Seasar2023 Workshop-

Longyearbyen, 2-6 May 2023

Sensor Synergy

Ben Holt, Bertrand Chapron, dr.fab, Johnny A. Johannessen, Lucile Gaultier, Biao Zhang, William Perrie, Jose da Silva, Thibault Taillade, Marcus Engdahl, Diego Fernandez, Brittany Lockhart, Mitch Porter, Nicolas Rascle, Romain Husson, Craig Donlon, Justin Stopa.

Additional contributions are welcome to the White Paper.

Sensor Synergy

- Key objectives
- Innovation (new findings and achievements)
- Remaining knowledge gaps and deficiencies
- Outlook and recommendation
    - bigger-picture view of what is missing
    - specific actions / experiments / instruments / missions

Sensor Synergy - Surface Gradient Detections

(i) **Infrared- and microwave** radiometer-based sea surface temperature;

(ii) **Imaging spectrometer**-based chlorophyll distribution and concentration;

(iii) **Altimeter**-based sea surface height anomalies;

(iv) **SAR**-based surface roughness (induced by currents, waves, wind, surfactants);

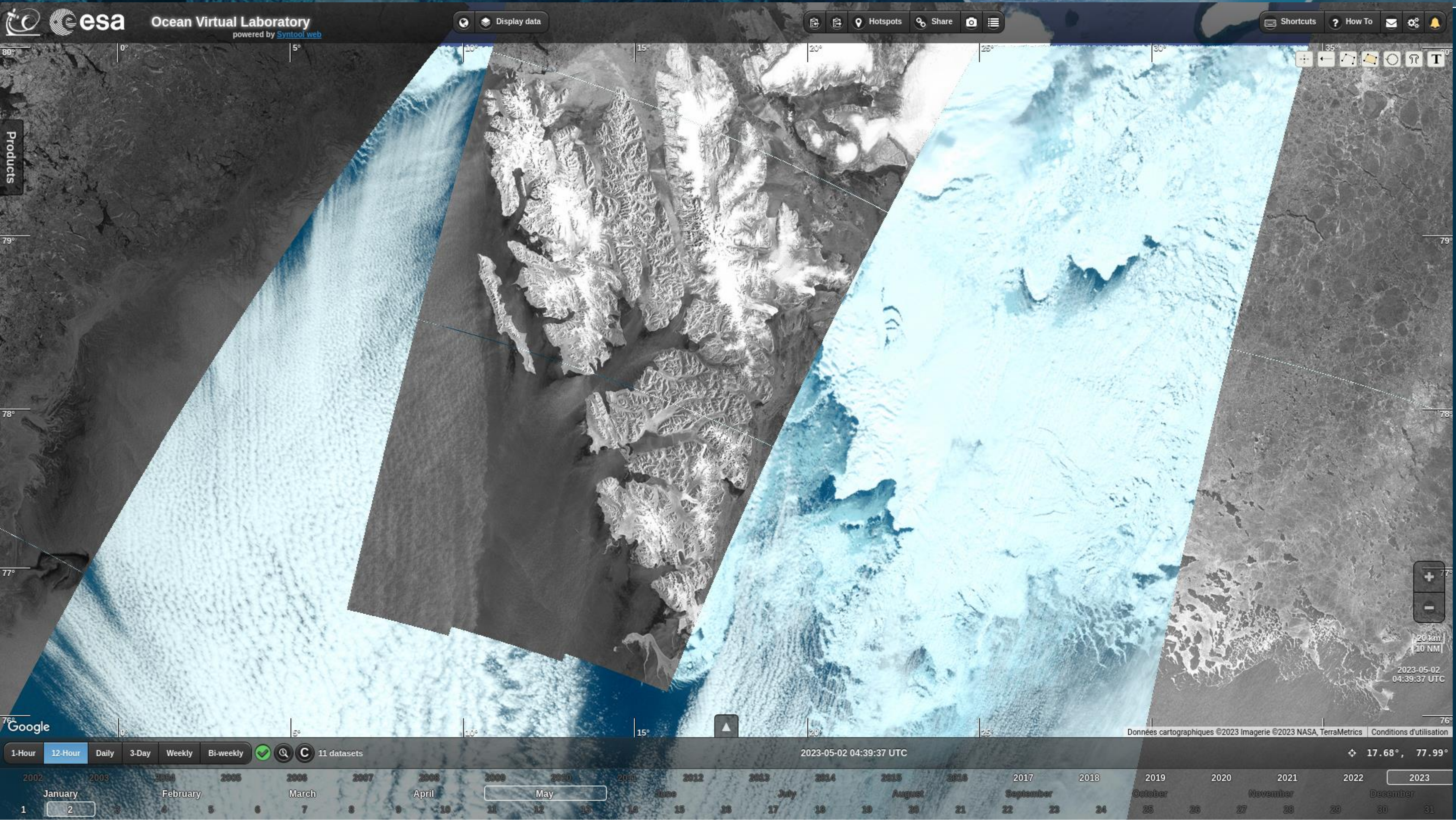
(v) **Scatterometer** based surface roughness;

(vi) **SAR**-based range Doppler shift;

(vii) **Visible**-derived sun-glitter

(viii) **Sea ice – ocean** boundaries (and derived variables)

An Example from Yesterday



SAS Flight
on 1 May 2023
marked by red
line/arrow

Red circles
snatshot phot
from window-
seat

Satellite Sensor Synergy – Strength and Goals

Instantaneous ocean surface observation from space, at synoptic scale O(100 km) and resolution of 100 m to 10 km, reveal a mixture of oceanic and atmospheric signatures and processes, e.g. ocean waves, wind, internal waves, wind streaks, hurricanes, PL, filaments, upwelling, meanders, fronts, spiralling eddies, convergence, surfactants, oil spill, sea ice.

These features and underlying processes are expressed due to a broad range of imaging mechanisms, some of which are not easily accessible from in situ ocean observations.

Challenging to derive quantitative insight on how the processes influence energy pathways, buoyancy budgets, 3D motions in the upper ocean and in the ABL, physical-biological interactions in the upper ocean, and how they structure and concentrate floating material.

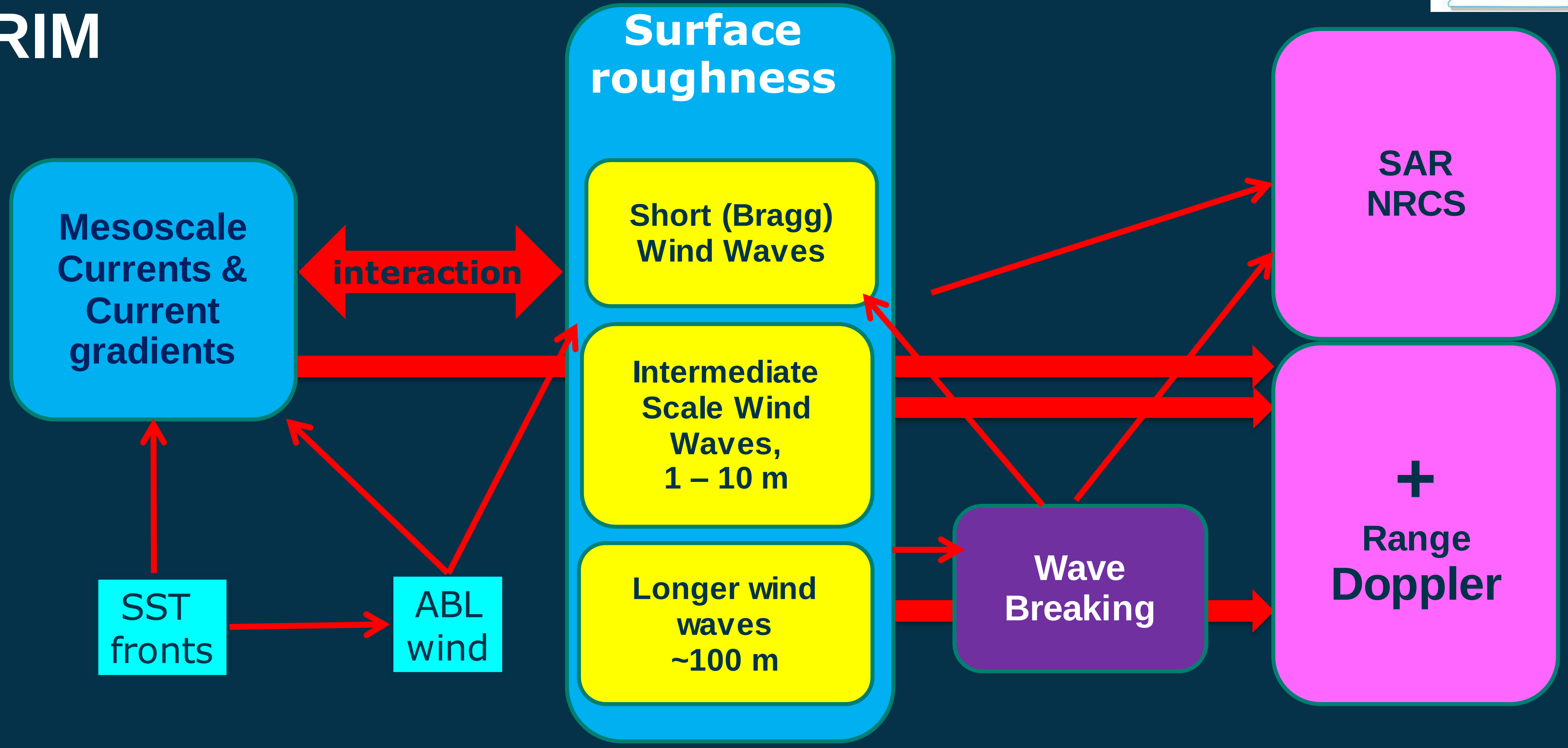
Near real-time monitoring and quantitative interpretation of mesoscale upper ocean processes and dynamics will advance with consistent use of sensor synergy

Sensor synergy shortcut detection limitations by each individual sensor

Should be systematically applied in assessing new satellite sensor capabilities

"Radar Imaging of meso-scale current features" Kudryavtsev et al., JGR, 2005 (Part 1); Johannessen et al., JGR, 2005 (Part 2), Chapron et al., 2006; Kudryavtsev et al., 2012

DOPRIM



Synergetic Approach to Ocean Dynamics: Scales ~ 100 km to ~ 1 km

MDT
MDT+SLA

SST, ΔSST
OC, ΔOC

σ, Δσ, Doppler,
ΔMSS (~ Δσ)

SSS, ΔSSS

τ, Δτ (impact on ABL)

$\underline{U} = \underline{U}_{mean} + \underline{U}'_{pert}$

Divergence of U

Curl of U

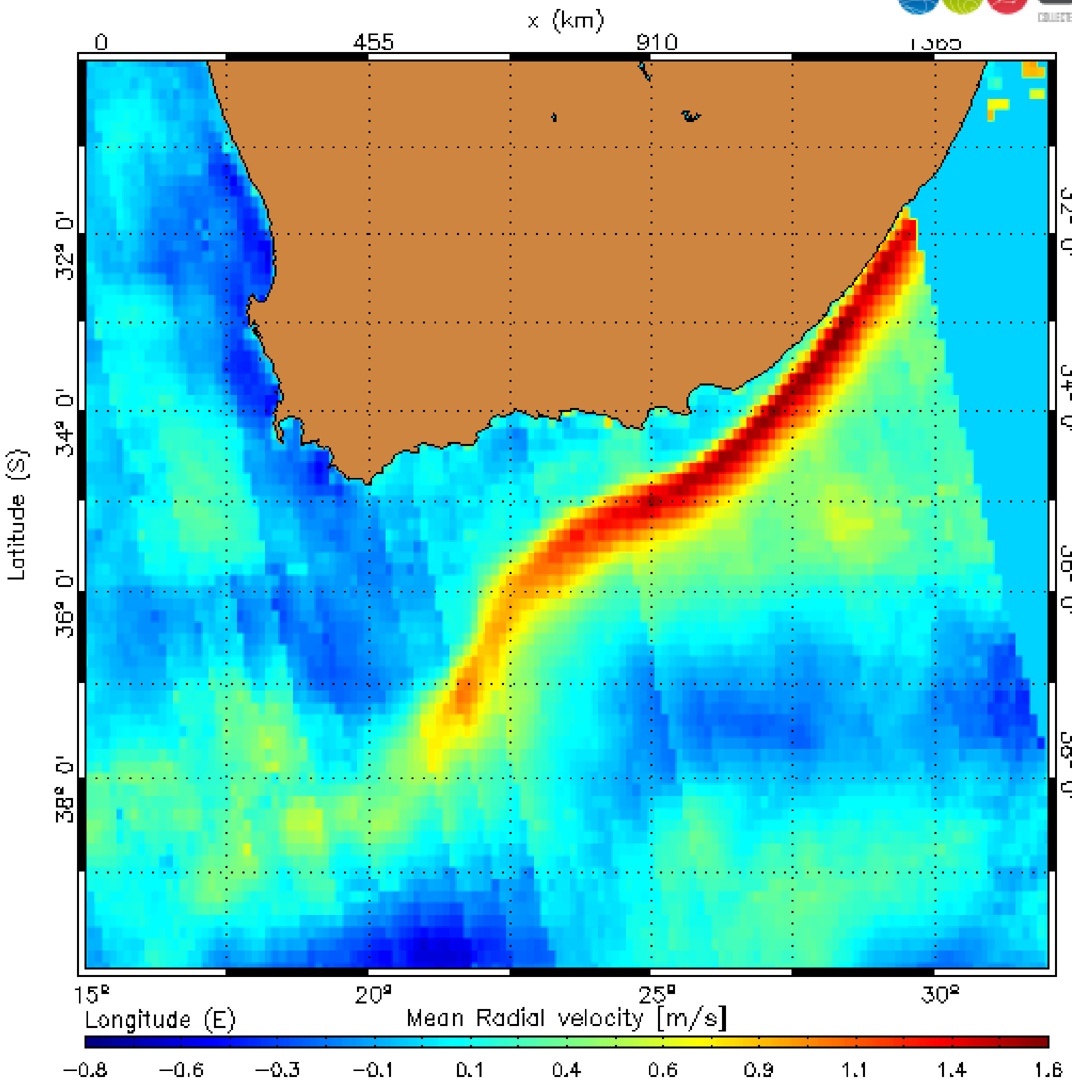
Ekman Current and NIO

Mixed Layer Depth

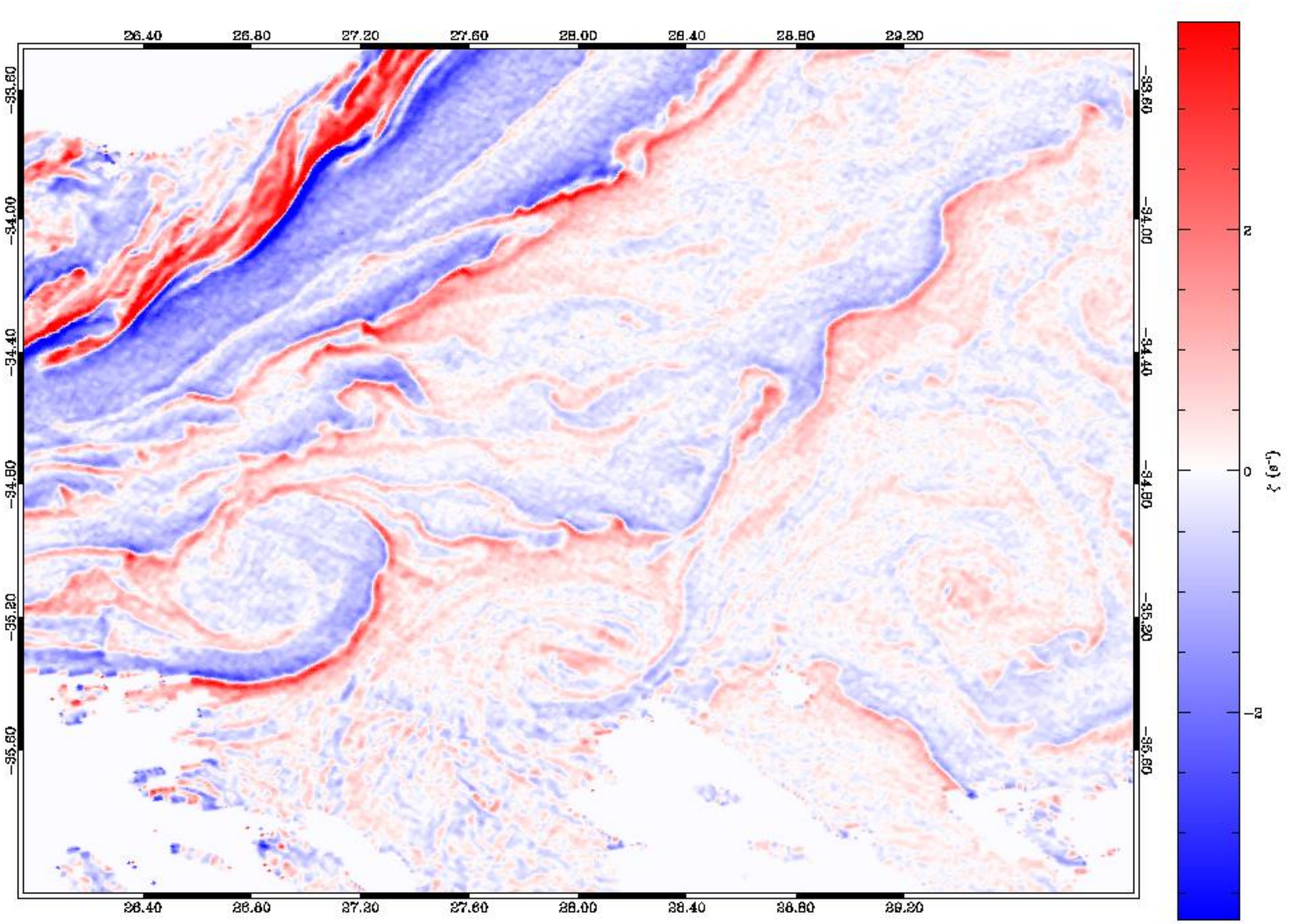
Develop and apply common tools and methods (gradient detectors, Lyaponov, MCC, SQG, DOPRIM, et)

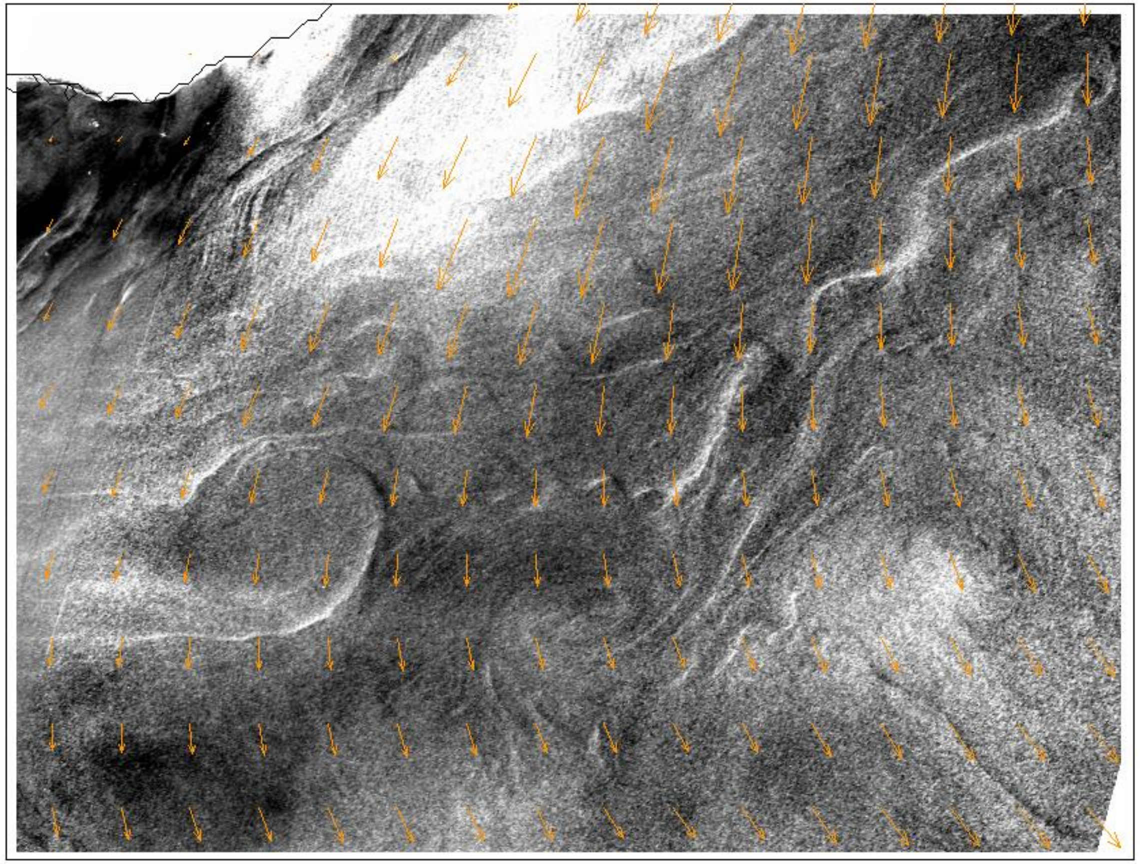
Make a consistent transfer of these fields to 2D surface dynamics and next to 3D upper (500m) ocean dynamics combined with models

Agulhas main stream velocity: Mean of all Ascending acquisitions since July 2007



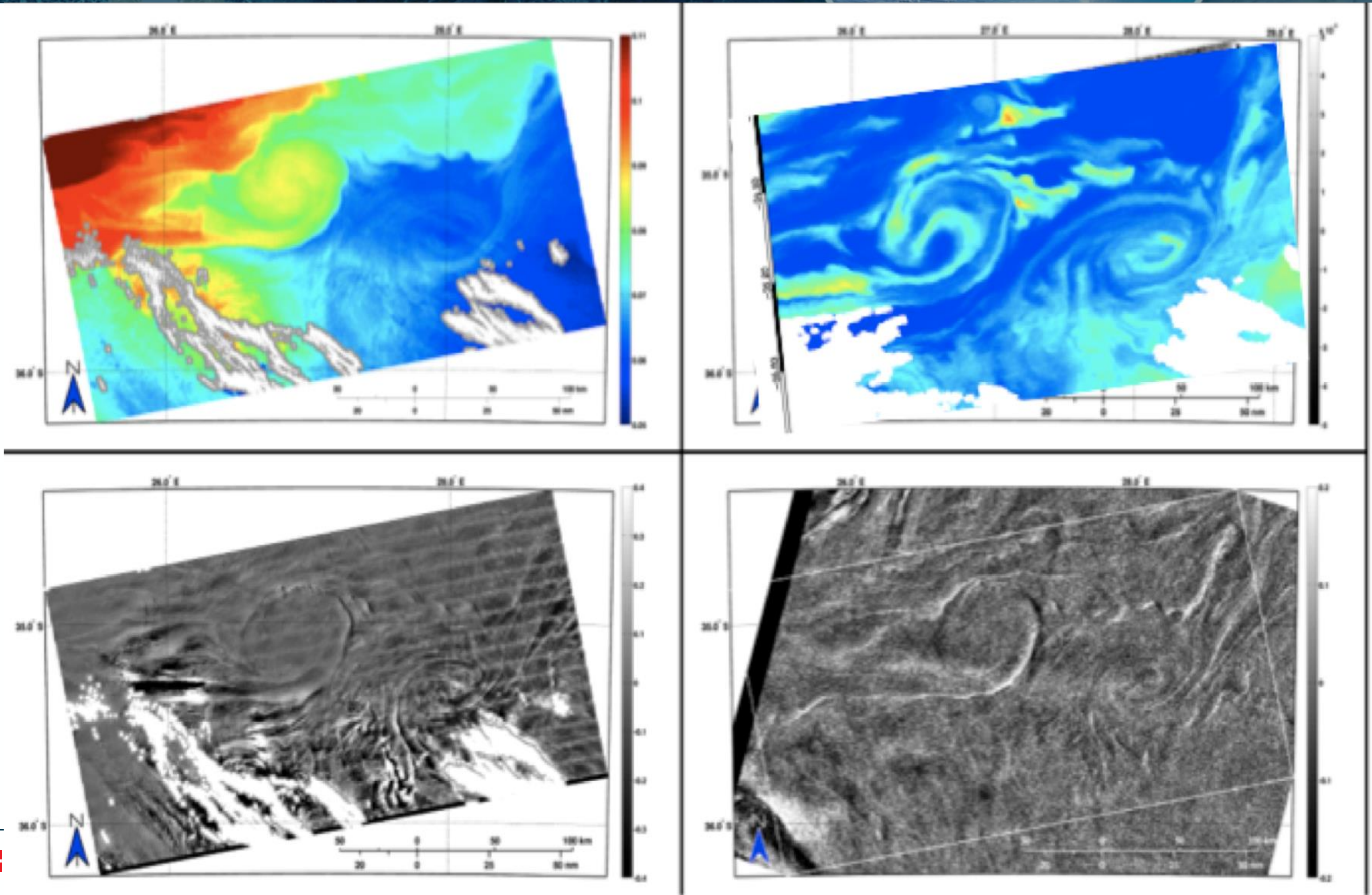
MODIS Brightness temperature and ENVISAT radar roughness variations



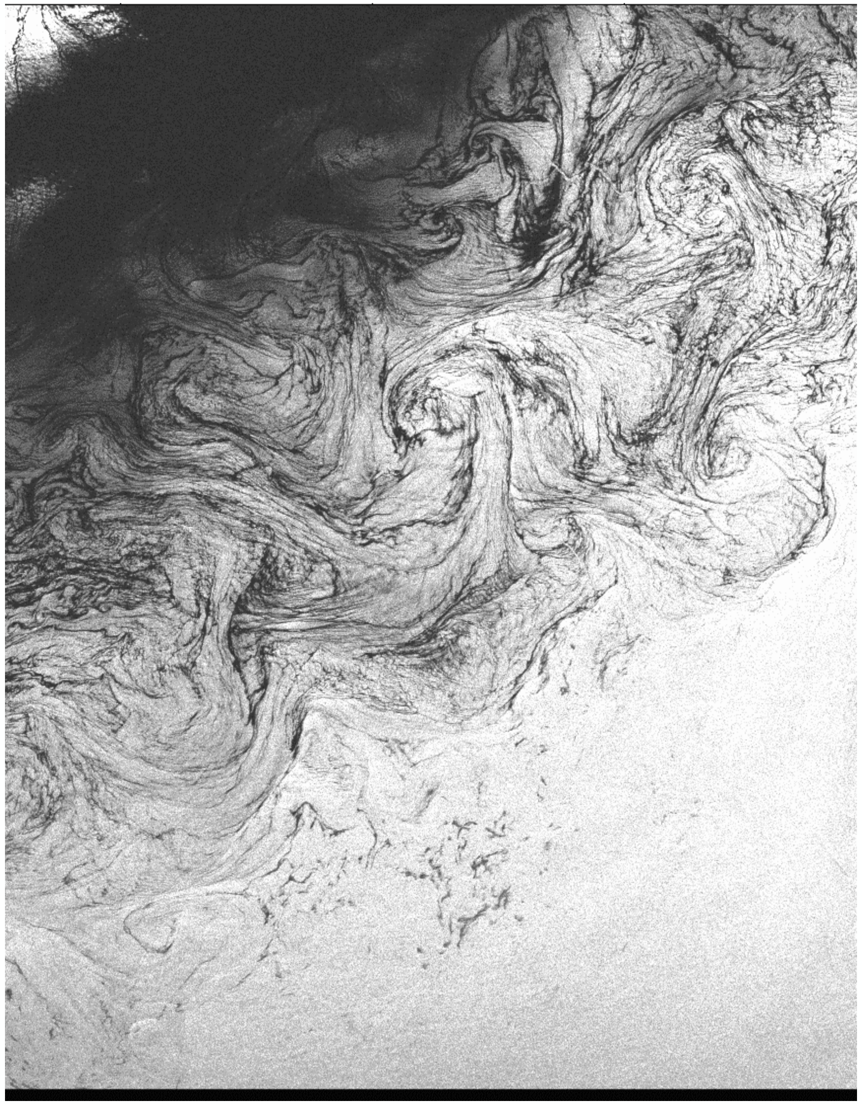


and SQG-derived vorticity

And towards more synergy

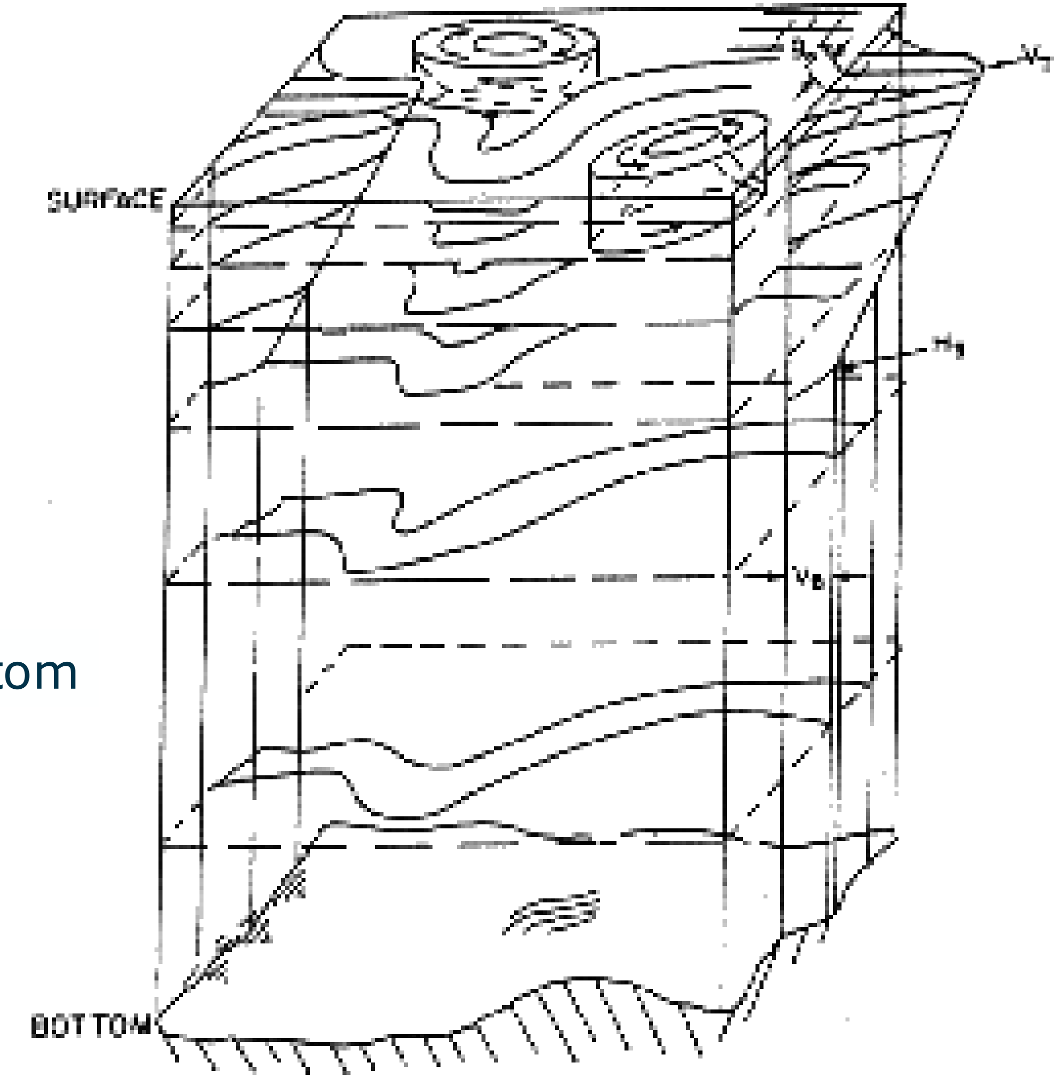


From mesoscale surface expression to upper ocean structure



SURFAE

bottom

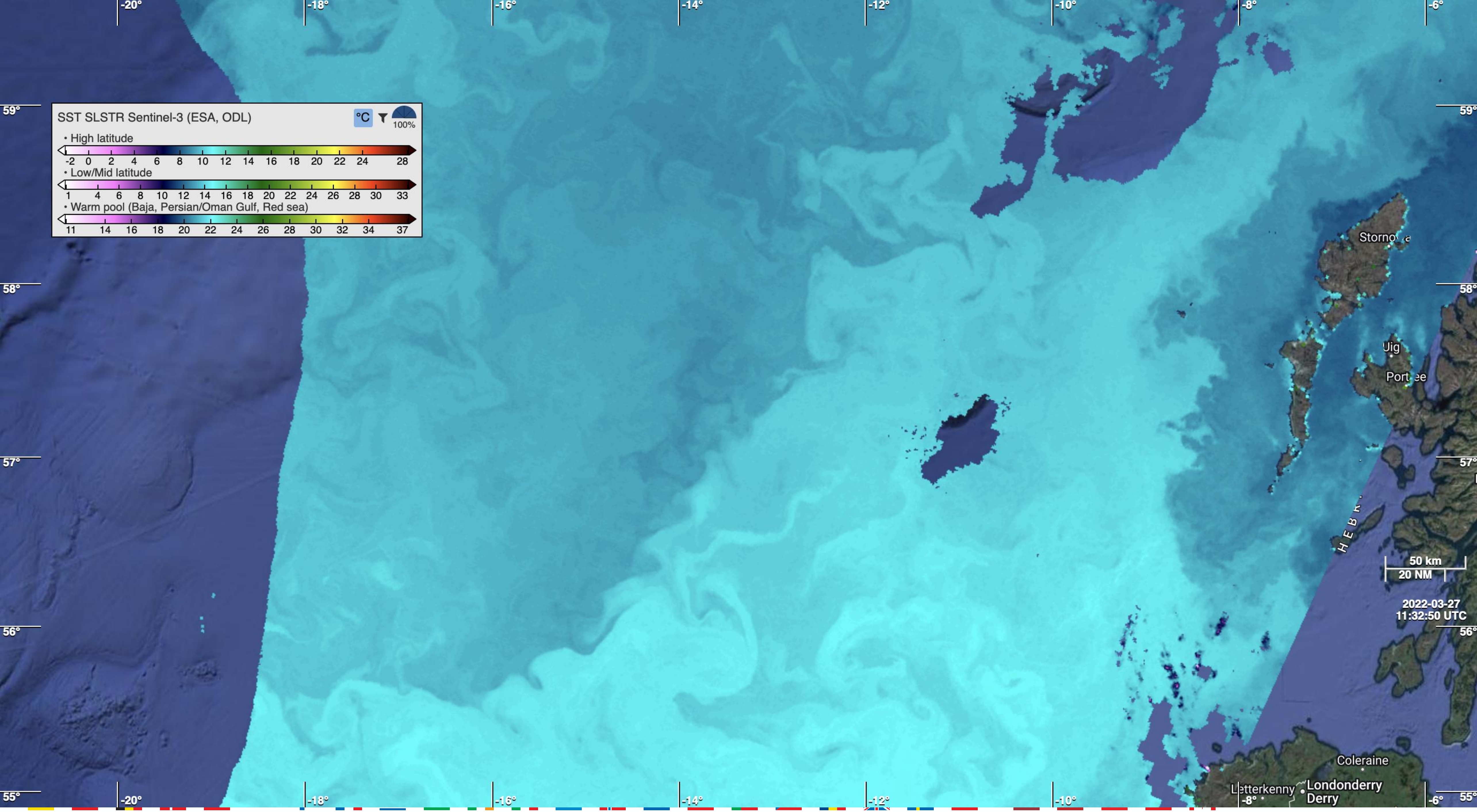


eNATL60 OGCM

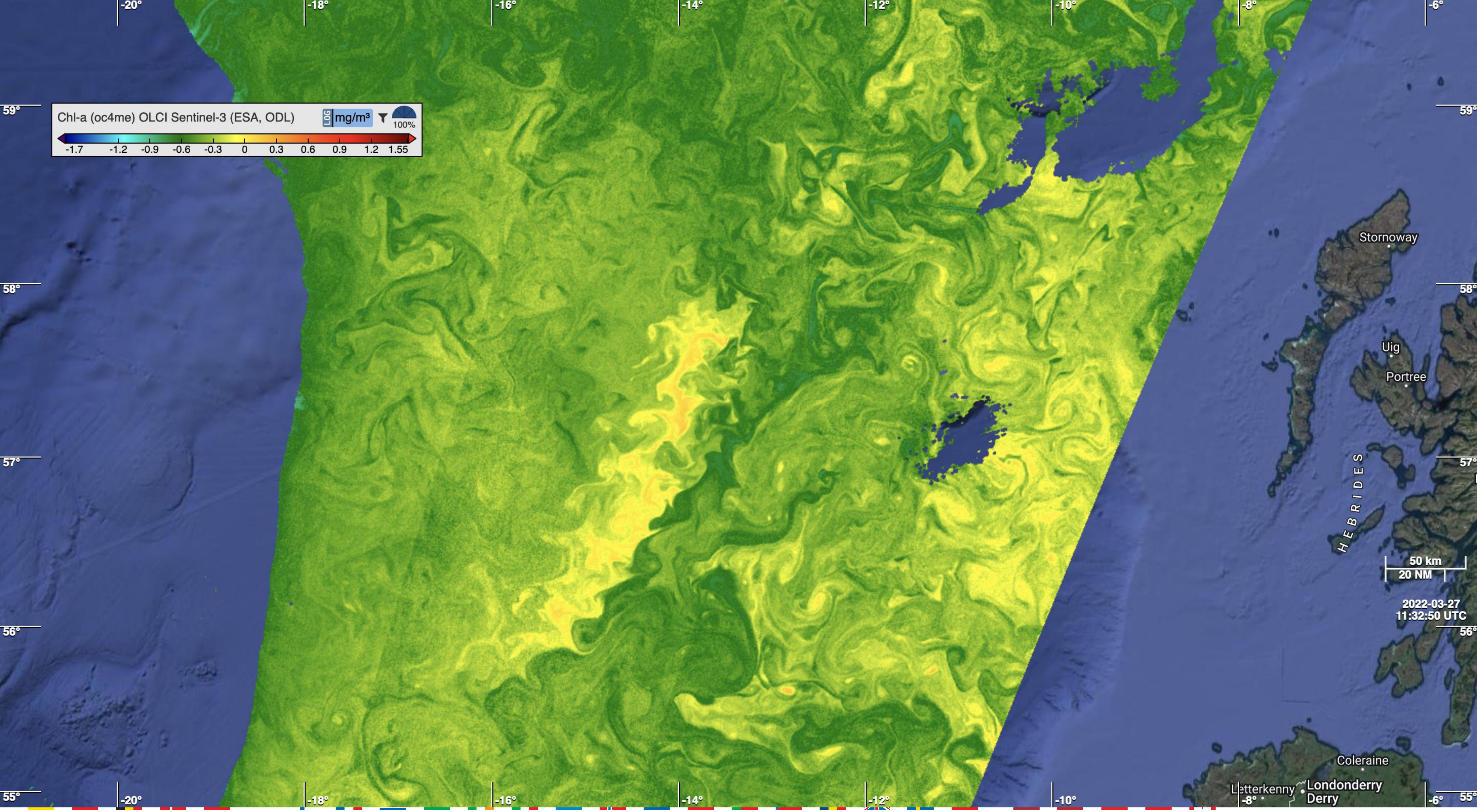
Mixed Layer Depth

L. Brodeau and
J. Le Sommer

IGE, Grenoble

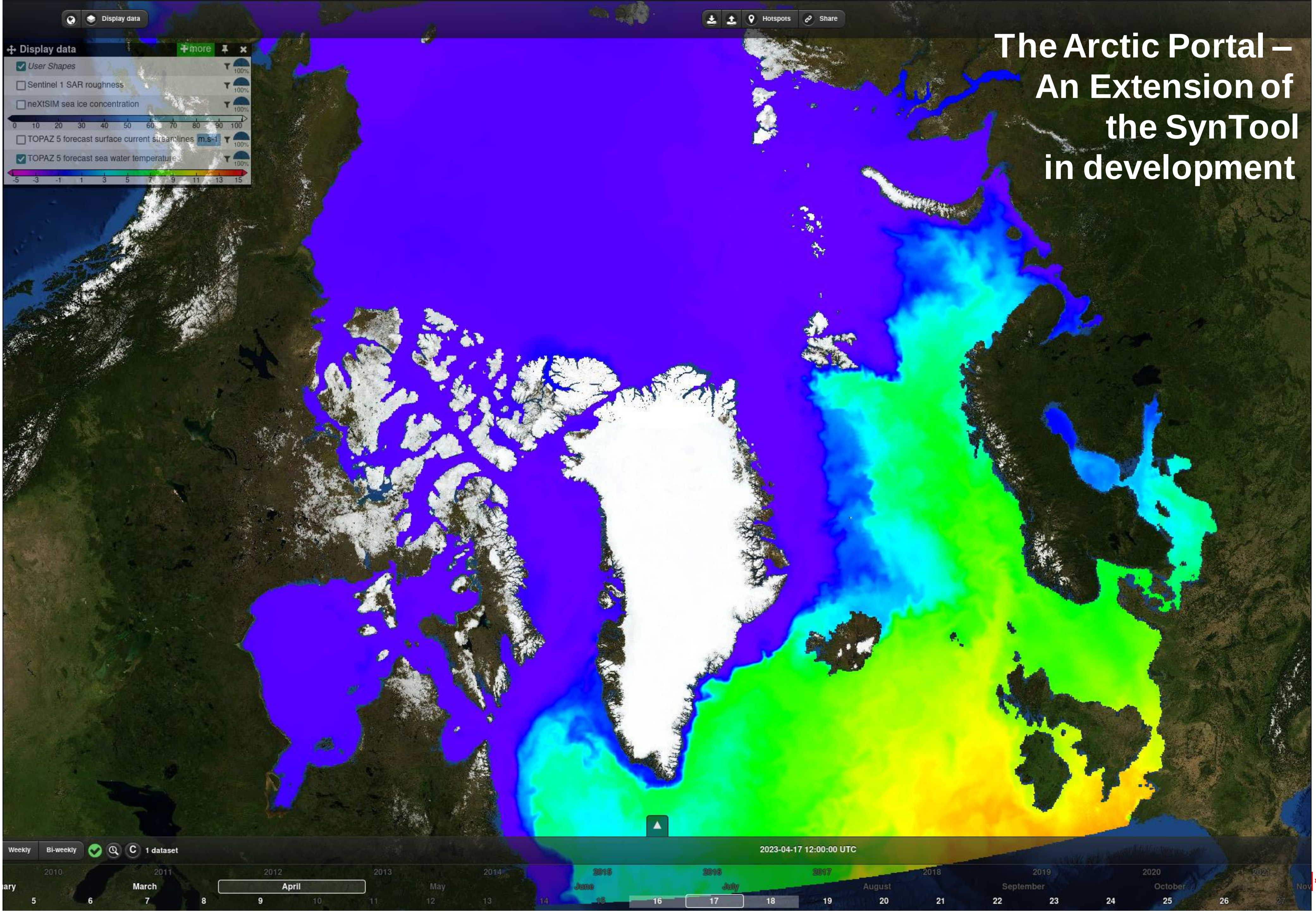


SST SLSTR Sentinel-3 (ESA, ODL)
°C
100%
• High latitude
-2 0 2 4 6 8 10 12 14 16 18 20 22 24 28
• Low/Mid latitude
1 4 6 8 10 12 14 16 18 20 22 24 26 28 30 33
• Warm pool (Baja, Persian/Oman Gulf, Red sea)
11 14 16 18 20 22 24 26 28 30 32 34 37
-20° -18° -16° -14° -12° -10° -8° -6°
59° 58° 57° 56° 55°
Uig
Coleraine
Londonderry
Derry
50 km
20 NM
2022-03-27
11:32:50 UTC

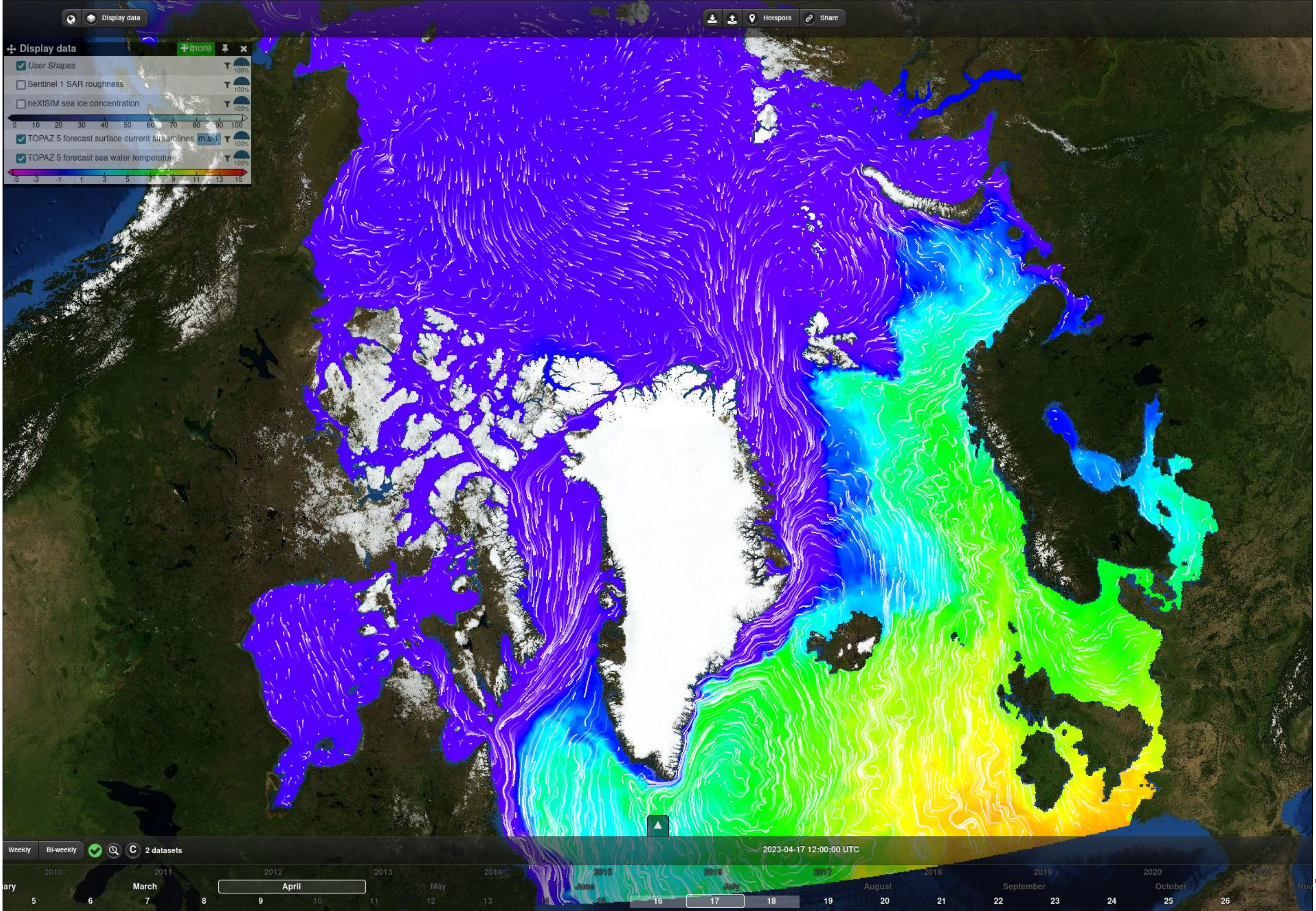


Chl-a (oc4me) OLCI Sentinel-3 (ESA, ODL)
LOG mg/m³
100%
-1.7 -1.2 -0.9 -0.6 -0.3 0 0.3 0.6 0.9 1.2 1.55
-20° -18° -16° -14° -12° -10° -8° -6°
59° 58° 57° 56° 55°
Stornoway
Uig
Portree
HEBRIDES
50 km
20 NM
2022-03-27
11:32:50 UTC
Coleraine
Letterkenny
Londonderry
Derry

The Arctic Portal – An Extension of the SynTool in development

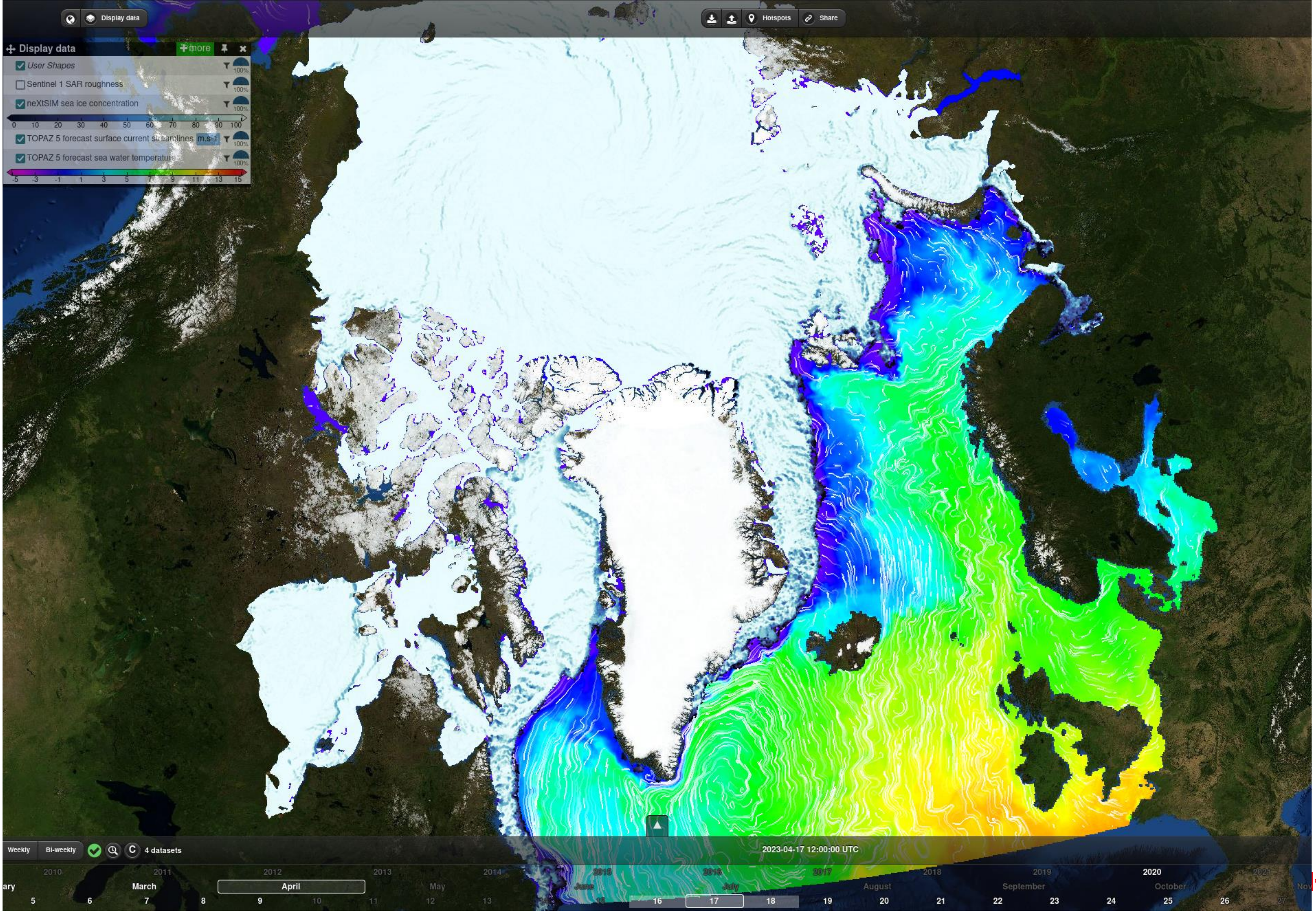


- April 17, 2023
- TOPAZ 5 forecast SST

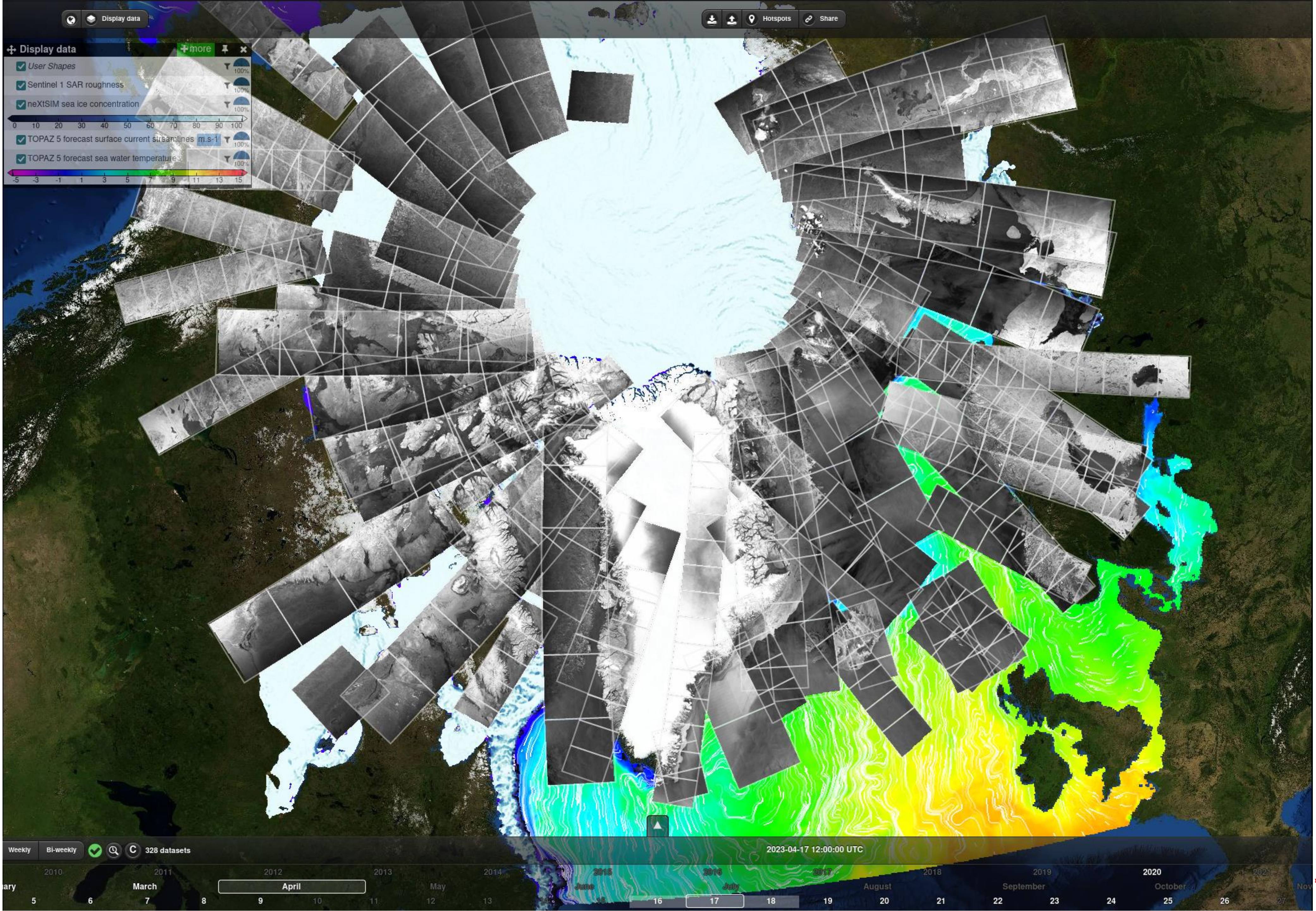


- April 17, 2023

- TOPAZ 5 forecast SST
- TOPAZ 5 forecast current

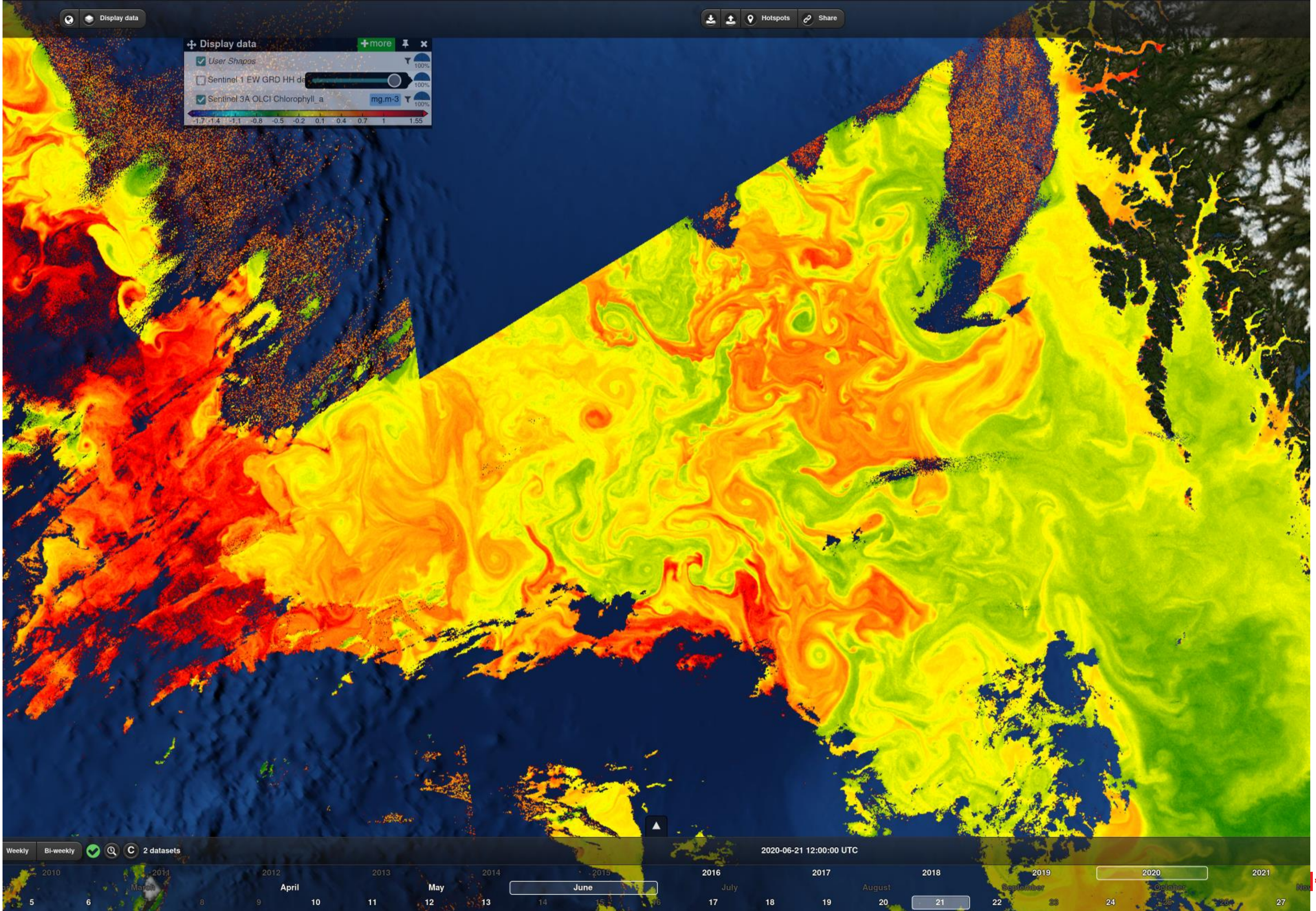


- April 17, 2023
- TOPAZ 5 forecast SST
- TOPAZ 5 forecast current
- NeXtSIM sea ice concentration

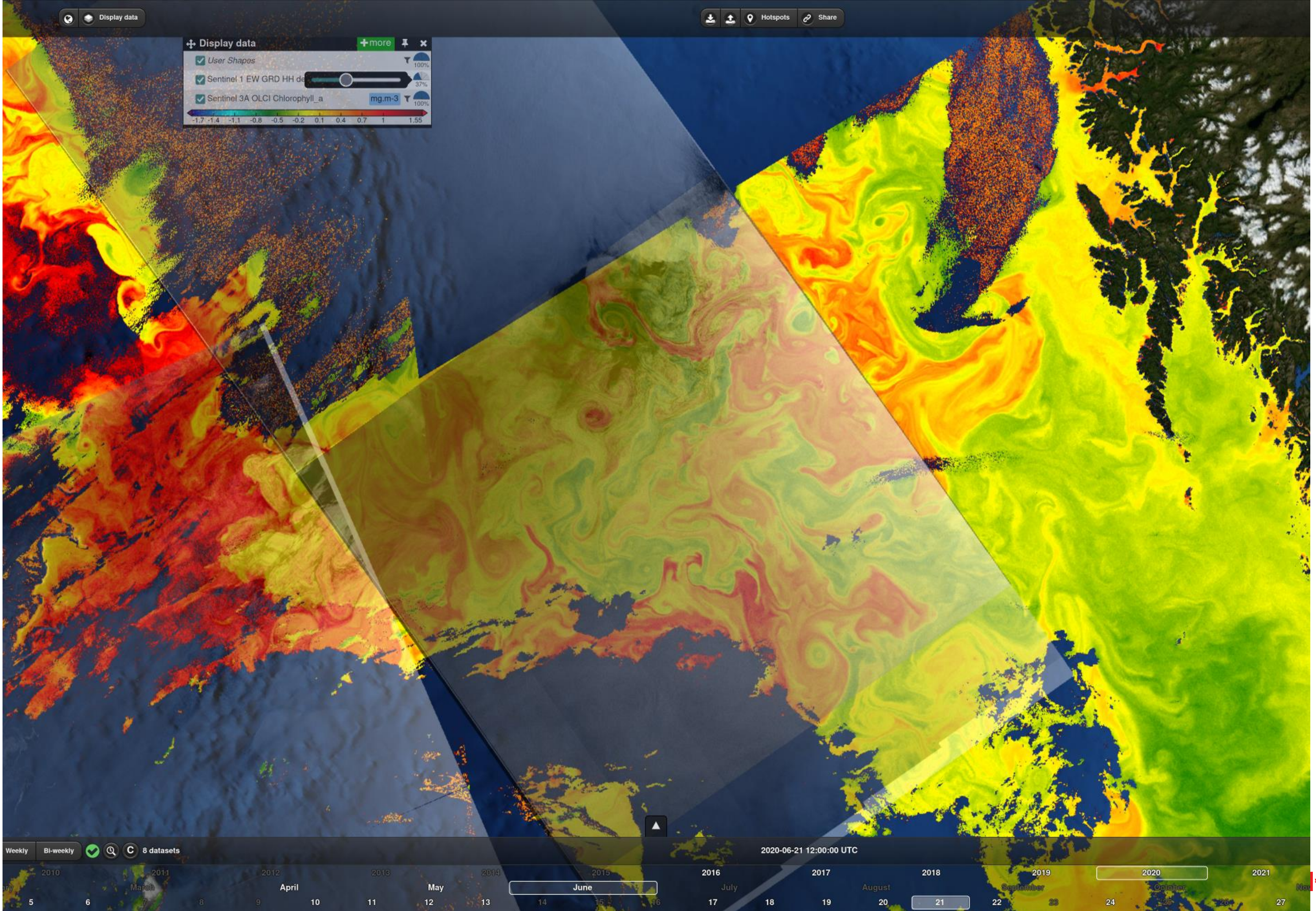


- April 17, 2023

- TOPAZ 5 forecast SST
- TOPAZ 5 forecast current
- NeXtSIM sea ice concentration
- Sentinel 1 SAR roughness (over 3 days)

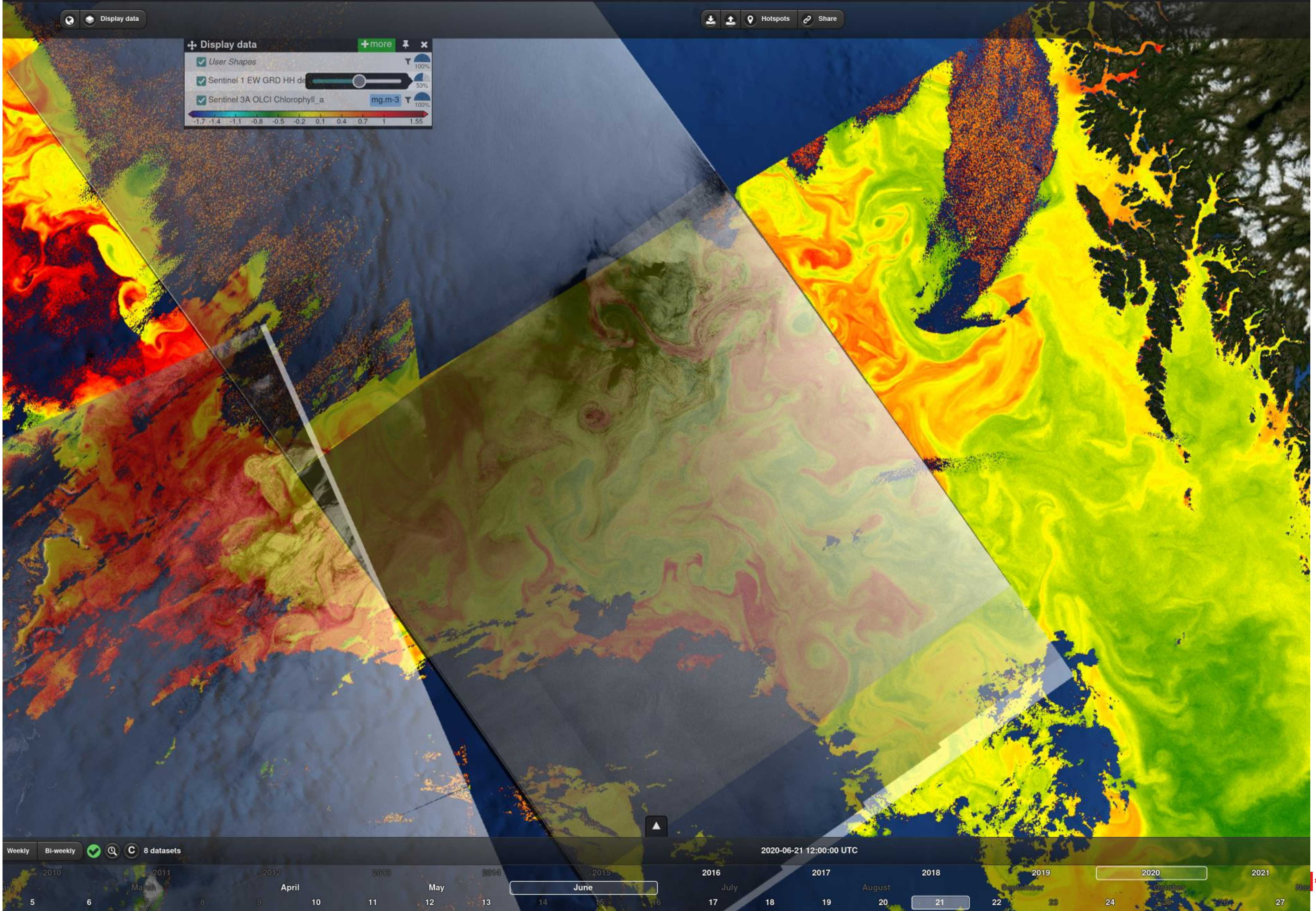


- June 21, 2020
- Sentinel 3 Chloropyll-a



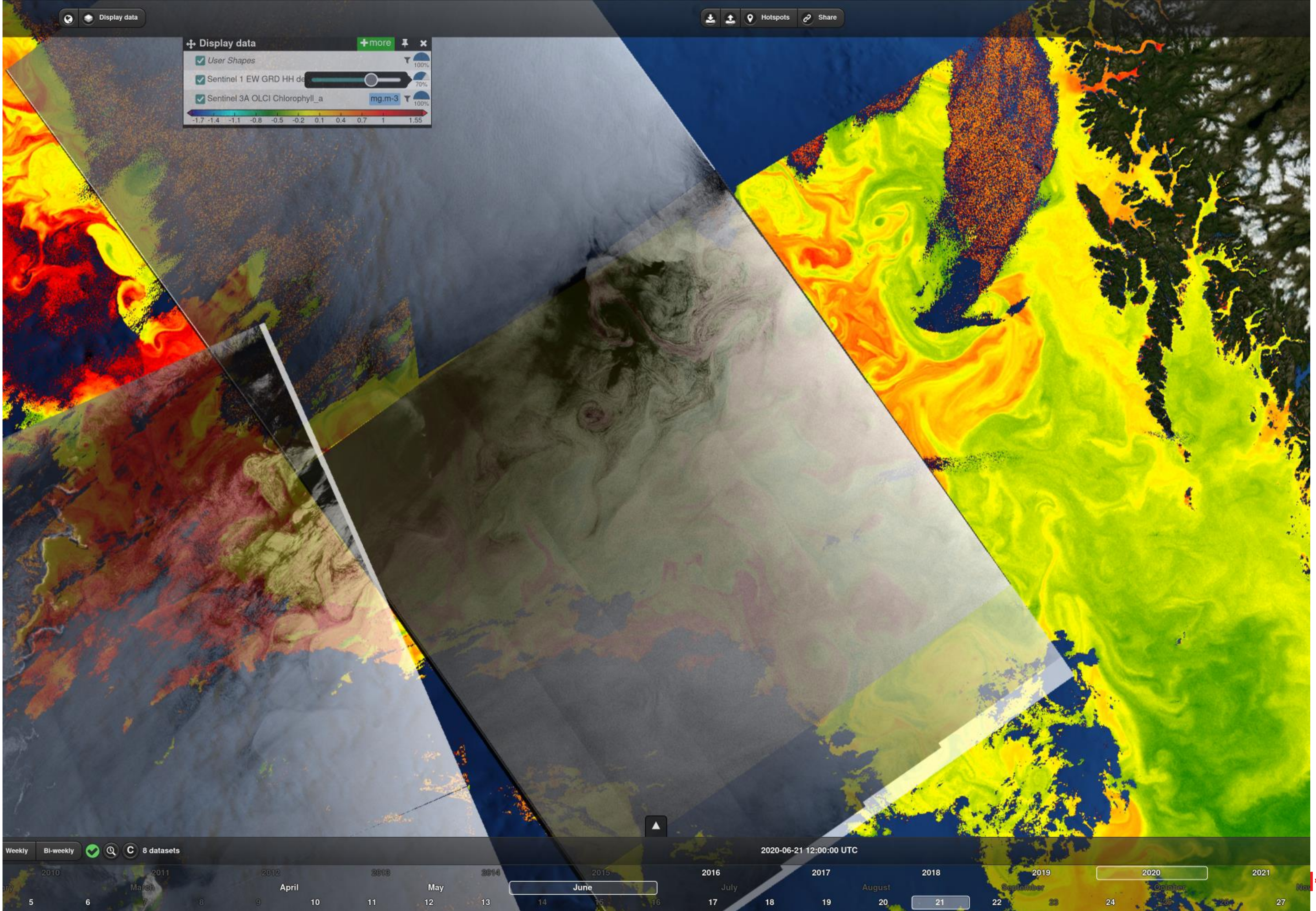
- June 21, 2020

- Sentinel 3 Chloropyll-a
- Denoised Sentinel 1 SAR



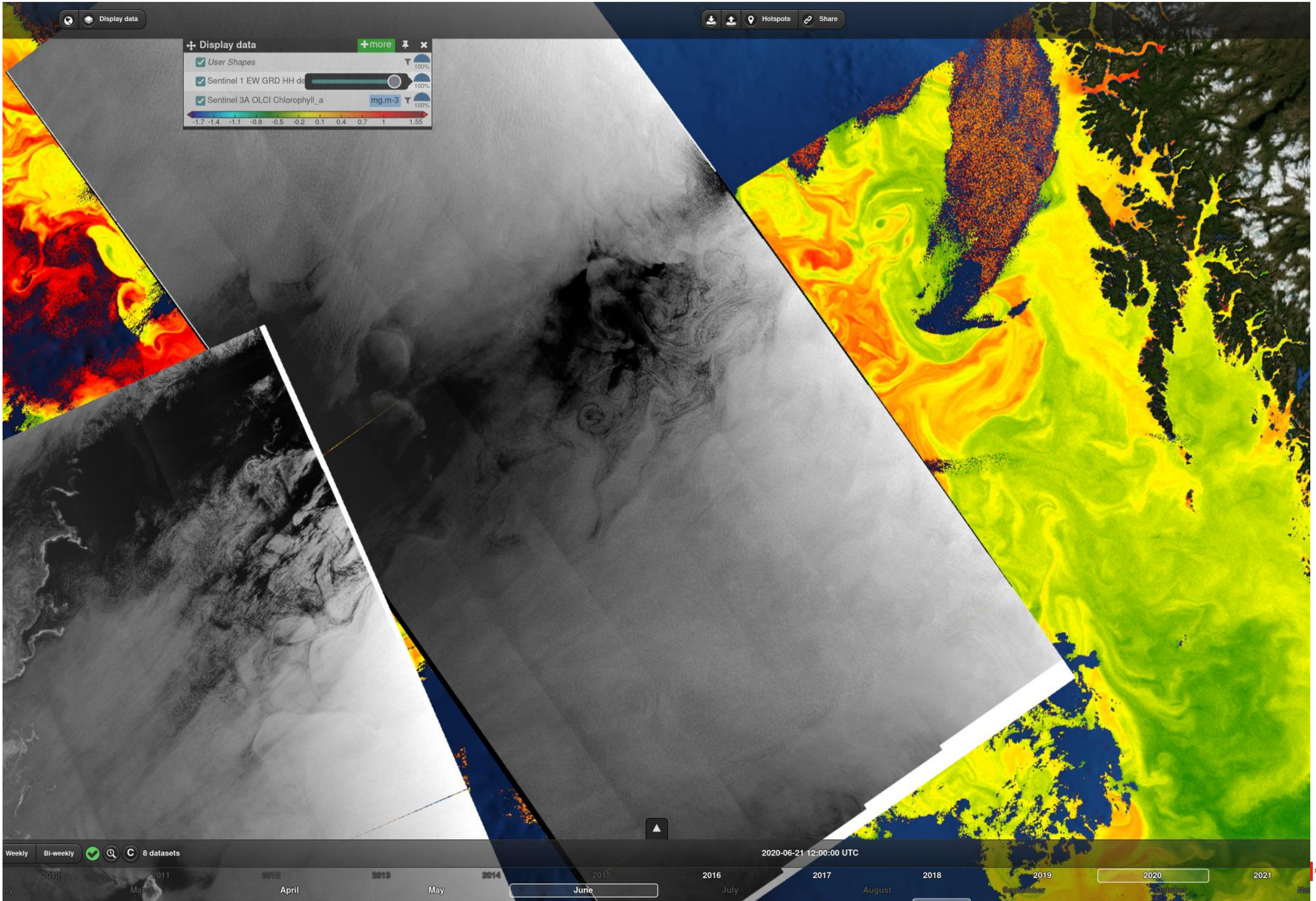
- June 21, 2020

- Sentinel 3 Chloropyll-a
- Denoised Sentinel 1 SAR



- June 21, 2020

- Sentinel 3 Chloropyll-a
- Denoised Sentinel 1 SAR

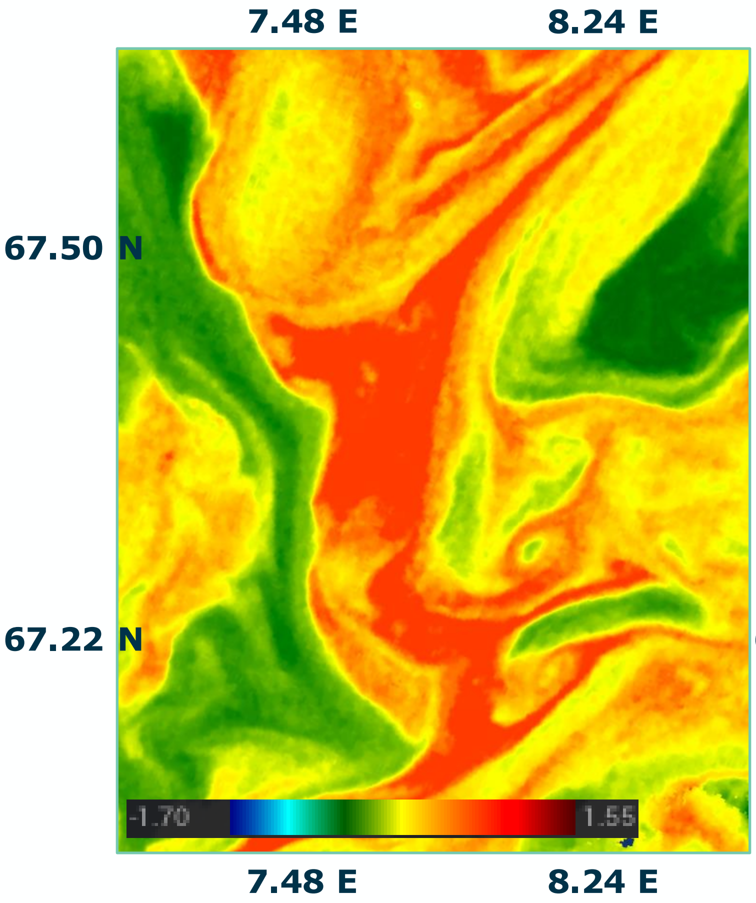


- June 21, 2020

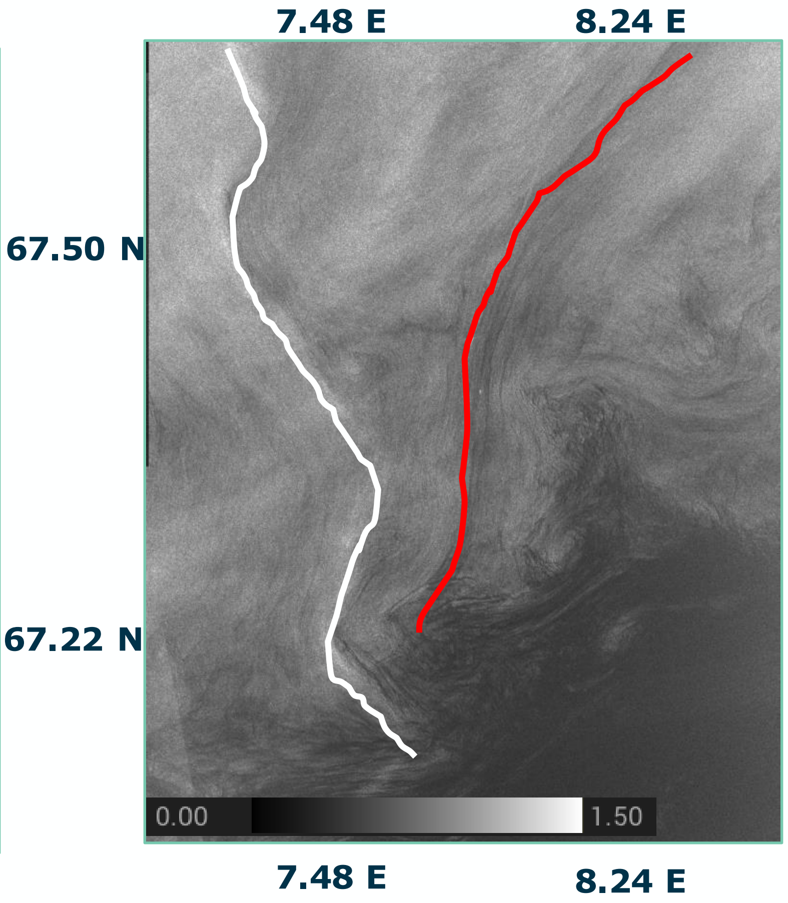
- Sentinel 3 Chloropyll-a
- Denoised Sentinel 1 SAR

Bright front in SAR image – Surface Convergence

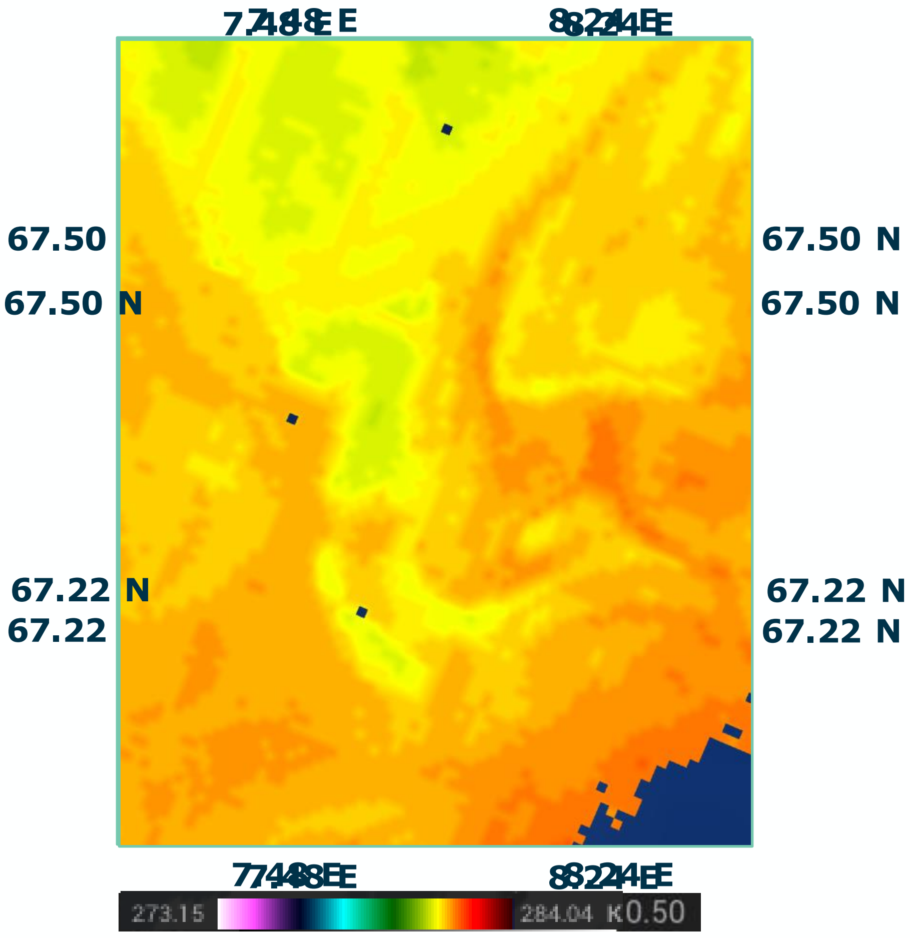
Dark bands in SAR image – Dark filament connected with high Chl conc.



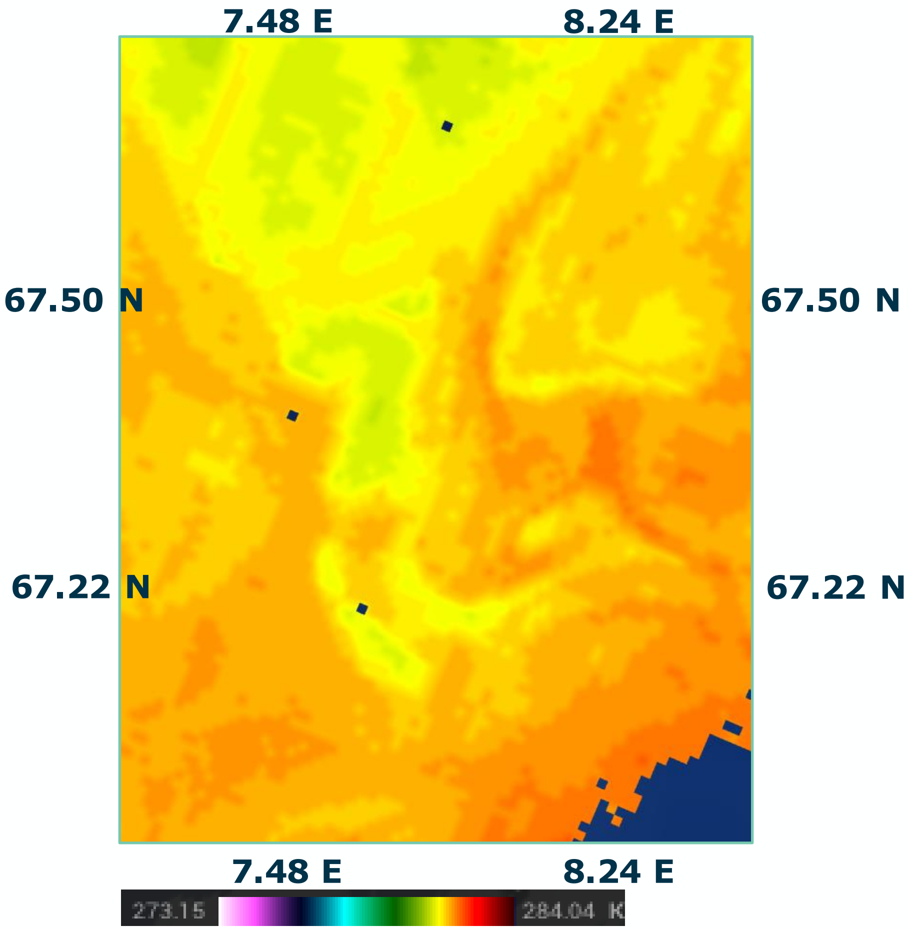
S3_olci_20210603



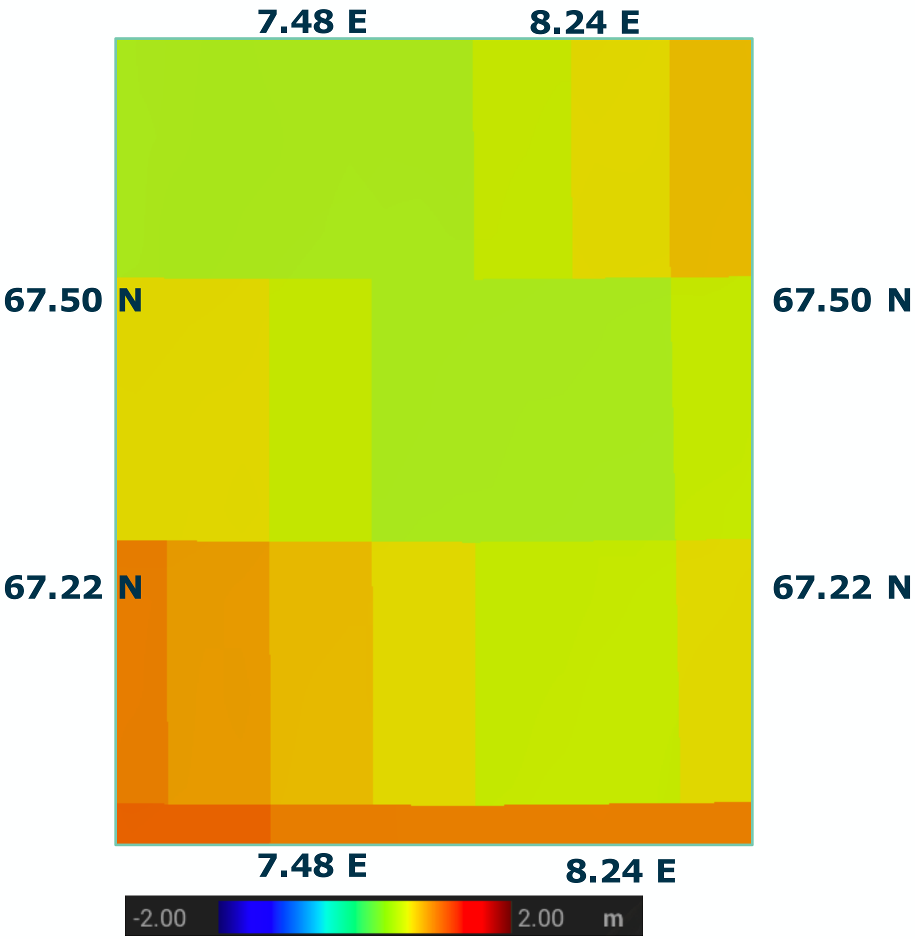
S1_WI_20210603



S2_MSIL1C_20210603



S3_SST_20210603



Absolute dynamic topography

Objectives

Fronts, Eddies, and Other Features in the Western Pacific and Micronesia from SAR and Other Multi-Sensor Data

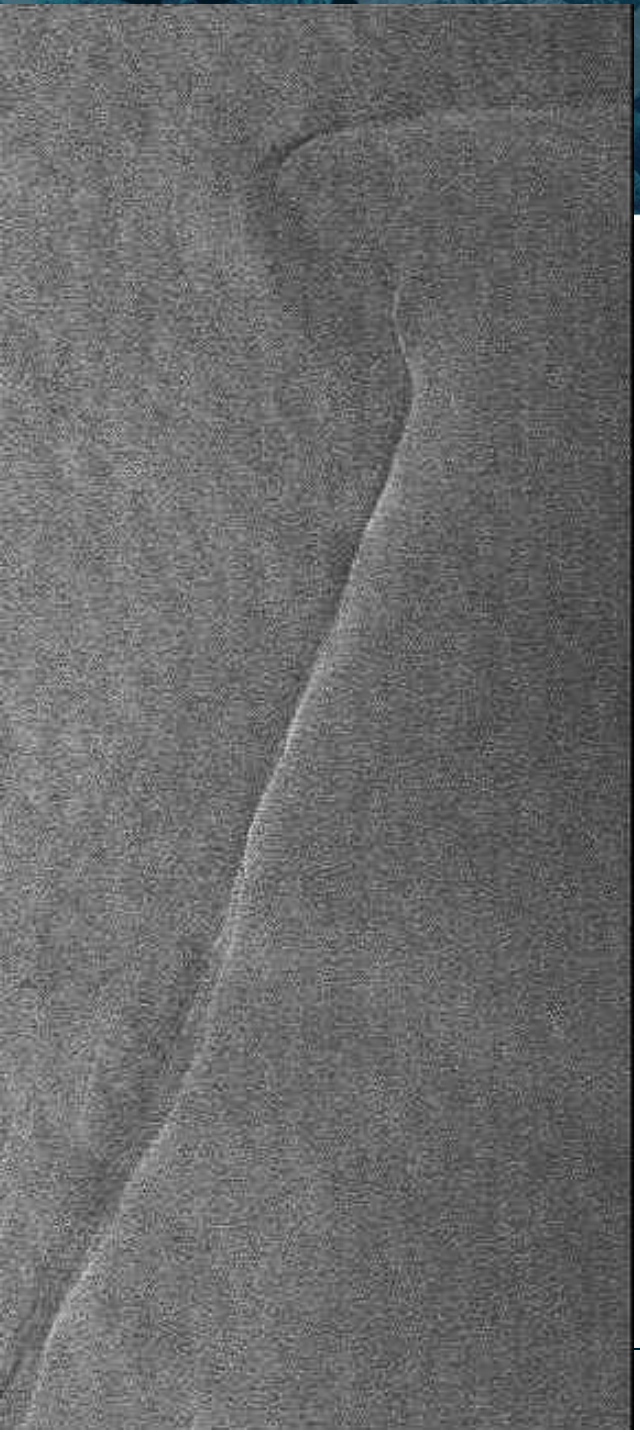
Benjamin Holt
Brittany Lockhart
Jet Propulsion Laboratory, California Institute of Technology

Mitch Porter, Doug Comer
CRSM Foundation

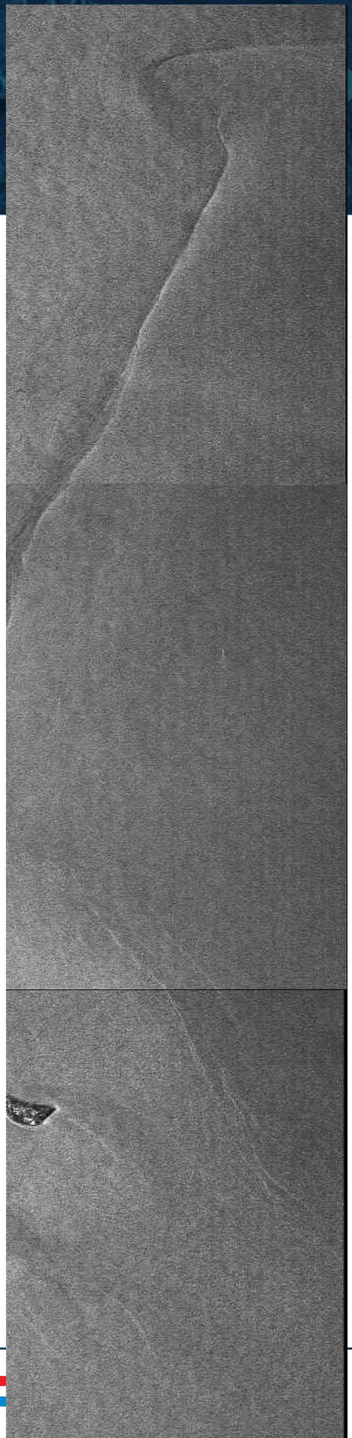
ESA SeaSAR
Svalbard, May 2-6, 2023

Focus of talk:

- Examined ALOS-1 and Sentinel-1 SAR imagery, MUR SST, OSCAR Currents, CCMP Winds to understand presence of frontal and submesocale features
- Fronts apparently associated with opposing winds and currents along SST gradients



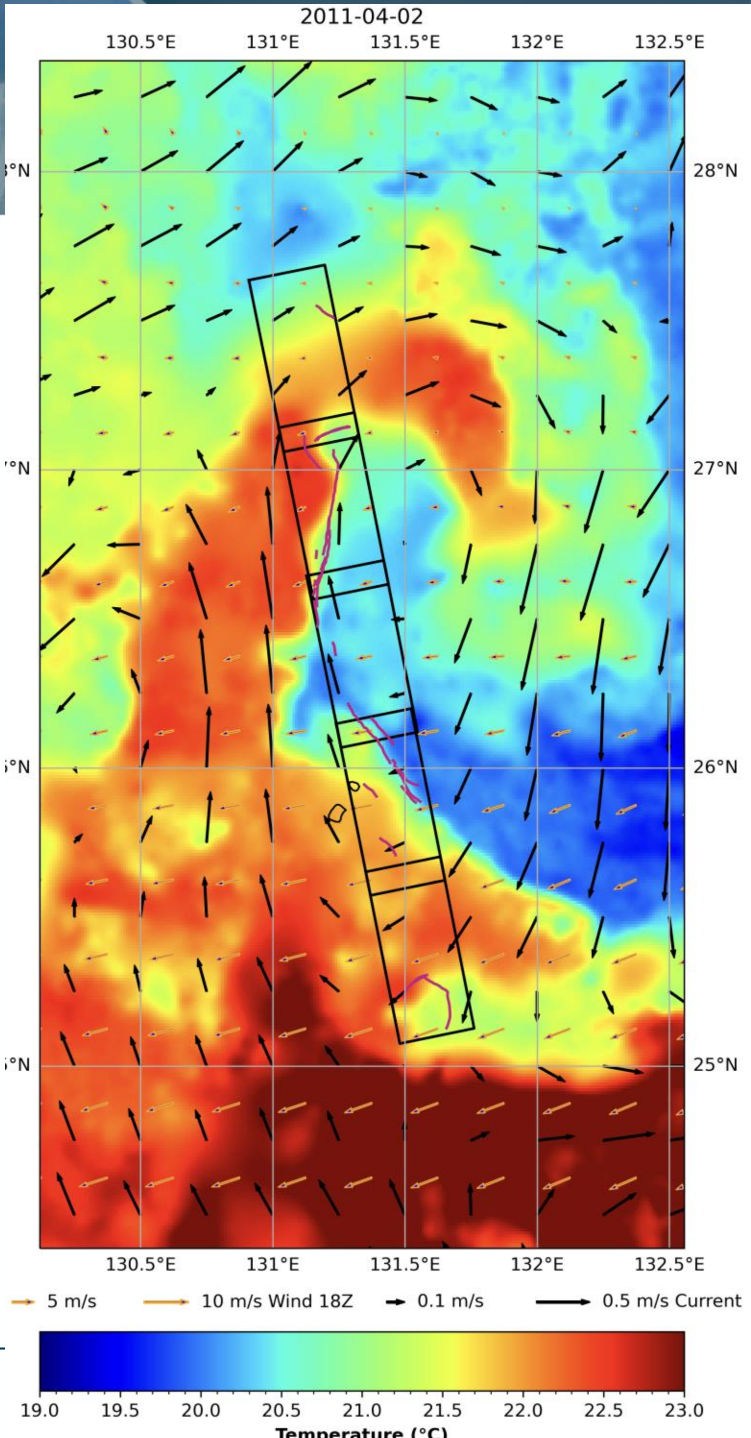
ALOS-1 SAR
2011-04-02



Magenta lines indicate sharp fronts

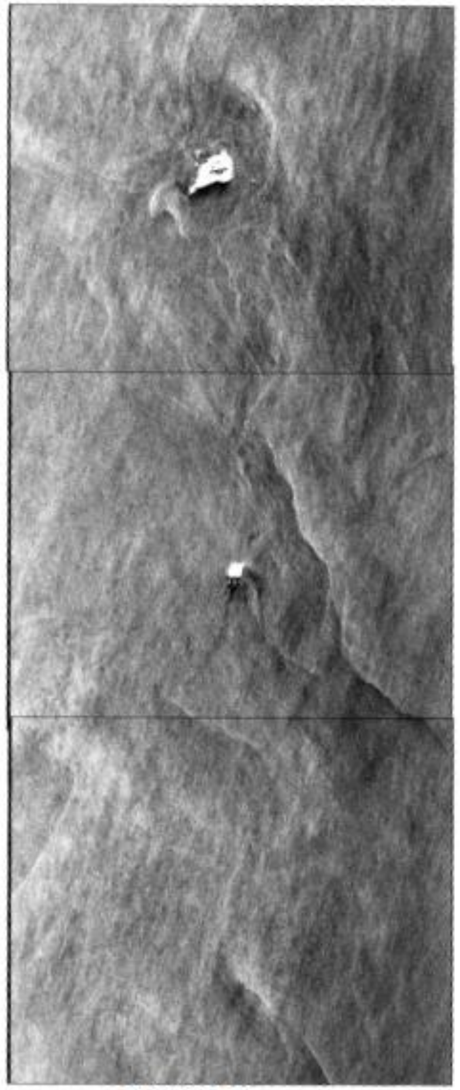
Fronts associated with ~2°C temperature gradient

Wind direction 90° to current direction

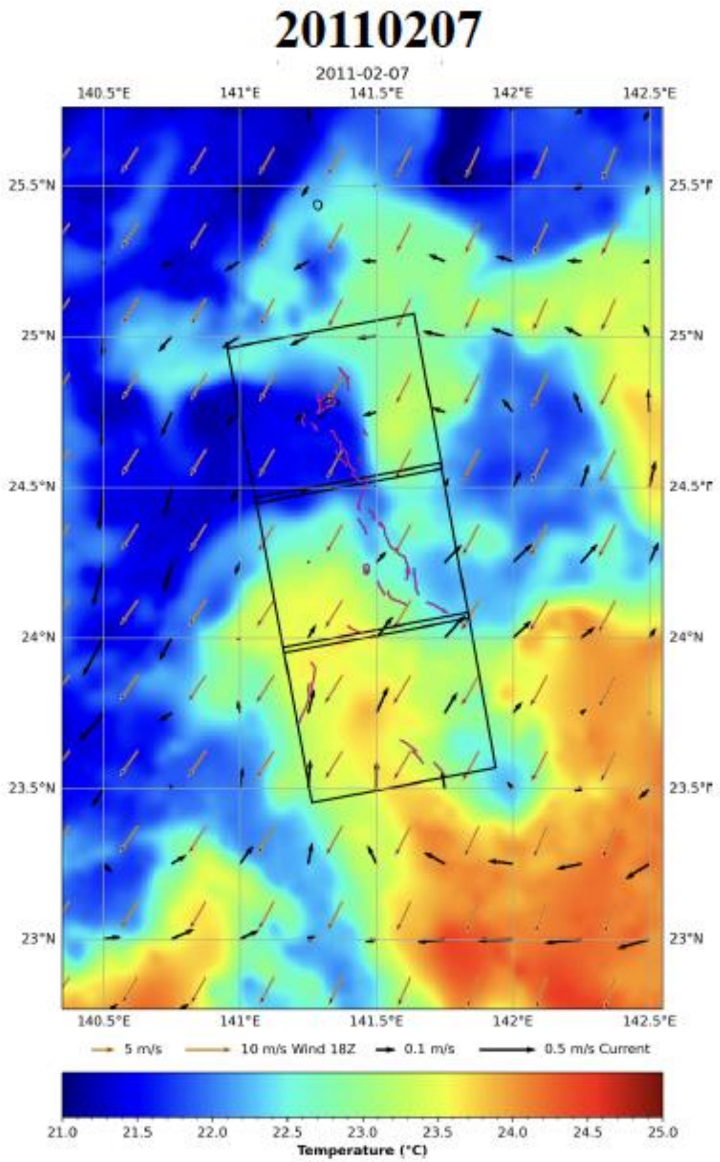


Thermal and Rougness Front

ALOS-1 SAR (268470)



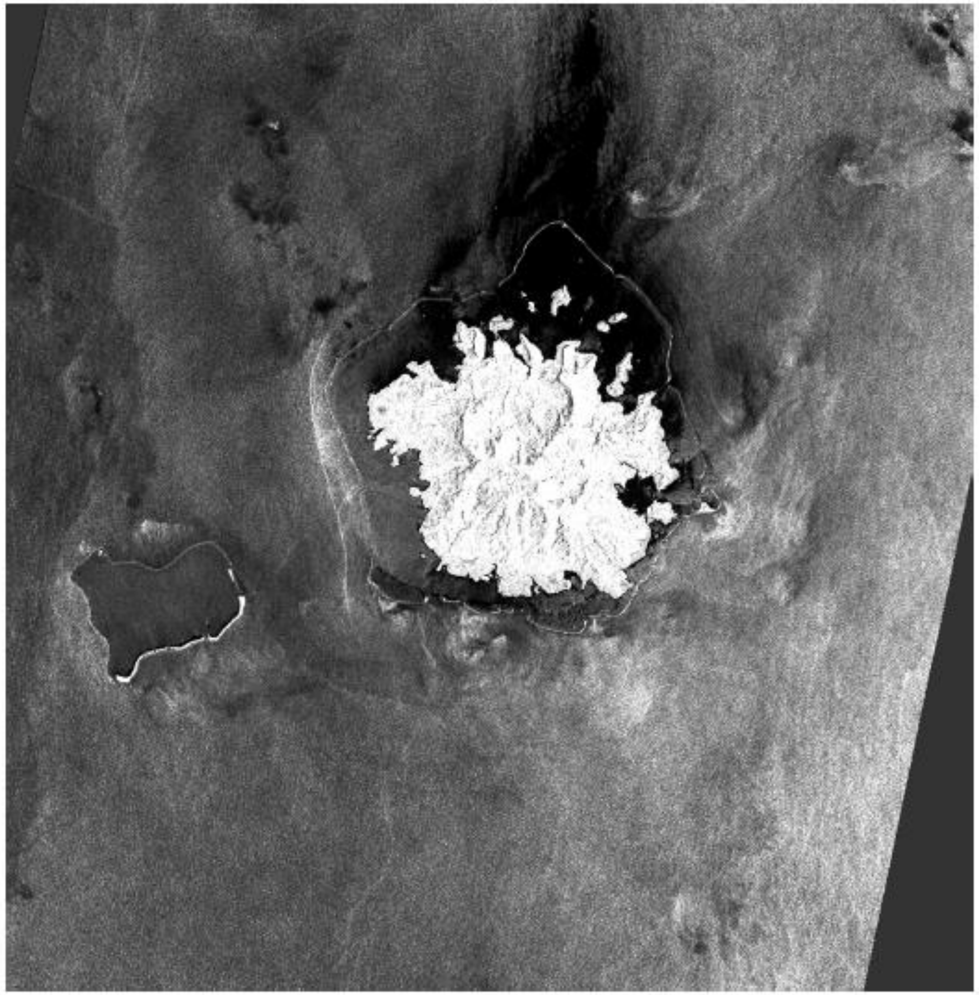
60X180 km

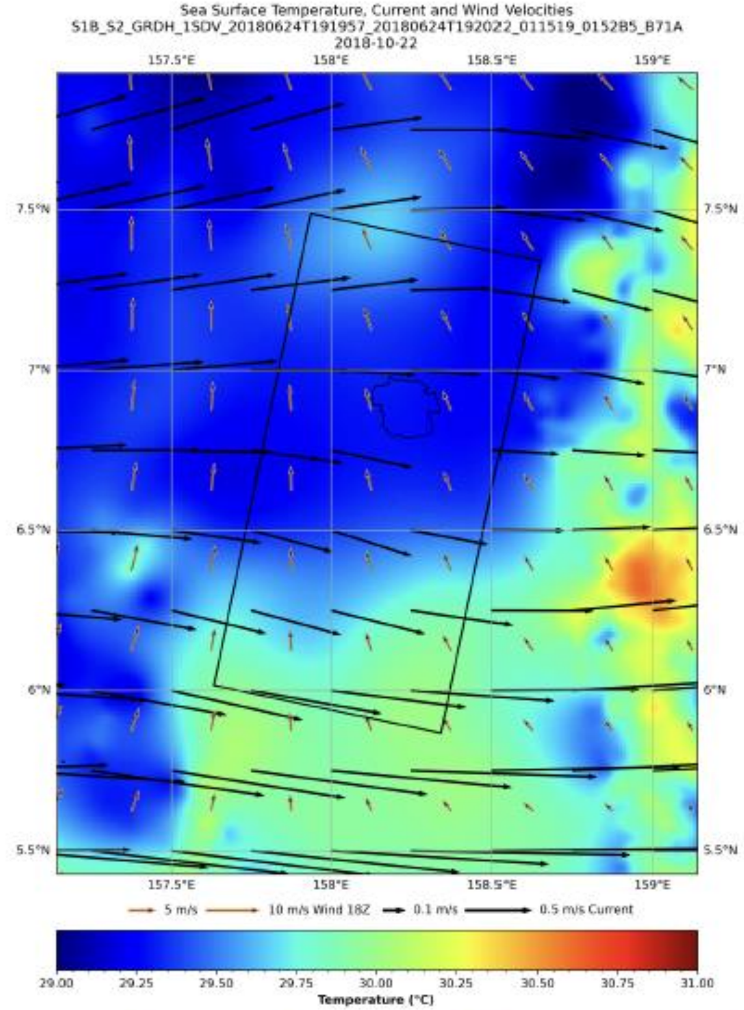


- Magenta lines indicate sharp fronts
- Fronts associated with ~1°C temperature gradient and island bathymetry
- Wind direction 180° to current direction

Fronts-waves-bathymetry

Pohnpei, Micronesia
Sentinel-1B, 20181022





- **Converging fronts related to winds, current, bathymetry**
- **Small vortices near island related to tidal flow, openings**

Summary

- *Convergent fronts identified in open ocean appear to be related to temperature and current gradients, orthogonal wind forcing, flow around shallow bathymetry. Identified in unusual collection of SAR oceanic imagery (ALOS-1).*

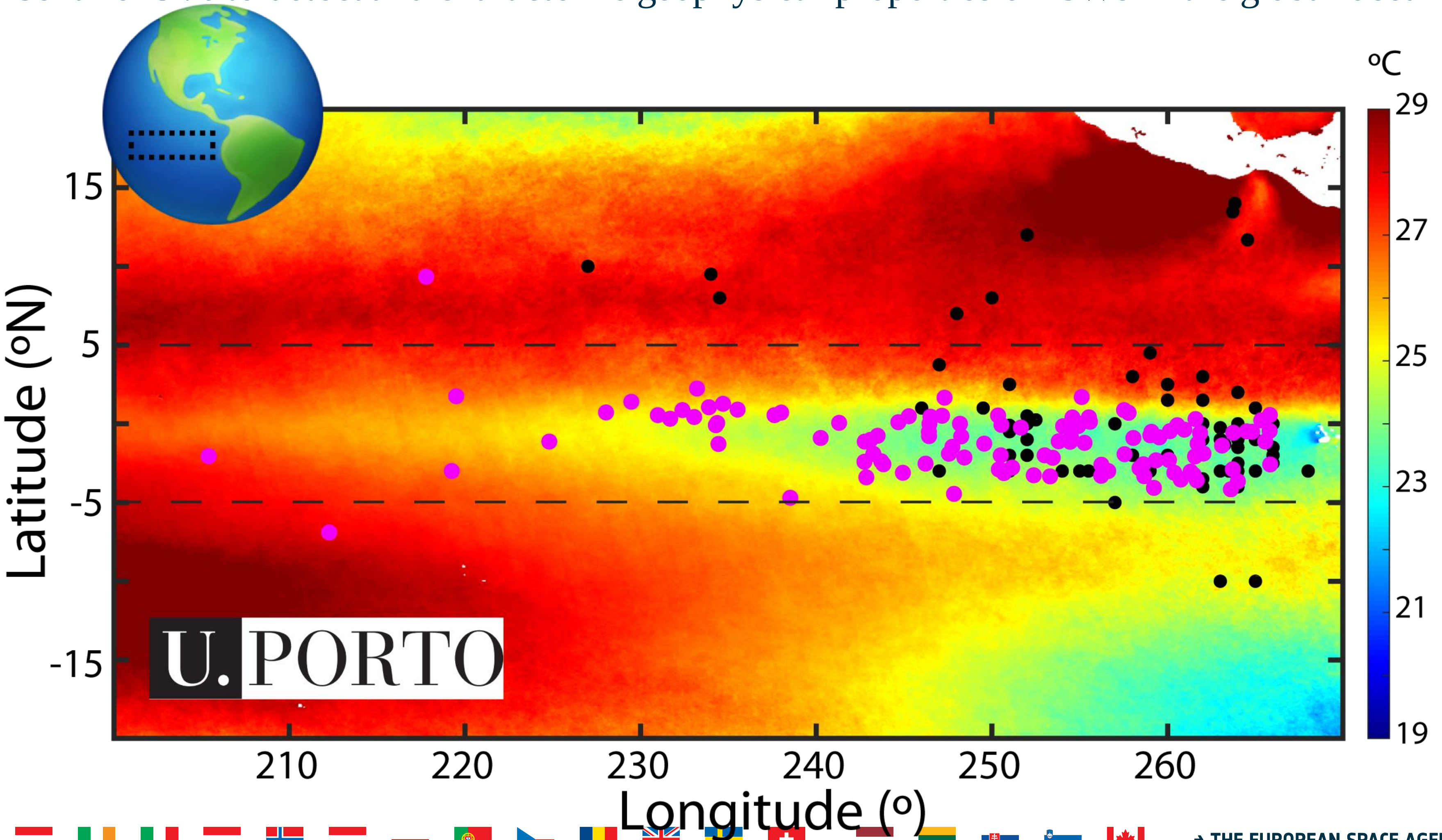
- *Time series of Pacific island showed dominant strong seasonal winds and waves, as well as detailed submesocale circulation patterns during seasonal periods of reduced winds and varying directions.*

- *Combined SAR observations with SST, ocean current, and wind data to examine ocean forcing conditions that form convergent fronts. Plan to quantify SAR patterns based on gradients.*

- *Recommend increased observations of SAR imagery 1) away from coastal regions (oceanic) in equatorial, subtropical oceans and 2) larger island groups*

Key objectives of research work at **U.PORTO – Courtesy of Jose da Silva**

1. Investigate the origin (and consequences to ocean mixing) of Internal Solitary Waves (ISWs) in the Pacific cold tongue near the equator, in a zonal band stretching from 210º to 265°E, away from any steep bottom topography.
2. Use SAR altimeter onboard Sentinel-3 /6 to detect and characterize geophysical properties of ISWs in the global ocean.

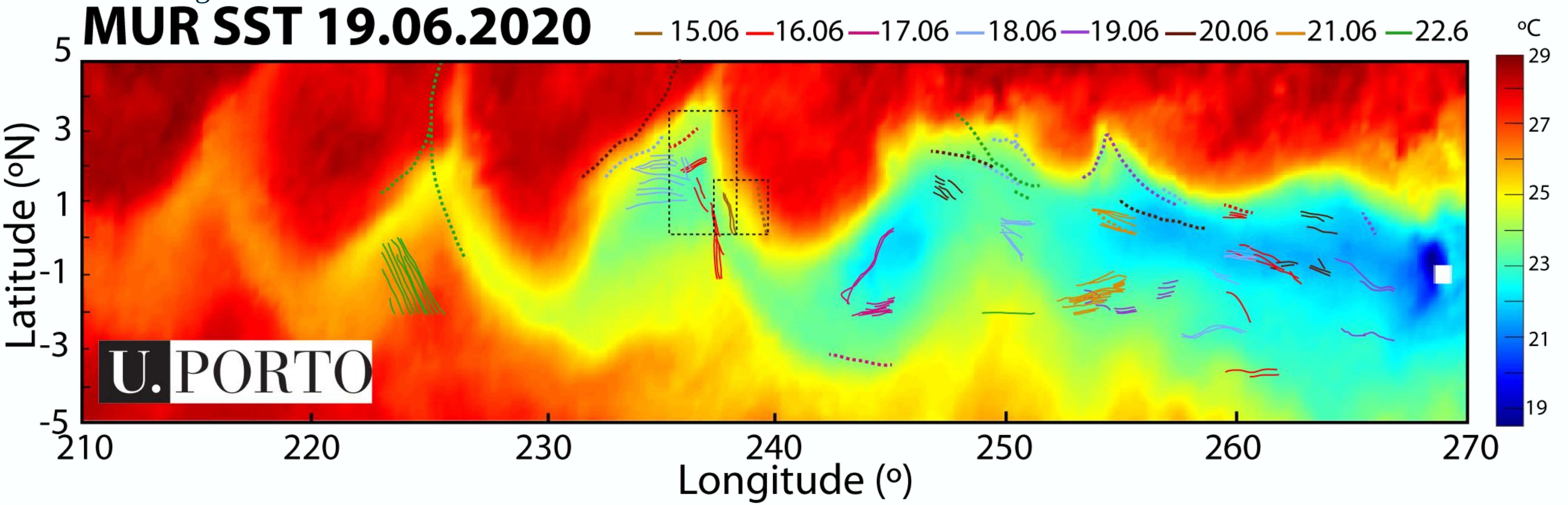


Spatial distribution of the ISWs found in Sentinel-3 OLCI images (magenta dots) for the year 2020. The black dots are the ISWs reported in Jackson et al. (2012). A MUR SST annual average image for the year 2020 is shown in the background.

New findings and achievements

U.PORTO

1. Within the equatorial band these ISWs waves propagate in multiple directions.
2. Some of the waves' characteristics such as wavelengths, crest lengths and time scales are estimated from Sentinel-3 observations (in the absence of available SAR images).
3. In total we identified 116 ISW trains during one full year (2020), with typical length scales between crests of 1500 m and crest lengths of hundreds of km.



Spatial distribution of the fronts (dotted lines) and ISW packets (solid lines), identified in the visible imagery of Sentinel-3, between 15th June and 22nd June 2020. The colour for each day is identified in the upper part of the map. A MUR SST image, dated 19th June 2020, appears in the background.

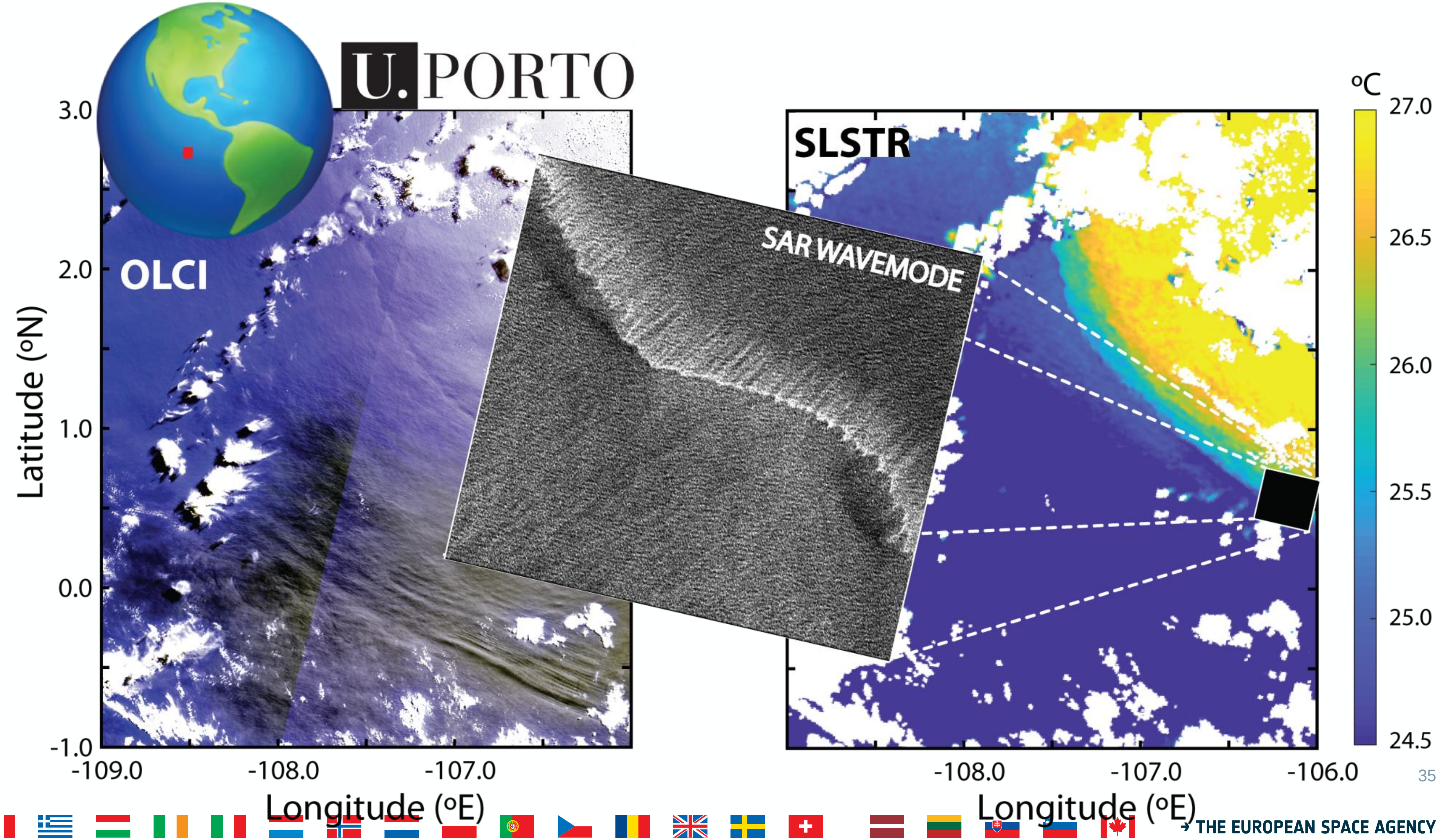
Remaining knowledge gaps and deficiencies

U.PORTO

Sentinel’s -1 SAR WAVEMODE is inappropriate to observe the full picture of this phenomenon; We need Sentinel-1 data in **IMAGE MODE** to be able to complete the picture and understand the full extent on ocean mixing of these newly observed internal waves.

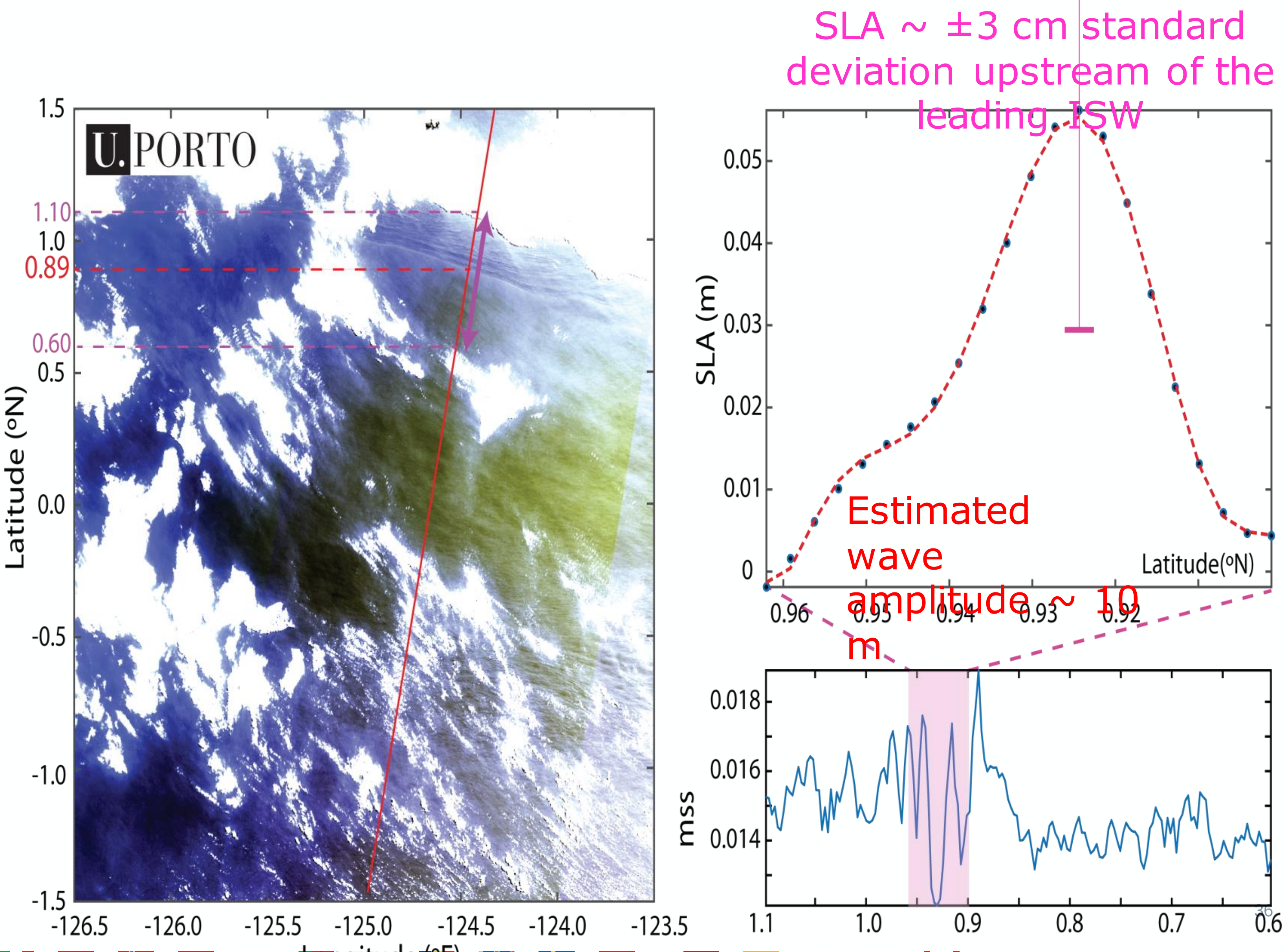
Left: OLCI true colour image showing evidence of an ocean front associated to Tropical Instability Waves (TIWs) and generation of ISWs (bottom right);
Right: SLSTR showing an ocean front and gravity current release;
Middle: SAR WAVEMODE from Sentinel-1, showing a gravity current.

ISW are generated by buoyant gravity currents, themselves originated from TIWs, having sharp fronts detectable in thermal infrared satellite images.



Outlook and recommendation **U.PORTO**

- Make a dedicated experimente of Sentinel’s-1 **IMAGE MODE** in the equatorial region of the Pacific, even if just for a limited period of time.
- The experimente’s period should be chosen during a La-Niña ENSO (or neutral) years, as during El-Niño less fronts are present, and the generation of waves may be diminished.
- New SAR missions (e.g. **SEASTAR**) should consider similar dedicated experiments in the Equatorial Pacific, which ought to be coordinated with future field campaigns.
- SAR altimetry’s advanced new modes may detect Sea Level Anomalies (SLA) produced by



Wider Significance

- We found generation of long-crested (typically 300 km) ISWs by relatively long-lived buoyant gravity currents, themselves originating from TIW dynamics within the cold tongue of the Pacific
- Travelling along the thermocline in the Equatorial Pacific cold tongue, these ISWs are subject to strong vertical velocity shears, leading to conditions of "marginal instability" and strong mixing.
- All these processes, including the strong dissipation rates associated with the gravity currents measured in Warner et al. (2018), may in the end impact El Niño Southern Oscillation (ENSO) irregularity and predictability (Holmes et al. 2019;Warner and Moum 2019).
- The association reported here of sharp ocean fronts and gravity currents with generation of large scale ISWs in the open ocean may turn out to be more common than previously thought.
- New observation techniques with appropriate resolutions may uncover new insights and quantifications of the cascade of turbulent energy from large to small and smaller scales.
- For this reason, it is suggested that a comprehensive **SAR IMAGE MODE experiment**, conducted in the study region, may clarify the issues uncovered in our preliminary study at U.PORTO

Polar Low Detection and Tracking from Multi-Temporal Synthetic Aperture Radar and Radiometer Observations

Biao Zhang & William Perrie
Bedford Institute of Oceanography, Canada

03/04/2023

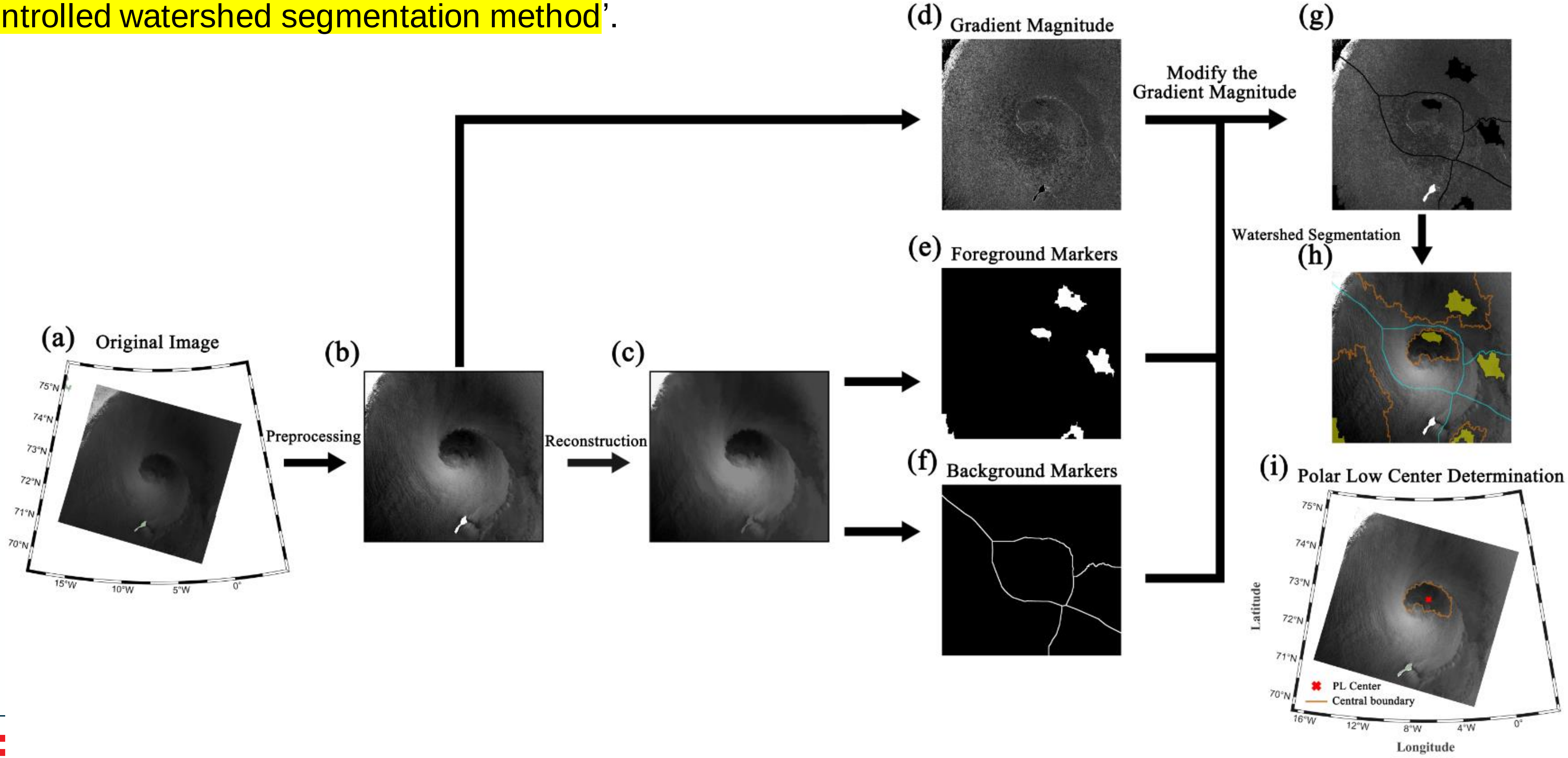
- Polar lows remain difficult to observe and forecast due to their short lifetime (<48 hours) and small horizontal scales (200~1000 km)

- Satellite remote sensing is an important method to monitor polar lows because of the sparse synoptic observing network that exists in subarctic and Arctic oceans.

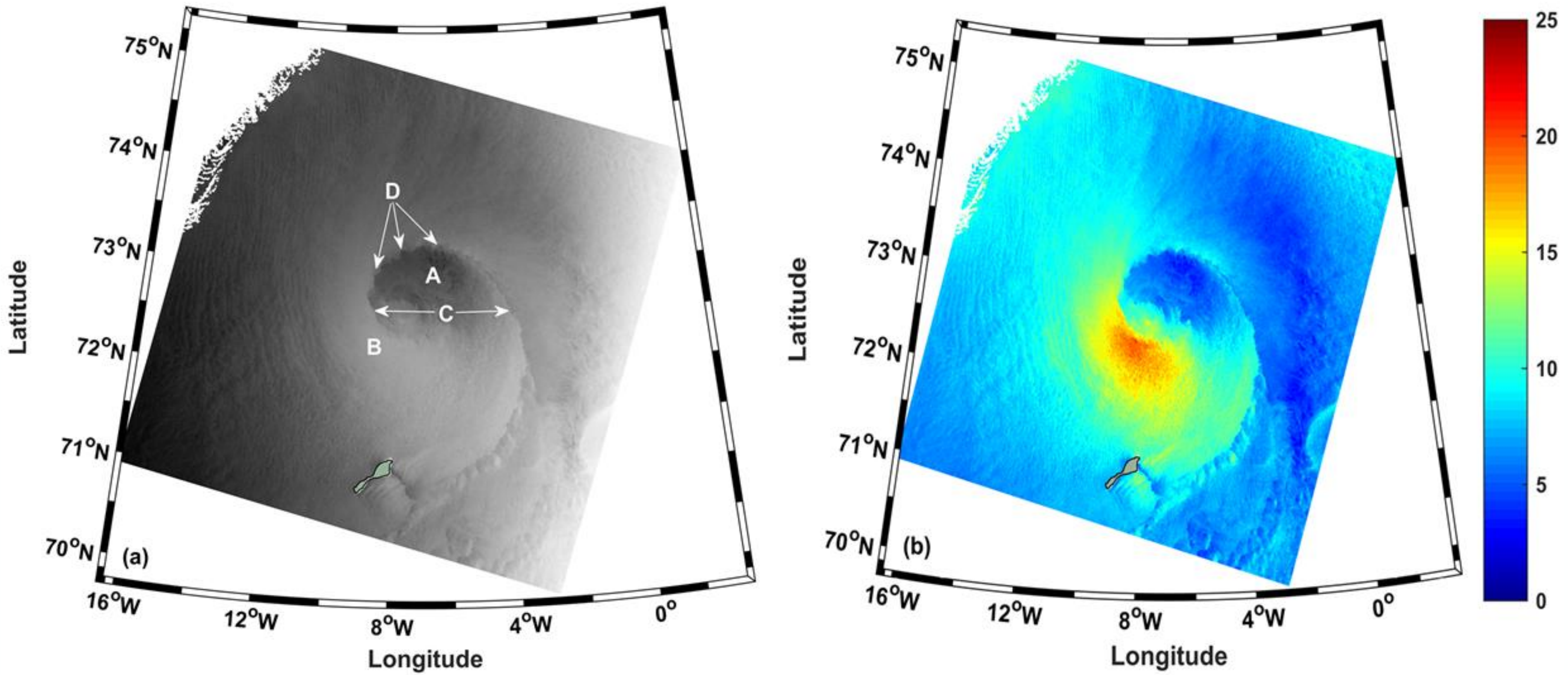
- Previous studies subjectively identified polar lows by visual inspection of satellite thermal infrared imagery. However, subjective visual analysis is time-consuming and inevitably involves error in polar low detections.

- We present an automatic procedure to objectively detect and track polar lows occurring in the Greenland Sea using spaceborne synthetic aperture radar (SAR) and passive microwave radiometer data.

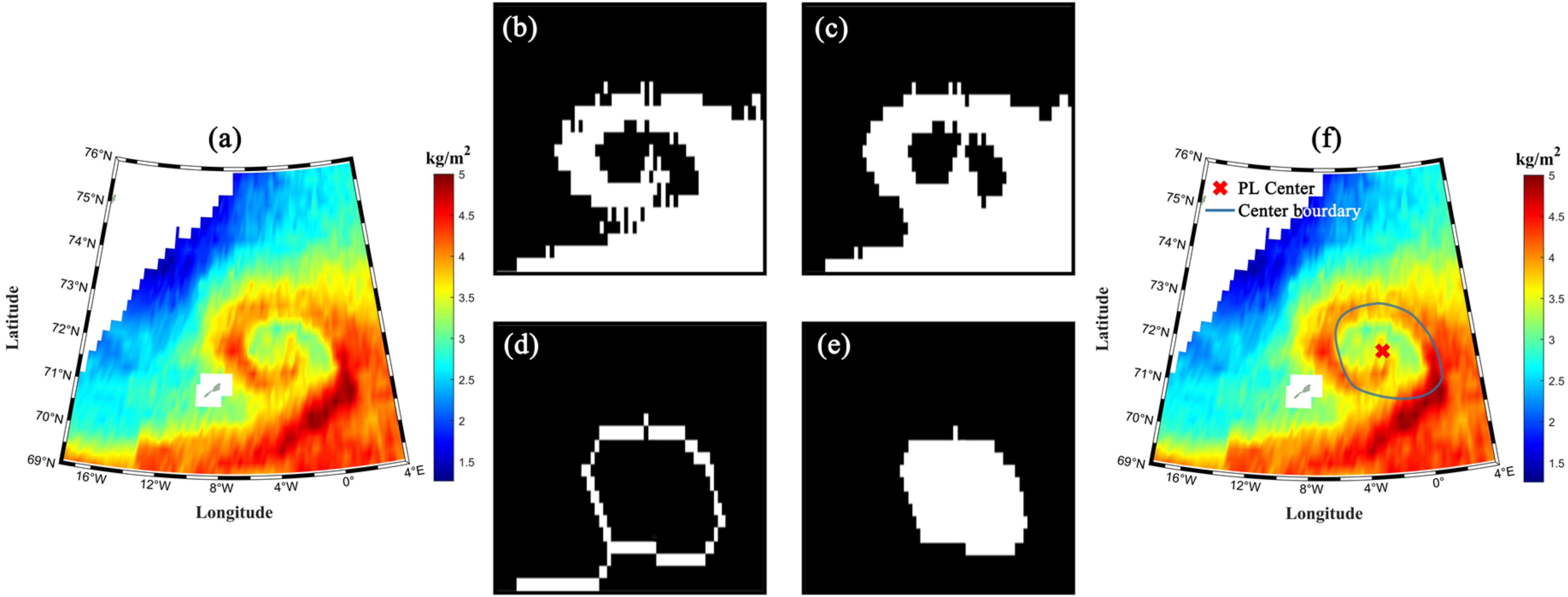
- We determine the polar low center from a high-resolution synthetic aperture radar image based on the ‘marker-controlled watershed segmentation method’.



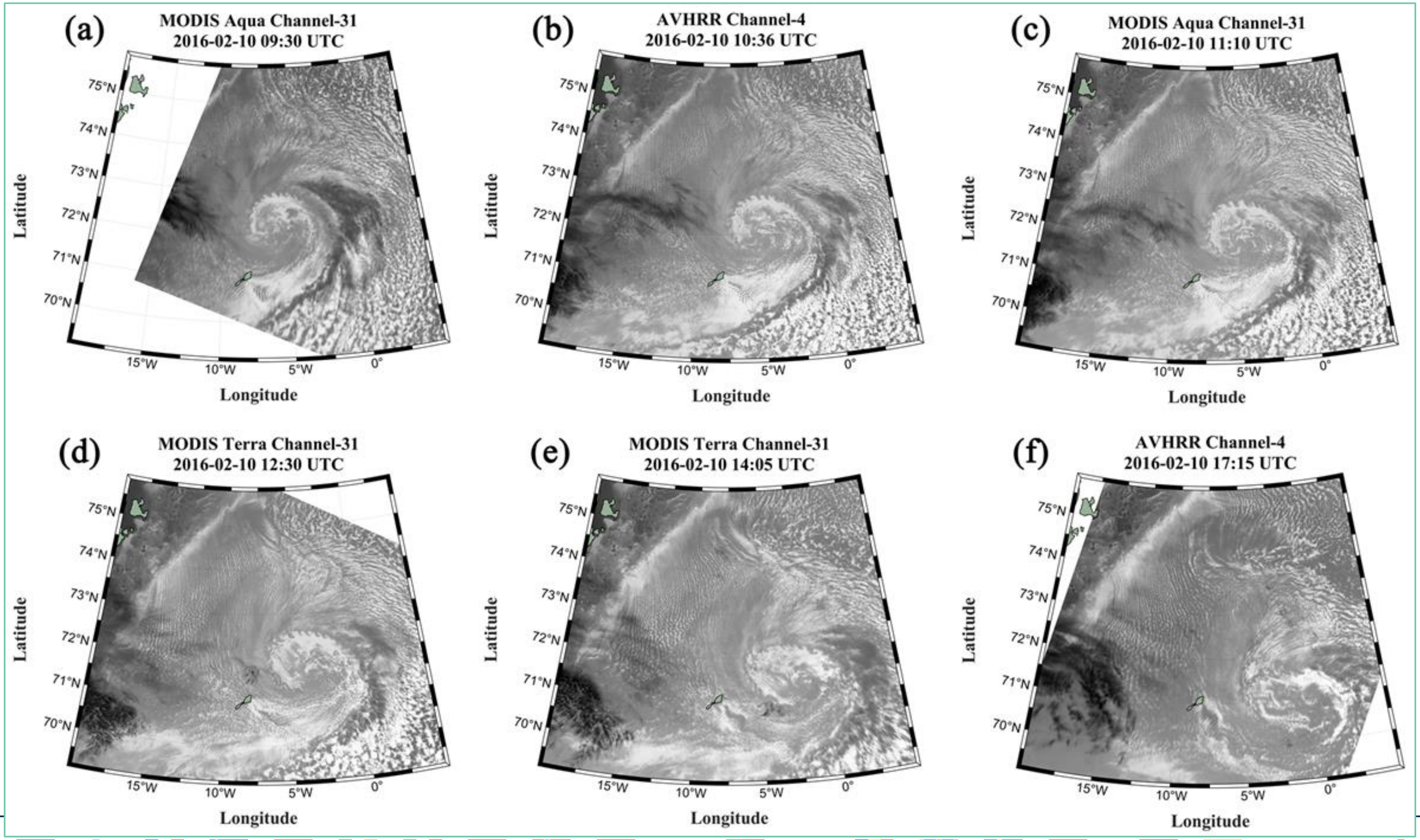
- SAR-derived high-resolution wind fields reveal fine-scale structure features of a polar low and confirm its presence.



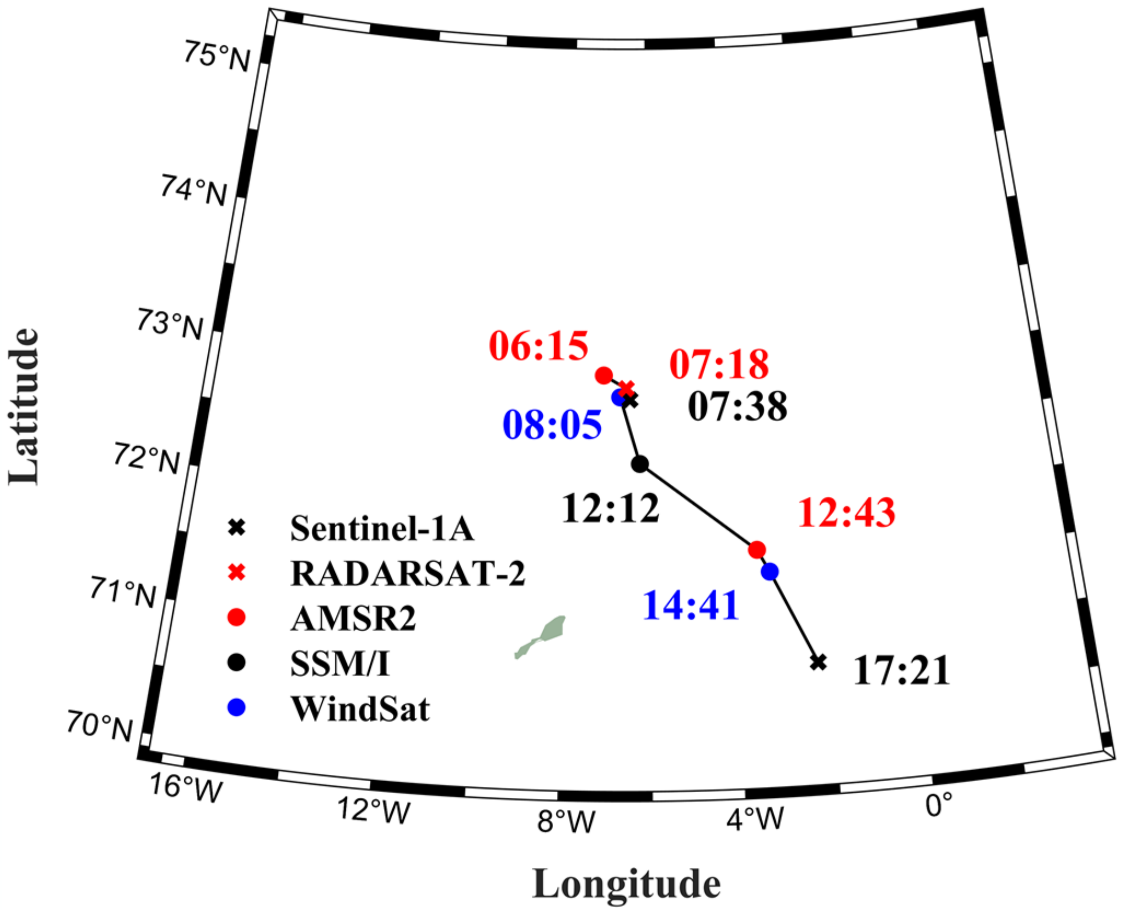
- We also use radiometer atmospheric vapor content data to determine the center location of polar low based on a morphological image processing algorithm (Thinning).



- Cloud vortex signatures visible on optical satellite (MODIS & AVHRR) thermal infrared imagery further confirm the existence of polar low detections from SAR and radiometer observations.



- Thus, the polar low track is identified via multi-temporal SAR + radiometer observations for its short lifespan (~12 hr).



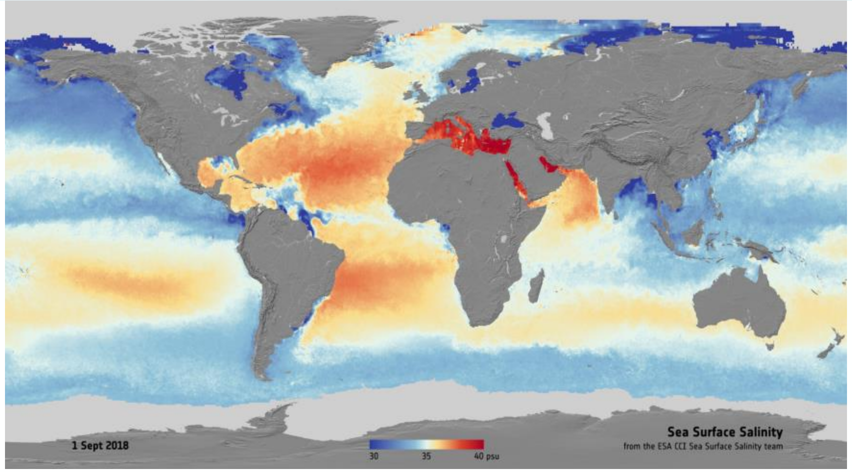
Can we retrieve SSS with polarimetric SAR ?

Thibault Taillade, Marcus Engdahl, Diego Fernandez

17/04/2023

Sea Surface Salinity from Space

- Salinity plays an important role in ocean circulation
- Estuaries:
    - Critical for natural habitat (interest in biology)
    - Complex sedimentation process (interest in hydrology)
    - Improve understanding of estuaries dynamics



- Two main constraints for coastal areas monitoring with current spaceborne sensor:
    - Resolution 30/50 km : Usual remote sensing sensor for salinity retrieval (SMOS, SMAP .. L-band)
    - Side-lobe illumination for hot land surfaces restricts passive systems to remain hundreds of km from the shore line.

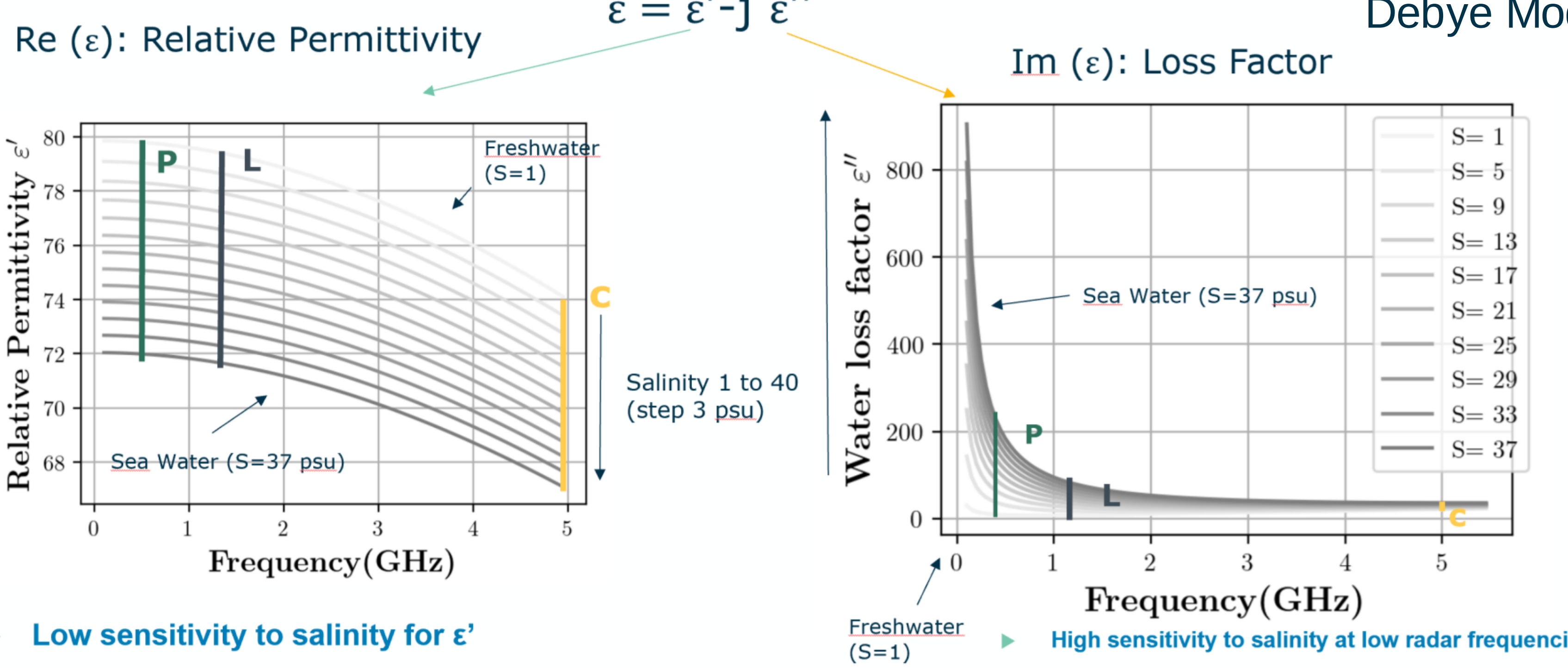
→ Can SAR help monitoring SSS in coastal areas ? (First and only experience Dehouck, 2002)

→ Interests to revive the topic with upcoming BIOMASS mission (2024)

Dielectric Properties of saline water

$\varepsilon = \varepsilon' - j\,\varepsilon''$

Debye Model : (Klein and Swift, 77)



- Low sensitivity to salinity for ε'
- High sensitivity to salinity at low radar frequencies for ε''

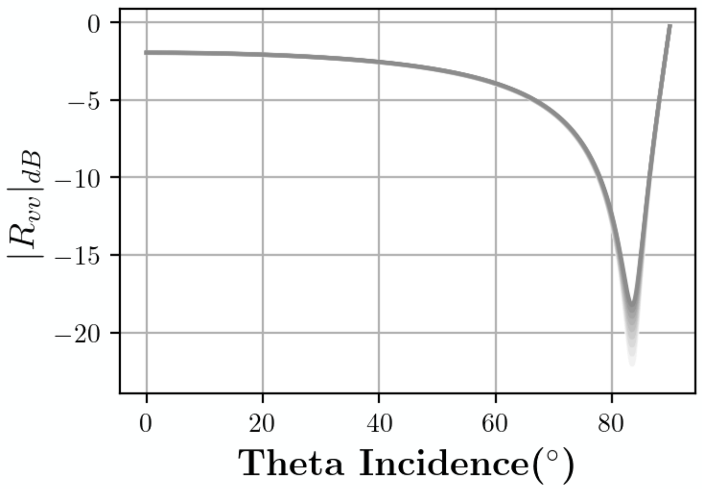
- Dielectric properties of seawater is sensitive to Salinity (and Temperature) at low frequency
- So are the Fresnel Coefficients, this should impact:
  - NRCS (Normalized radar cross section)
  - CPD (copolarized phase difference)
- Now the question regarding actual SAR measurements:

→ **How large is this contribution compared to the other variation sources ? (roughness from wind, current etc.)**

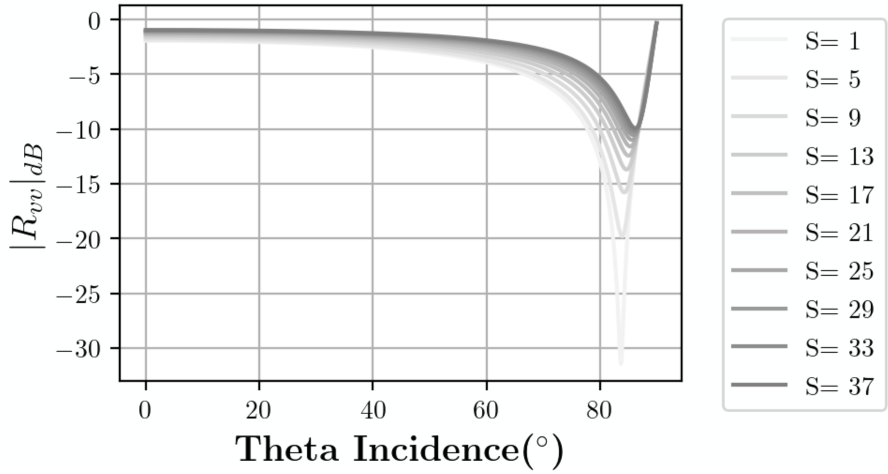
→ **How to physically minimize variations brought by the roughness and capture physical properties variations**

Fresnel coefficients and backscattering properties

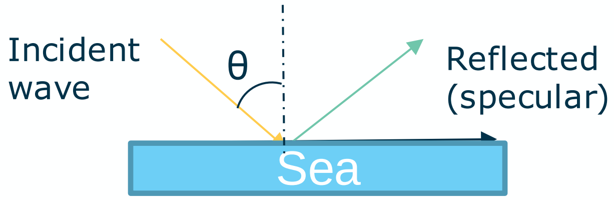
Modulus RVV – C band



Modulus RVV – P band



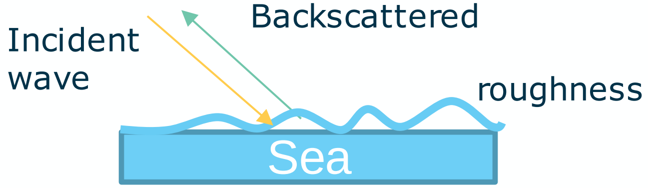
Specular



$$R_{hh} = \frac{\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}$$

$$R_{vv} = \frac{-\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}{\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}$$

Backscattering



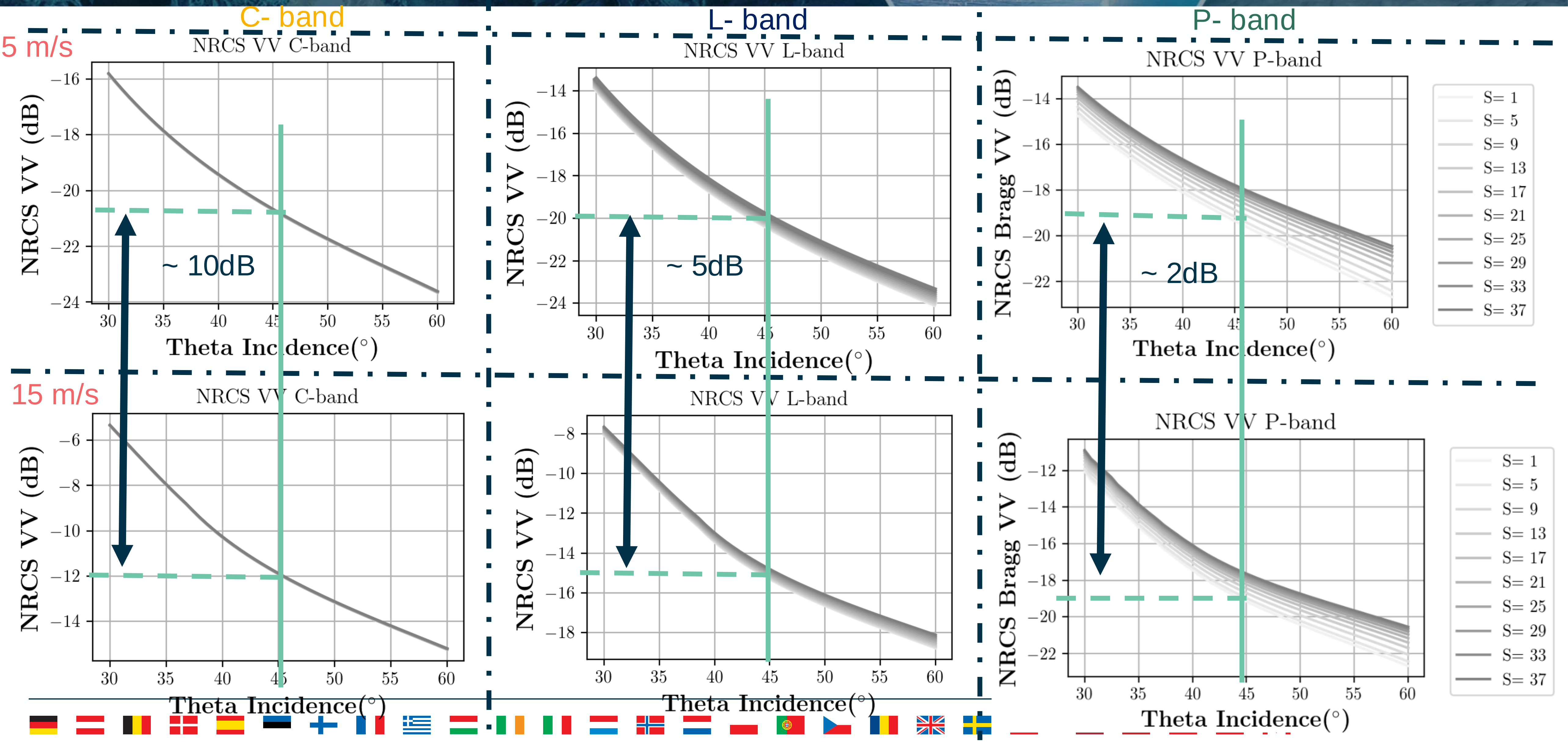
Forward modelling:

NRCS = function (θ, ε (f,SSS,SST), roughness) [Kudryavtsev, 2005]

CPD = function (θ, ε (f,SSS,SST), roughness) [Paillou, 2014]

→ How well decreasing the operating frequency enable to disentangle the dielectric properties of seawater from the roughness (wind)?

Bragg Modelling NRCS VV variations with incidence θ for direction φ=0°



Challenges, opportunities and way forward

- Decreasing frequency has the expected effect :
  - 1) Sensitivity to dielectric properties strongly increases
  - 2) Sensitivity to roughness (wind) strongly decrease

- Promising at P-band but still close to current SAR detection limit (NESZ, accuracy, sensitivity)

- Strongly challenging in coastal area (need for Synergy different frequency SAR and other EO sensors)

- Coherent polarimetric Forward Models/GMF ?

- Prepare for selection of sites for validation/experiment during BIOMASS mission with other collocated EO sensors (Is there a site in coastal already with sufficient equipment ?)

- Open discussion on experiment with BIOMASS for oceanography (Waves, Doppler, bathymetry ..)

Context:

1) Optical measurements to validate currents observed by Radars and SARs

STREAM-R +O , ODYSEA satellites

STREAMex ESA project

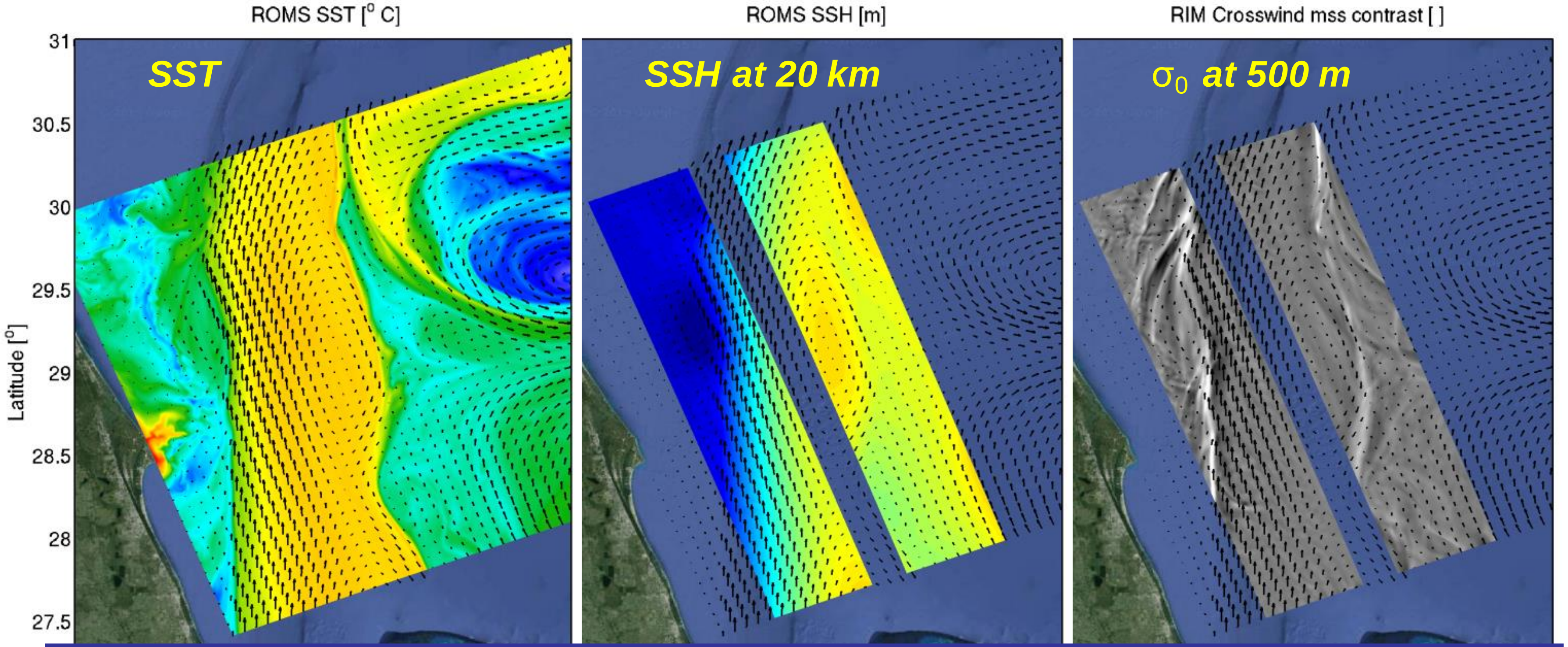
current directly deduced from wave phase speed

2) Optical measurements to help interpreting scatterometry at high resolution

Use of SWOT SSH + σ_0

HARMONY multi-azimuth scatterometry

Future current measurements :
Surface roughness to retrieve surface current gradients

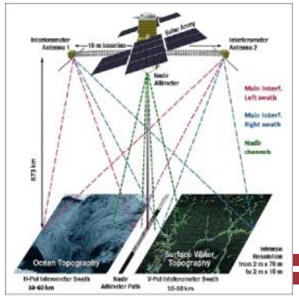


Gulf Stream numerical modelling of waves (WW3 or RIM) and ocean (ROMS)

(From Morrow et al 2019)

SWOT mission (2022)

SSH at 20 km



Surface roughness at 500 m

Future Harmony measurement involves SAR surface roughness at high resolution with azimuth diversity between fore and aft “beams”.

What can we anticipate?

Harmony in Stereo Config. viewing geometry:

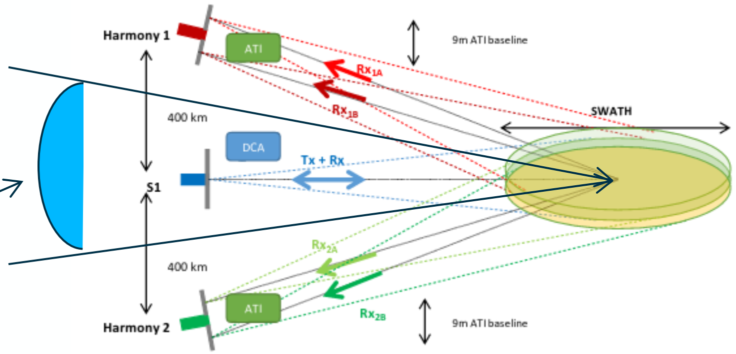
C-band roughness

S1 incidence angles: [20° 45°]

Harmony incidence angles [32° 48°]

Harmony azimuth difference [54° 27°]

Time delay 0 sec



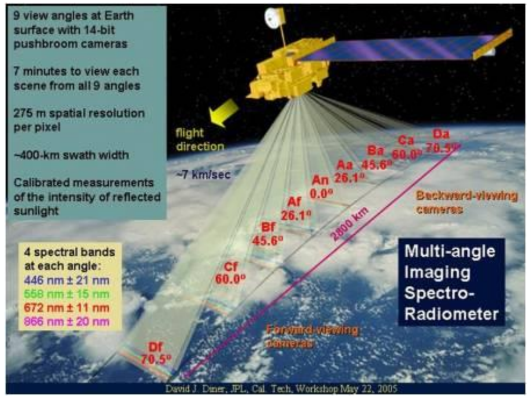
MISR sunglint:

Optical roughness

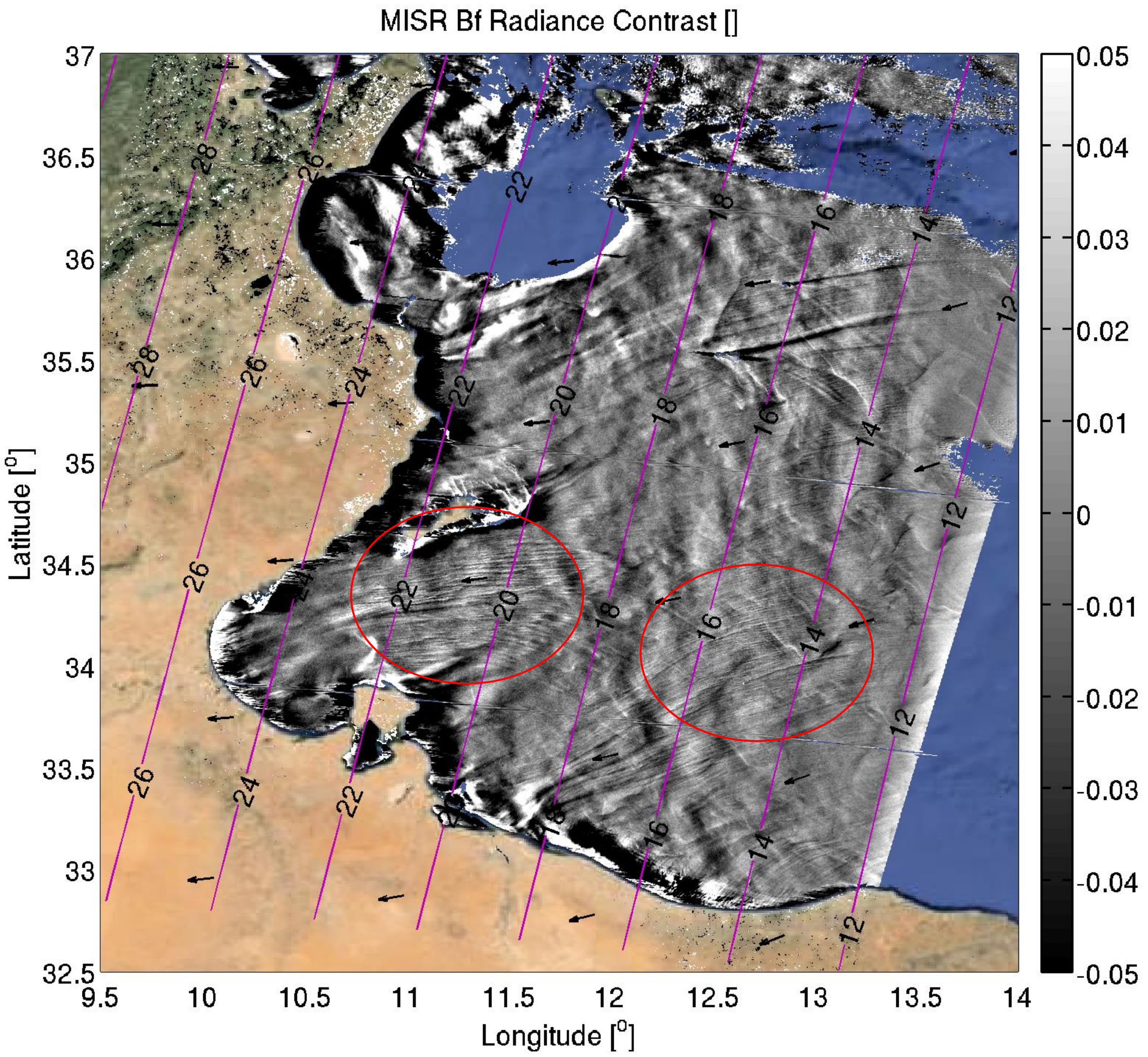
Incidence angles [0° 22°]

Azimuth difference [15° 165°]

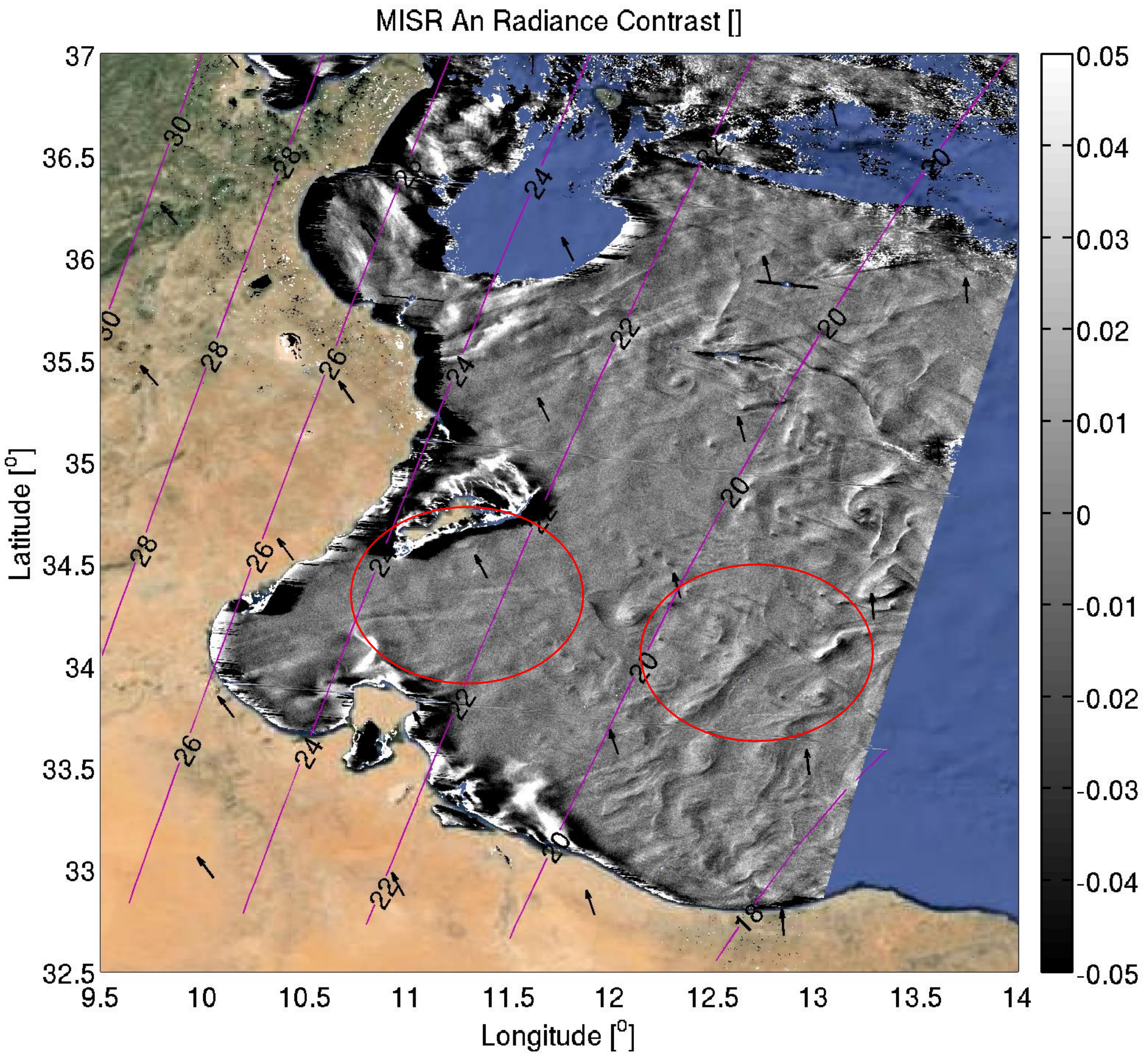
Time delay 45 sec < T < 7 min



20120303 Lybia: atmospheric rolls visible in upwind view and invisible in crosswind view

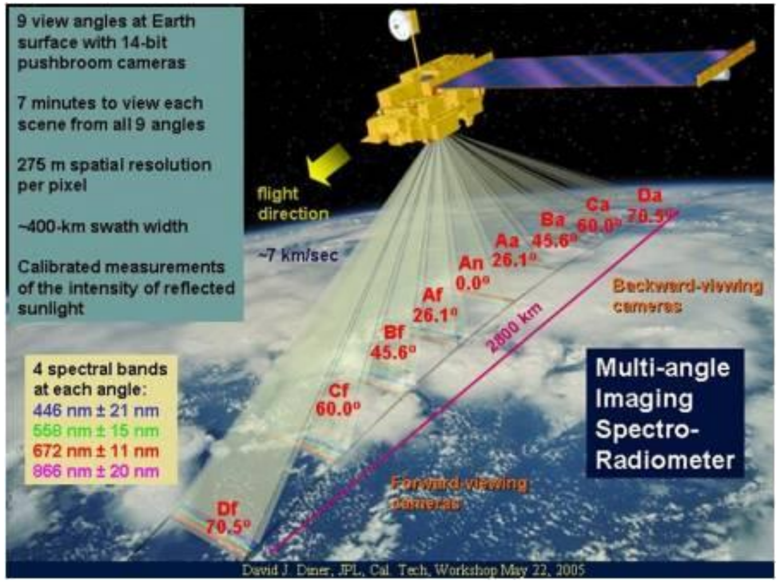


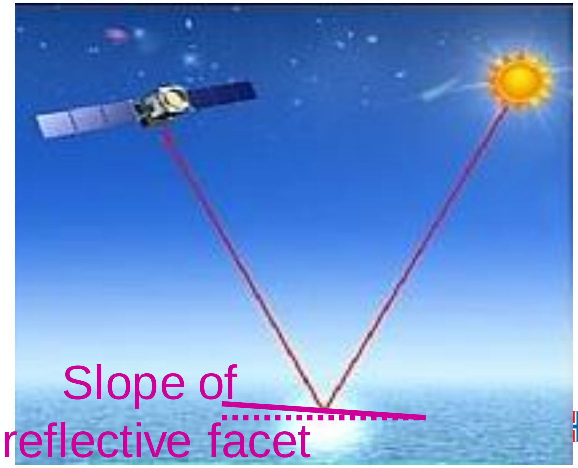
20120303 Lybia: atmospheric rolls visible in upwind view and invisible in crosswind view

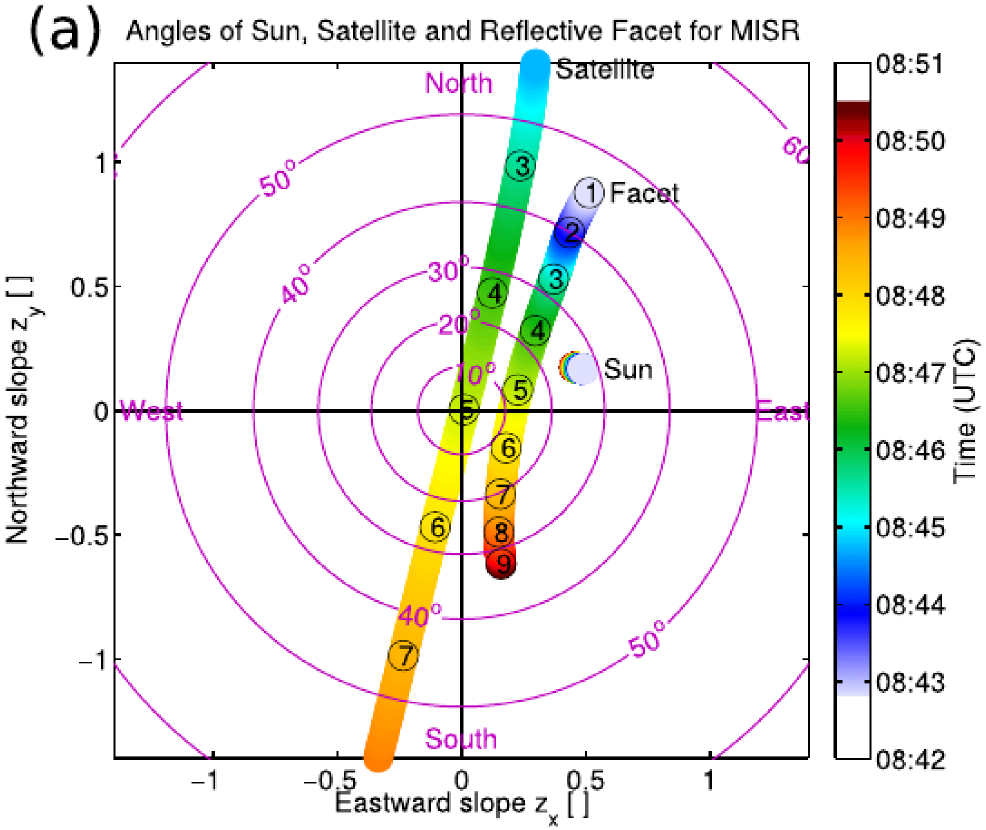


Proposition of a viewing geometry dedicated to wind, waves, current and bathymetry

Example of MISR multi-look sensor (onboard Terra)

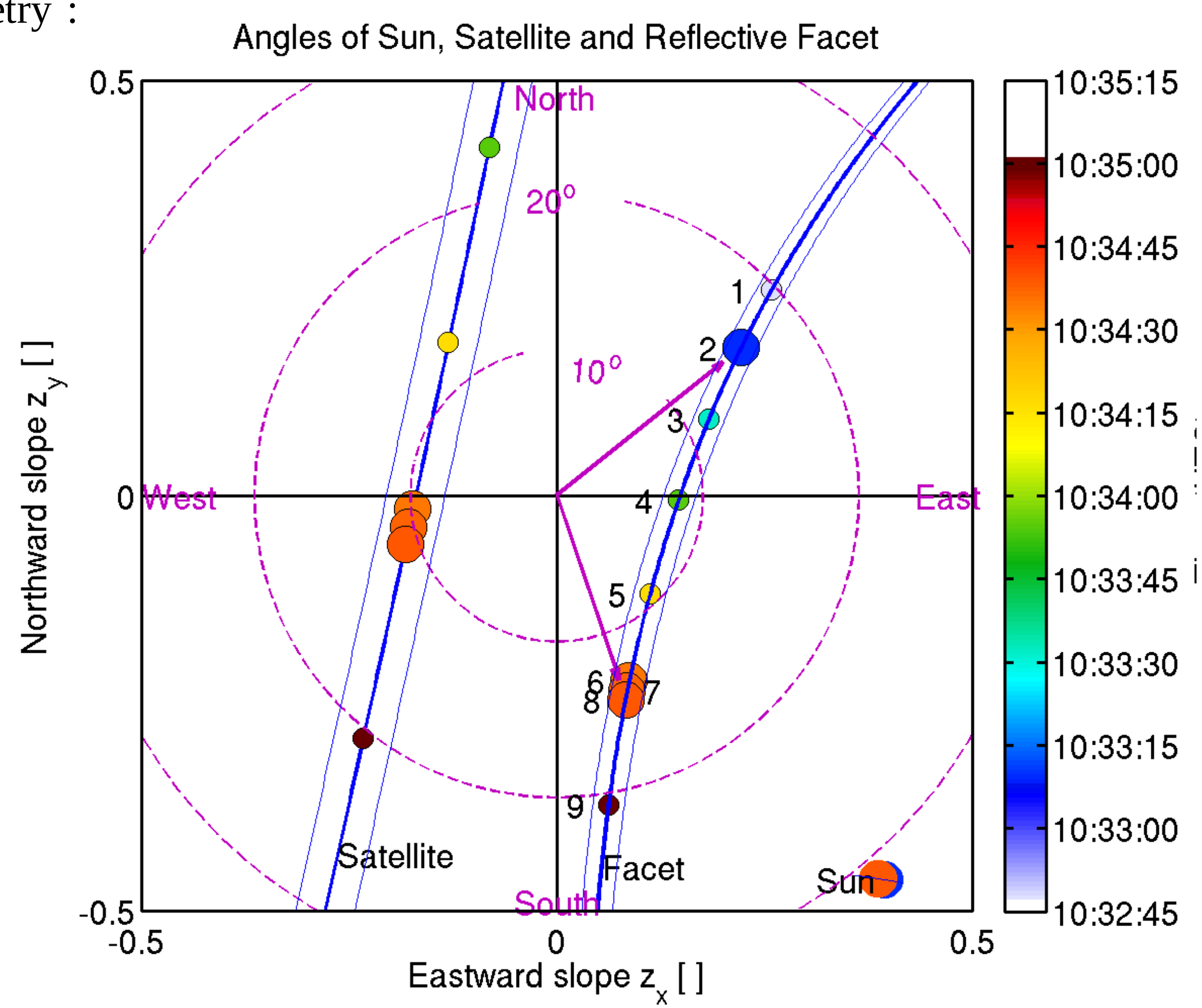






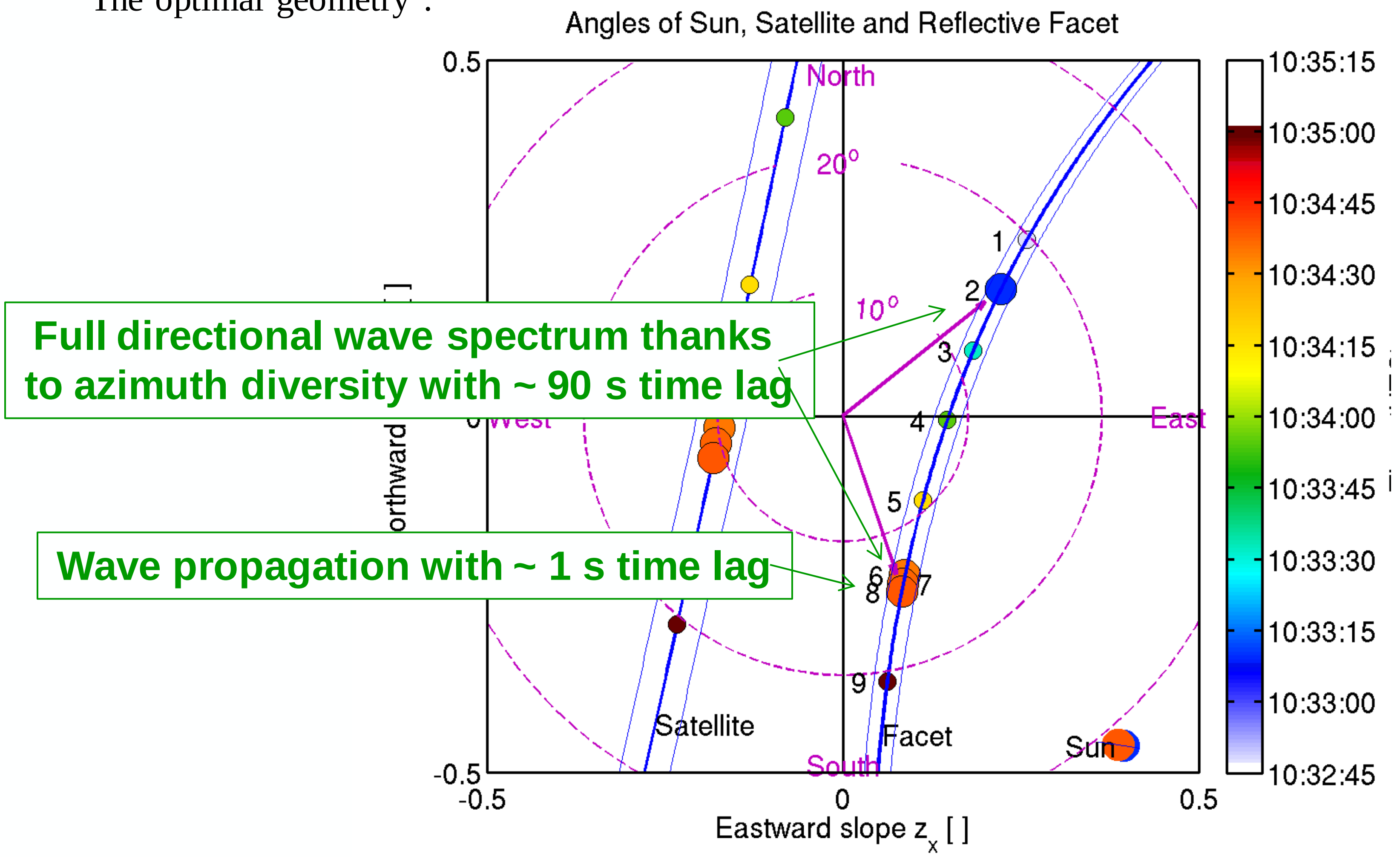
Proposition of a viewing geometry dedicated to wind, waves, current and bathymetry

The optimal geometry :



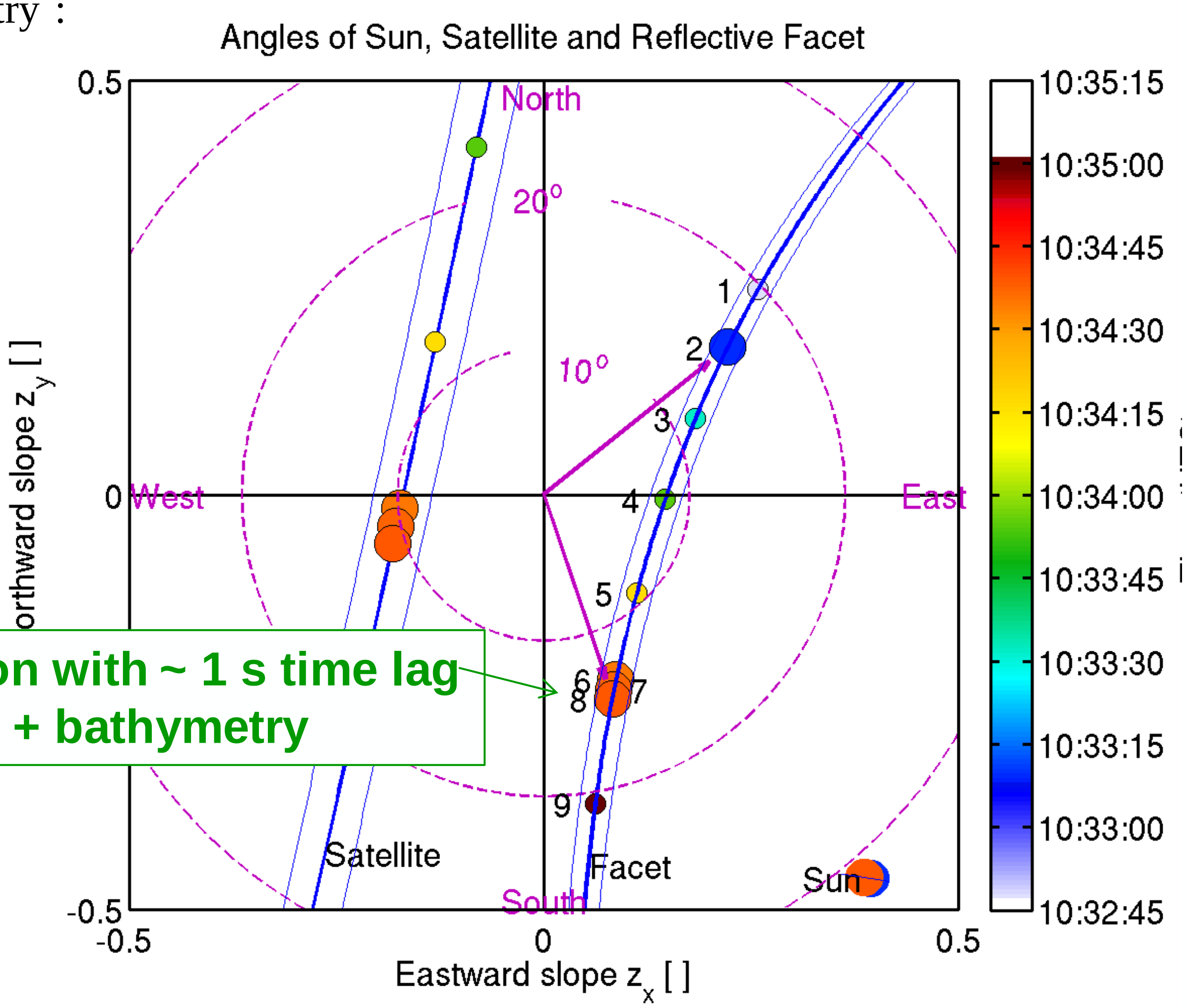
Proposition of a viewing geometry dedicated to wind, waves, current and bathymetry

The optimal geometry :



Proposition of a viewing geometry dedicated to wind, waves, current and bathymetry

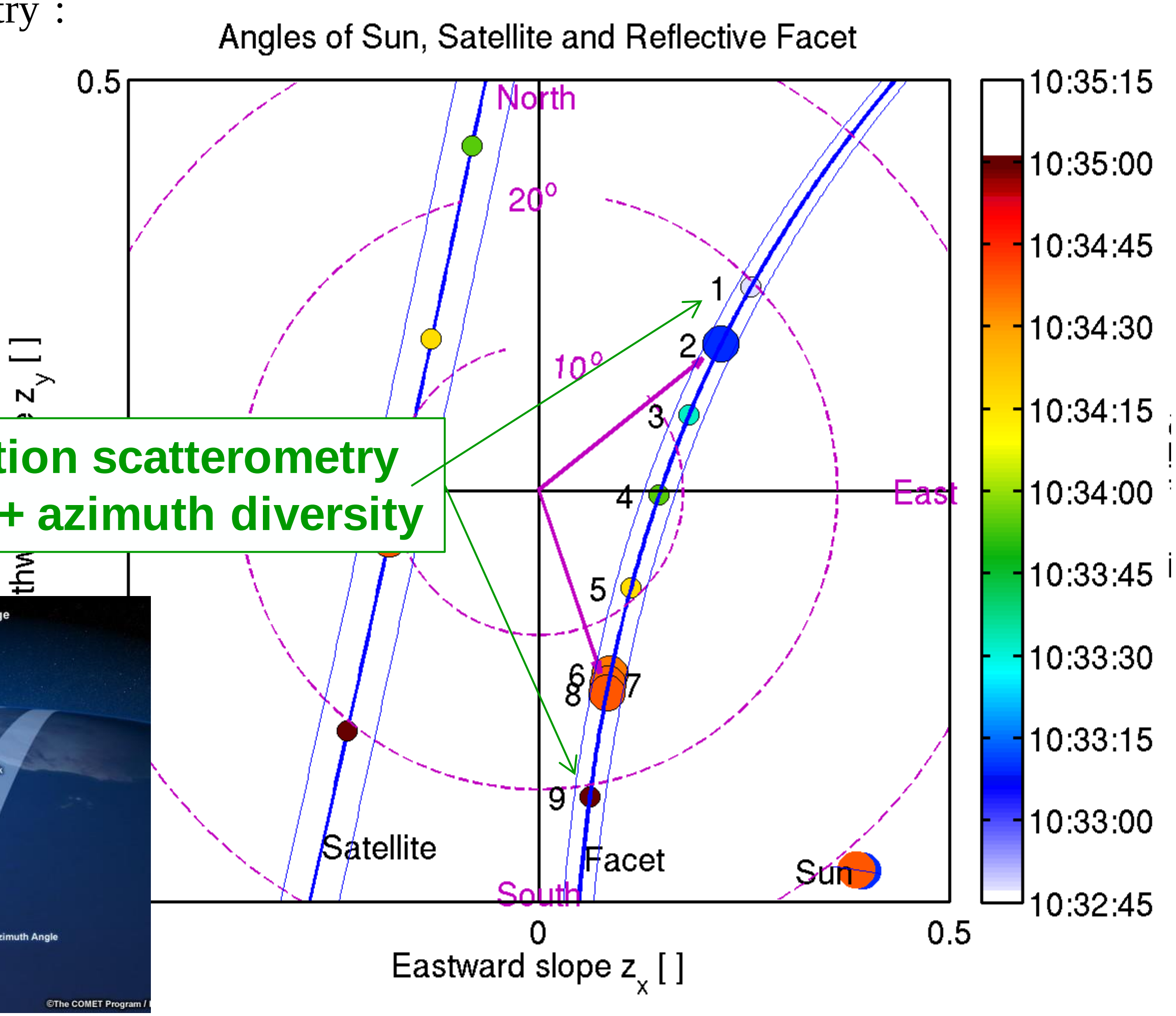
The optimal geometry :



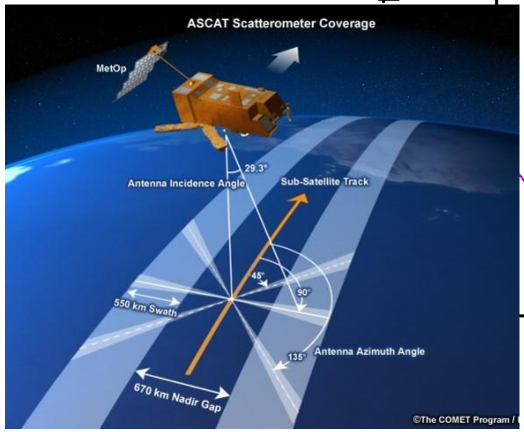
Wave propagation with ~ 1 s time lag
-> current + bathymetry

Proposition of a viewing geometry dedicated to wind, waves, current and bathymetry

The optimal geometry :



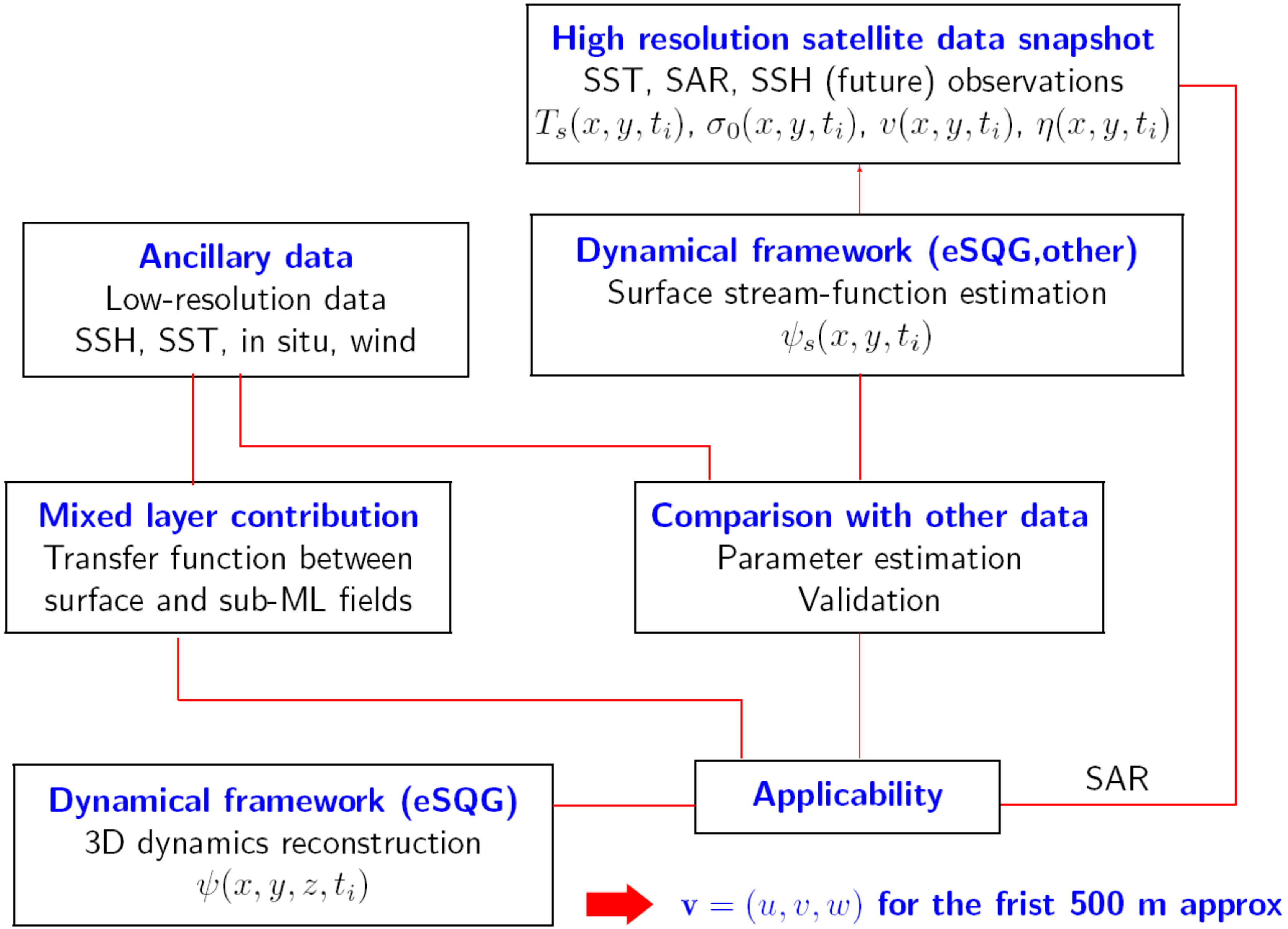
High resolution scatterometry using zenith + azimuth diversity

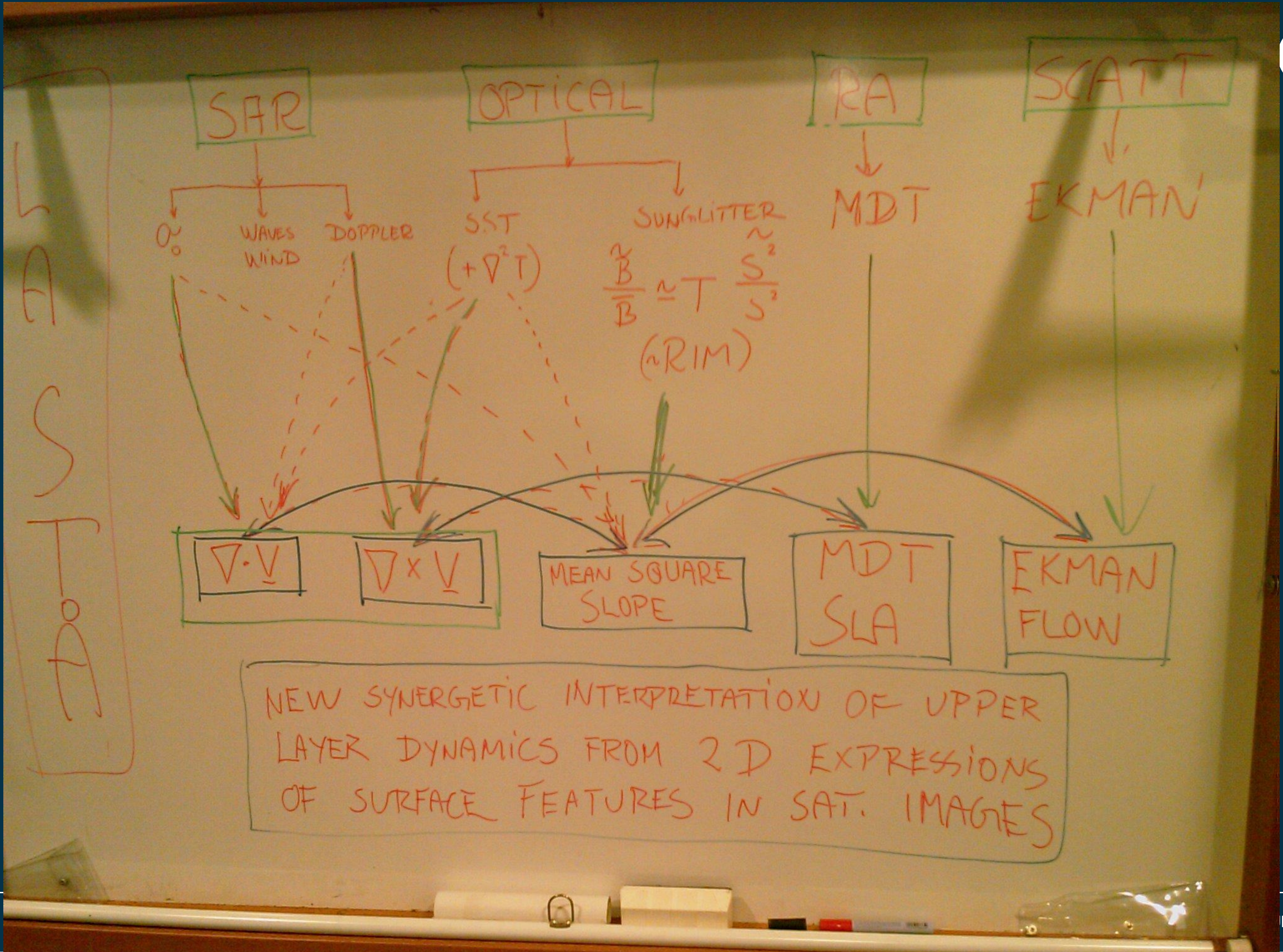


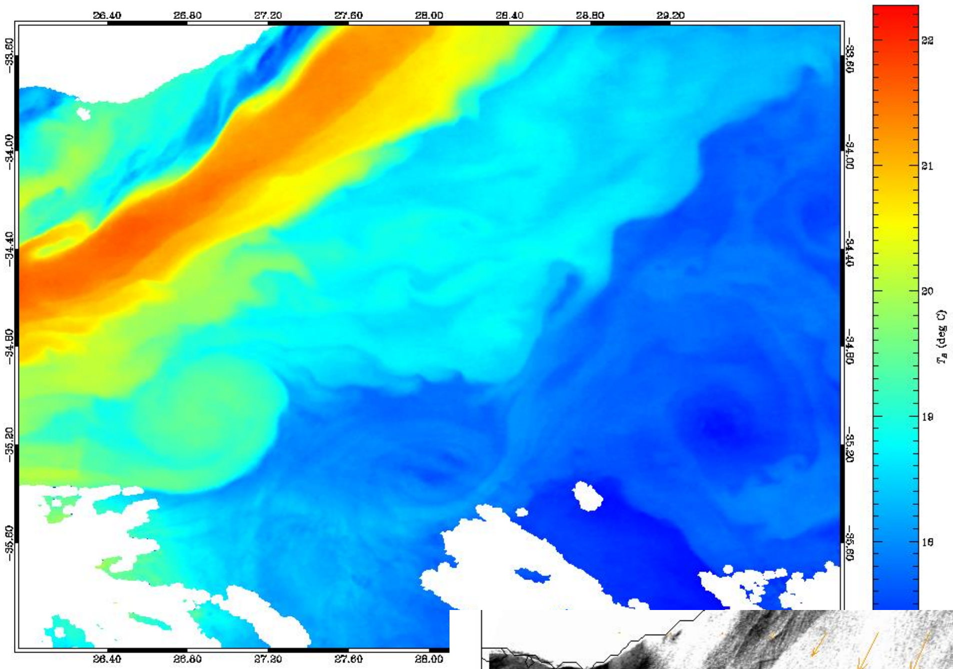
Conclusion and future work

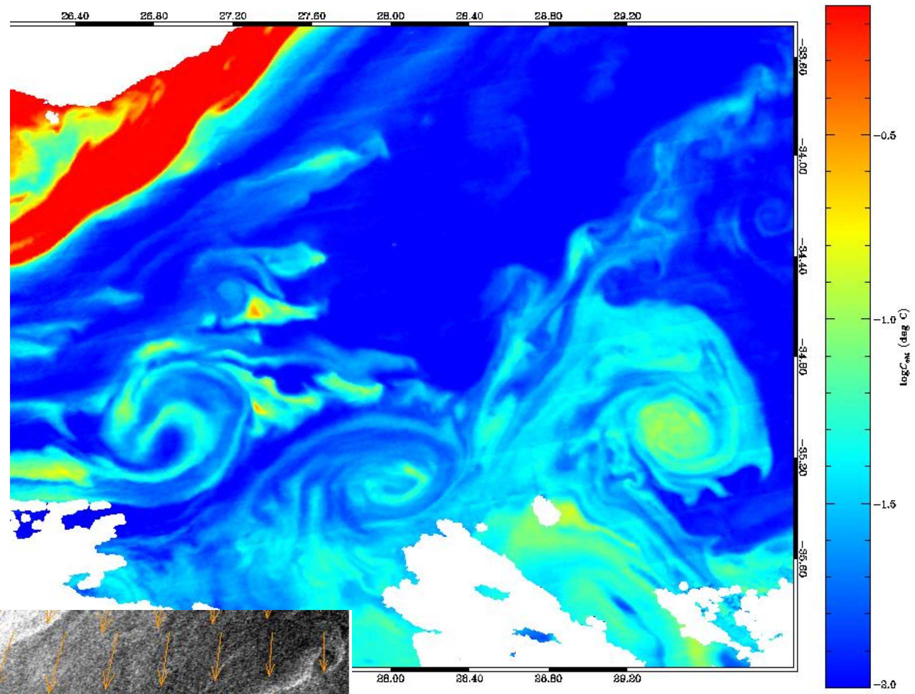
- Proceed towards framework for 2Dto3D (Chl, SST, roughness, mixed layer depth)
- Continue to extend and improve multi modal visualization platform
- Invoke model fields and in-situ data
- Take advantage of natural laboratories (Agulhas C., Gulf Stream, Med Sea, Lofoten basin, Fram Strait, etc…)
- Propose supersites for new approved mission validation invoking use of sensor synergy
- Propose multisensor observation products (frontal boundaries, eddy classification) for model simulation and validation
- Sensor synergy strengthen time-space coverage
- Sensor synergy give valuable input to orbit selection, coverage and phasing

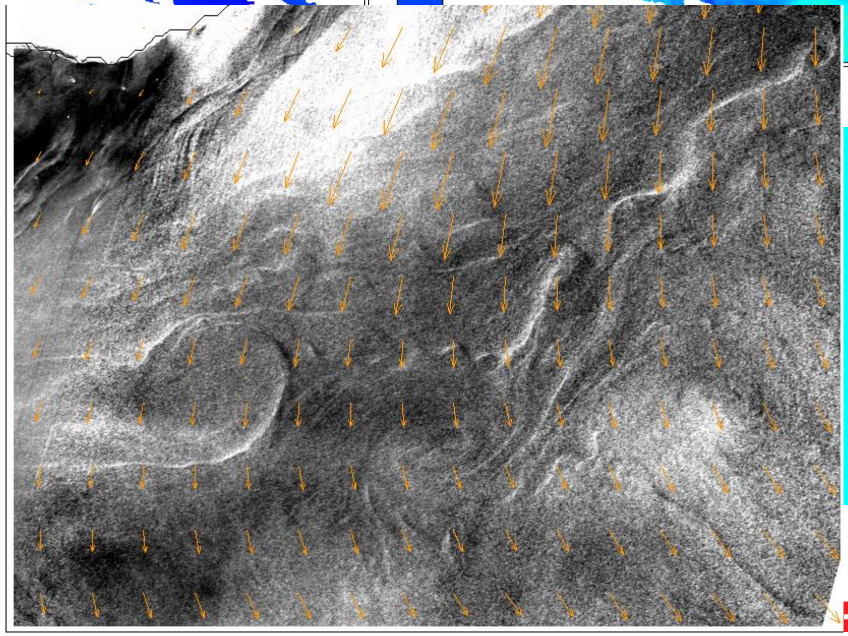
High resolution 3D ocean dynamics reconstruction from surface data




SAR
OPTICAL
RA
SCATT
WAVES
WIND
DOPPLER
SST
SUNGLITTER
MDT
EKMAN
(~RIM)
∇·V
∇×V
MEAN SQUARE SLOPE
MDT
SLA
EKMAN FLOW
NEW SYNERGETIC INTERPRETATION OF UPPER LAYER DYNAMICS FROM 2D EXPRESSIONS OF SURFACE FEATURES IN SAT. IMAGES

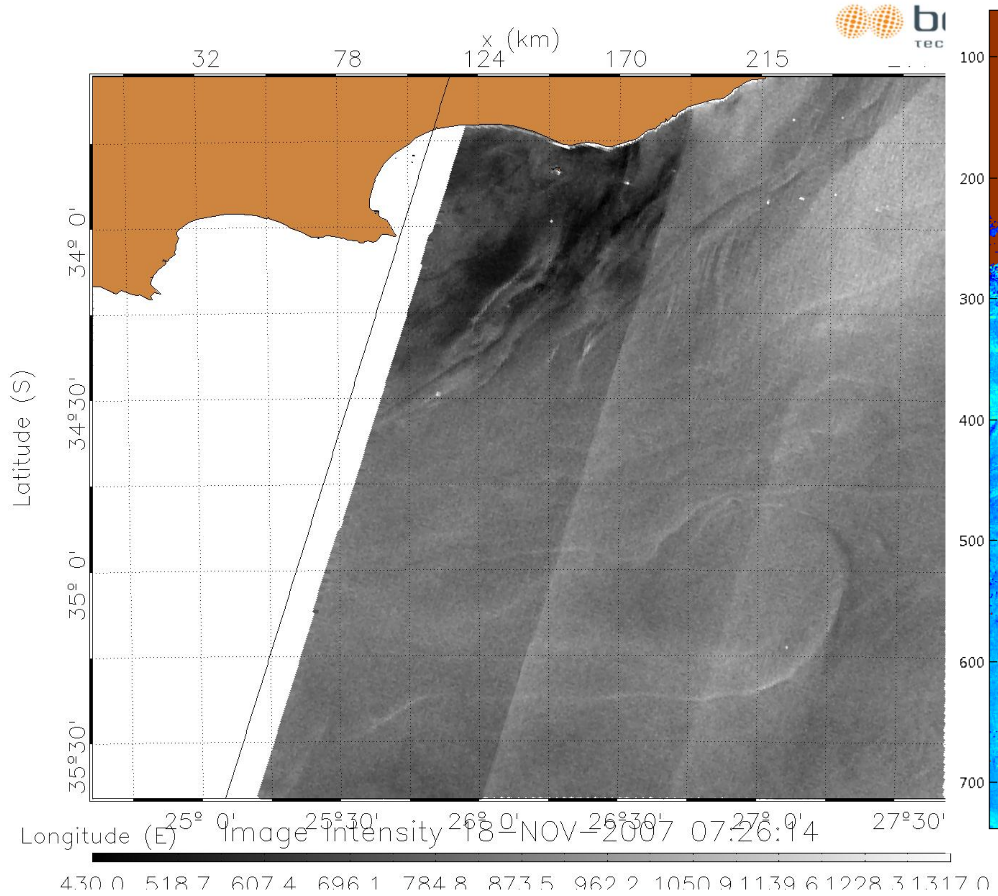


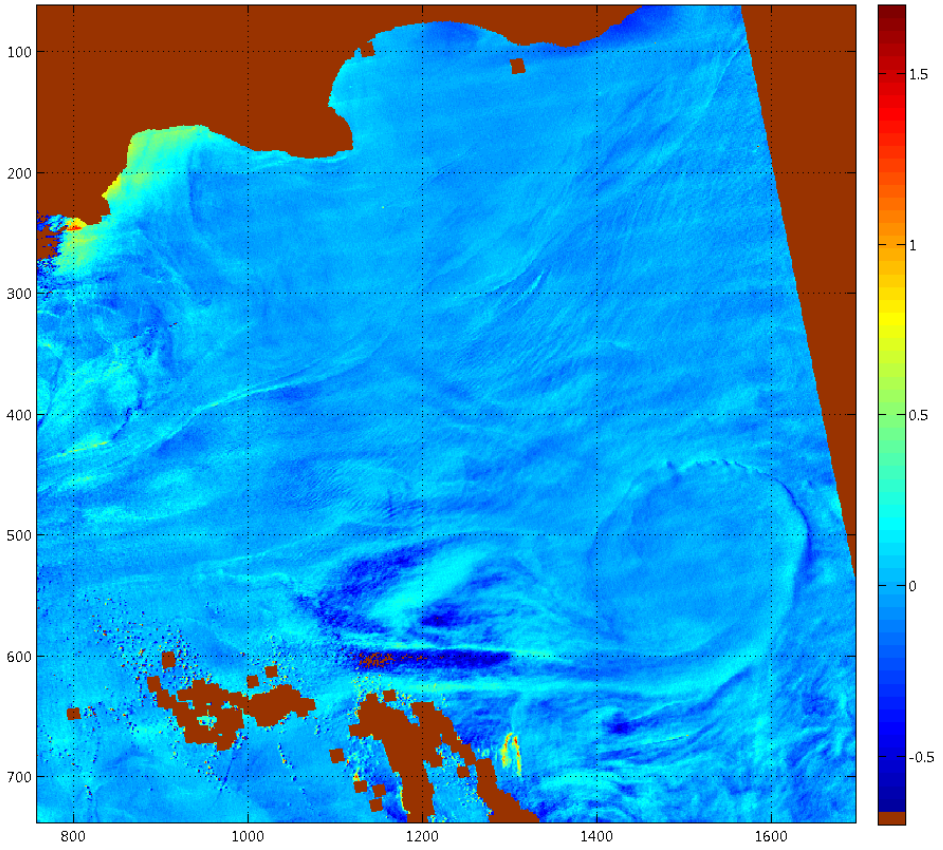




Synergy: MODIS Brightness temperature and colour along with ASAR

About 5 hours apart in acquisitions





Envisat ASAR Backscatter

MODIS Sunglitter

Sensor Synegy – Key Objectives

- A common driver for the expression of gradients and frontal boundaries is the surface currents and their spatial changes and meandering pattern including formation of eddies, filaments, internal waves, upwelling, convergence.

- Satellite derived surface gradients:
  (i) infrared- and microwave radiometer-based sea surface temperature;
  (ii) imaging spectrometer-based chlorophyll distribution and concentration;
  (iii) altimeter-based sea surface height anomalies;
  (iv) SAR-based surface roughness including wind seas and swell modulation;
  (v) SAR-based range Doppler shift;
  (vi) Optical derived sunglint anomalies

- Near real-time monitoring and quantitative interpretation of mesoscale upper ocean processes and dynamics will advance with consistent use of sensor synergy

- Sensor synergy shortcut detection limitations by each individual sensor

- Must be systematically applied in assessing new satellite sensor capabilities

Sampling or undersampling the mesoscale

Fronts	Sensor	Coverage		
		Swath	Spatial Resolution	Revisit Time
SST	Microwave	~ 2000 km	25 km	Daily
	Infrared	~ 1000 km	300m – 1 km	Cloud limited
Chlorophyll	Spectrometer	~ 1000 km	300m – 1 km(10m)	Cloud limited
SSH	Radar altimeter	Track data	25 km	>weekly
Roughness	SAR	100-400 km	~ 1 km	weekly (region)
Waves	SAR + RA (SWH)	20km-20km	~ 10 m	>weekly
Current	SAR Doppler	100-400 km	>1 km	>weekly