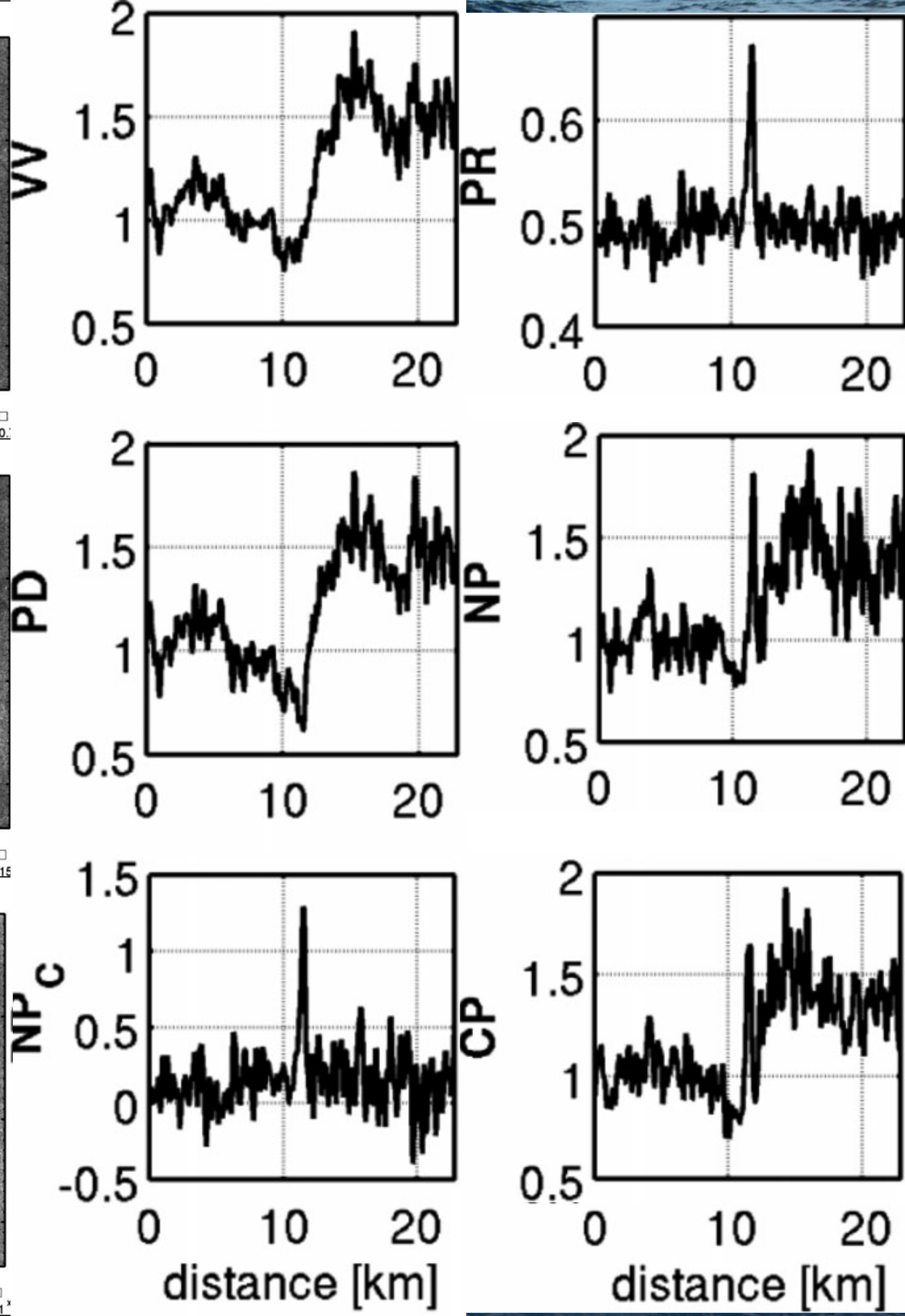
Cross polarized signal (CP)

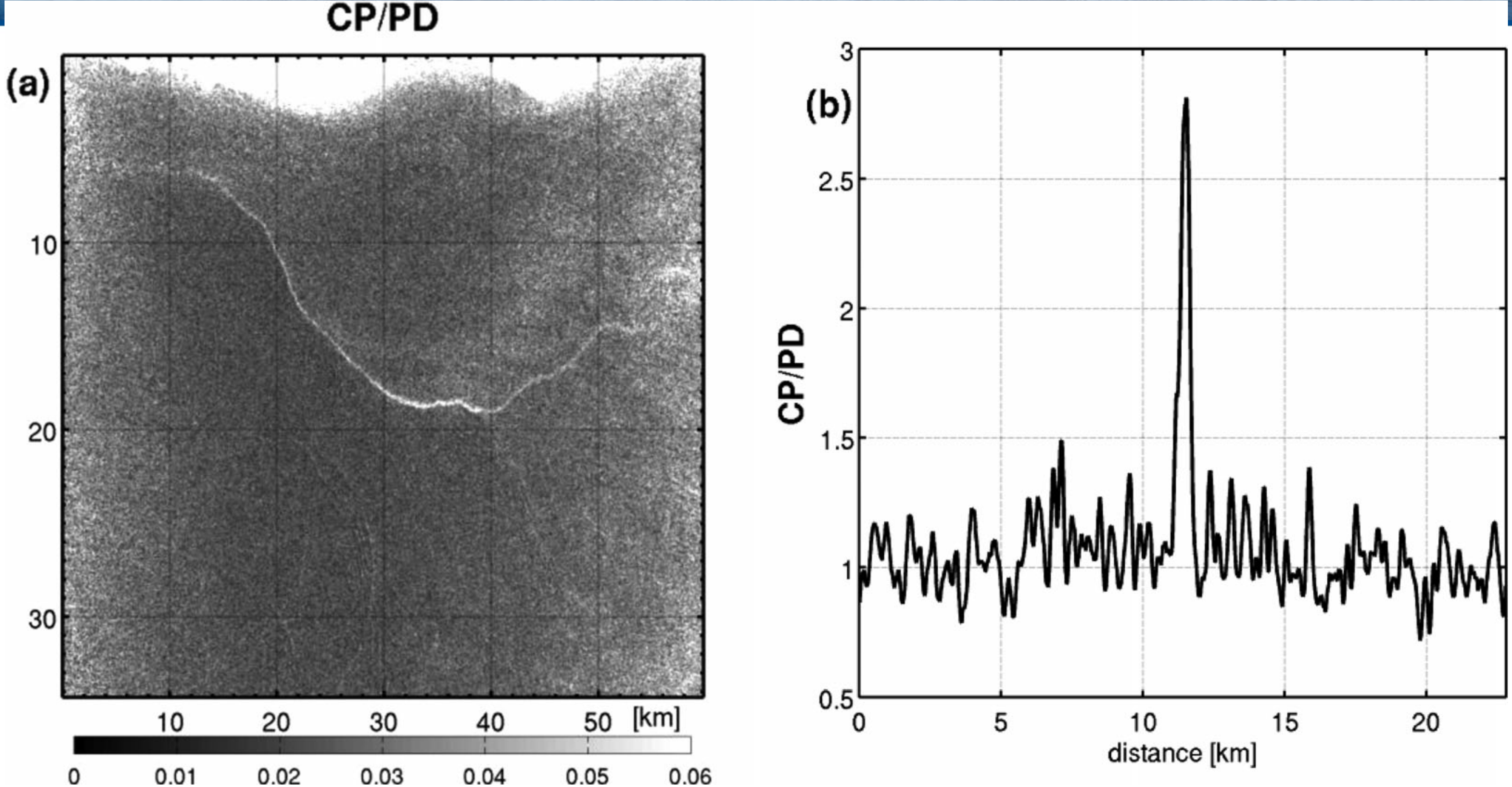
$$CP = (\sigma_0^{vh} + \sigma_0^{hv})/2,$$



Kudryavtsev et al., 2014


VV
(a)
T2
PR
(b)
PD
(c)
NP
(d)
NP c
(e)
CP
(f)
10
20
30
40
50
[km]
0
0.01
0.02
0.03
0.04
0.05
0.06
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.005
0.015
0.025
5
15
-0.01
-0.005
0.2
0.4
0.6
0.8

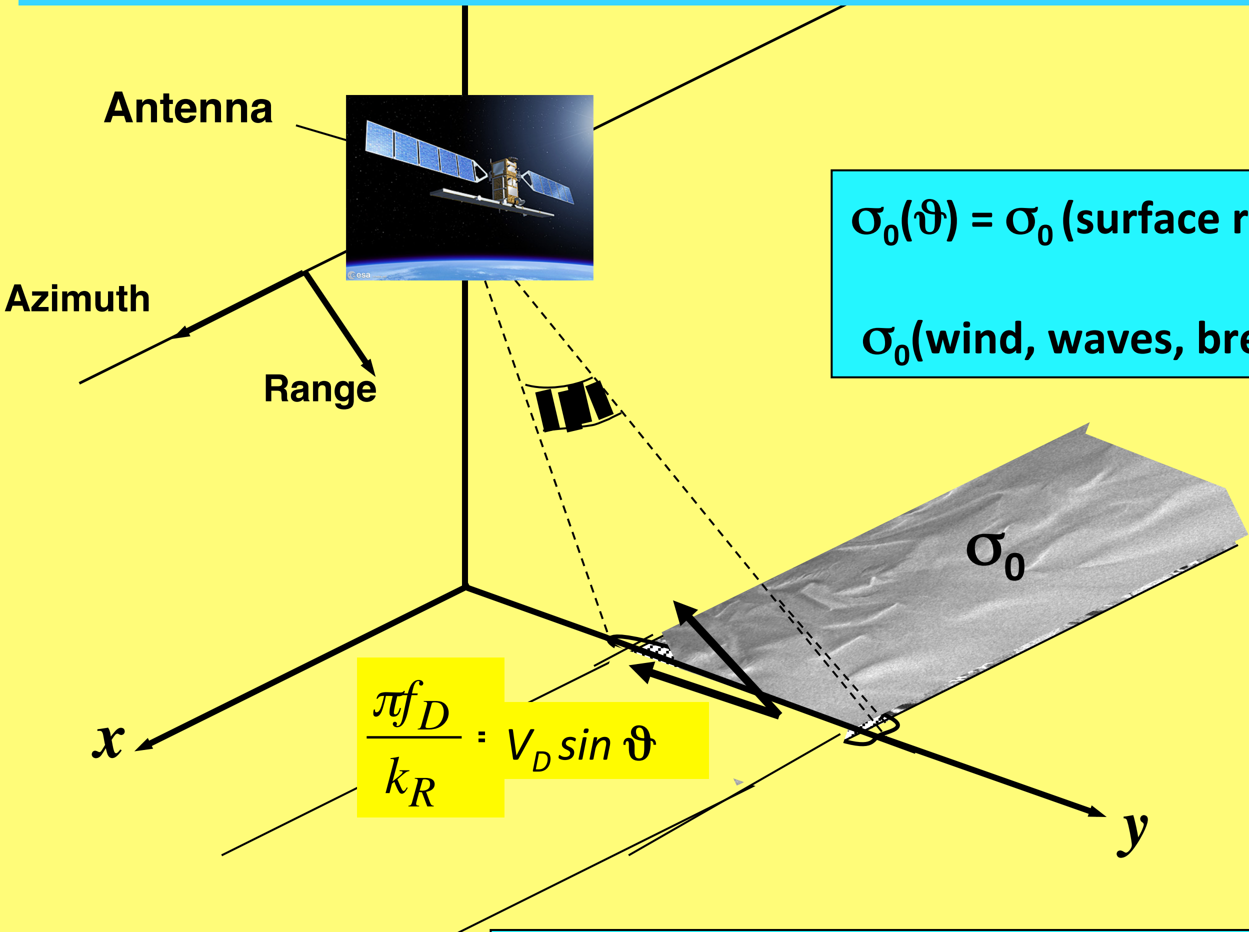

VV
PR
PD
NP
NP c
CP
0.5
1
1.5
2
0.4
0.6
-0.5
0
10
20
distance [km]
distance [km]




Both the wind variability and the wave-current interaction contribute to the CP signal. The first contribution is primarily removed by considering the ratio of the cross-polarized NRCS and the polarization difference.

Kudryavtsev et al., 2014

# SAR Imaging of Roughness and Doppler Shift



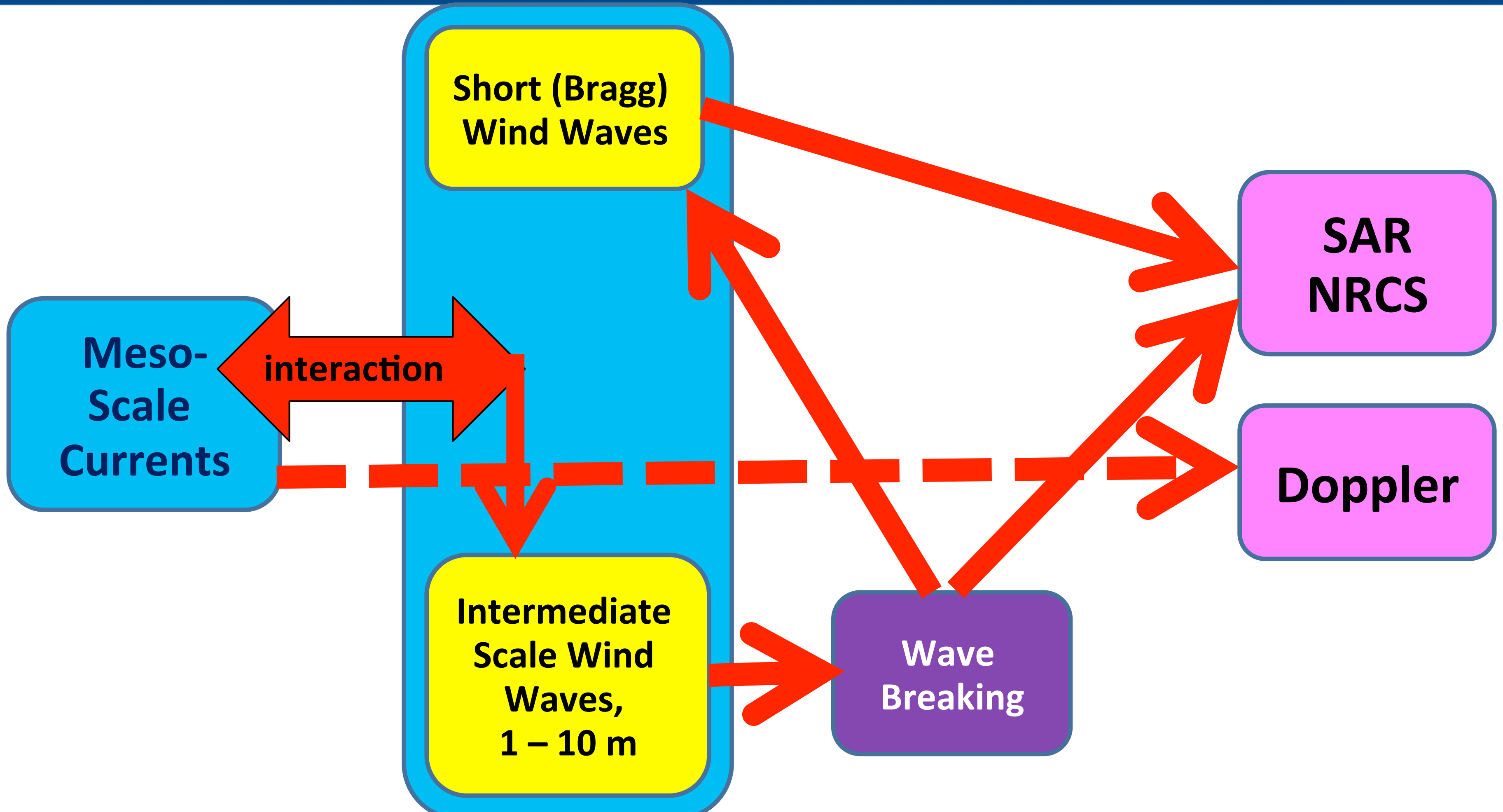

$$\frac{\pi f_D}{k_R} = V_D \sin \vartheta$$

$\sigma_0(\vartheta) = \sigma_0$ (surface roughness) =

$\sigma_0$(wind, waves, breaking, current

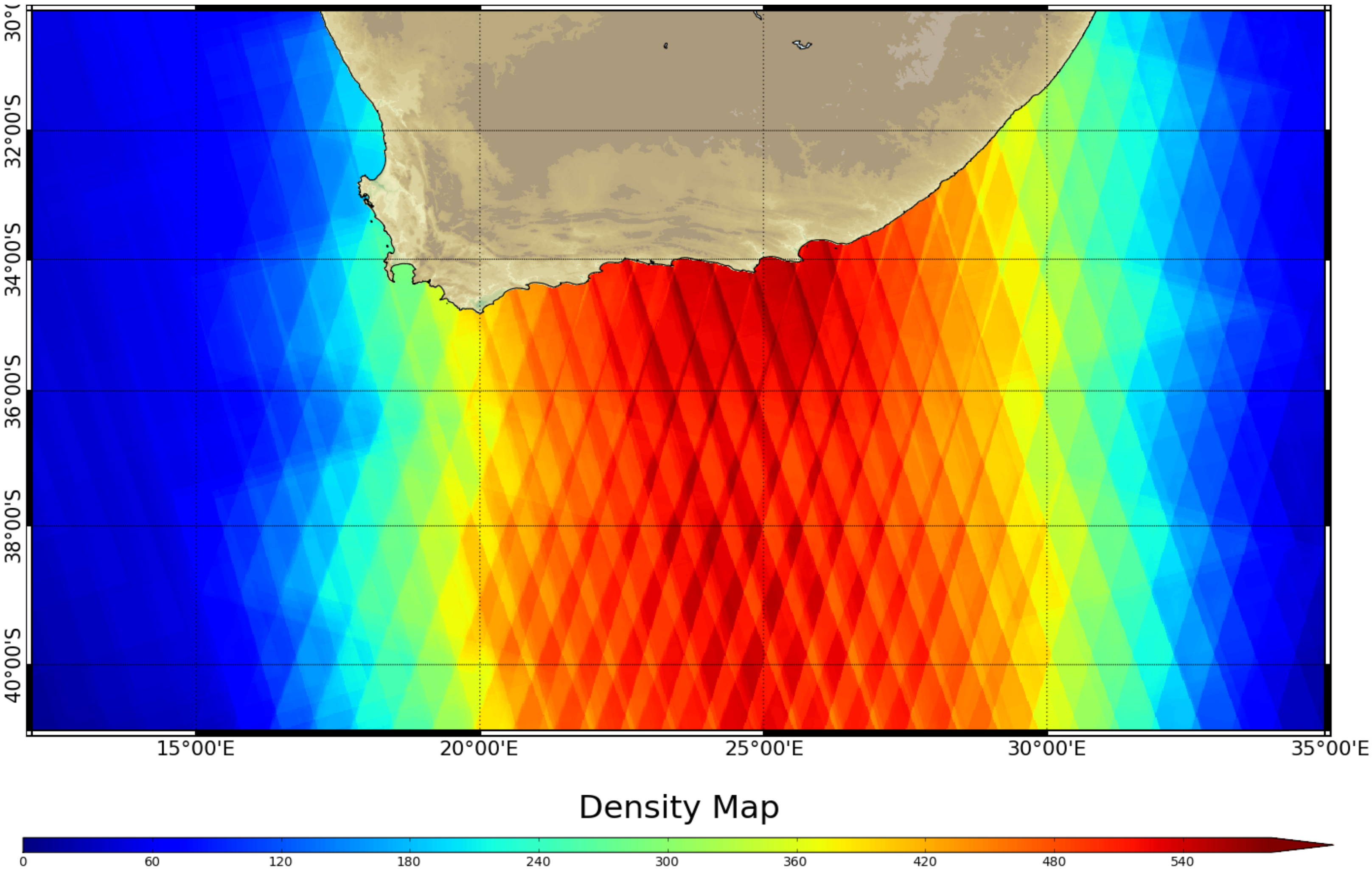
$V_D = V_D$ (wind driven scatterer, waves, breaking, current)

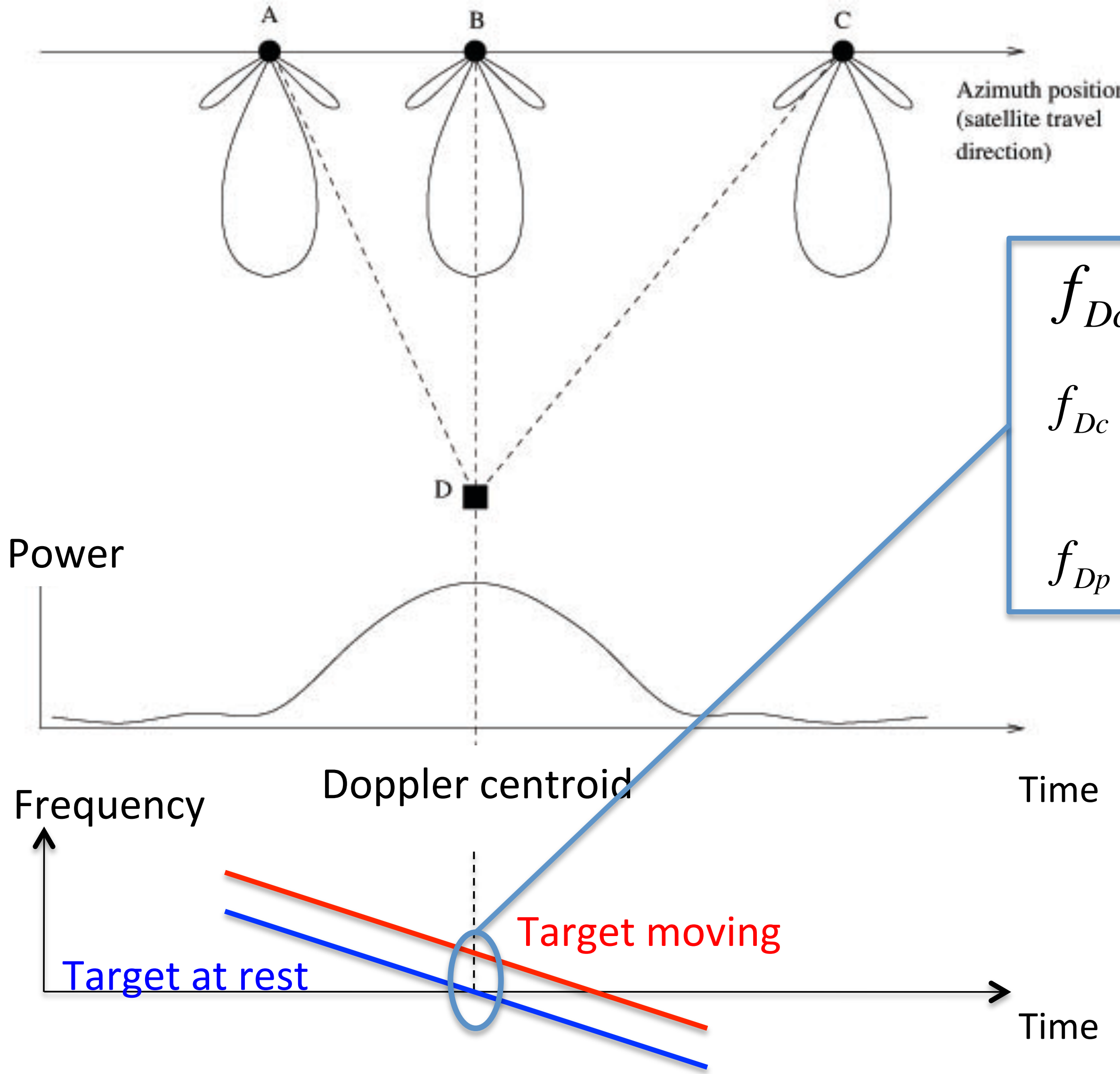
# SAR Imaging Observations & Simulation Modelling




“Radar Imaging of meso-scale current features” ---- Kudryavtsev et al., JGR, 2005 (Part 1); Johannessen et al., JGR, 2005 (Part 2); Chapron et al, 2005; Johannessen et al., JGR, 2008

# Envisat ASAR Coverage of the Greater Agulhas Current






$$f_{Dca} = f_{Dc} - f_{Dp}$$

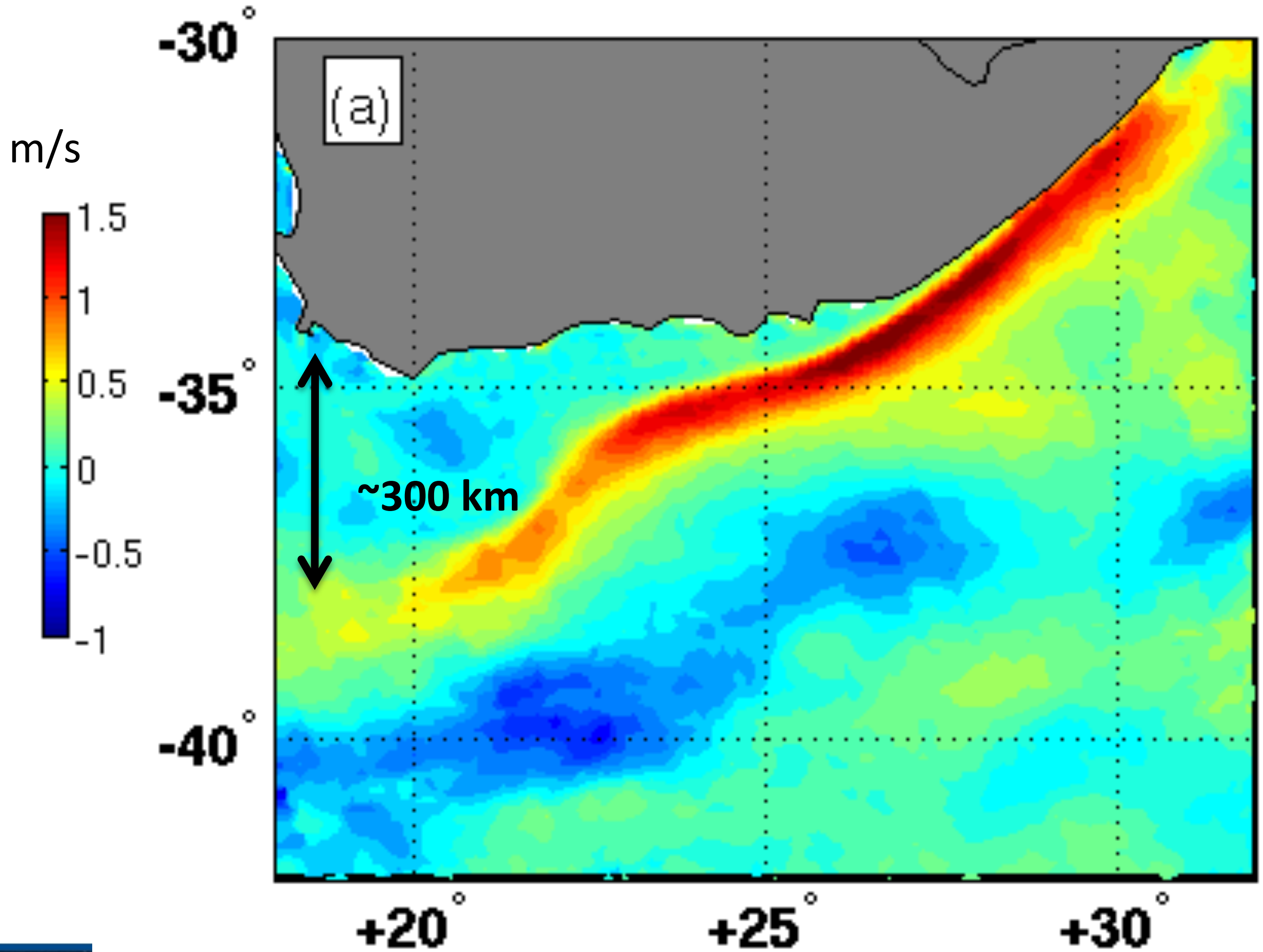
$f_{Dc}$ : estimated Doppler centroid frequency shift

$f_{Dp}$ : predicted Doppler shift

Chapron et al. (2003, 2005)
Hansen et al 2012

# Doppler Centroid Frequency Shift

# Range Doppler Velocity Map – mean of ~600 asc. Aq.

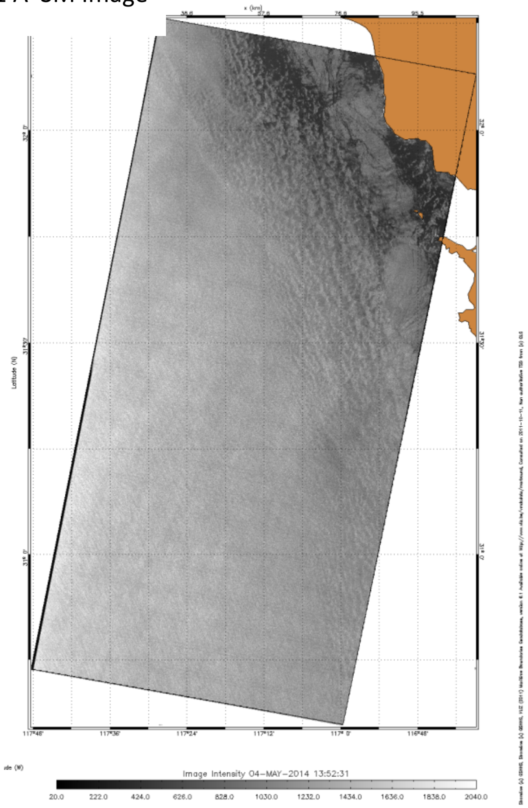



Accuracy about 2-4 cm/s

Johannessen et al., 2014

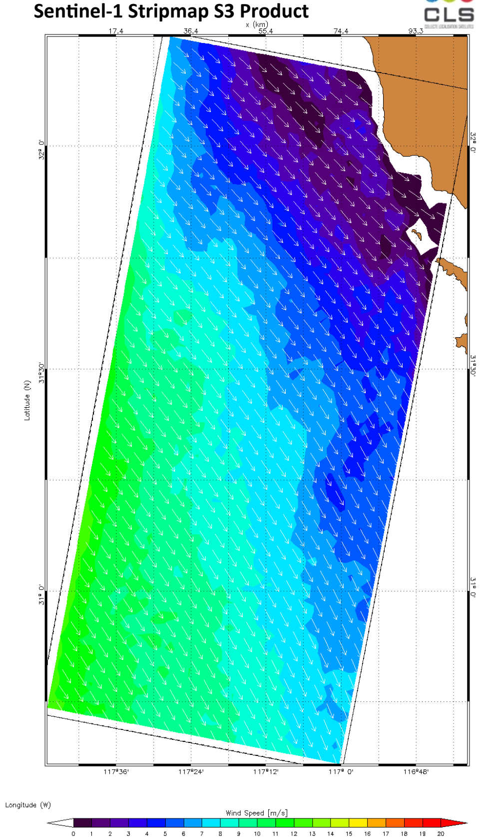
## *First Wind measurement with S-1 A*

S-1 A  SM Image

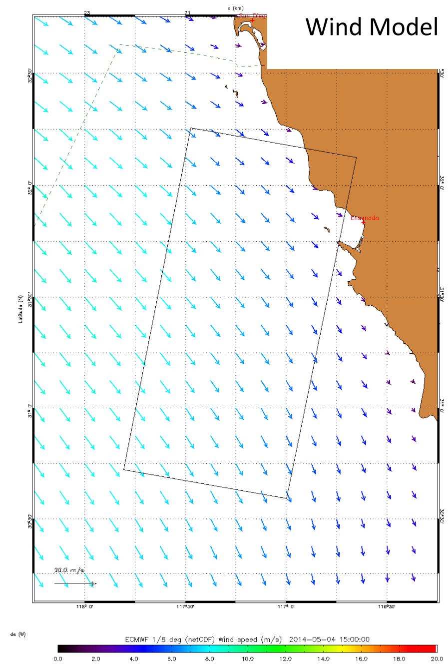



04-May-2014 13:52:32 (UTC)

**Sentinel-1 Stripmap S3 Product**



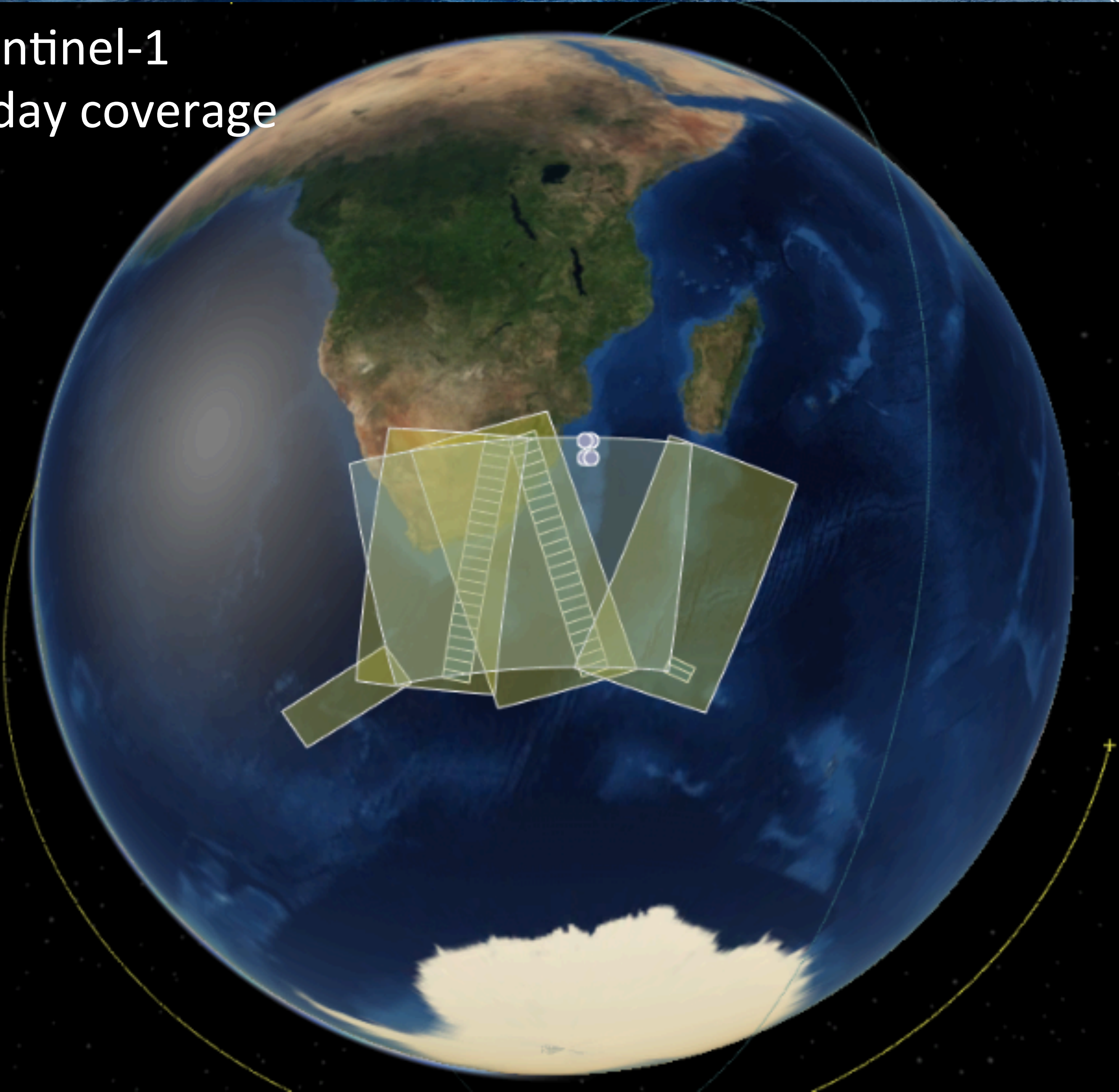

Wind Model

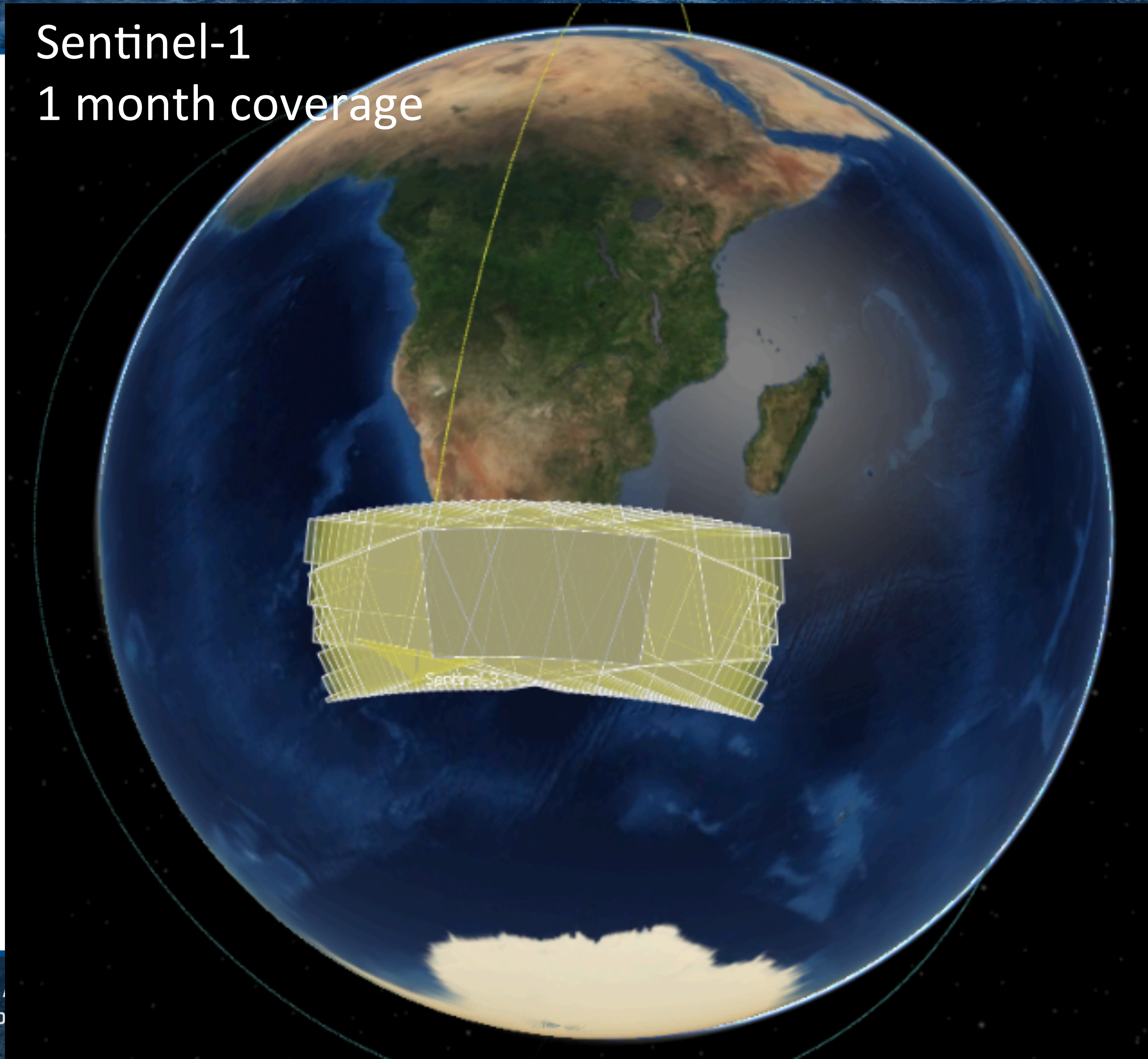



- S-1 A is able to measure relative wind variations at very high resolution (1 km here)
- Wind fields estimates will benefit from dual polarization for extreme events such as hurricanes.

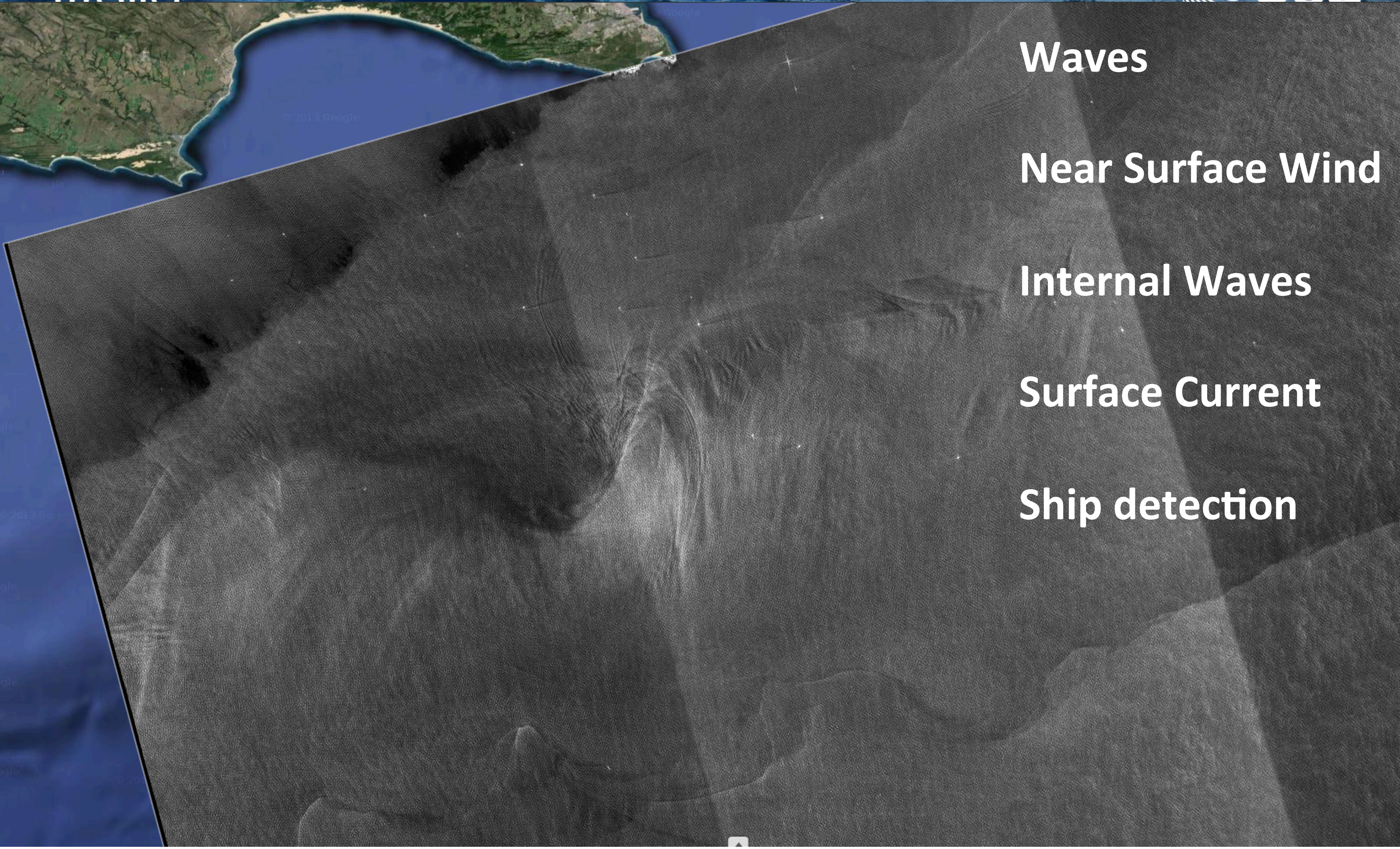
Sentinel-1

1 day coverage




Sentinel-1
1 month coverage
Sentinel-3

# Sentinel-1 acquisition 24 August 2014



Waves

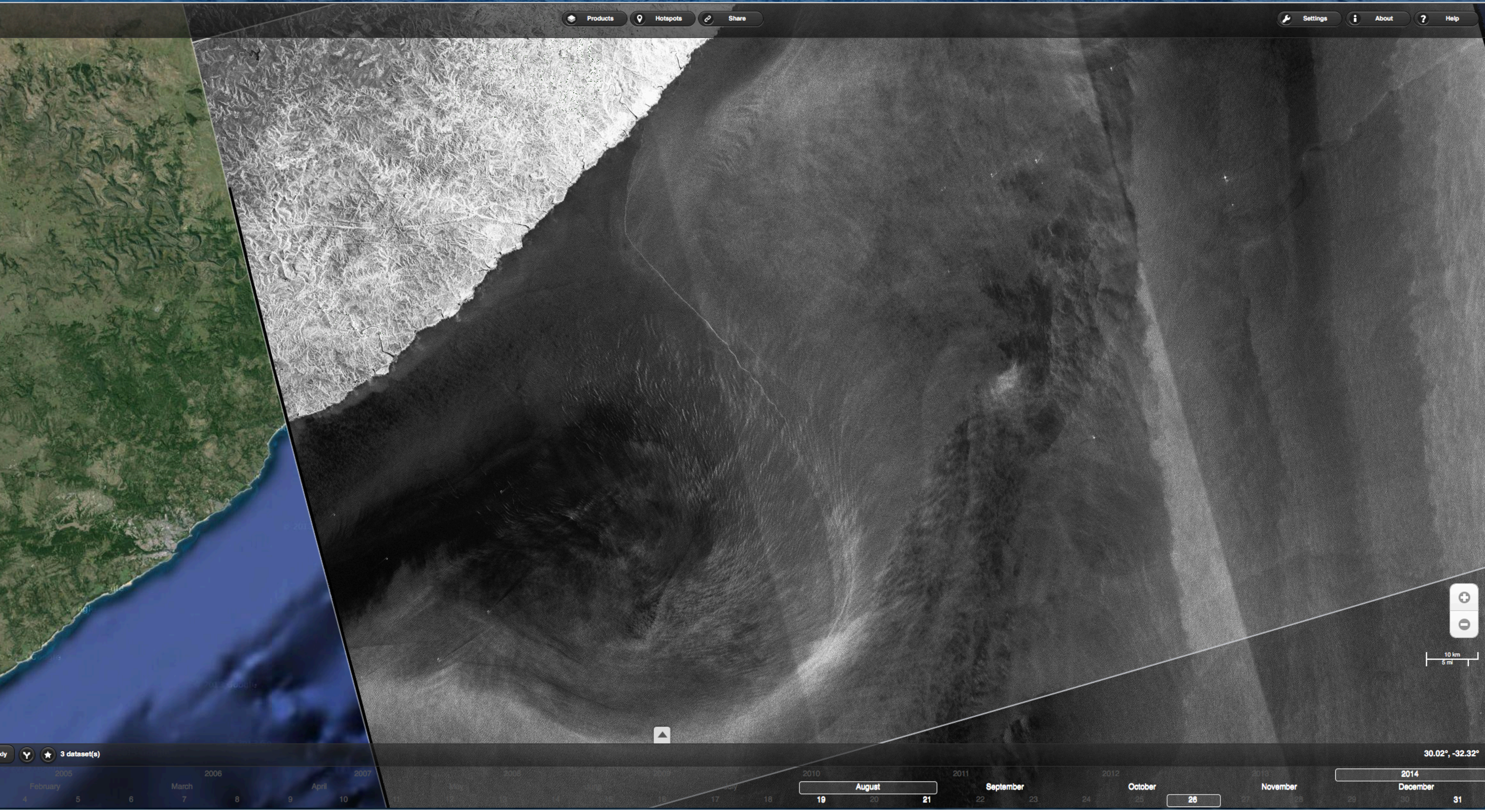
Near Surface Wind

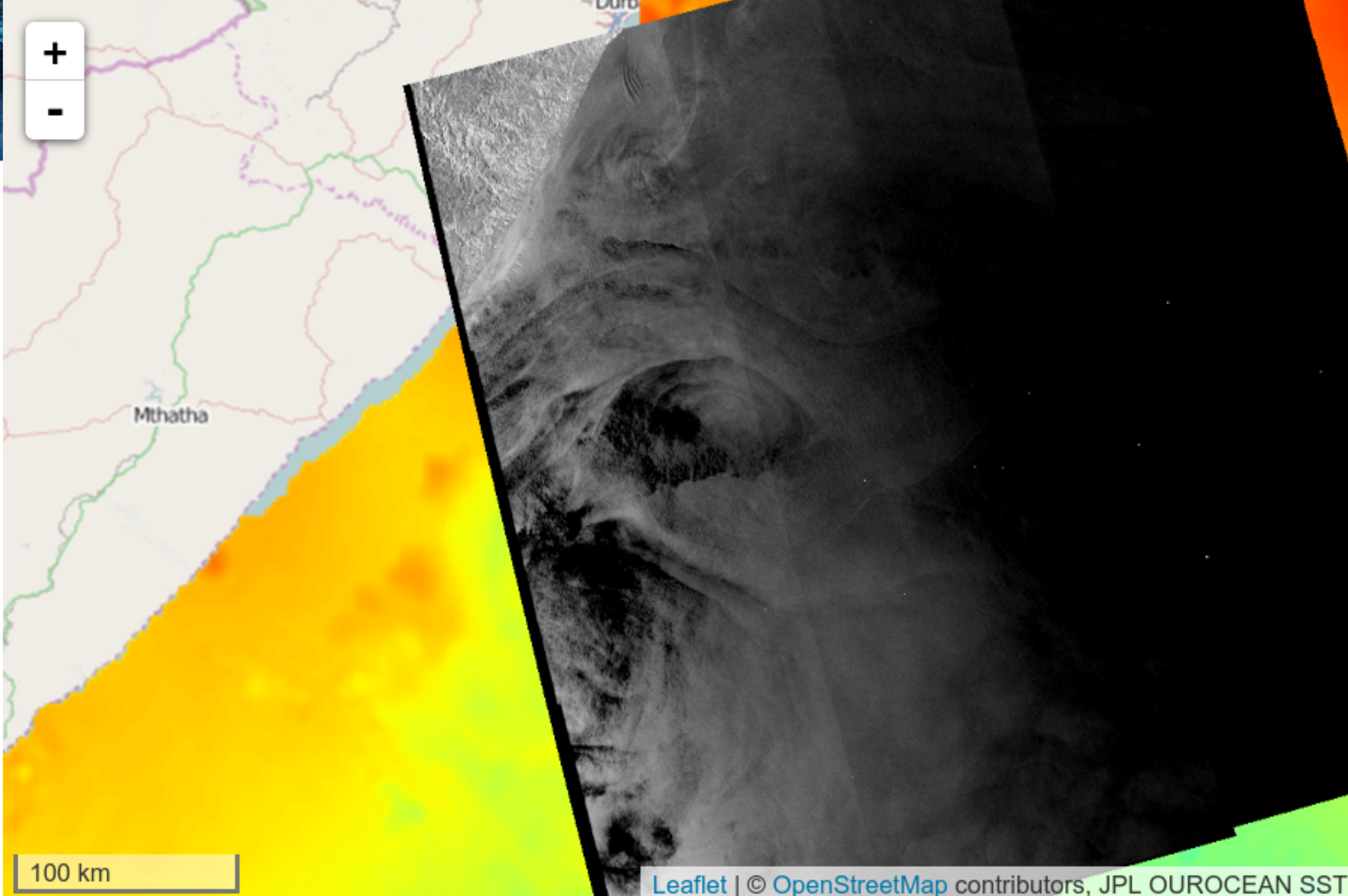
Internal Waves

Surface Current

Ship detection

# Sentinel-1 SAR on 26 August 2014

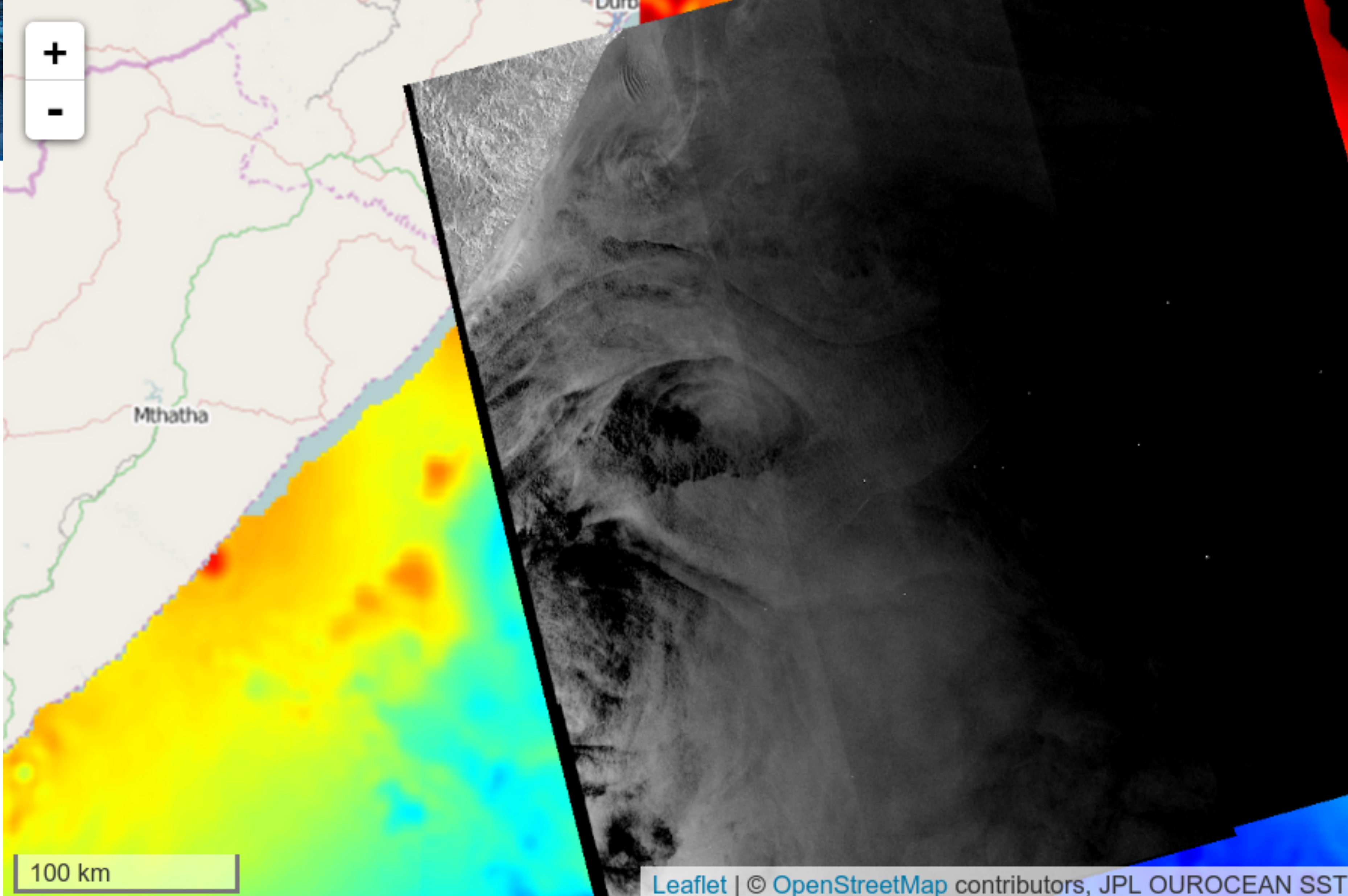





Min SST: 14 Max SST: 25

Show HH ☑ 100

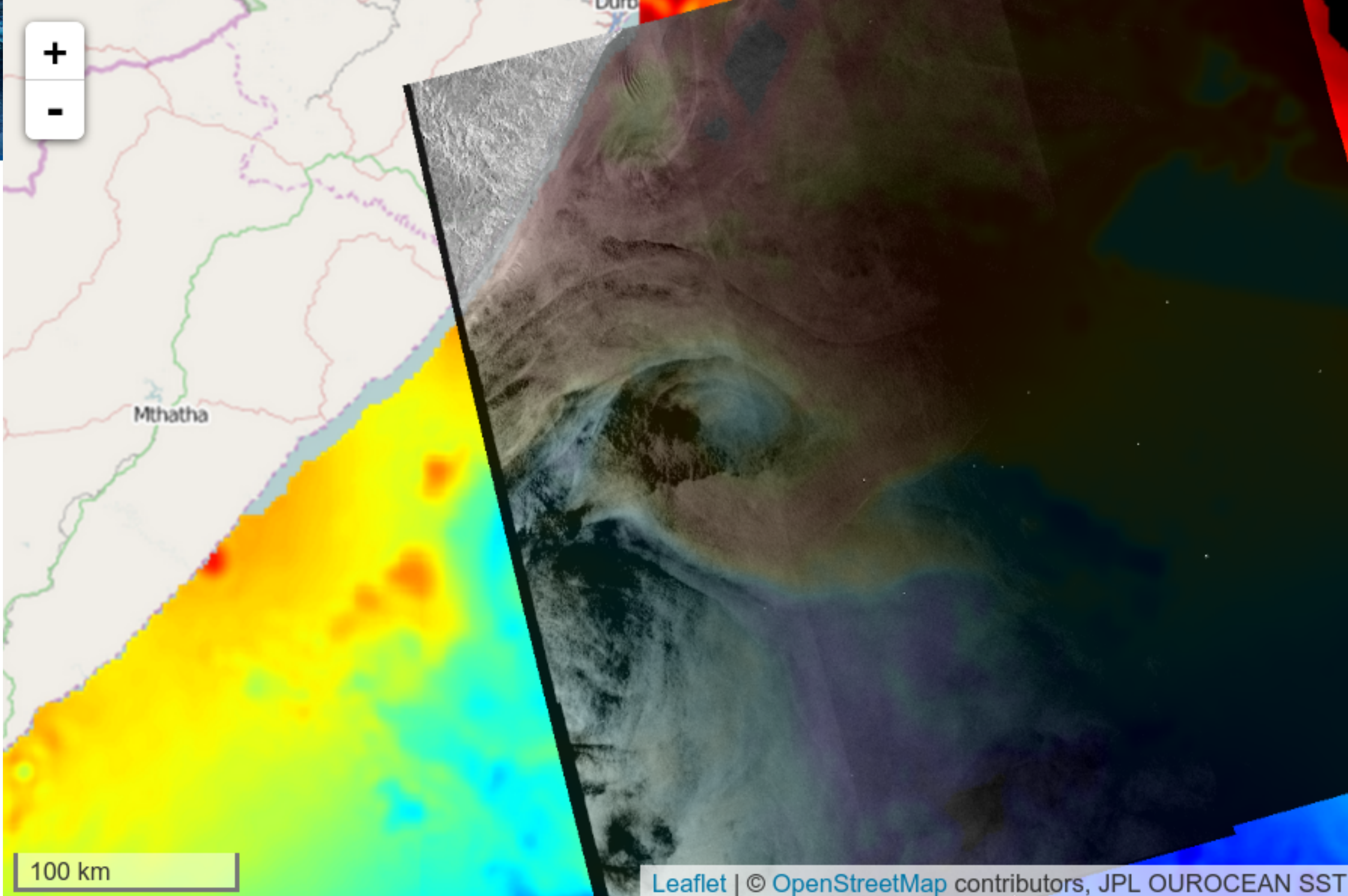
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 100

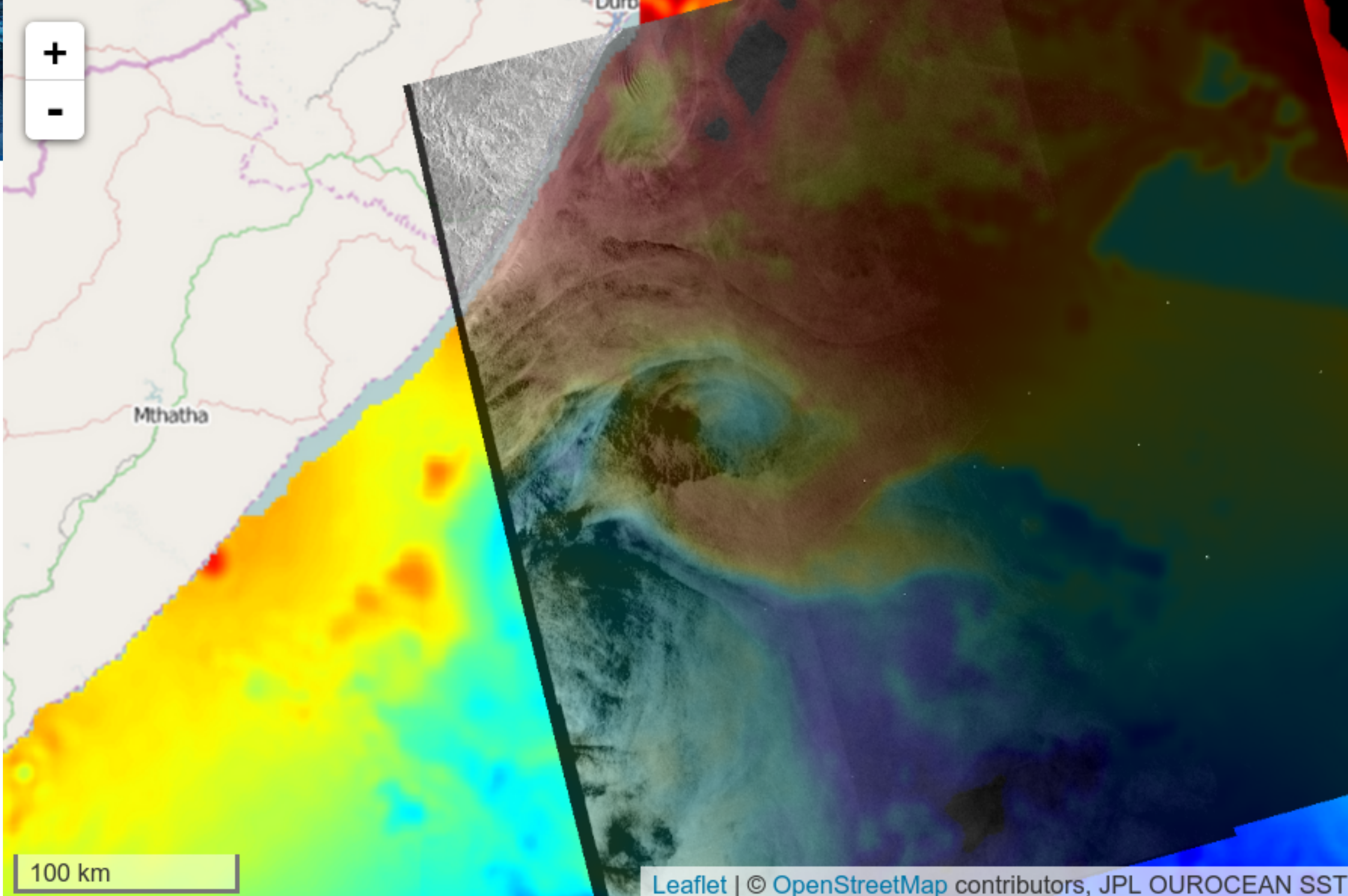
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 90

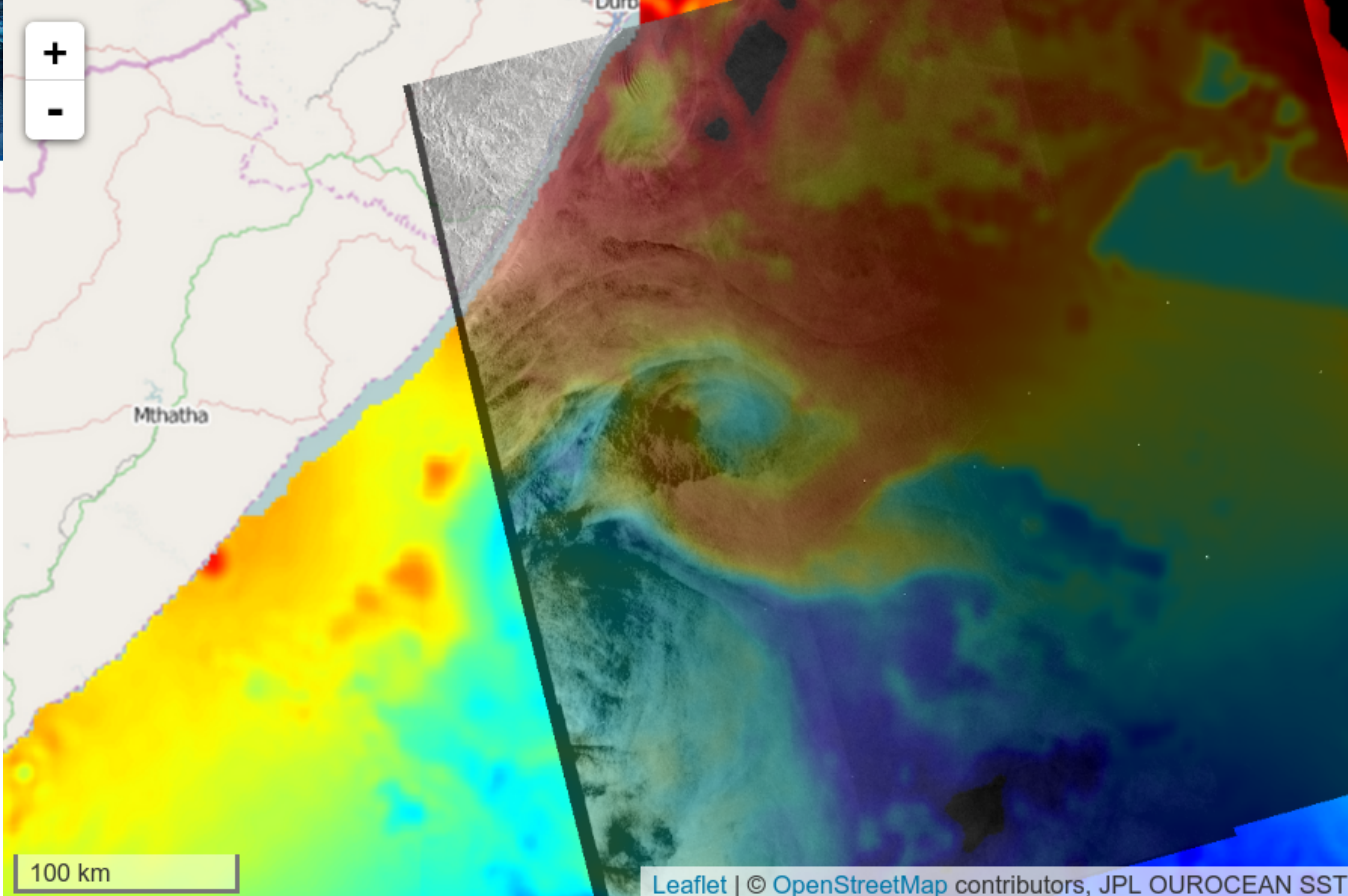
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 80

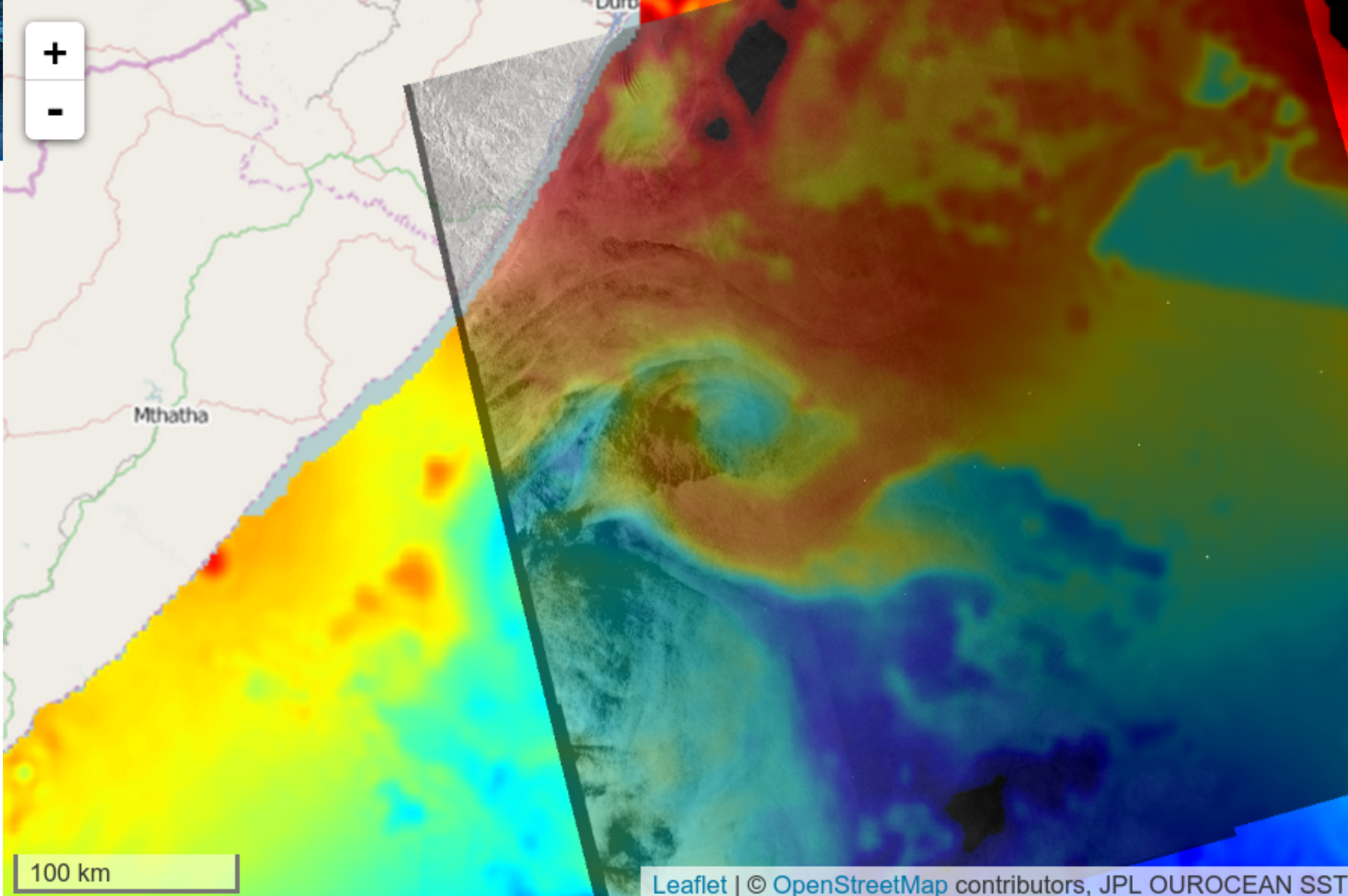
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 70

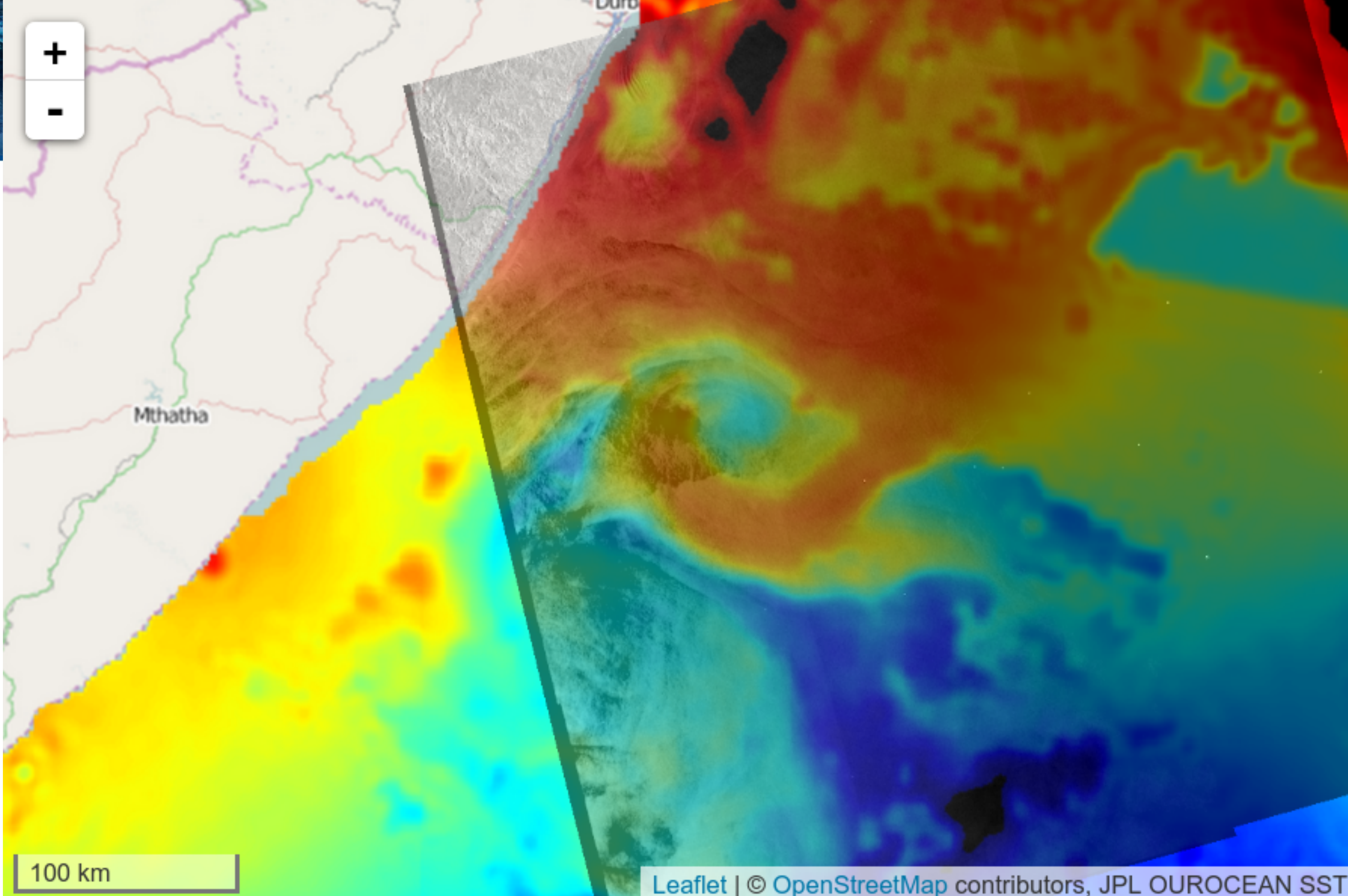
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 60

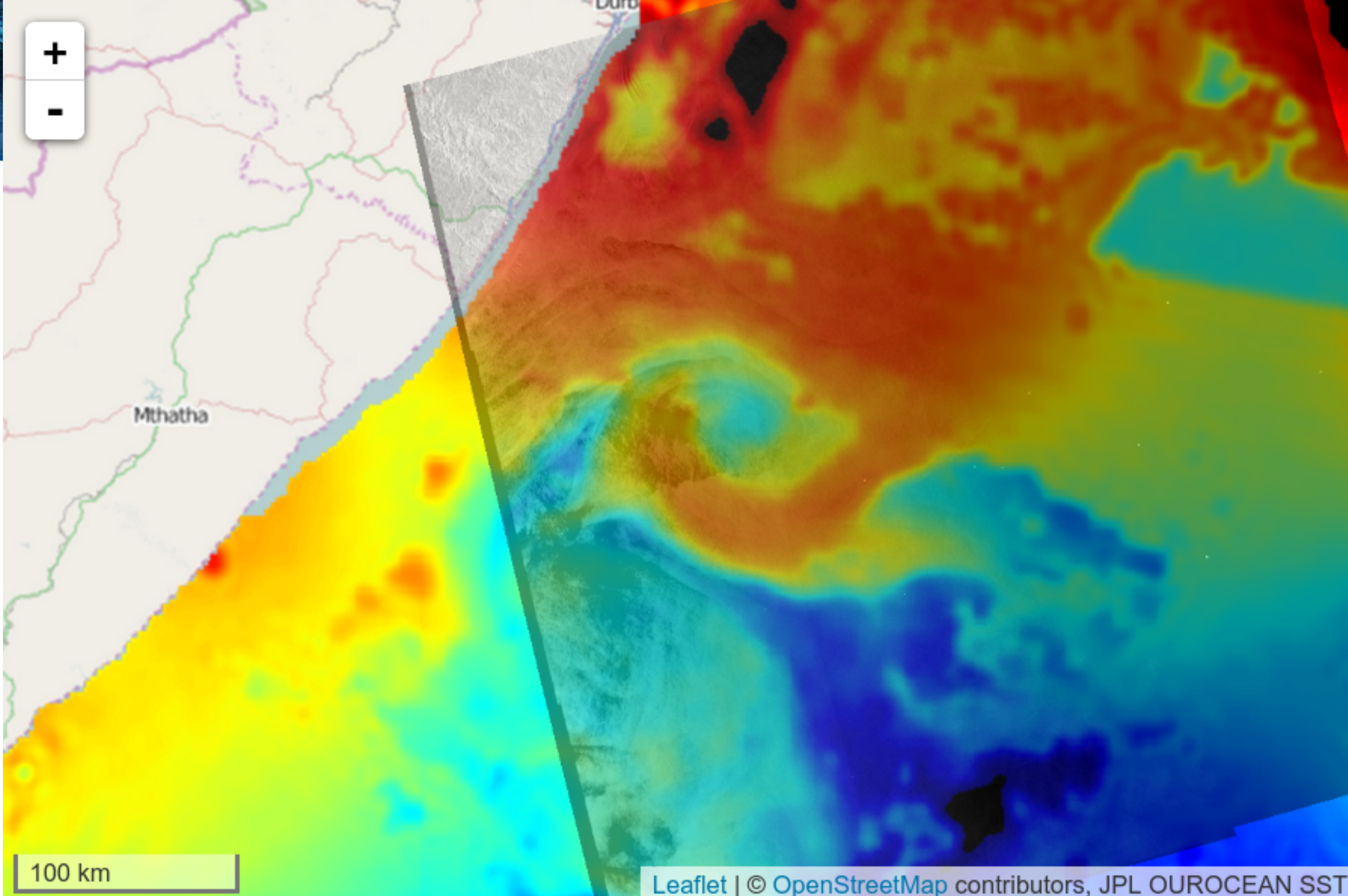
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 50

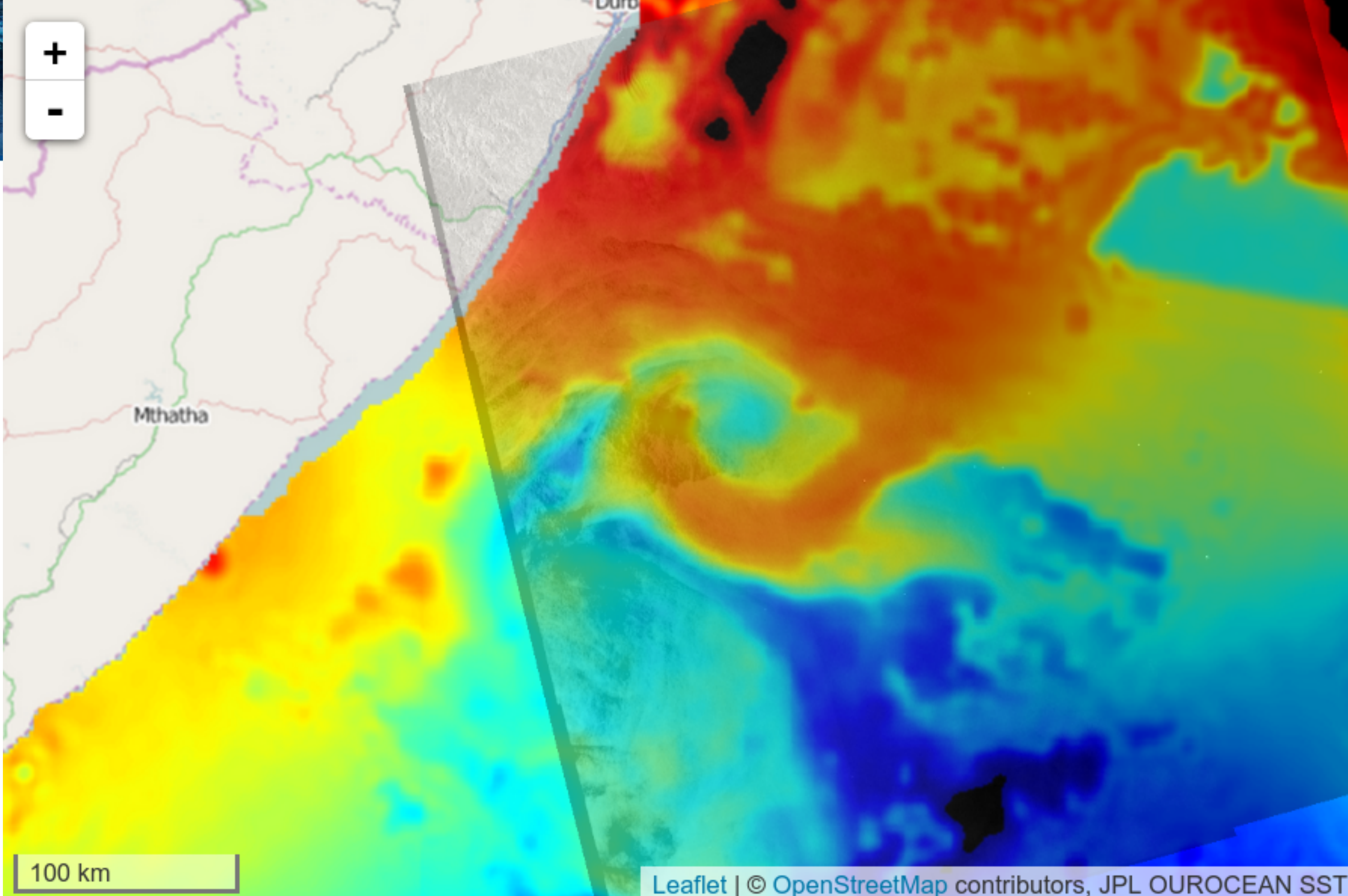
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 40

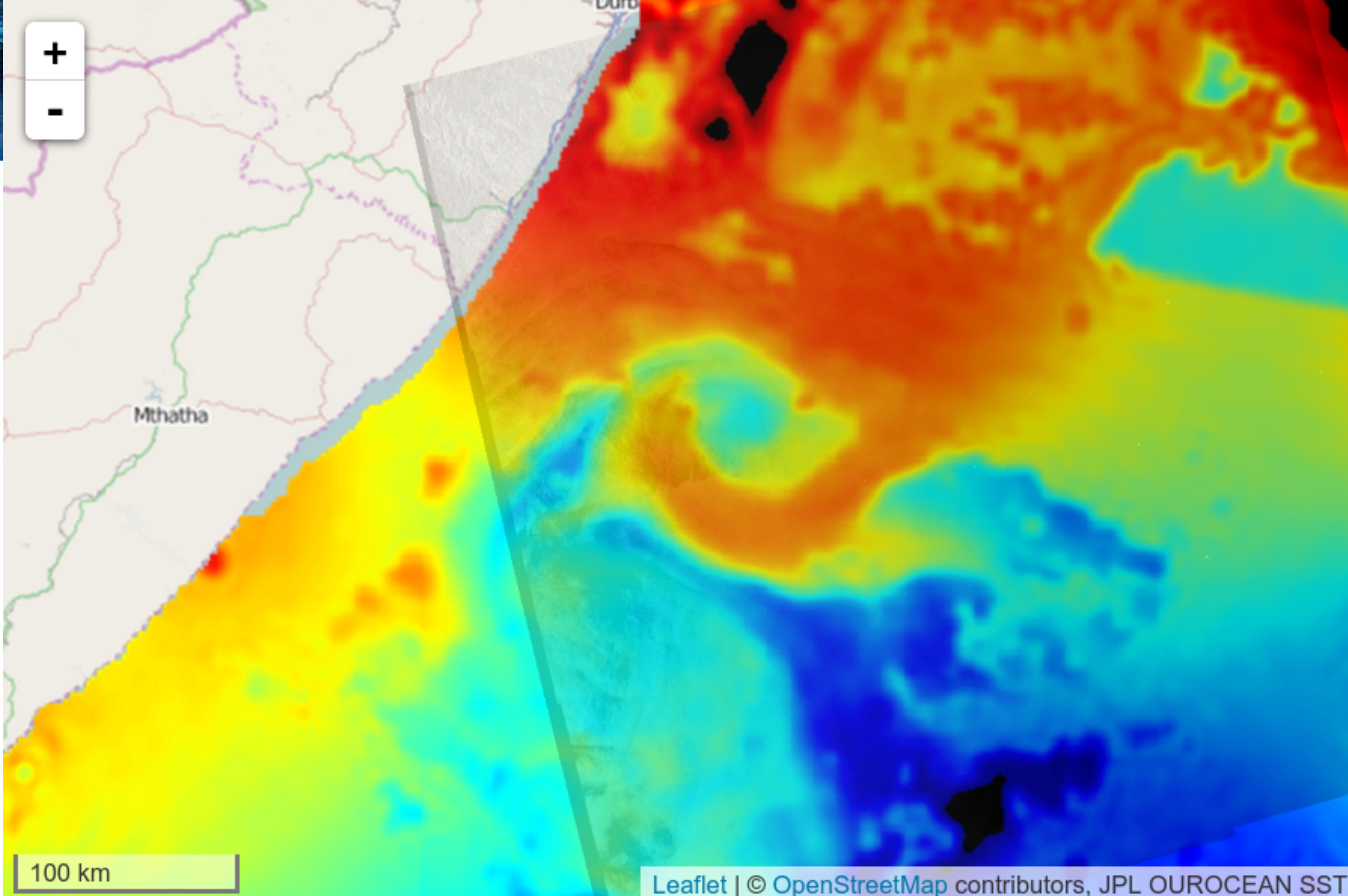
**NANSEN-CLOUD** 2014-10-15
**SST** GHRSST / JPL
**SAR** SENTINEL-1




Min SST: 19 Max SST: 23

Show HH ☑ 30

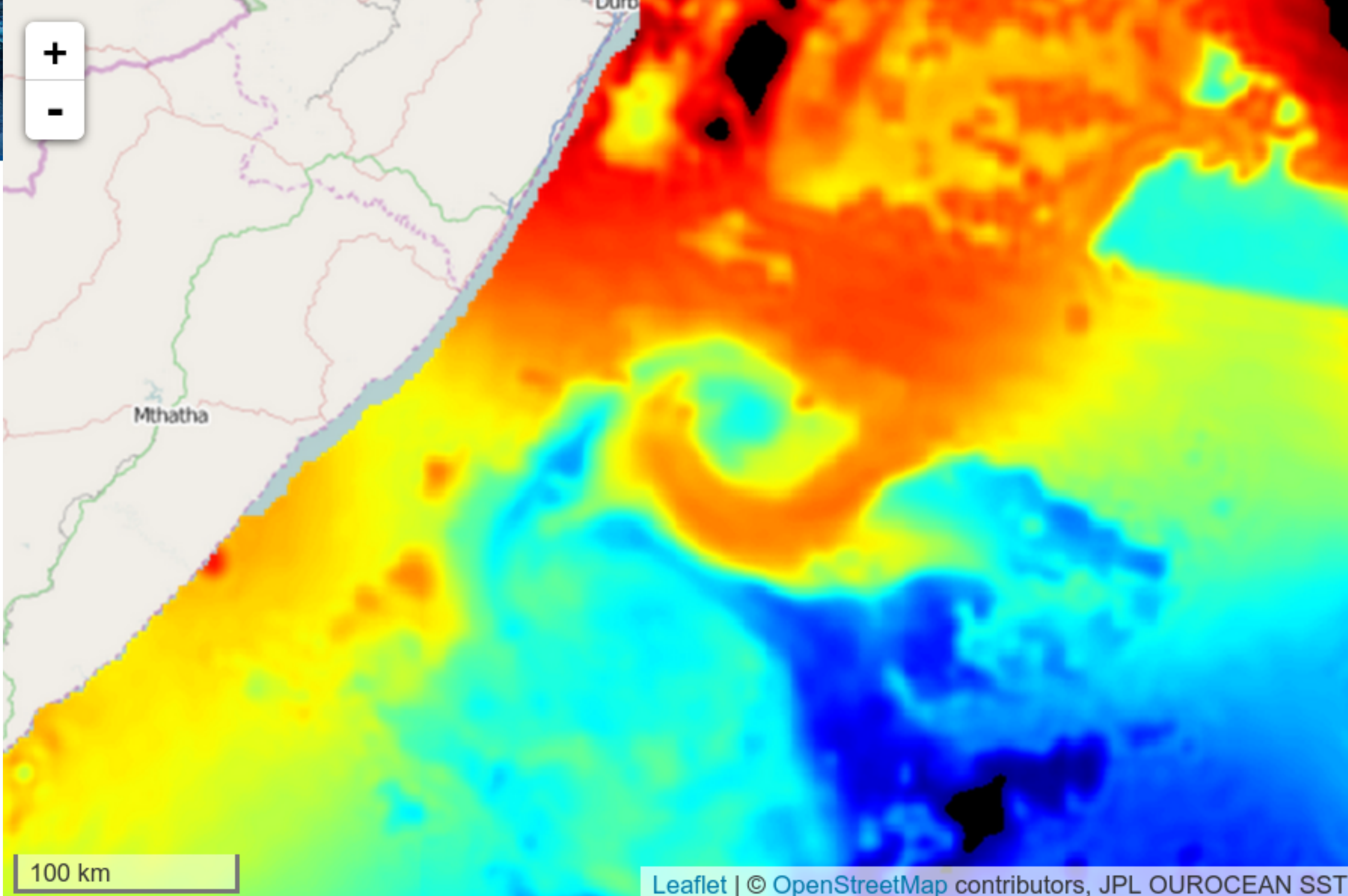
| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 20

| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |




Min SST: 19 Max SST: 23

Show HH ☑ 0

| | |
|---|---|
| **NANSEN-CLOUD** | 2014-10-15 |
| **SST** | GHRSST / JPL |
| **SAR** | SENTINEL-1 |

# SENSOR SYNERGY

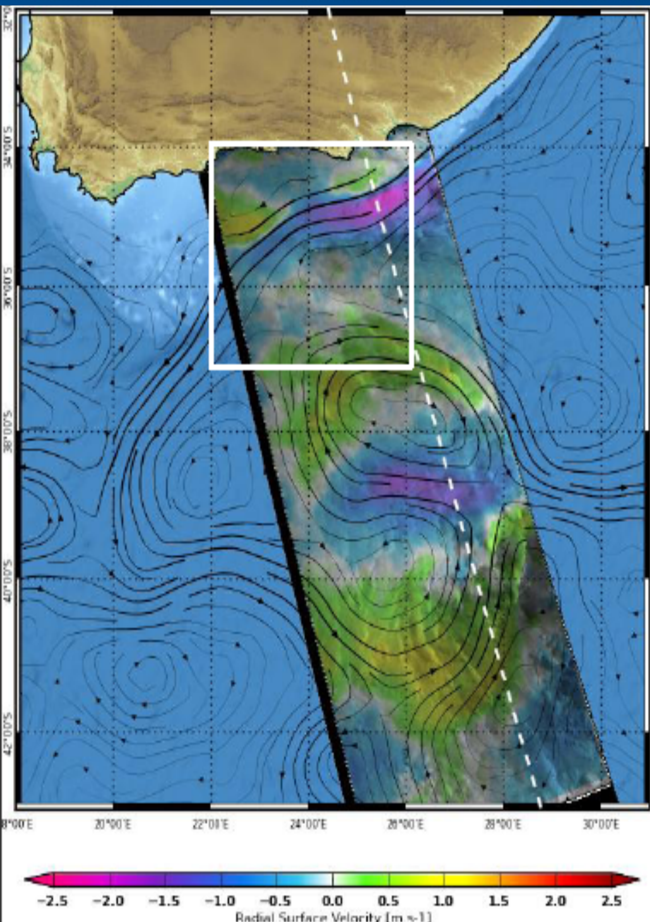



Fig. 1: Radial surface velocity from SAR. Sea State contribution has been removed by combining ECMWF wind and CDOP model. Geostrophic component of the ocean surface current from altimetry (DUACS) is overlaid. White dotted lines indicate the transect used for direct comparison between SAR, altimetry and Mercator model.

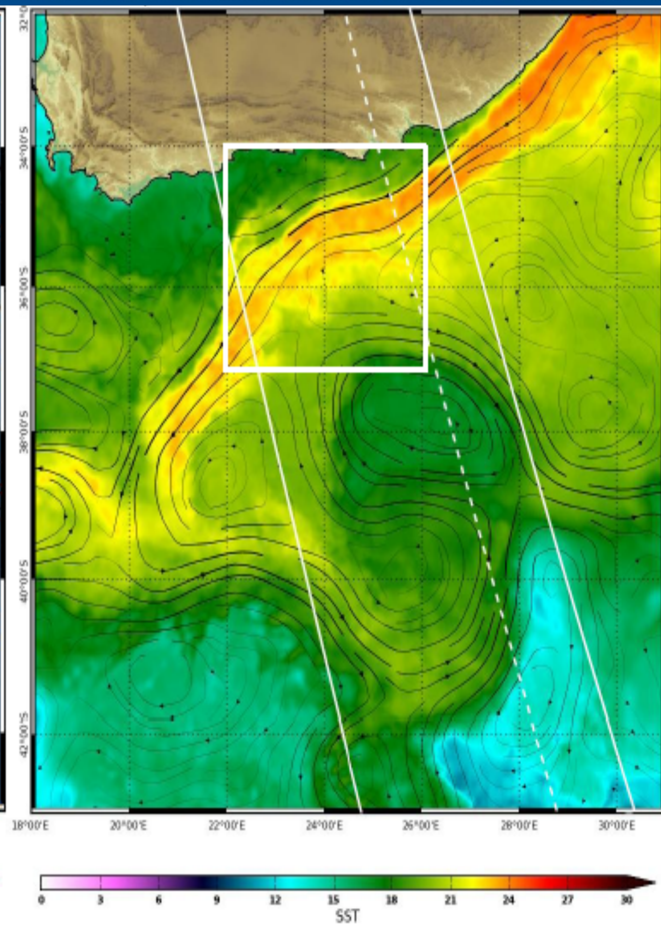
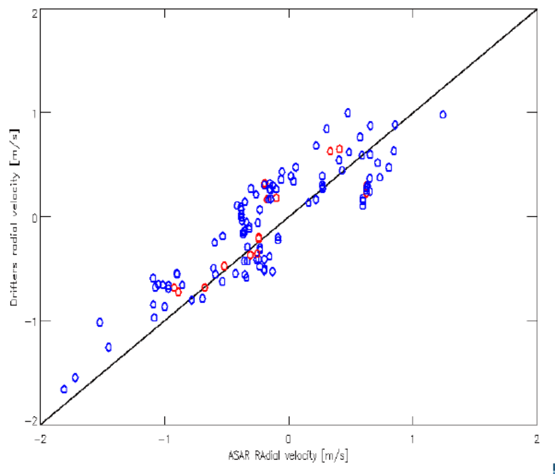



Fig. 2: Sea Surface Temperature from Odyssea (CERSAT). Geostrophic component of the ocean surface current from altimetry (DUACS) is overlaid. White dotted lines indicate the transect used for direct comparison between SAR, altimetry and Mercator model.




GlobCurrent

http://www.globcurrent.org