Discovering Ocean Dynamics from Space: C-band active microwave observations to support studies of mesoscale and submesoscale dynamics

NRCS at C-Band From ENVISAT/ASAR, Radarsat-2 and Sentinel-1 SAR-In co- and cross-polarization.
A Coherent Analysis

IFREMER team

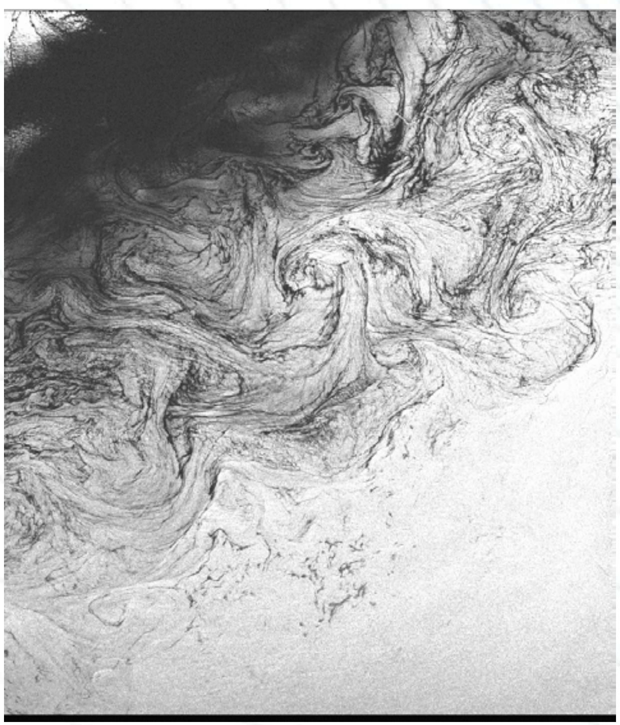
Plymouth, AMT2017,

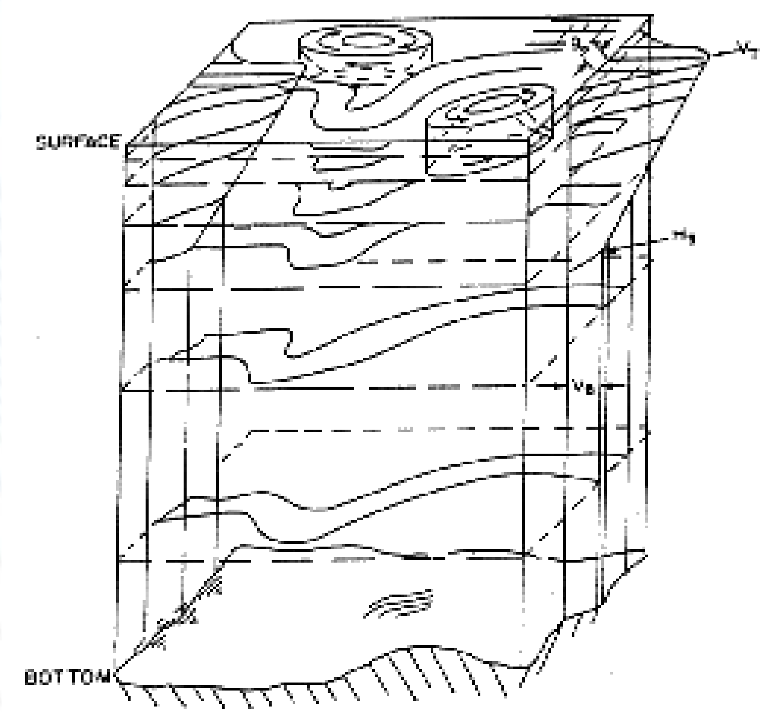
An Earth Observation Challenge: 3D dynamics of the upper ocean

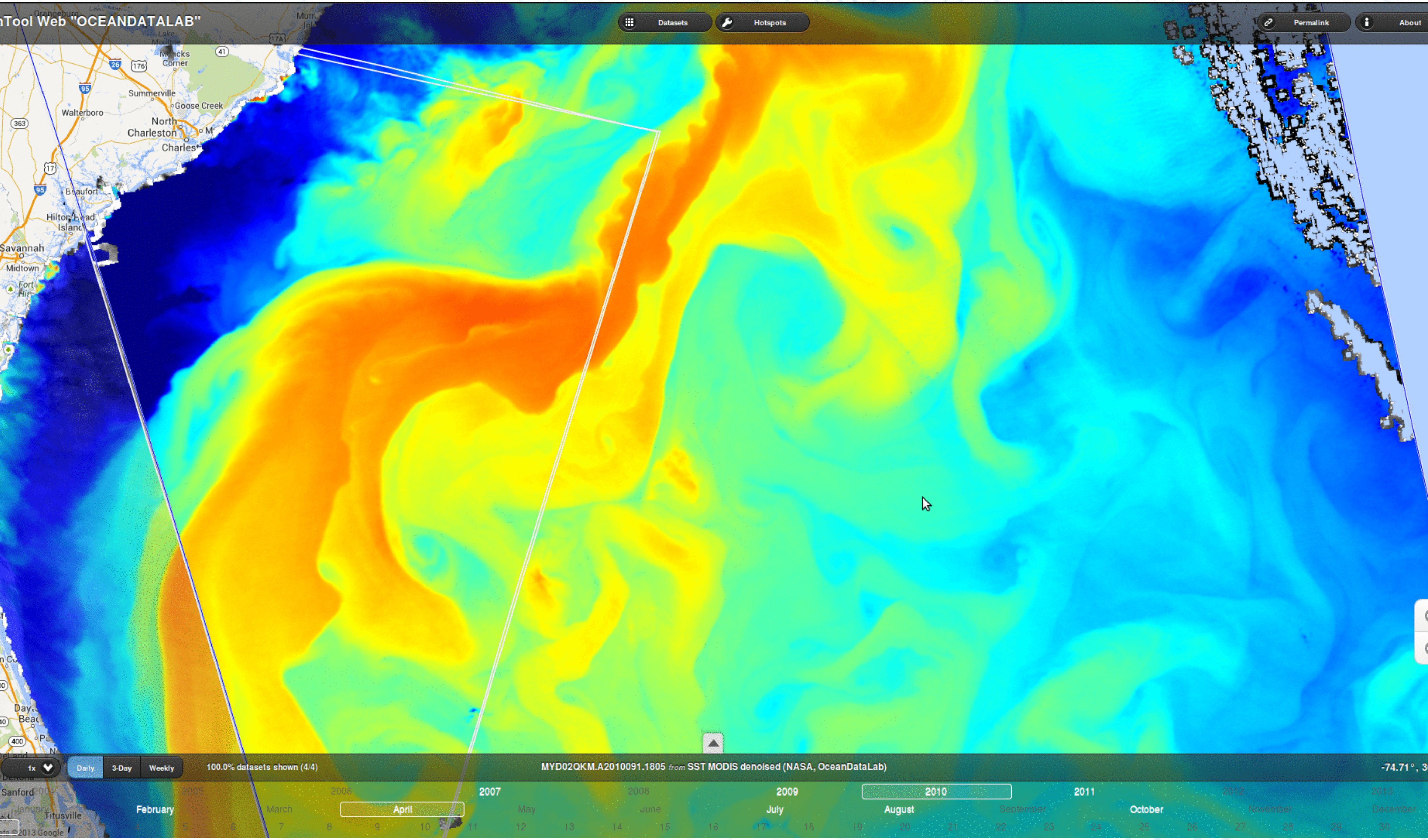
P. Niiler (2009) Oceanography in 2025

Oceanography of 2025 will require observations and realistic modeling of the circulation patterns that contain the vertical motion of the upper 200 m. Models will be compared not by how well they assimilate or replicate the sea level or reproduce the geostrophic velocity, but rather by how their internal vorticity and thermal energy and fresh water balances maintain ageostrophic velocity structures and the associated vertical circulations. This task calls for development and implementation of continued new methods and instruments for direct velocity observations of the oceans.

Sub-mesoscale (10 km eddies) and high resolution radar sea surface roughness variations






nTool Web "OCEANDATALAB"
Datasets
Hotspots
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About
Daily
3-Day
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MYD02QKM.A2010091.1805 from SST MODIS denoised (NASA, OceanDataLab)
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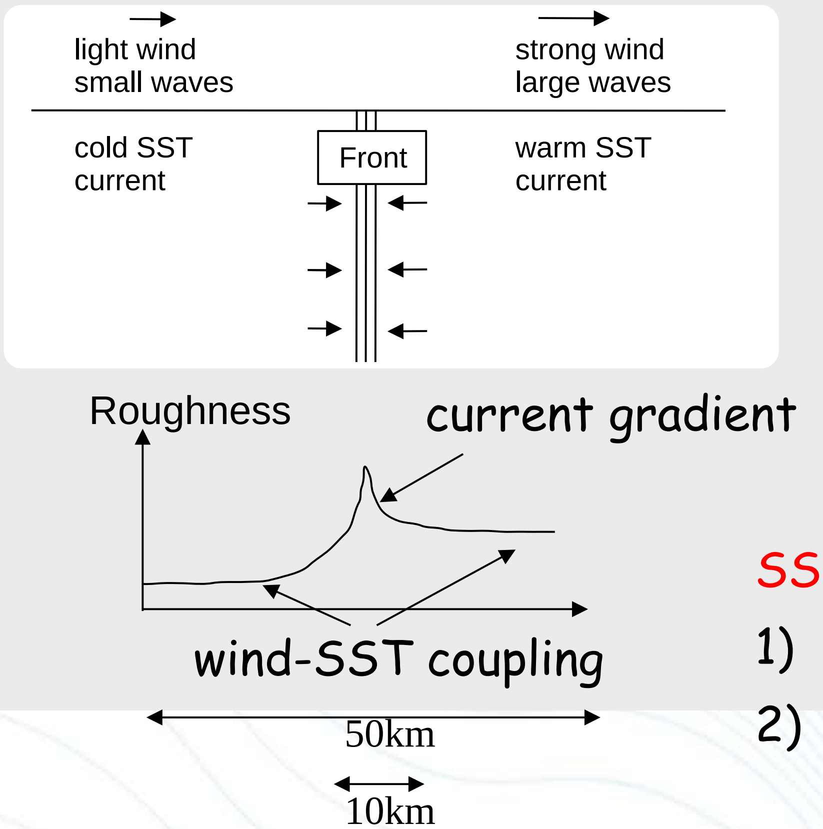
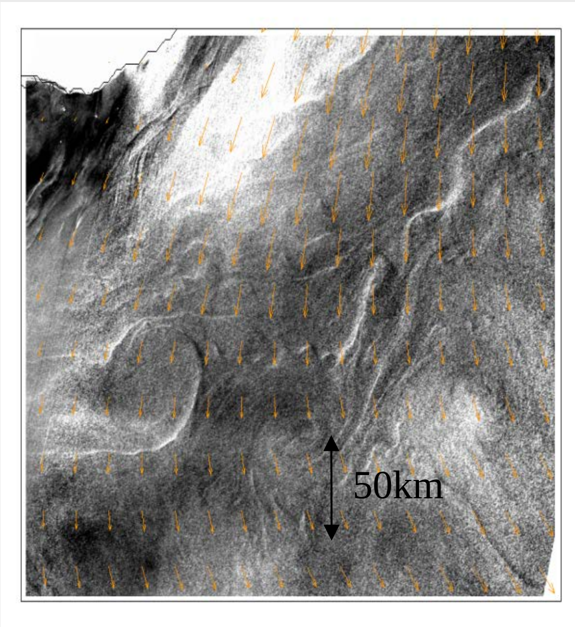


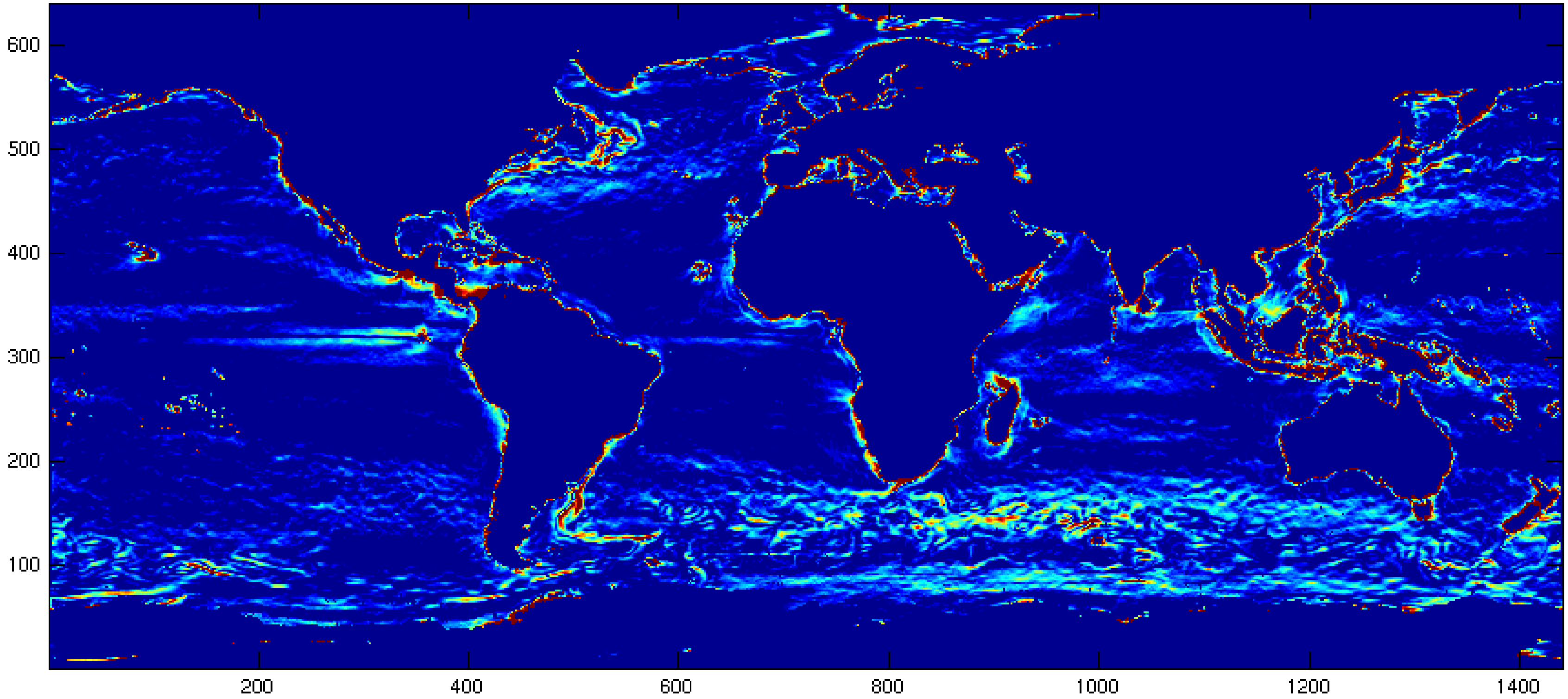


SST fronts and roughness gradients collocated

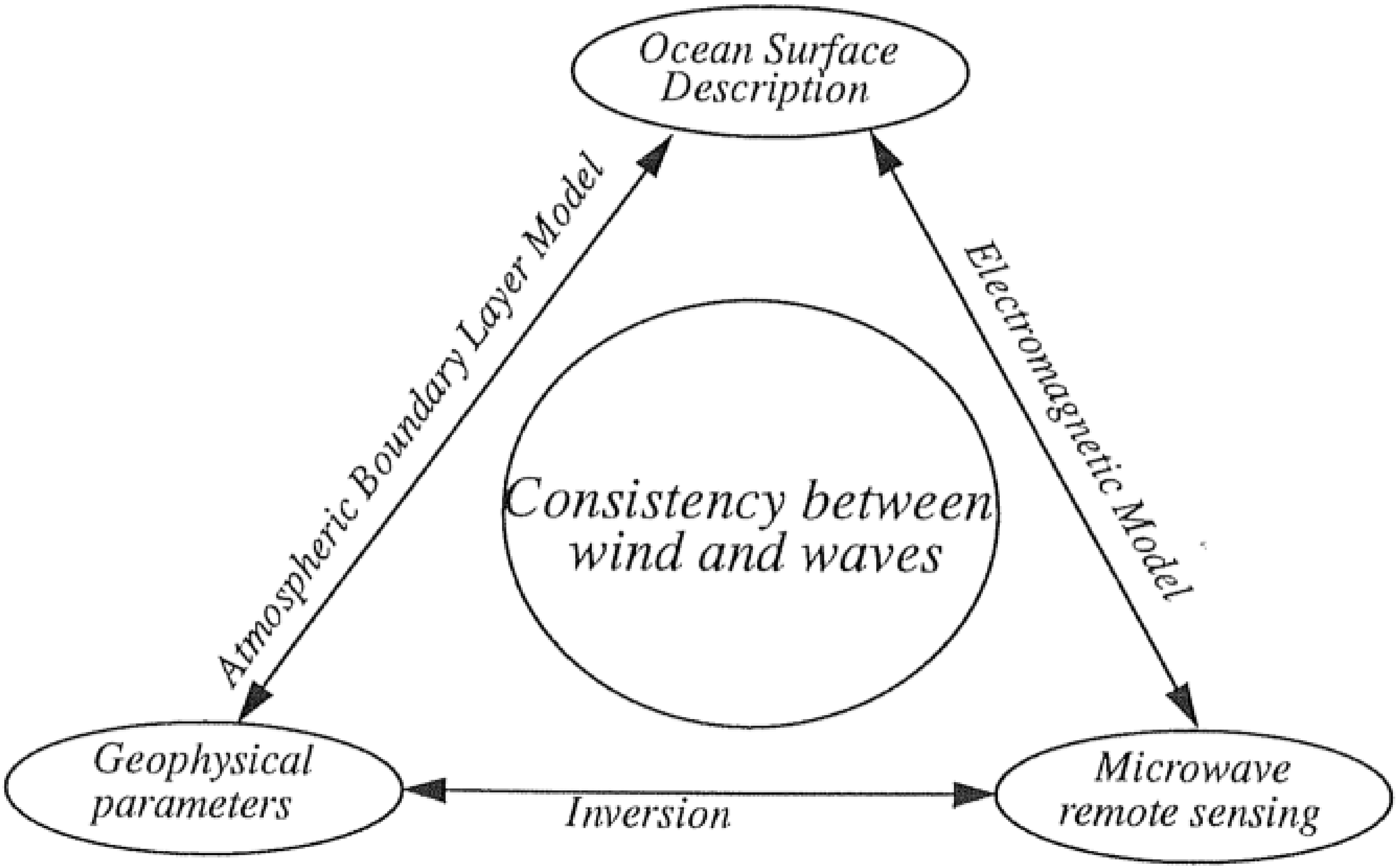
1) scales 10-50 km SST/wind coupling
2) scales 2-10 km wave/current coupling

Essentially related to the surface slope statistics (mean square slope MSS) of intermediate waves (roughly 1 m range)
Those waves are related to local wind and **current** (and surfactants)

Meso-scale Air-Sea Interactions (High-pass filtered surface wind speed)



An Earth Observation Challenge: 3D dynamics of the upper ocean ->A consistent approach (T. Elfouhaily, 1997)



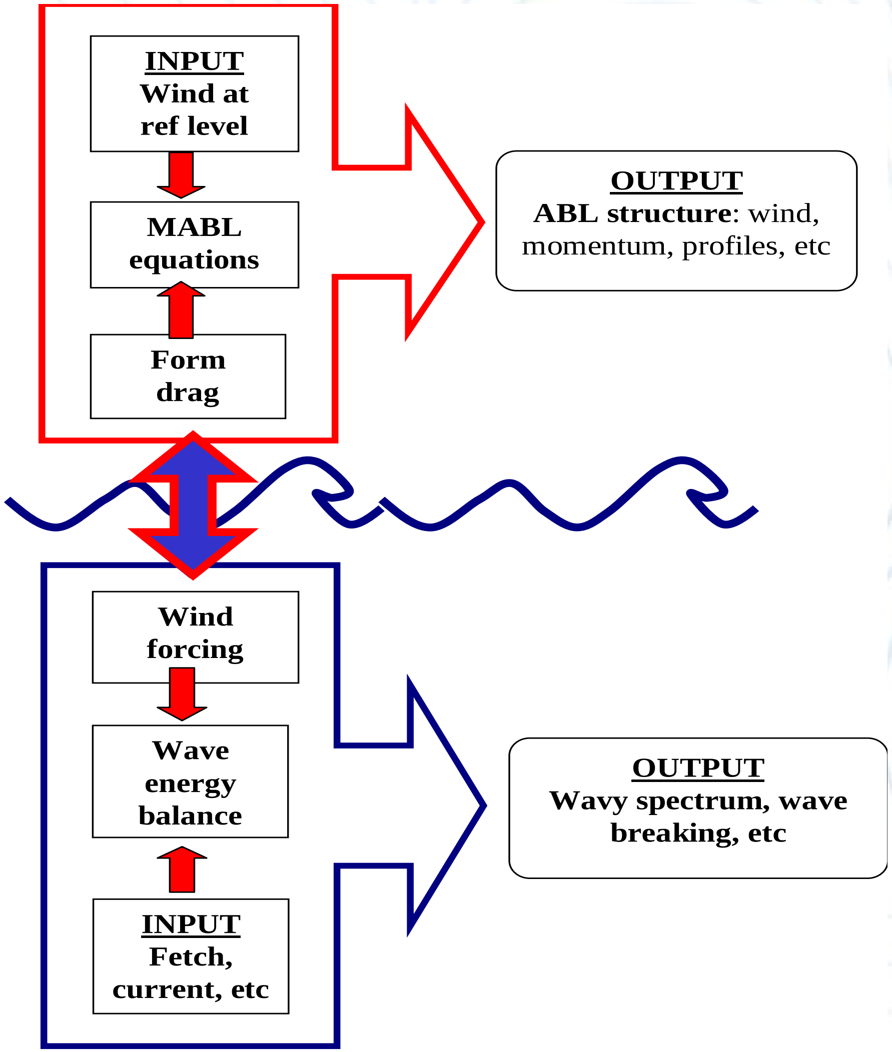
Air-Sea Interaction Model Tool

1. Revised Wind-over-wave-coupling model

Kudryavtsev, Chapron and Makin, J. Geoph. Res. , 119, 1217-1236, 2014

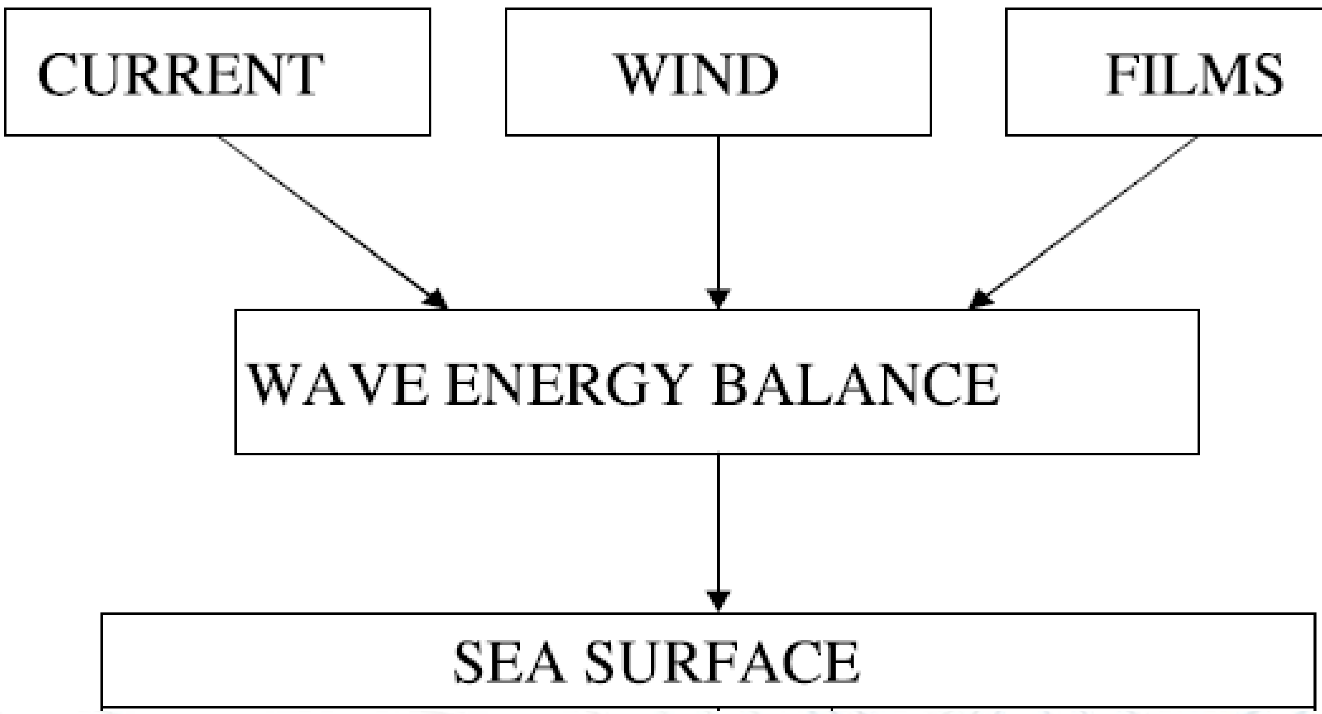
2. utilizing improved wind waves description

Yurovskaya et al., J. GEOPH. RES., 118, 1-15, doi:10.1002/jgrc.20296, 2013



Sea Surface Roughness changes: interpretation framework

$$\frac{\partial N(\mathbf{k})}{\partial t} + \left(c_{gi} + u_i\right)\frac{\partial N(\mathbf{k})}{\partial x_i} - k_j \frac{\partial u_j}{\partial x_i}\frac{\partial N(\mathbf{k})}{\partial k_i} = Q(\mathbf{k})/\omega \qquad Q(\mathbf{k}) = \beta_\nu(\mathbf{k})\omega E(\mathbf{k}) - D(\mathbf{k}) - Q^{nl}(\mathbf{k}) + Q^{wb}(\mathbf{k})$$

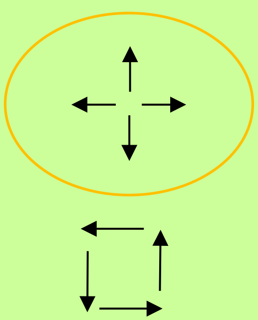


$$\partial \tilde{N}(\mathbf{k})/\partial t + c_{gi}\partial \tilde{N}(\mathbf{k})/\partial x_i = \omega^2 k^{-5}\left[\omega^{-1} m_k^{ij} u_{i,j} B_0 - \tilde{B}/\tau + \tilde{\beta} B_0 + \tilde{I}_{sw}\right]$$

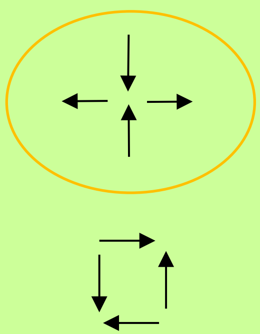
$$m_k^{ij} = k_j \partial \ \ln \ N_0/\partial k_i$$

Only 2 over 4 types of current deformations will sign on the roughness image.

$$\begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} D+S_t & -R+S_h \\ R+S_h & D-S_t \end{bmatrix}$$

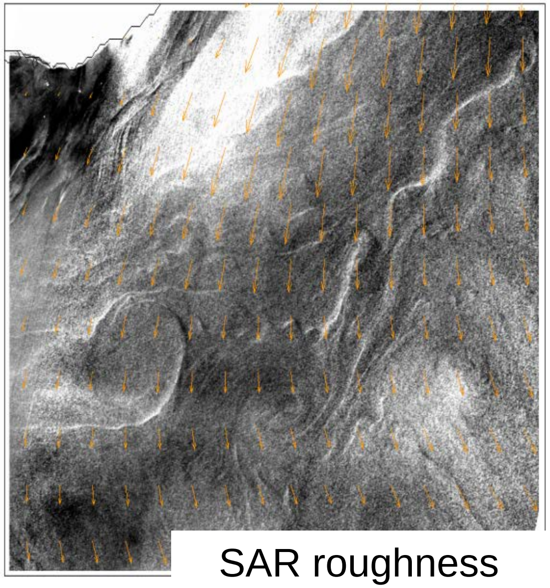


$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \quad S_t = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y},$$
$$R = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad S_h = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}.$$



Which type of currents will sign?

- rotational currents
- **divergent currents**
- shear in the wind direction
- **strain in the wind direction**



SAR roughness

- Divergent currents appear independently of the wind direction
- Non divergent currents appear with a 45°-sensitivity to the wind/current angle.

Ocean surface radio-physics

- Numerous sensors
  - Passive/Active measurements, mono and-bi-static (L, C, Ku, Ka)
  - Incidence angles (active, passive)
  - Polarization sensistivity (active, passive)
  - Doppler information (active)
- Framework interpretation
  - Asymptotic EM models (deep-phase, small-eleevation and/or slope approximations, …
  - Empirical models

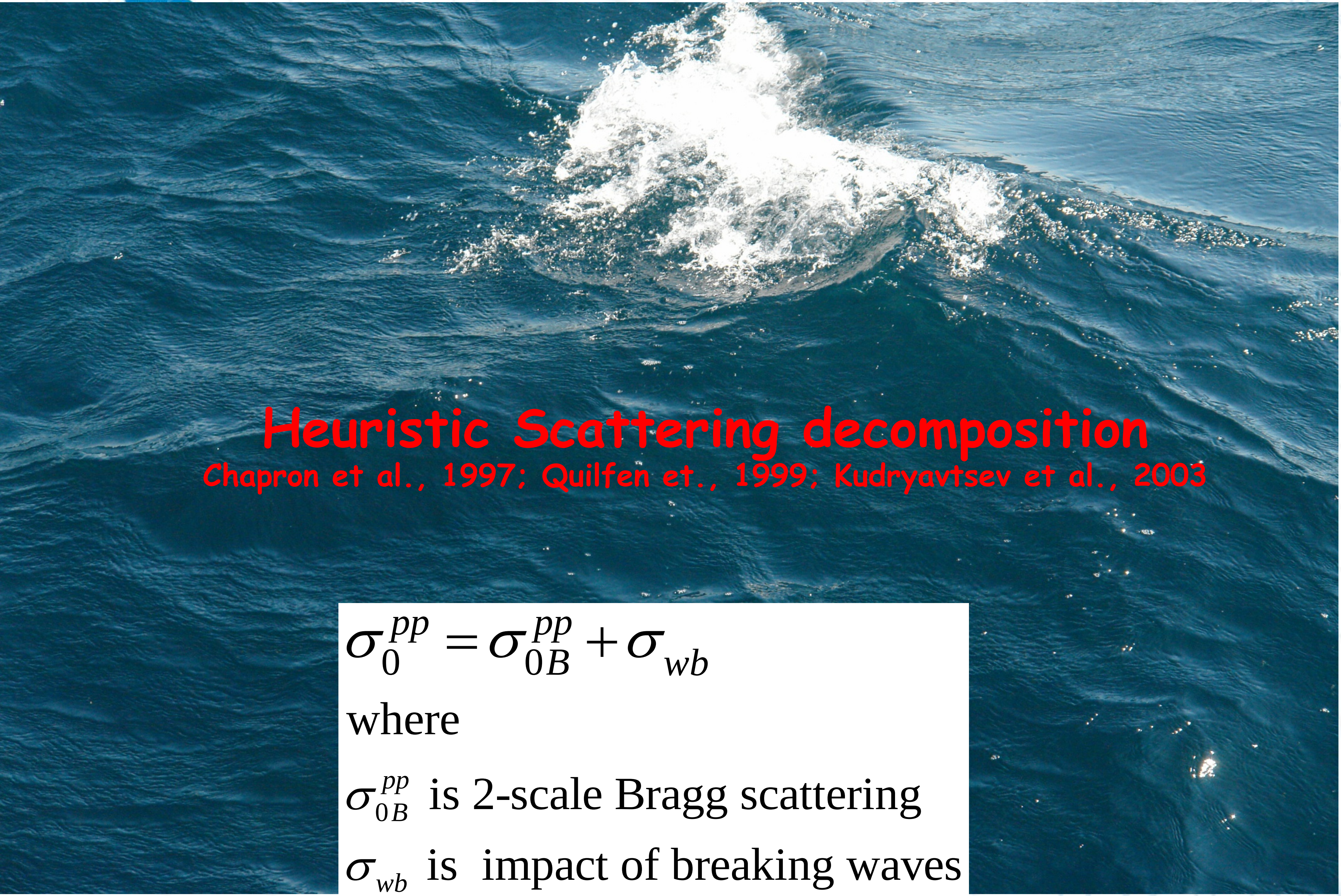
Active measurements

Practical implementation (Mouche et al., 2008)

- Extended-Kirchhoff asymptotic solution (time-varying surface)

$$\mathbb{S}(\boldsymbol{k}, \boldsymbol{k}_0) = \mathbb{N}_0(\boldsymbol{k}, \boldsymbol{k}_0) \int_{\boldsymbol{r}} e^{-iQ_z \Phi(\boldsymbol{k}, \boldsymbol{k}_0; \eta(\boldsymbol{r}, t))} e^{-i\boldsymbol{Q}_H \cdot \boldsymbol{r}} d\boldsymbol{r}$$

- « Effective » time-varying surface, polarization dependent
- Larger Doppler for horizontal polarization measurements
- Larger Upwind-downwind Doppler signatures



Heuristic Scattering decomposition

Chapron et al., 1997; Quilfen et., 1999; Kudryavtsev et al., 2003

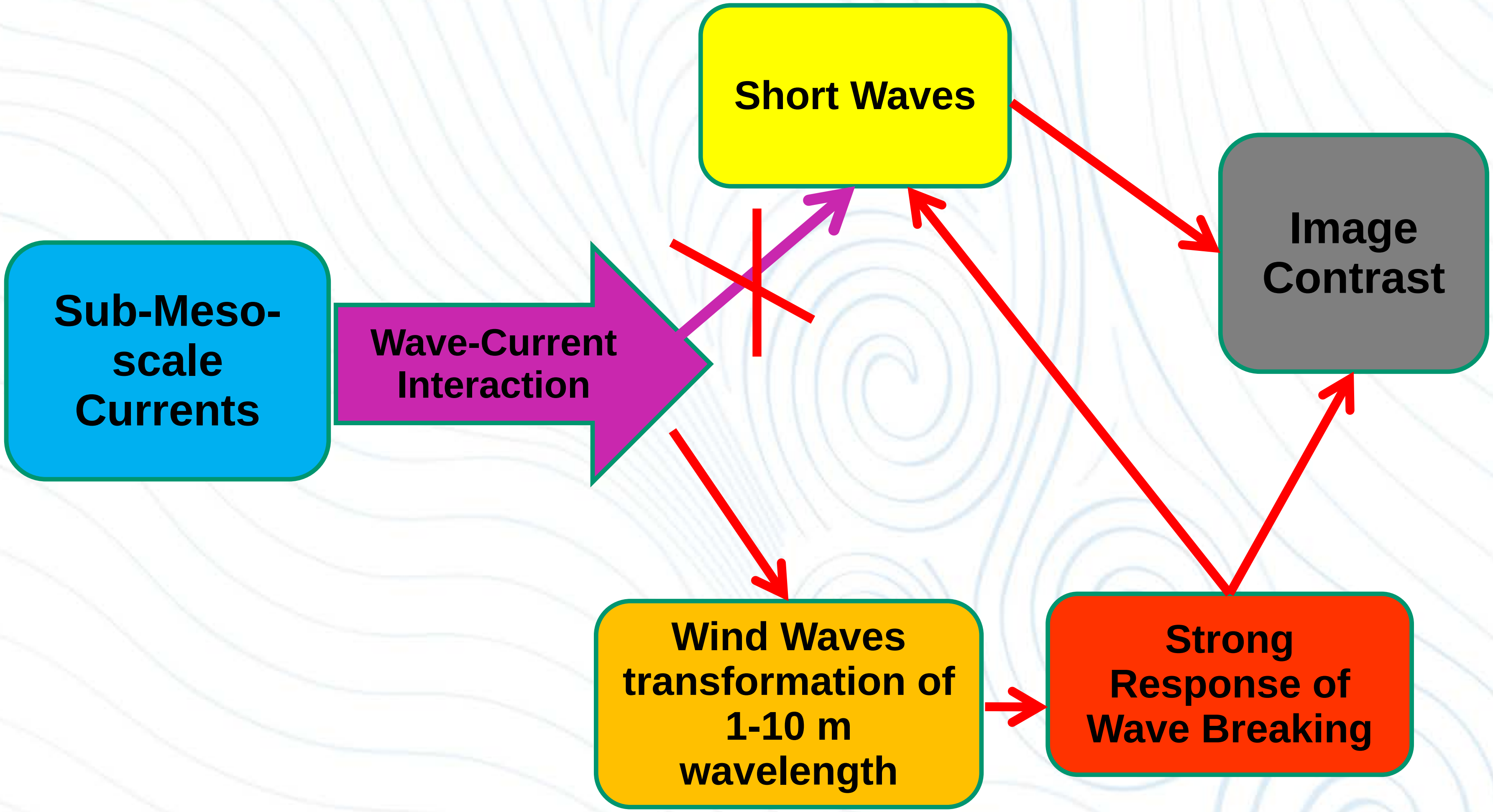
$$\sigma_0^{pp} = \sigma_{0B}^{pp} + \sigma_{wb}$$

where

σ_{0B}^{pp} is 2-scale Bragg scattering

σ_{wb} is impact of breaking waves

Radar and Optical Imaging Model (RIM and OIM)
Kudryavtsev et al., 2005; Johannessen et al., 2005, Kudryavtsev et al., 2012



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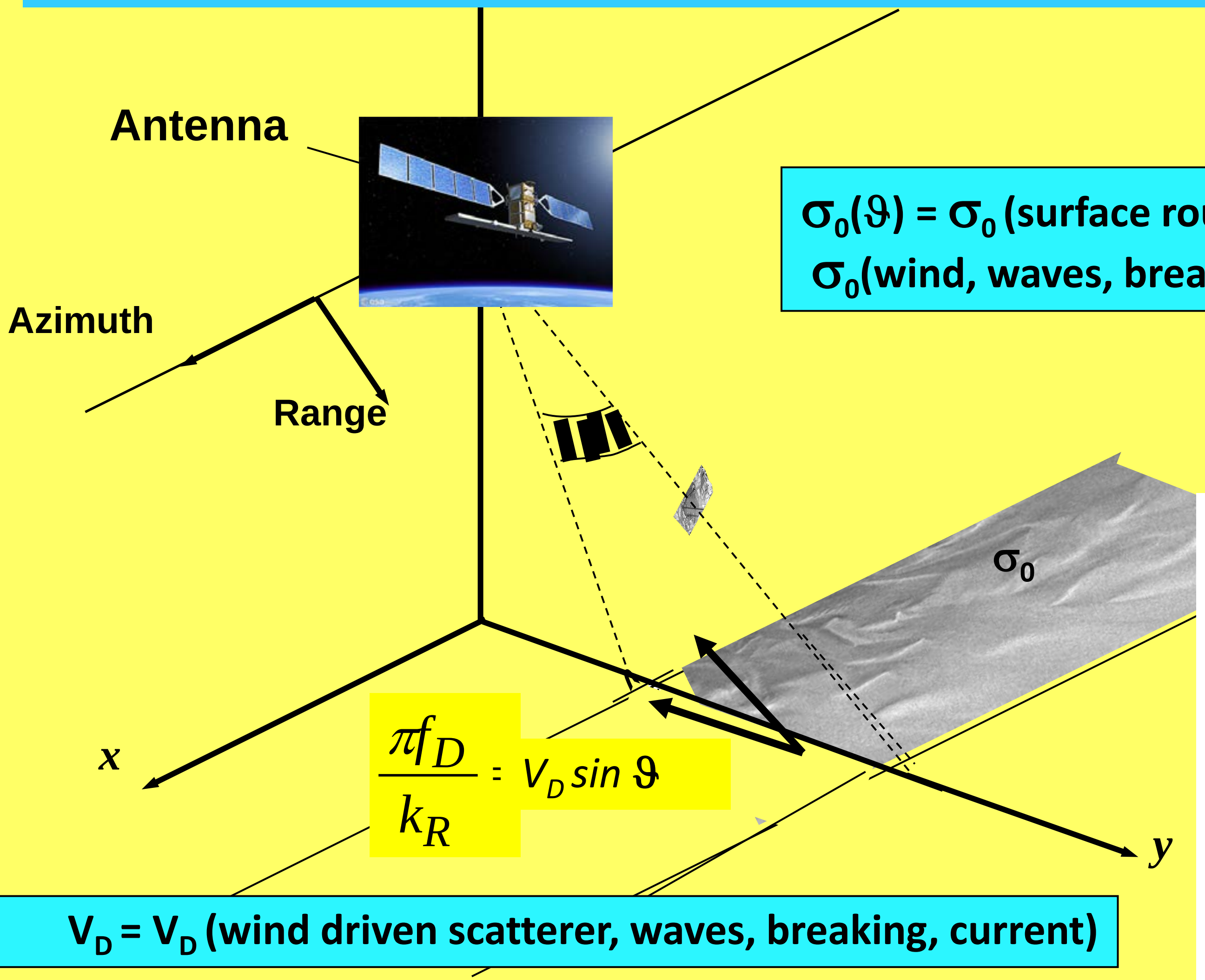
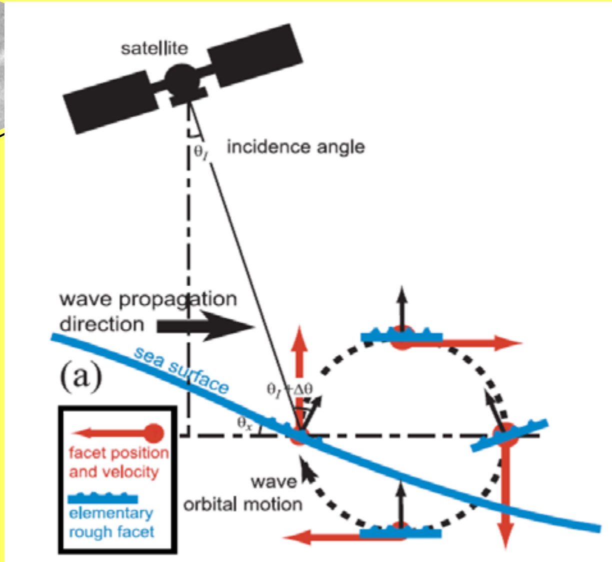
APPROACH: Combined Roughness and Doppler Shift



$\sigma_0(\vartheta) = \sigma_0$ (surface roughness) =
σ_0(wind, waves, breaking, current

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



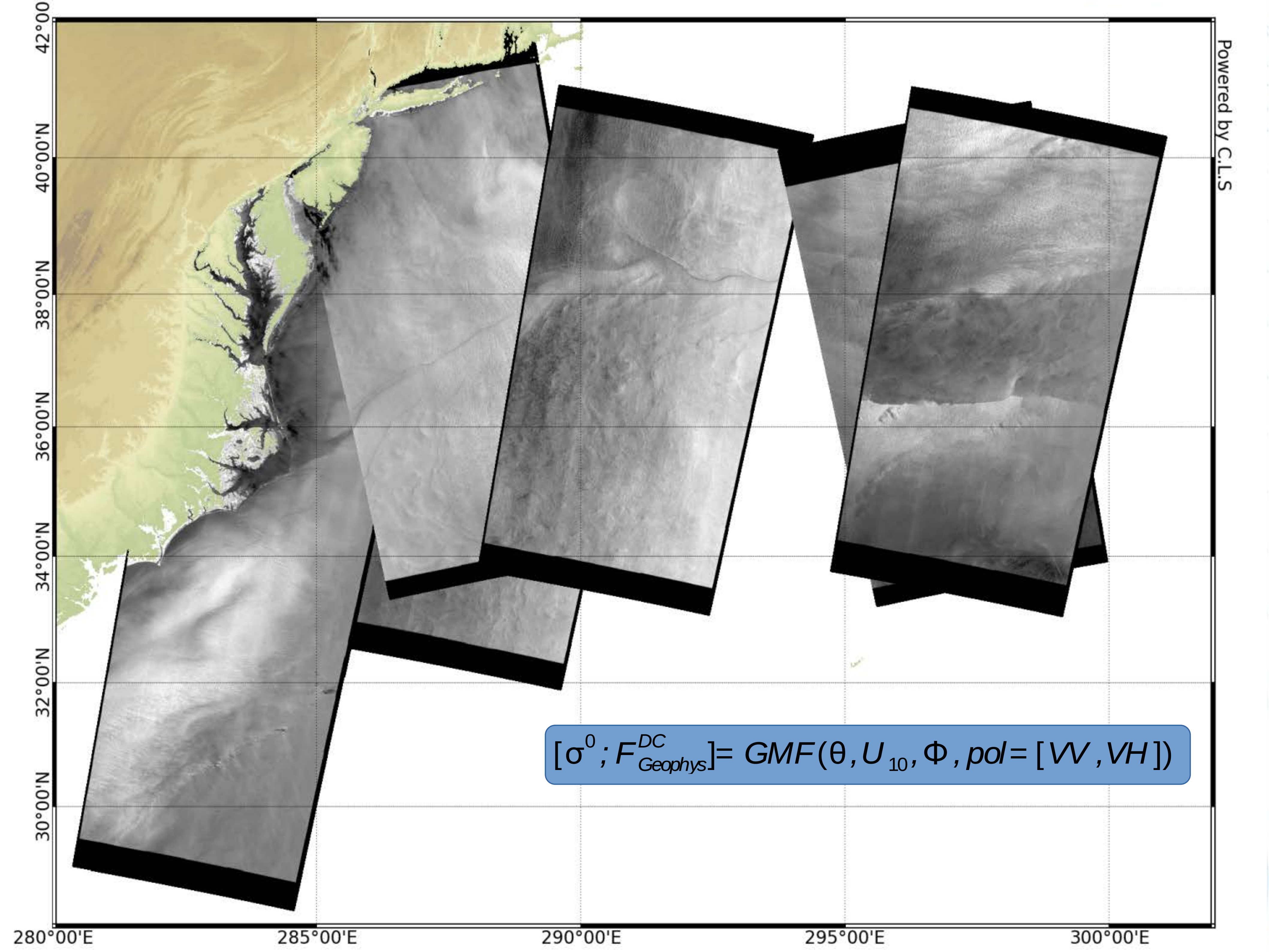
$V_D = V_D$ (wind driven scatterer, waves, breaking, current)

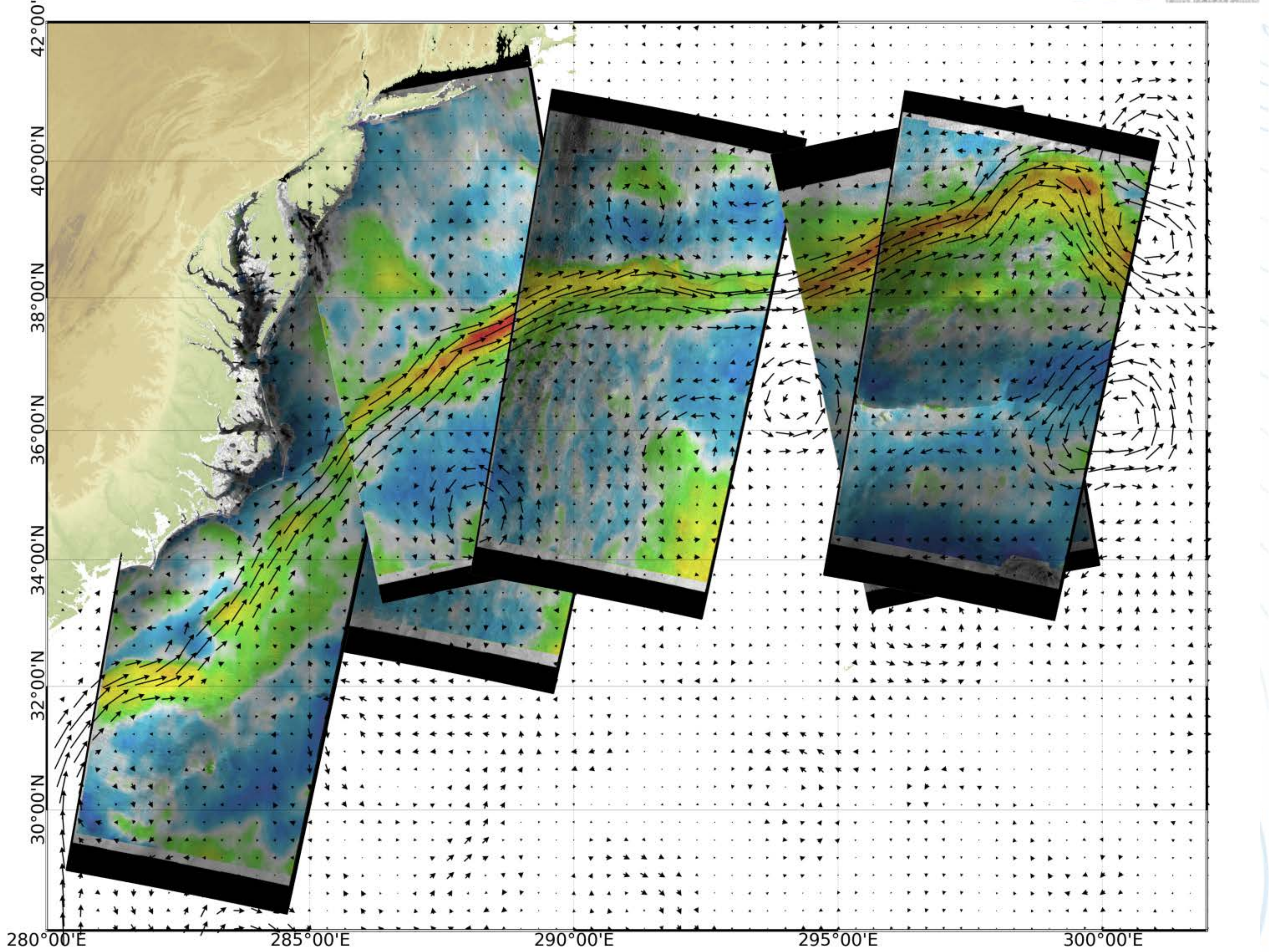
- RS-2 demonstrate the added values of cross-polarization NRCS for
  - ocean studies
  - Ultra high wind TC mapping capabilities

- ASAR Doppler analysis demonstrated the added values of Doppler in co-polarization for ocean surface velocities measurements. This opened opportunities for
  - Ocean surface velocity high resolution mapping
  - Wind direction retrieval
  - Other high resolution atmospheric phenomena (e.g. rain cell)

- Sentinel-1 A (S-1 B now) with C-band NRCS and Doppler measurement capabilities in both co- and cross-polarization.

- Next ESA/EUMETSAT scatterometer will have both VV and VH NRCS (but now Doppler capability)


42°00'N
40°00'N
38°00'N
36°00'N
34°00'N
32°00'N
30°00'N
280°00'E
285°00'E
290°00'E
295°00'E
300°00'E
Powered by C.L.S
$[\sigma^0; F^{DC}_{Geophys}] = GMF(\theta, U_{10}, \Phi, pol=[VV, VH])$



42°00'N
40°00'N
38°00'N
36°00'N
34°00'N
32°00'N
30°00'N
280°00'E
285°00'E
290°00'E
295°00'E
300°00'E

- C-Band SAR capabilities are still under-exploited for geophysical parameters retrieval:
  - Doppler and NRCS are not used together in a unique wind/current algorithm
  - Co- and cross-polarizations are not used together as well operationally

- The potential of co-location between SCAT and SAR is under-exploited

- Combined analysis of Doppler and NRCS from SAR can help to
  - Improve existing SAR algorithms
  - Prepare next EPS-SG scatterometers
  - Propose new concepts (e.g. for ocean surface current measurement)
  - Derive new geophysical parameters

C-band Polarization diversity and Ocean processes

- Case studies to reveal the potential of polarization combination to separate different processes at ocean surface.

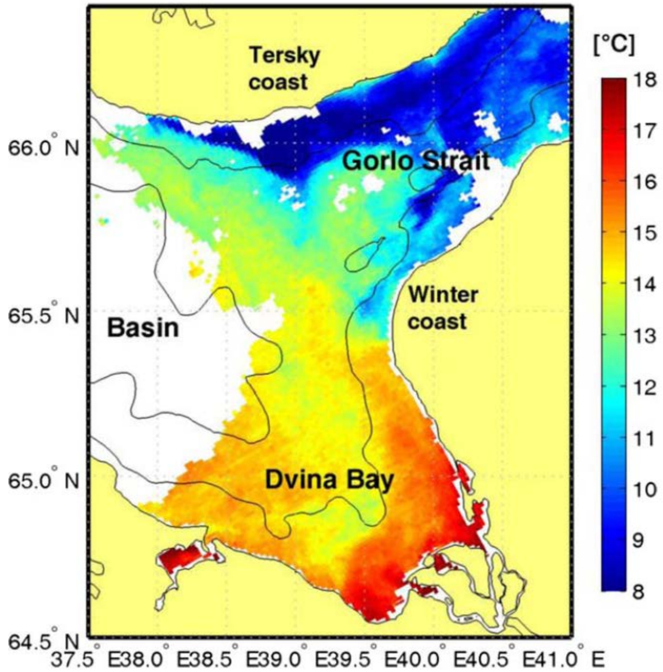


Figure 1. Map of the eastern White Sea with MODIS Aqua SST (28 July 2012 at 09:05 UTC) and overlain bathymetry contours at 50 m intervals. Bathymetry map is obtained from IBCAO Grid version 3.0 [Jakobsson et al., 2012].

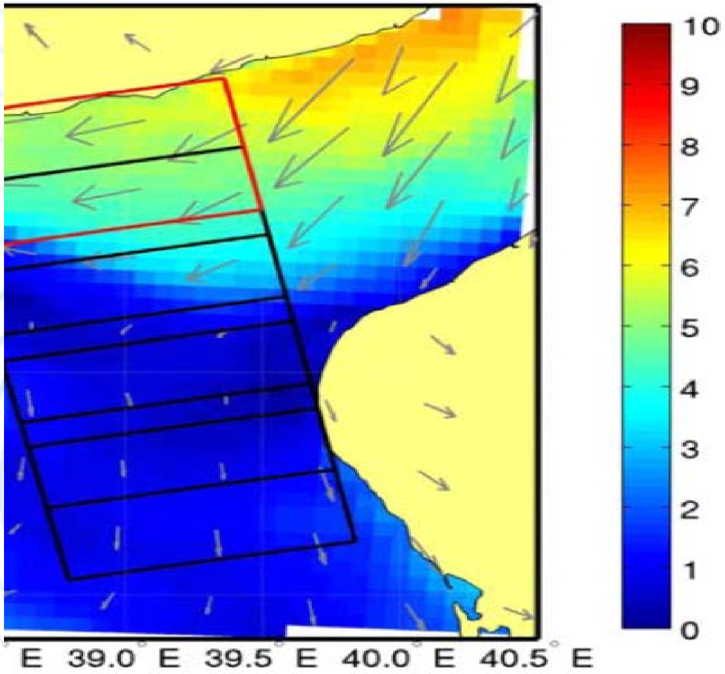
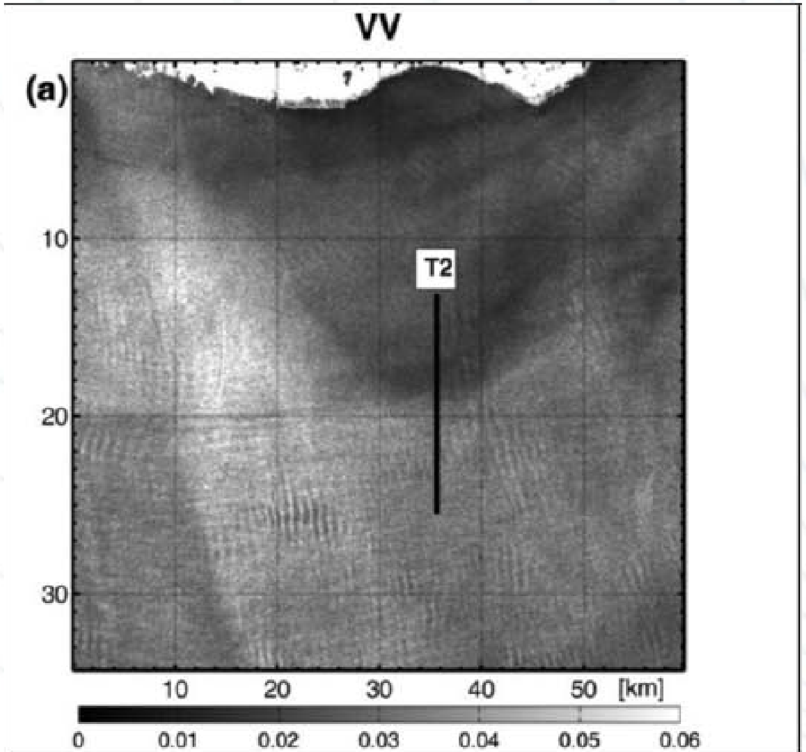
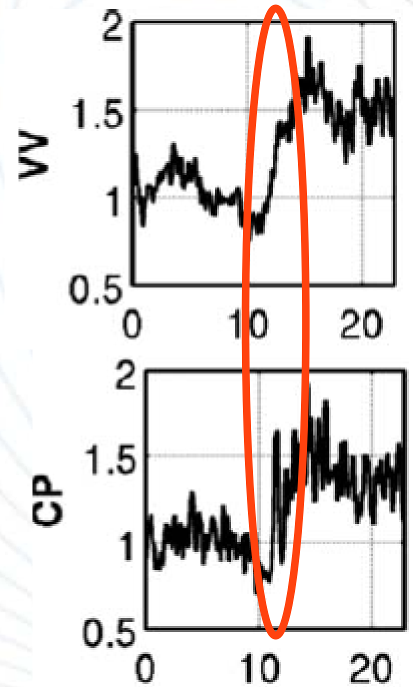


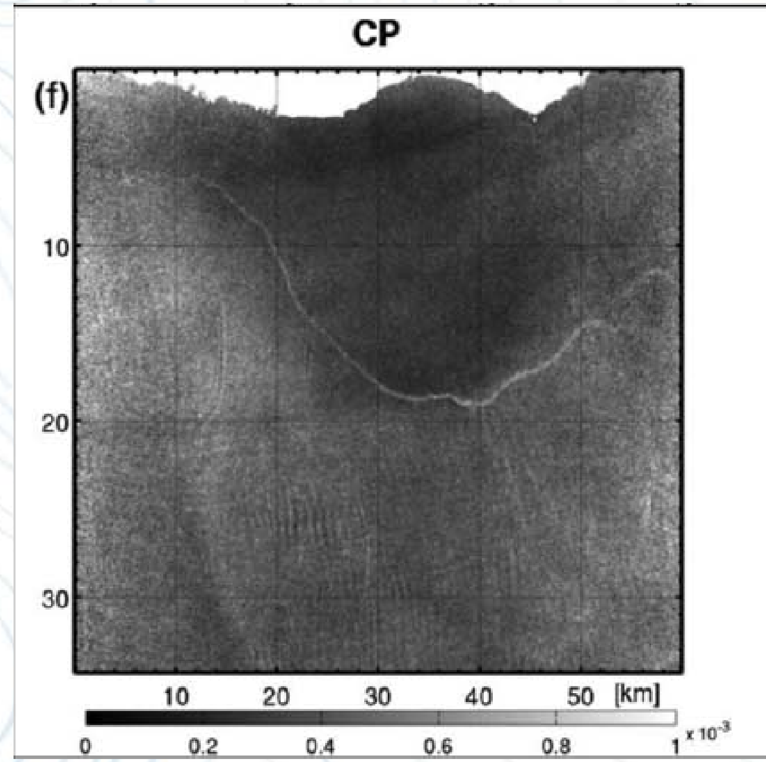
Figure 2. Wind velocity at 10 m height in the northwestern White Sea from MM5 model on 1 August 2012 with RADARSAT-2 SAR frame swaths overlain. SAR frame marked by red are considered in the present study.

Kudryavtsev, V., I. Kozlov, B. Chapron, and J. A. Johannessen (2014), Quadpolarization SAR features of ocean currents, J. Geophys. Res. Oceans, 119, 6046–6065, doi:10.1002/2014JC010173.

C-band Polarization diversity and Ocean processes





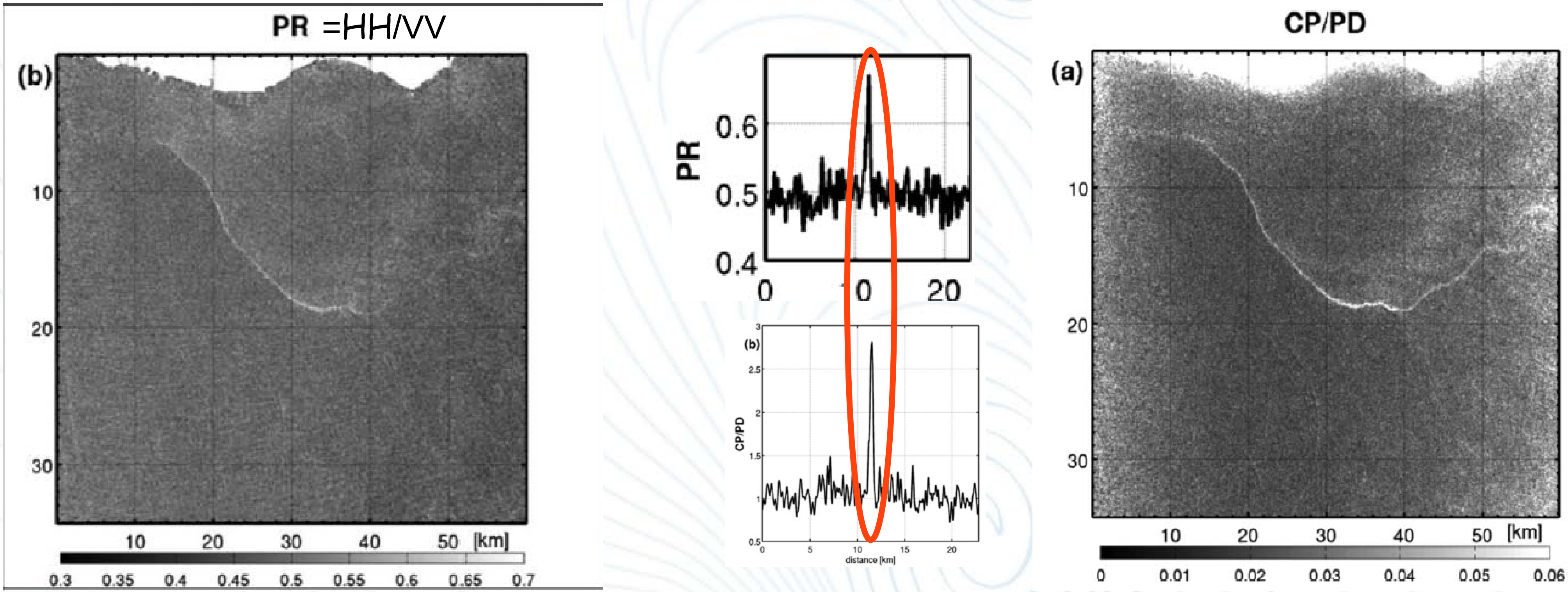


VV is more sensitive to the wind stress change due to modification of the stratification conditions (short scale adjustment) over the oceanic front than to the front (intermediate scale modification)

CP is equally sensitive to the wind stress change due to modification of the stratification conditions (short scale adjustment) over the oceanic front and to the front (intermediate scale modification)

Kudryavtsev, V., I. Kozlov, B. Chapron, and J. A. Johannessen (2014), Quadpolarization SAR features of ocean currents, J. Geophys. Res. Oceans, 119, 6046–6065, doi:10.1002/2014JC010173.

C-band Polarization diversity and Ocean processes



PR is more sensitive to oceanic front (intermediate scale) than to the wind stress change due to modification of the stratification conditions (short scale adjustment)

CP/PD is more sensitive to oceanic front (intermediate scale) than to the wind stress change due to modification of the stratification conditions (short scale adjustment)

Kudryavtsev, V., I. Kozlov, B. Chapron, and J. A. Johannessen (2014), Quadpolarization SAR features of ocean currents, J. Geophys. Res. Oceans, 119, 6046–6065, doi:10.1002/2014JC010173.

Polarization diversity: main simple idea

VV and HH polarized images to be combined to separate different surface properties:

-Polarizing short wind waves ~ 5 cm

-Non-polarized contribution (steep scatters and wave breaking)

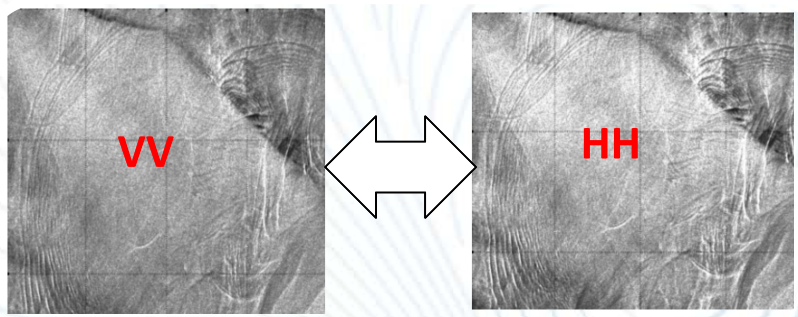
Polarization Difference, PD, short Bragg waves :

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

NP contribution from breaking waves :

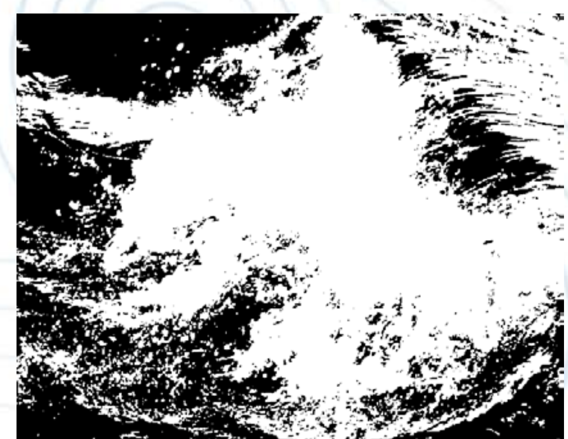
$$\sigma_{wb} = \sigma_0^{vv} - \Delta\sigma_0 / (1 - p_B)$$

where $p_B = \sigma_{0B}^{hh} / \sigma_{0B}^{vv}$ is PR for Bragg scattering

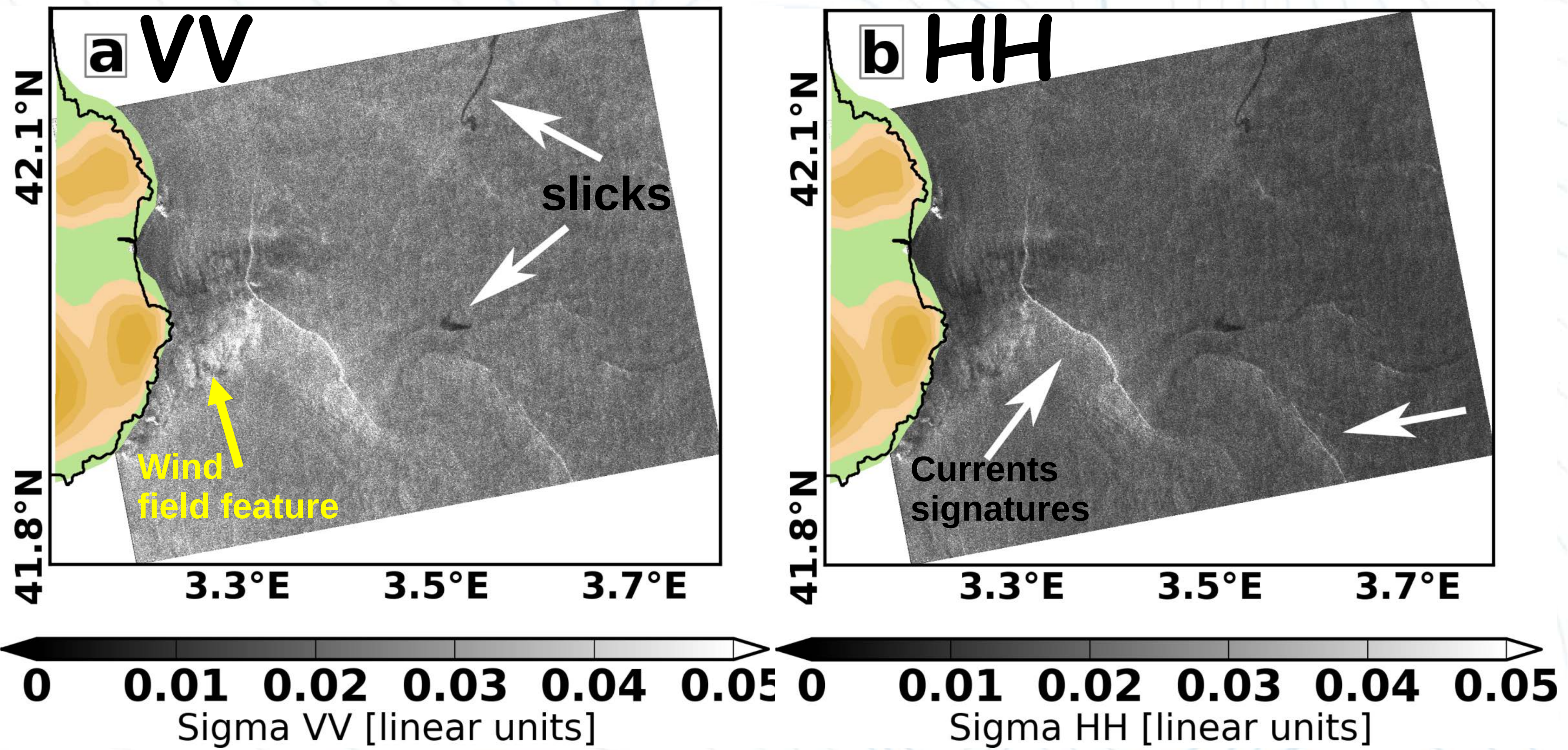


Polarized scattering
Short wind waves

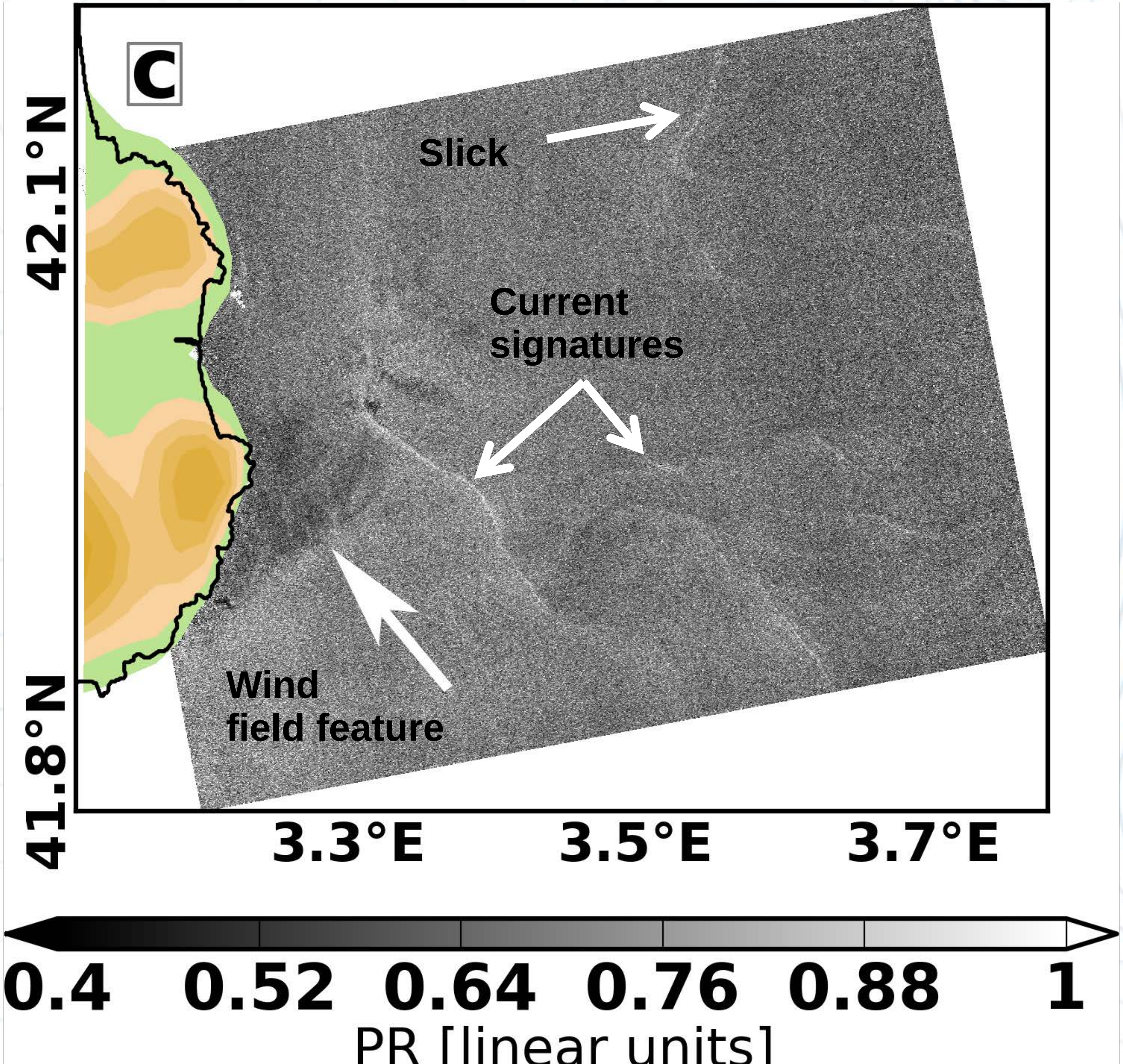
Non-polarized scattering
Wave breaking



Original VV and HH RS-2 SAR images



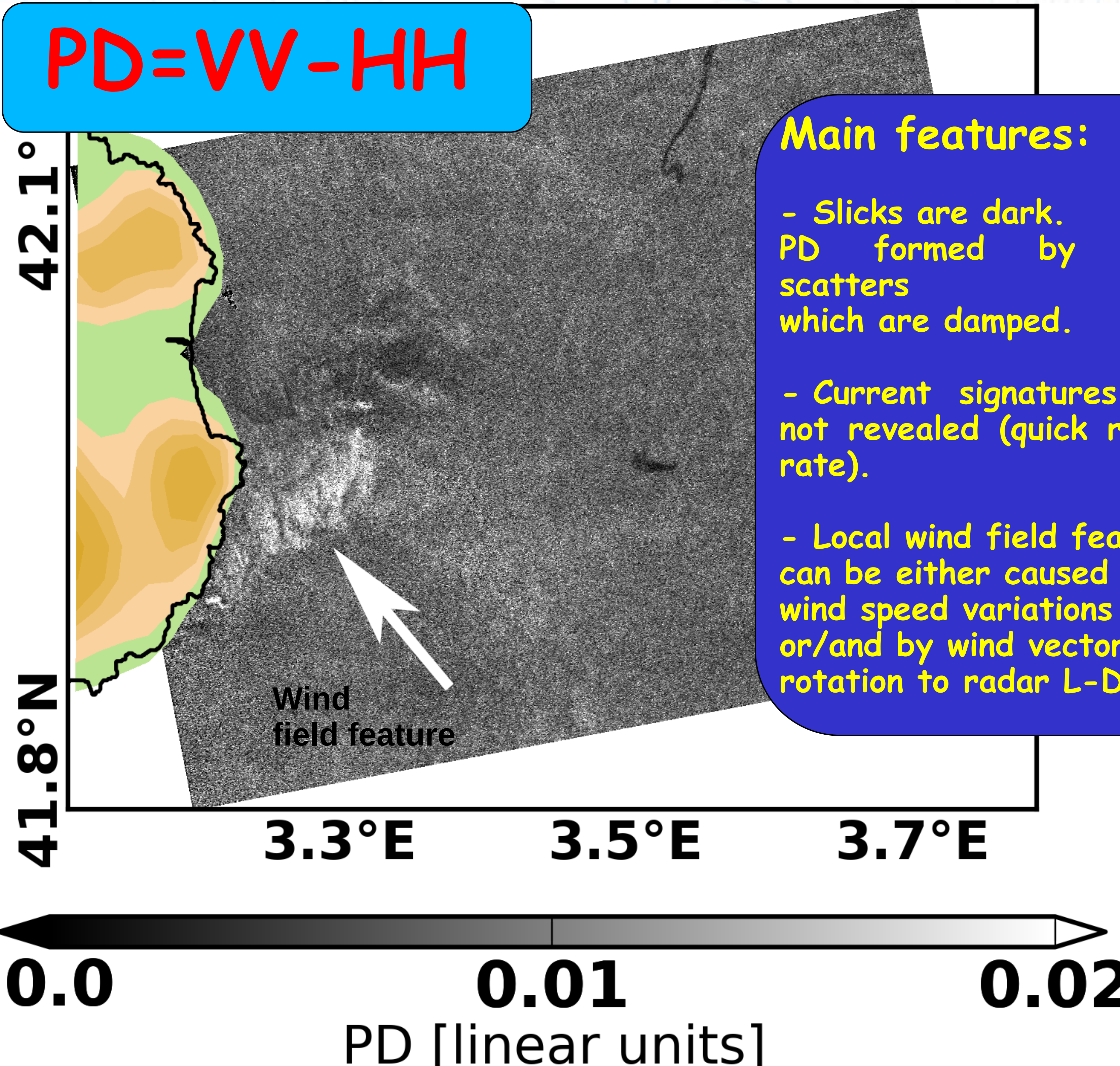
Polarization Ratio PR = HH/VV



The mean PR is - 1.5 dB … - 2 dB except coastal area, PR= - 2.5 dB close to a standard 2-scale Bragg model predictions.

PR attains PR=1 "bright" current signatures.

PD=VV-HH

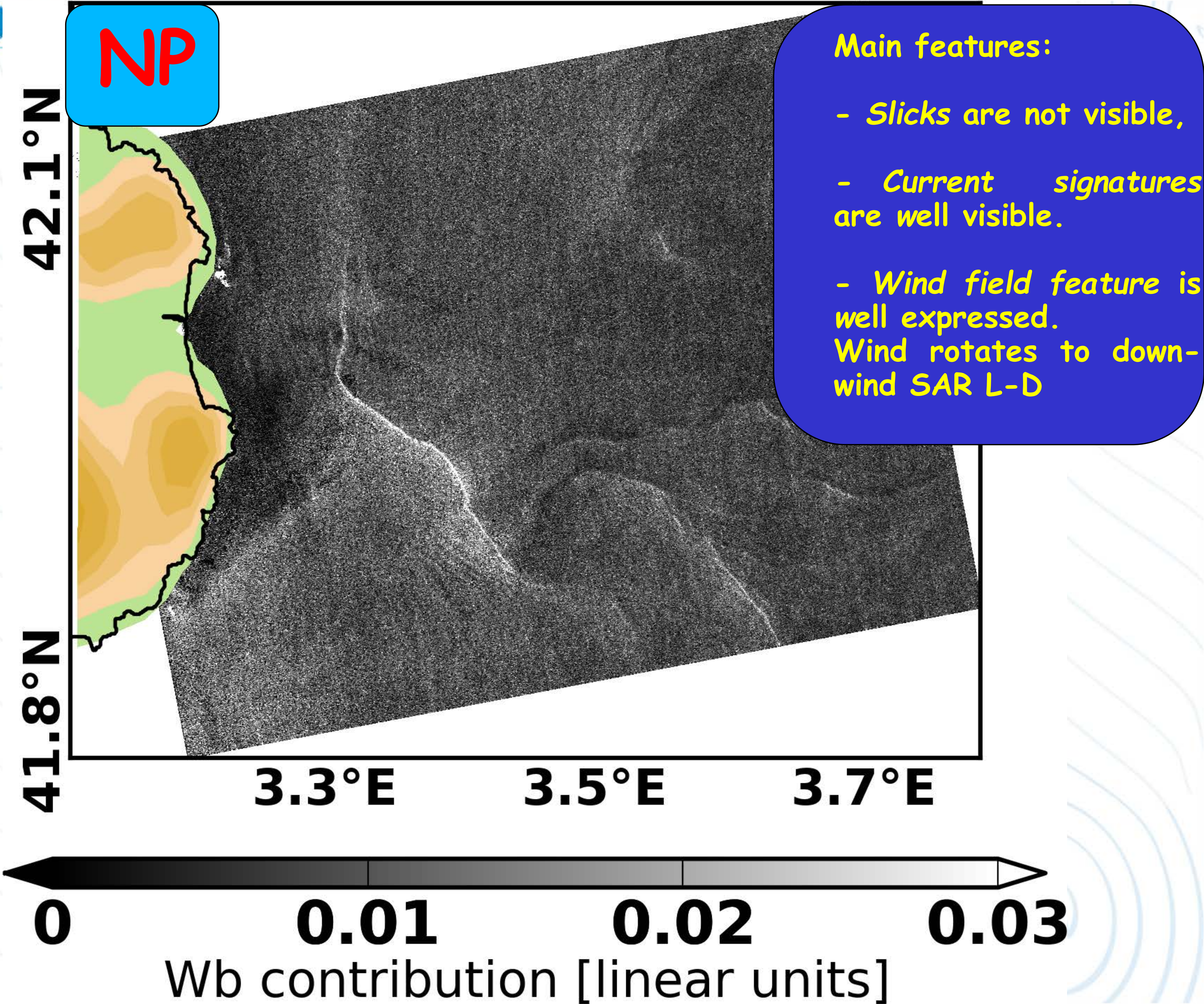


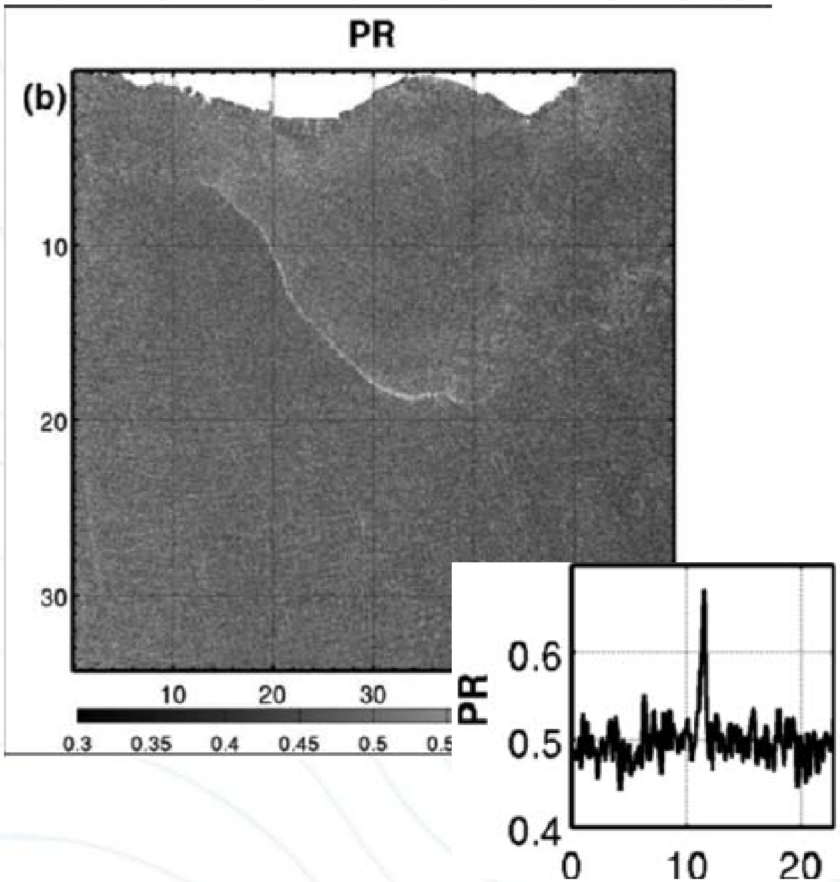
Main features:

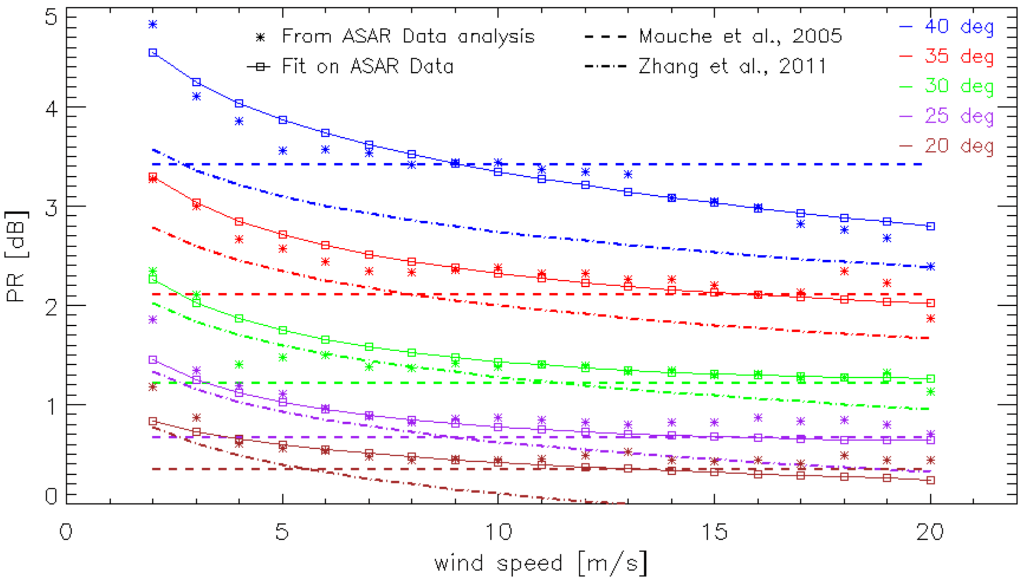
- Slicks are dark.
PD formed by resonant scatters which are damped.

- Current signatures are not revealed (quick relaxation rate).

- Local wind field features can be either caused by wind speed variations or/and by wind vector rotation to radar L-D.


NP
Main features:
- Slicks are not visible,
- Current signatures are well visible.
- Wind field feature is well expressed.
Wind rotates to down-wind SAR L-D
42.1°N
41.8°N
3.3°E
3.5°E
3.7°E
0
0.01
0.02
0.03
Wb contribution [linear units]





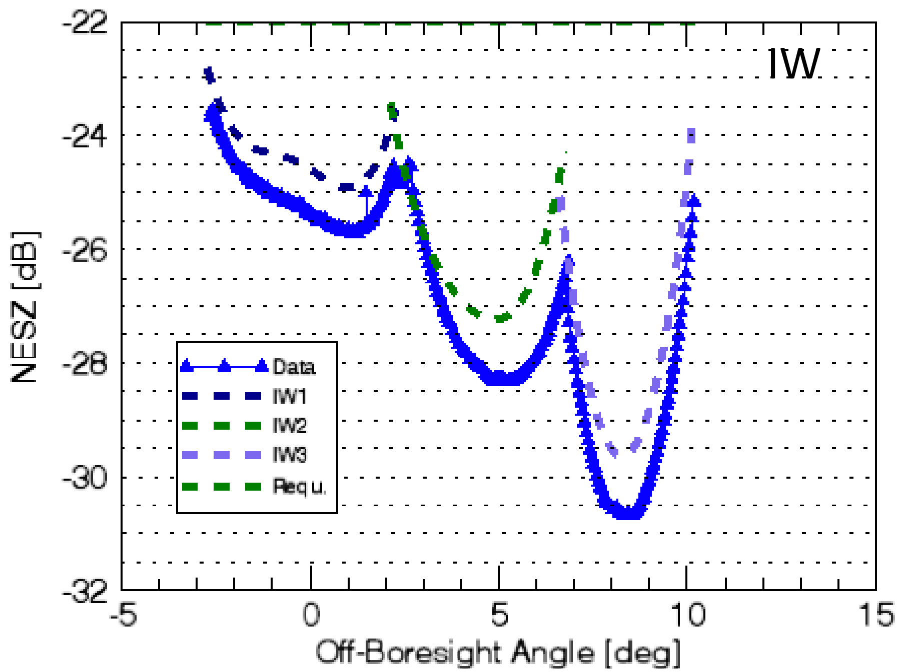
- Veryweak sensitivity to wind speed

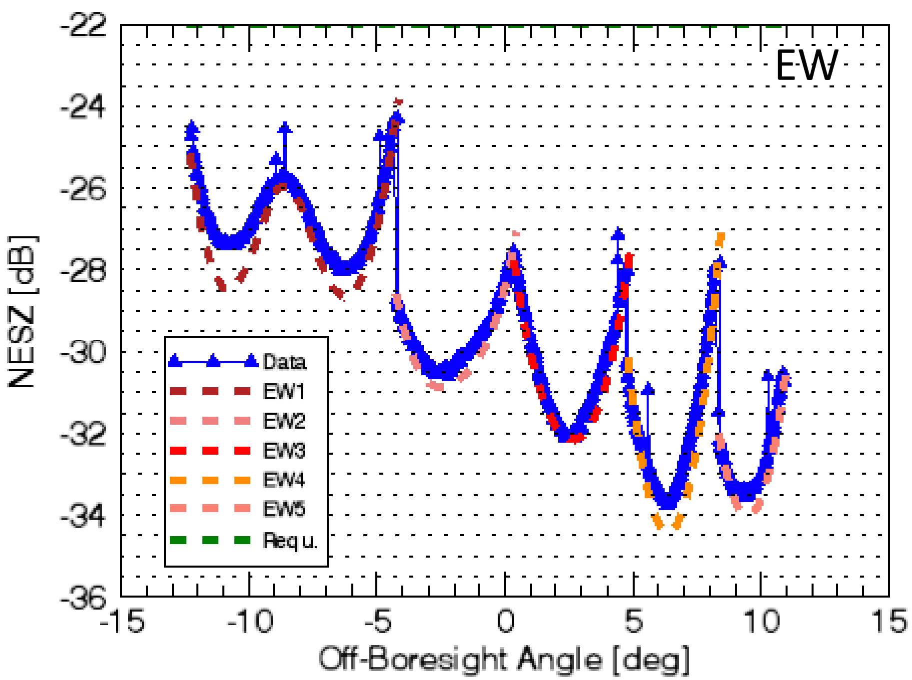
- At global scale a combination of NRCS in both VV and HH to get PR could filter out small scales variation due to wind and/or stability and more directly highlights intermediate scale effects (current)

Sentinel-1 A & cross-polarization

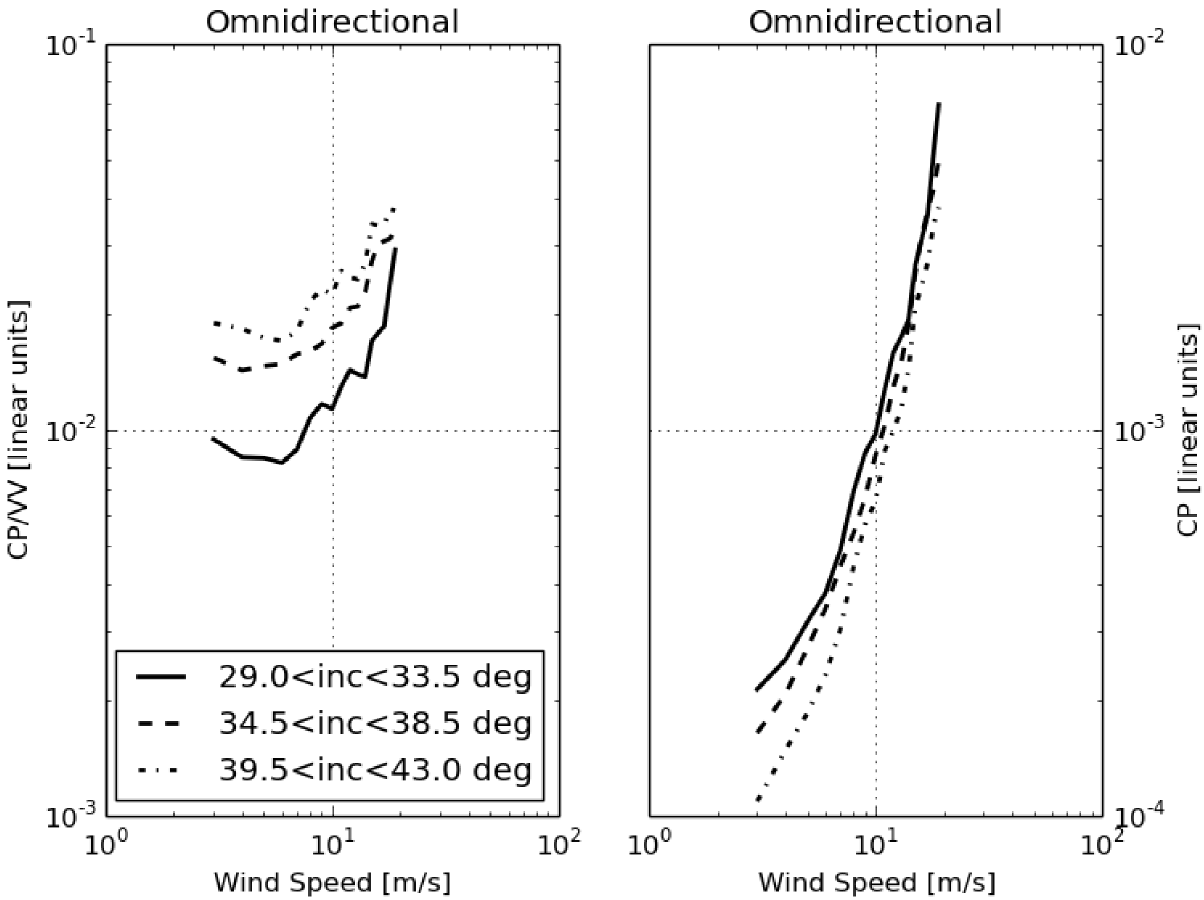
Sentinel-1 A & cross-polarization

- The signal is expected to be much lower than for co-polarization. Noise is the main limitation
- NESZ is measured over area of low backscatter (e.g. ocean under low wind speed) and compared with theoretical profiles (dashed line)
- Mission requirement is -22dB (- - -)
- NESZ is within the requirement and following very well the theoretical profile

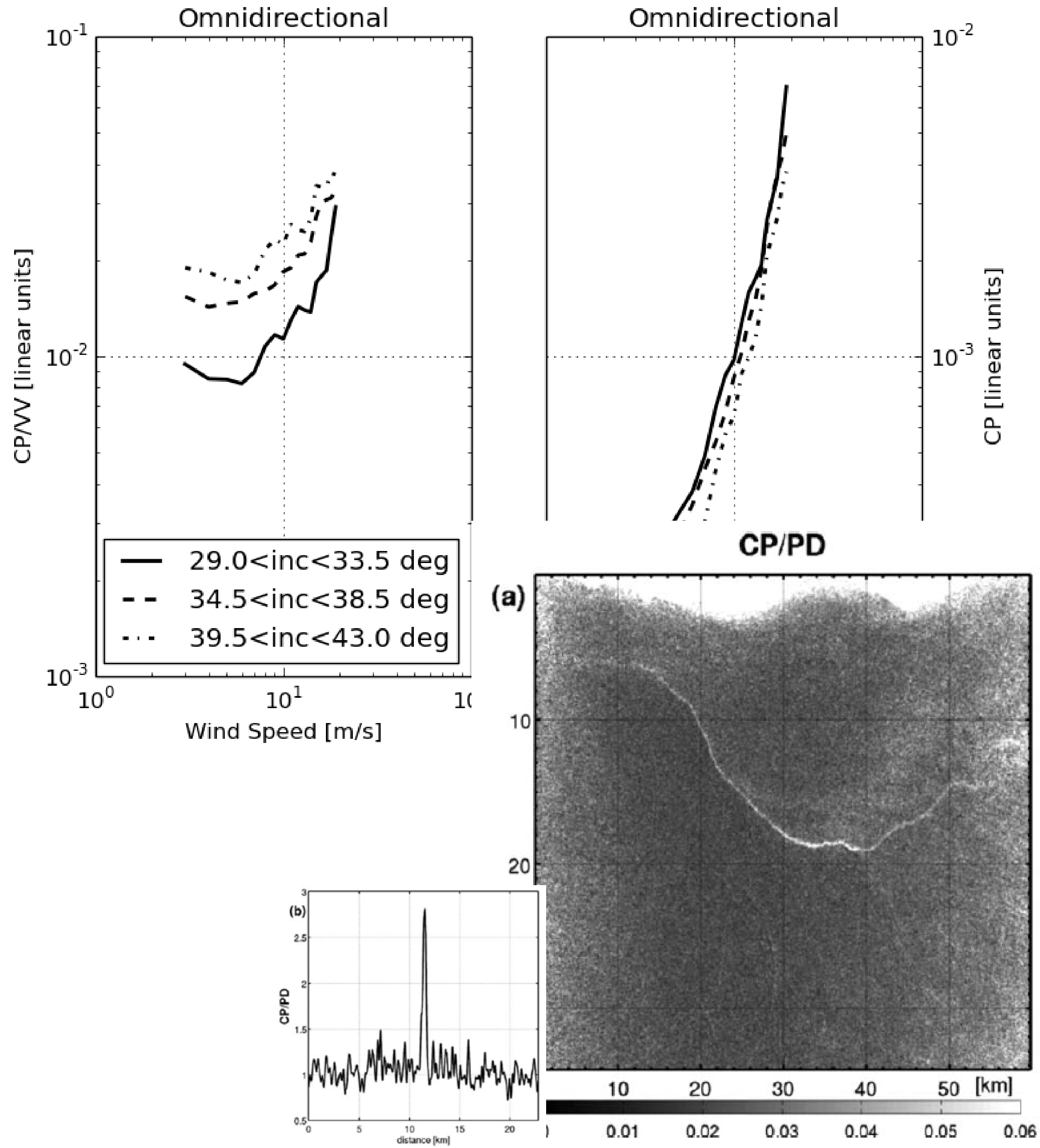




- Close co-variations between CP and co-pol under light to moderate wind conditions.
- Beyond 8-9 m/s, CP is then clearly found more responsive to wind speed change than PD.



- Close co-variations between CP and co-pol under light to moderate wind conditions.
- Beyond 8-9 m/s, CP is then clearly found more responsive to wind speed change than PD.
- Global analysis fully onsistent with the case studies, with a clear departure of CP/PD within the high wind speed regime (onset of wave breaking).



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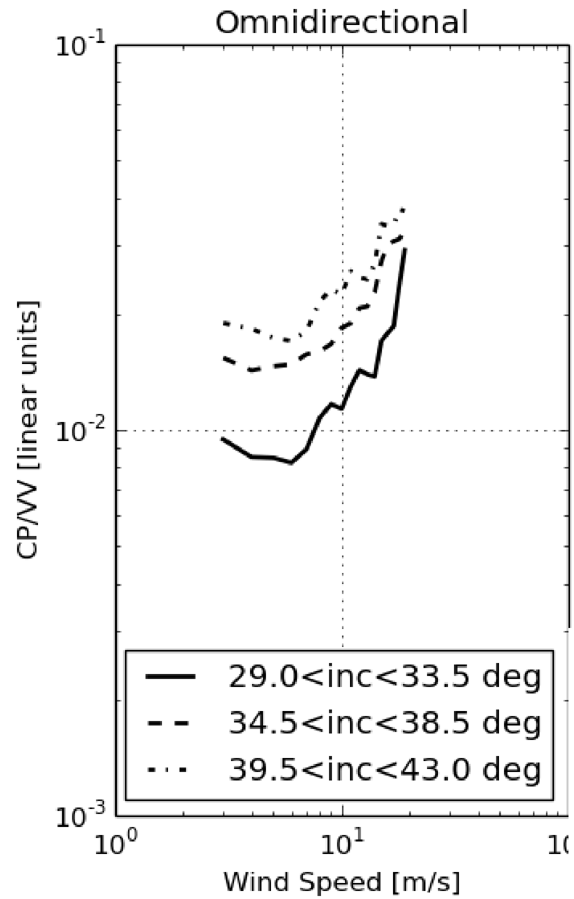
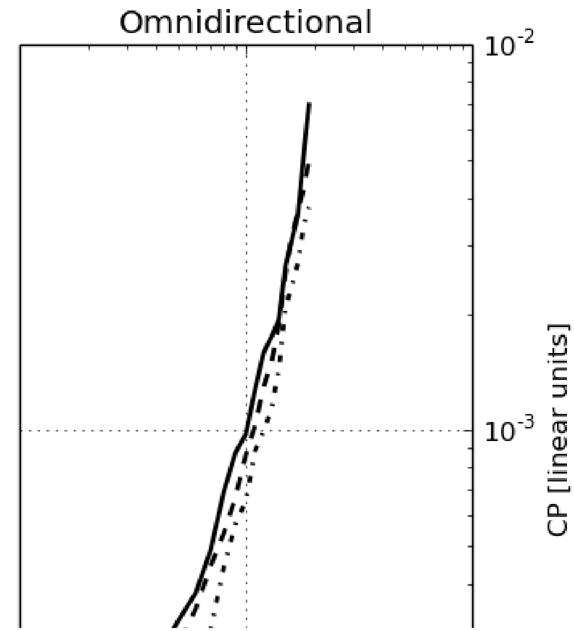
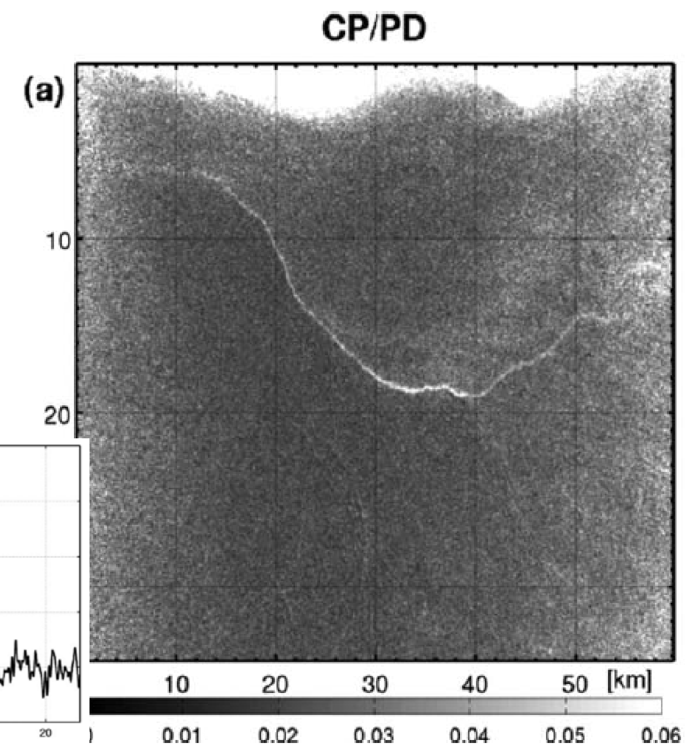
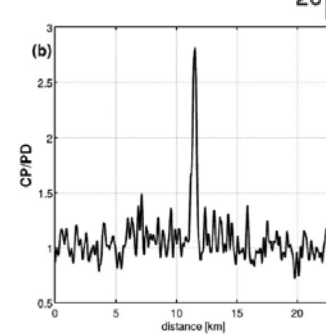






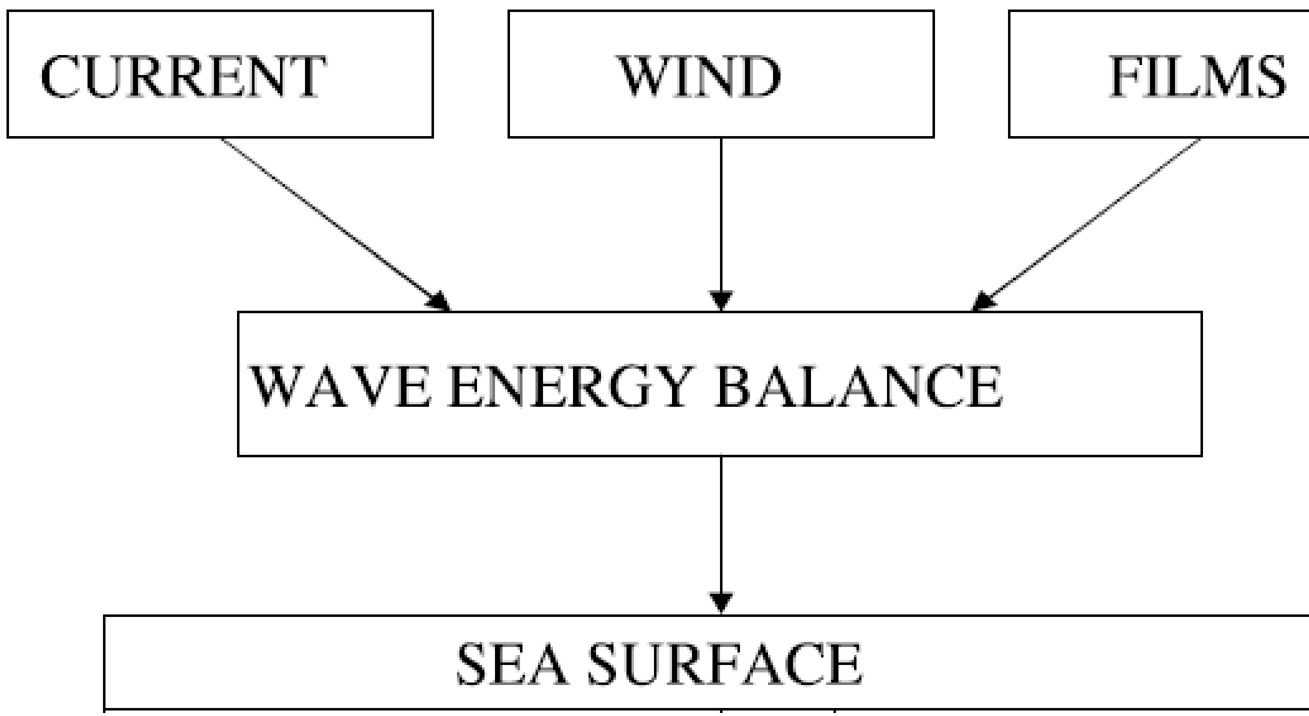


- At global scale with NRCS in both VV, HH and CP, we could imagine a combination of channel to filter out small scales variation due to wind and/or stability and exhibit intermediate scale effects (current)
- CP/VV could be an alternative for SCA or S-1

Conclusions & Discussions

Sea Surface Roughness changes: interpretation framework

$$\frac{\partial N(\mathbf{k})}{\partial t} + \left(c_{gi} + u_i\right)\frac{\partial N(\mathbf{k})}{\partial x_i} - k_j \frac{\partial u_j}{\partial x_i}\frac{\partial N(\mathbf{k})}{\partial k_i} = Q(\mathbf{k})/\omega \qquad Q(\mathbf{k}) = \beta_\nu(\mathbf{k})\omega E(\mathbf{k}) - D(\mathbf{k}) - Q^{nl}(\mathbf{k}) + Q^{wb}(\mathbf{k})$$



$$\partial\tilde{N}(\mathbf{k})/\partial t + c_{gi}\partial\tilde{N}(\mathbf{k})/\partial x_i = \omega^2 k^{-5}\left[\omega^{-1} m_k^{ij} u_{i,j} B_0 - \tilde{B}/\tau + \tilde{\beta} B_0 + \tilde{I}_{sw}\right]$$

$$m_k^{ij} = k_j \partial \ln \dot{N}_0/\partial k_i$$

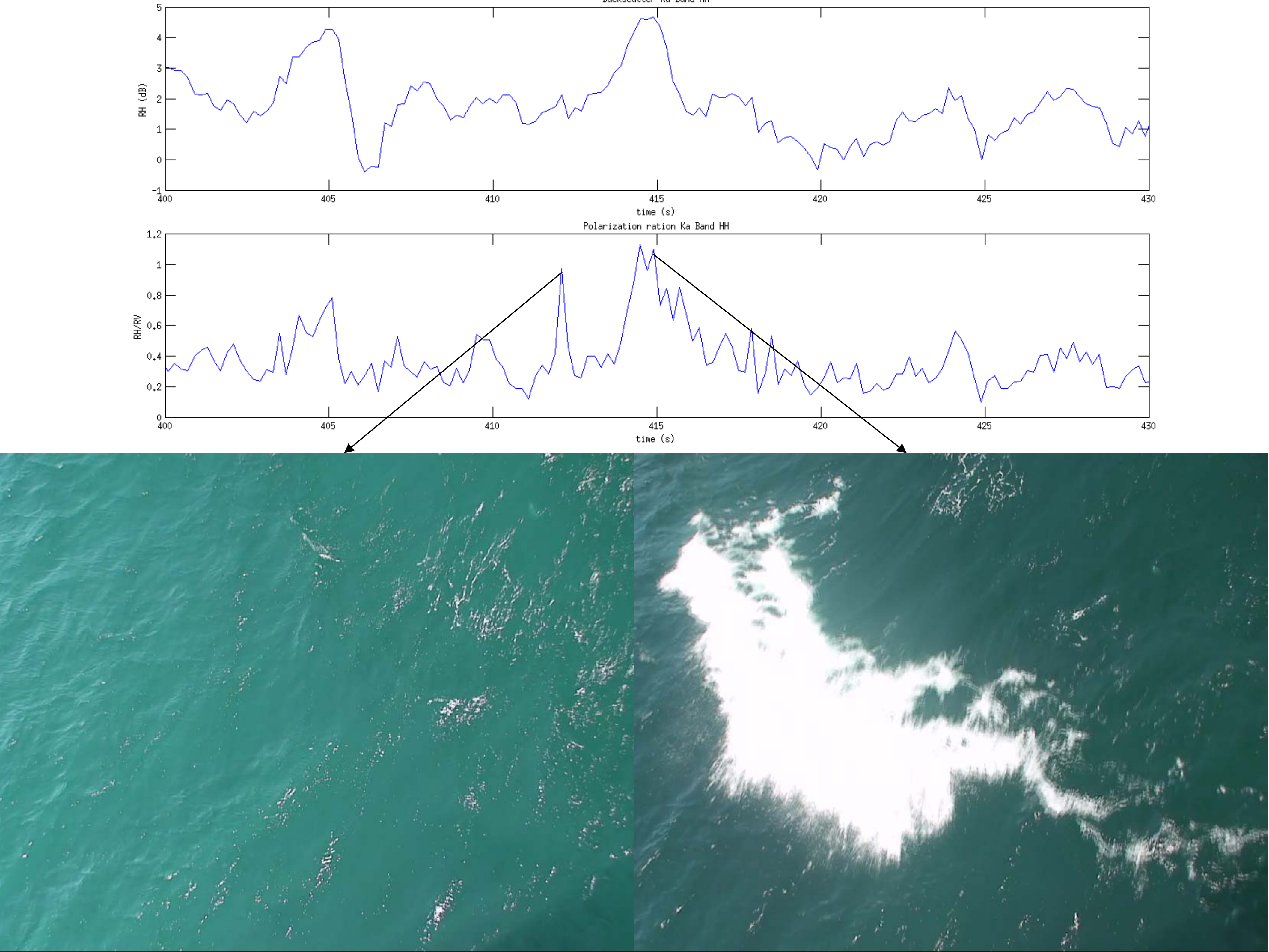
- From global and case studies, cross- and co-polarizations NRCS have complementary properties to offer means to quantitatively analyze the air-sea interface (e. g., momentum and gas fluxes, stability)

- Their combination can be considered to enhance/filter out geophysical processes (e.g. short scale surface current gradients, natural slicks), impacting small scale equilibrium:

  - CP/(VV-HH)
  - VV/HH

- The use of CP/VV could already be applied to Sentinel-1 A data (to further serve next ESA/EUMETSAT SCA).

- ------→ Imperative needs for in situ measurements



RH (dB)
time (s)
Polarization ration Ka Band HH
RH/RV
time (s)

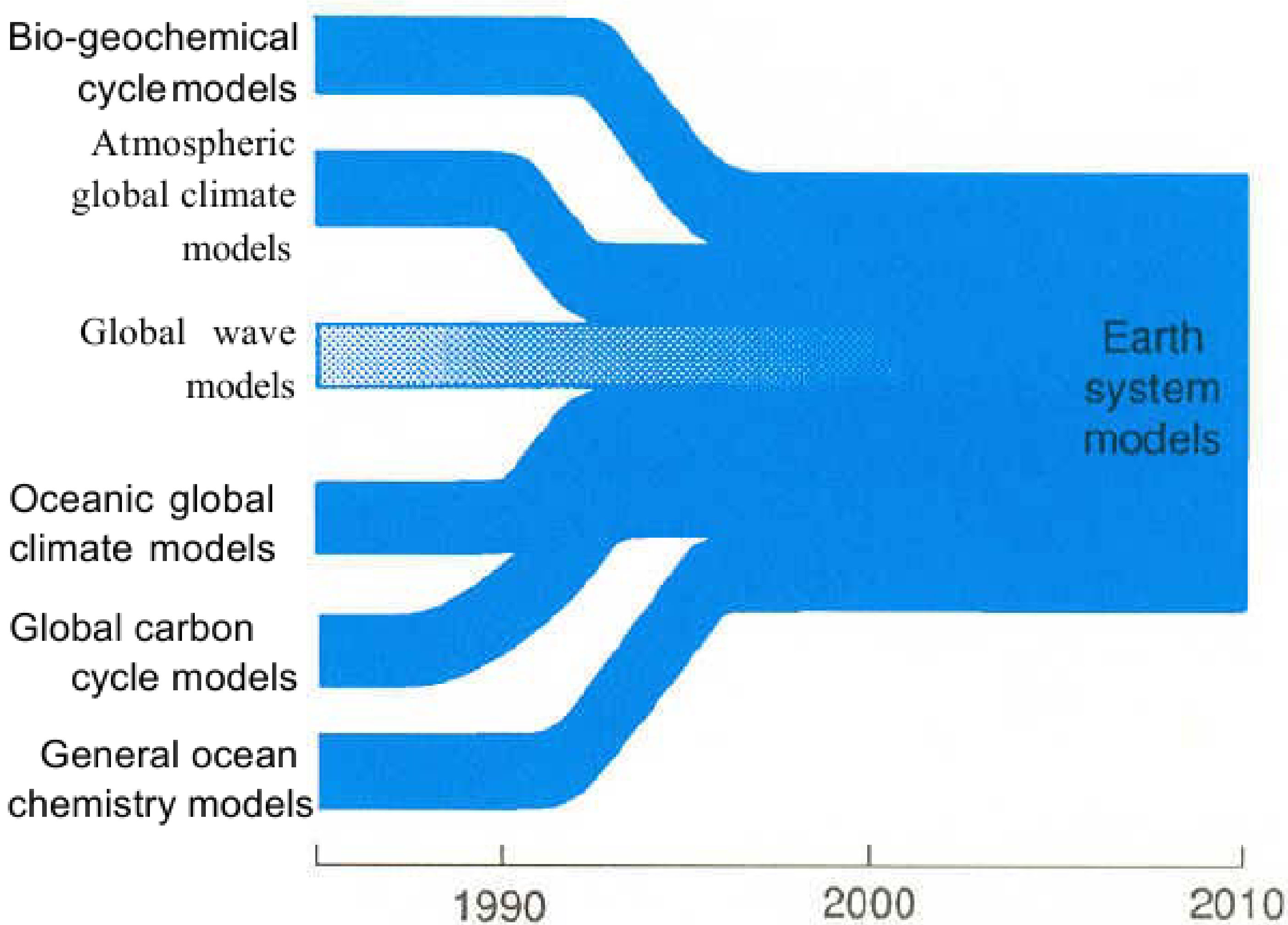


Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle modets developed in the context ot the World Climate and Global Change programs.