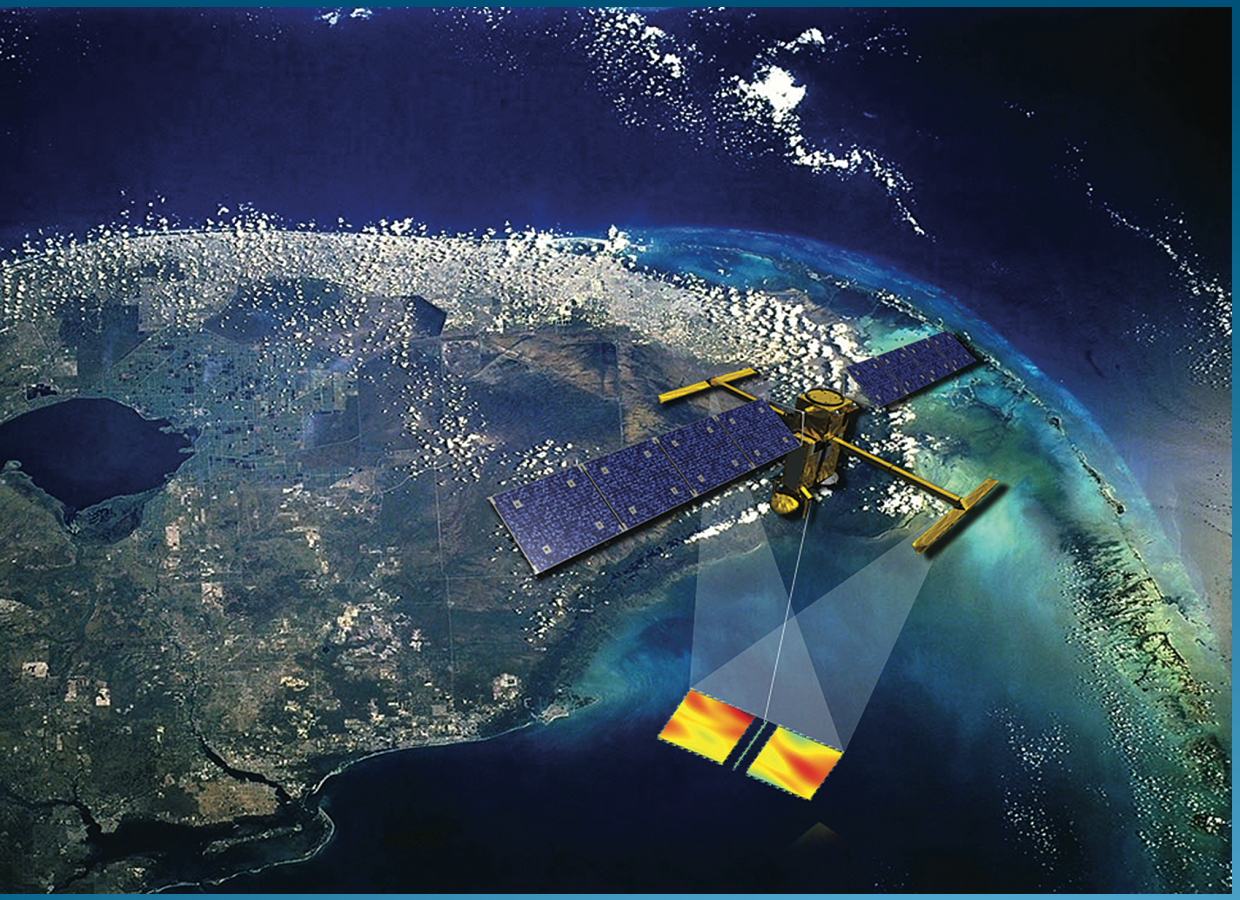
Observing the ocean surface topography at high-resolution by the future SWOT Mission



Rosemary Morrow
LEGOS, Toulouse, France
CNES Ocean Lead

Lee-Lueng Fu
JPL/NASA, US
NASA Ocean Lead

& SWOT Science Team

SWOT (Surface Water & Ocean Topography)

Ocean Topography objectives

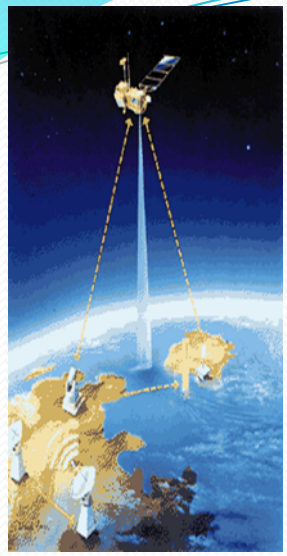
- Characterize the 2D ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 15 km and greater, for open-ocean, high-latitude and coastal/estuary studies.
- Observe the ocean tides and internal tides and their interaction with the ocean circulation, to better quantify ocean mixing & transport for climate studies

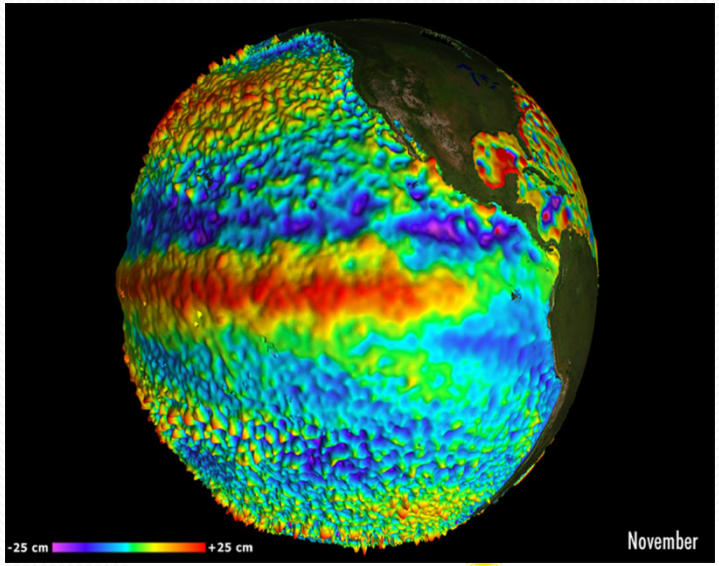
Surface Waters – Hydrology objectives

- To provide a global inventory of all terrestrial water bodies whose surface area exceeds (250m)2 (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (rivers).
- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

LEGOS NASA cnes CSA ASC UK SPACE AGENCY

Satellite Altimetry monitors key ocean processes



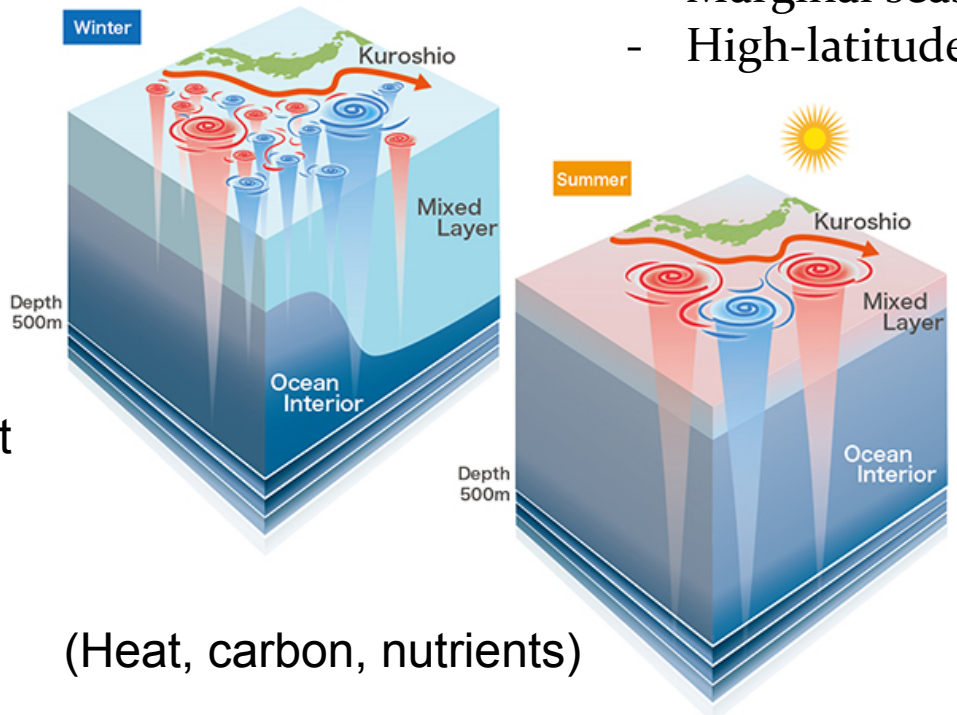


Today's conventional altimetry maps monitor :

- Global & regional sea level rise & circulation
- Deep, large mesoscale eddies > 100 km diameter

Missing smaller, rapid dynamics :

- Open ocean
- Marginal seas, coasts,
- High-latitudes



(Sub) mesoscale Fronts & eddies

50 % vertical transport

Predominant in deep winter mixed layers

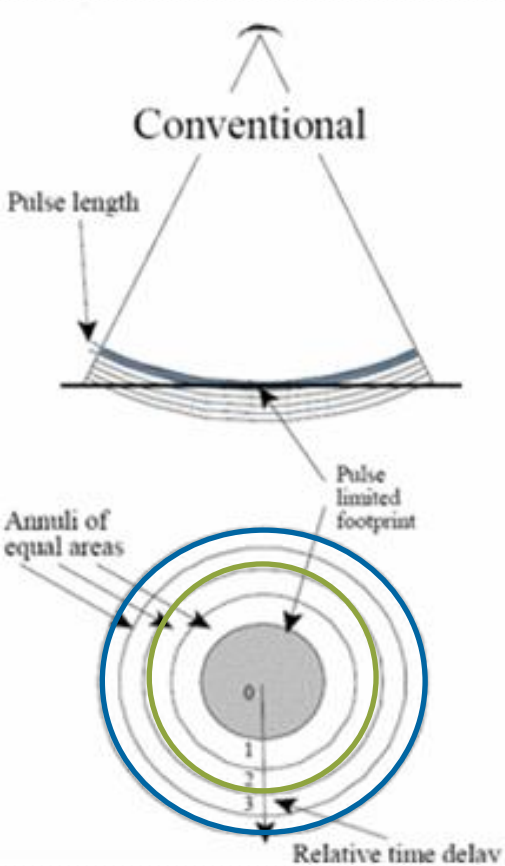
(Heat, carbon, nutrients)

Small Mesoscale processes

Horizontal Transport & mixing

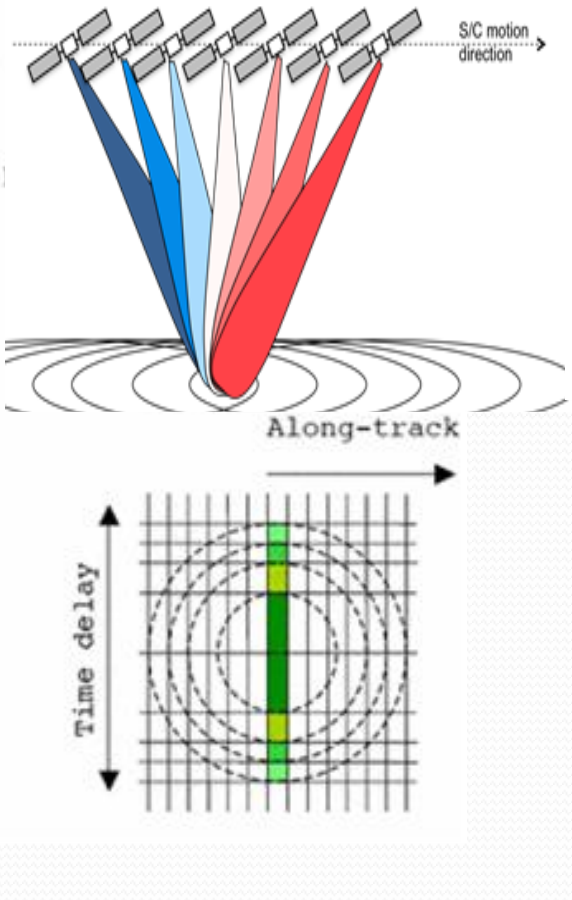
Innovation in altimetry : SAR & SAR/interferometry

Jason-class & Saral
Conventional Mode



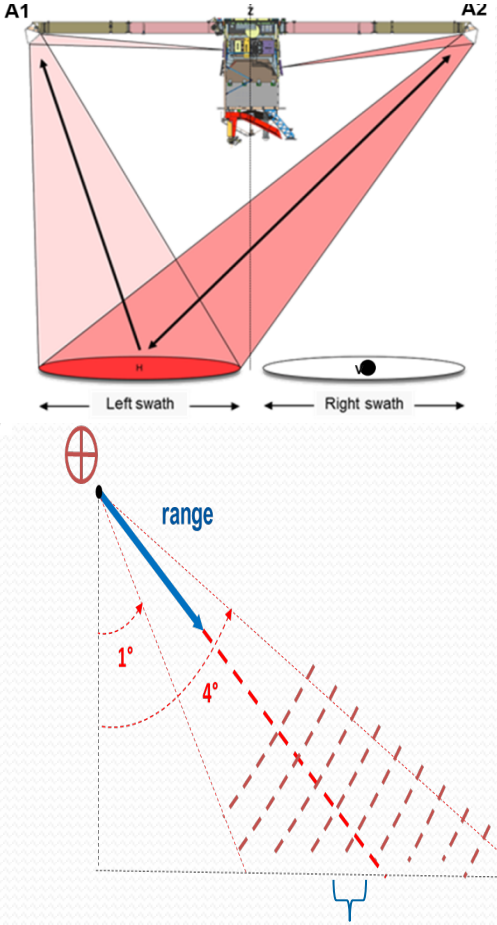
Signal & noise averaged over
5-7 km radius footprint
Medium noise

Sentinel-3 (2016) & Jason-CS (2020)
SAR nadir Mode



300 m alongtrack,
5 km radius crosstrack
Low noise

SWOT (2022)
Guanlan, WiSA
SAR interferometry

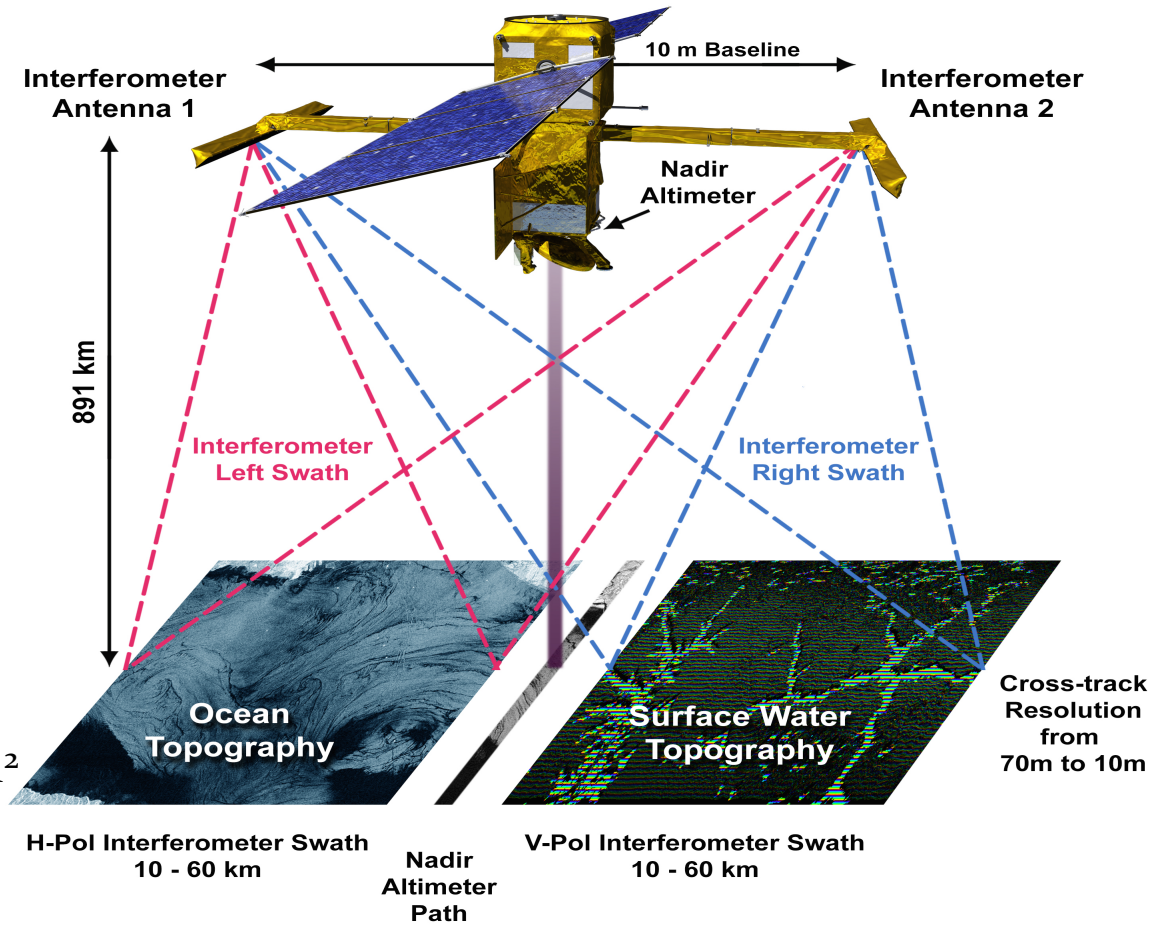


250m x 250m (or **2km²**),
50 km wide swaths
Very low noise

SWOT -2D measurement of surface water topography

Technical advance :
Wide-swath altimetry

- Ka-band SAR interferometric (KaRIn) system with 2 swaths, 50 km each
- All-weather heights and co-registered SAR imagery
- Conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/DORIS/LRA for POD.
- On-Board interferometric SAR processing over the ocean (500 m² resolution) for data volume reduction.



- Partnered mission with NASA, CNES & CSA, UKSA
- Mission duration 3.5 years
- Flight System: ~2400kg, ~2100W
- Launch Vehicle: SpaceX Falcon-9
- Target Launch Readiness: Feb 2022

Image Credit : K. Wiedman

Practicalities

- Orbits
- Ocean data Products
- Ocean SSH and SAR imagery
- High-resolution data over land – mask
- SWOT Ocean simulator

SWOT orbits

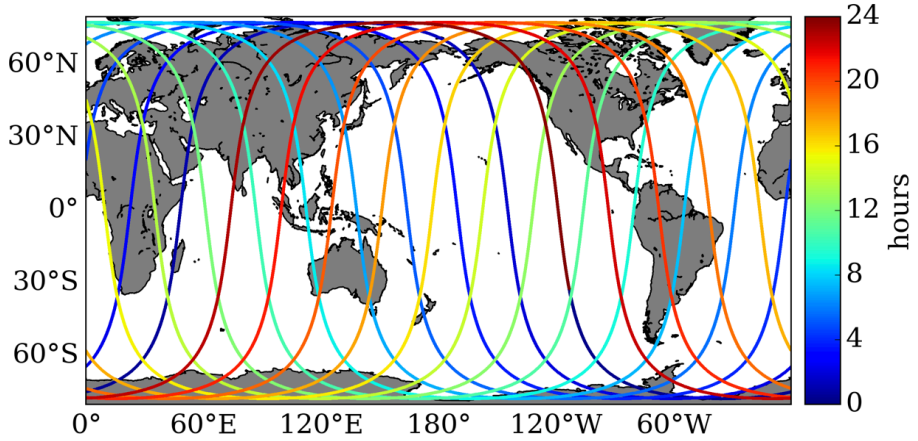
Nominal Launch date : Feb 2022

First 6 months : 1-day Calibration orbit : (orbit: 857 km, 77.60 Incl.,)

1st 3 months – instrument checkout

2nd 3 months – Jun-Aug 2022 – Science data available

- Ideal for ocean studies of rapidly evolving small mesoscales and submesoscales



- 6 mths, 1 day repeat
- 3 yrs, 21 day repeat

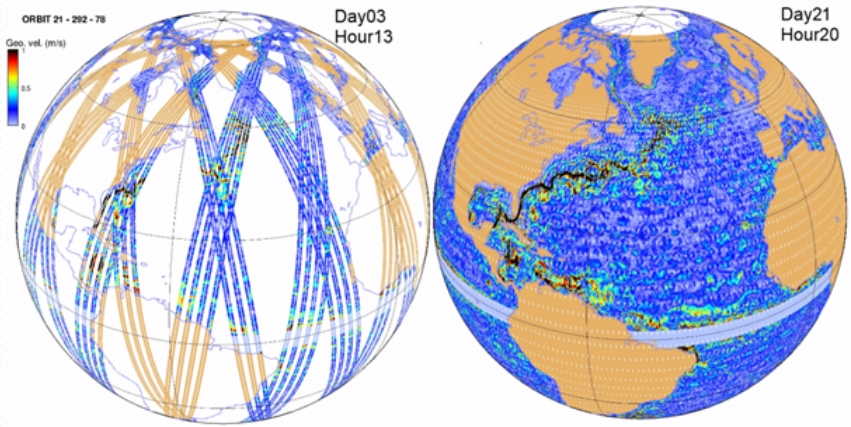
3-year 21-day repeat Science orbit
(orbit: 891 km, 77.60)

Nominally : Aug 2022 to Aug 2025

Full global coverage

1-day and 10-day sub-cycles for better mesoscale coverage

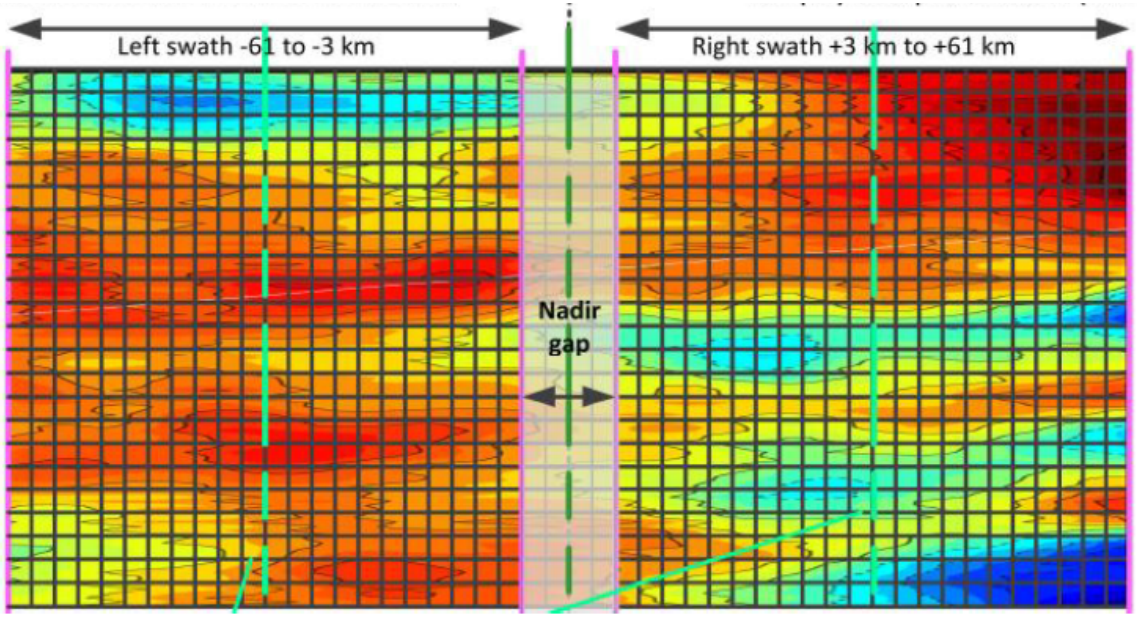
Orbit kmz files : AVISO+ SWOT orbits

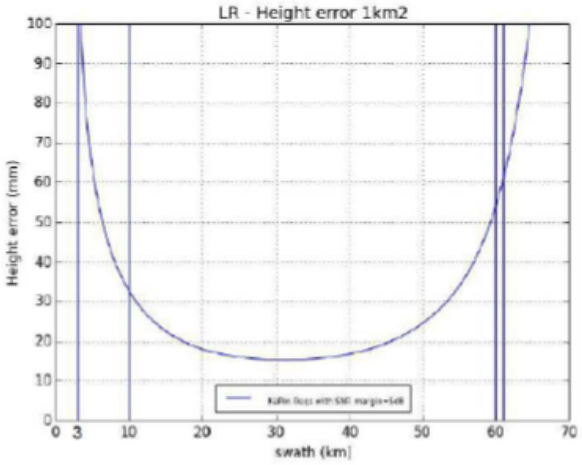


Global ocean data products – at 250m x 250m and 2x2 km

Swath co-ordinates & fixed-grid

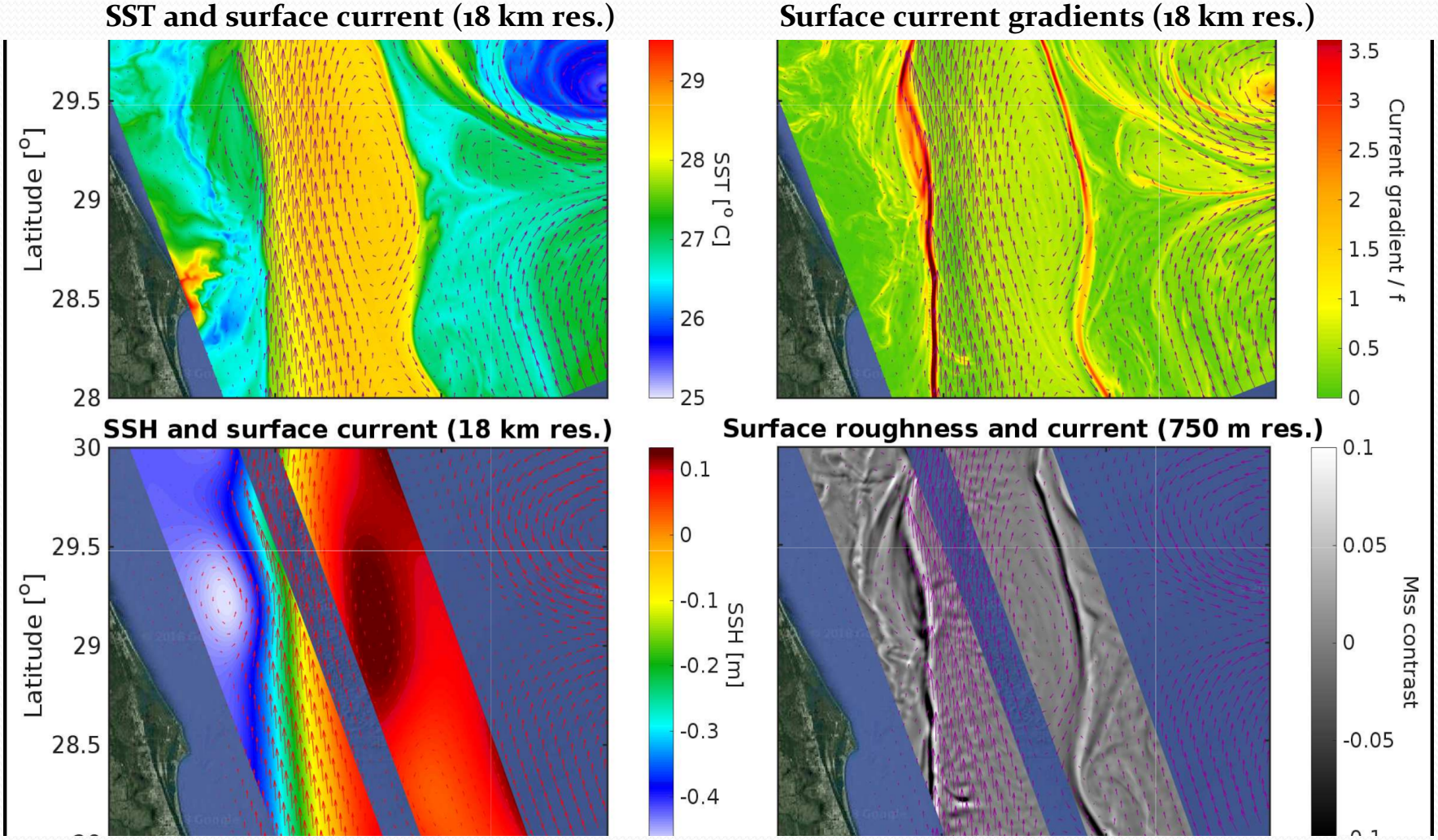
- **Basic SSH product** (**2 km** resolution/posting) (0.6 GB/day) **σ = 1.37 cm**
- **Expanded products (2 km):**
  - Full corrections (2.4 GB/day)
  - Wind/waves/s_0 (0.6 GB/day)
- **Expert high resolution product**: SSH & SAR images (**250m** posting / 500m res) (37 GB/day) **σ = 5.48 cm**





Height error is an order of magnitude less than Jason ! Varies across each swath (instrument, SWH dependent)

Colocated all-weather heights and SAR imagery for ocean front detection : model simulations

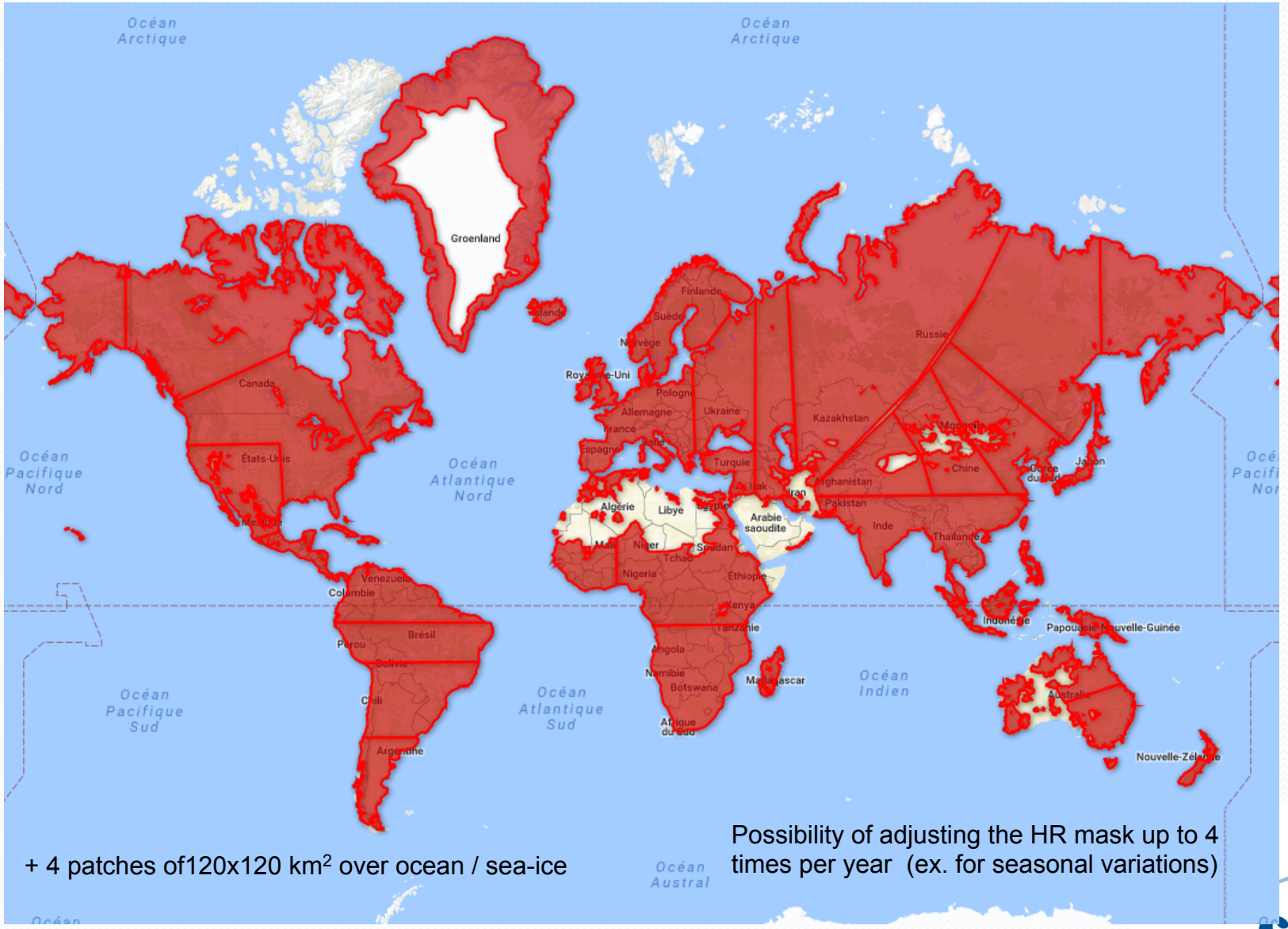


Upper panel : modelled surface currents & SST & currents & SST gradients
Lower panel : **simulated SWOT** swath of (left) SSH, geostrophic currents and (right) SAR surface roughness

credits Ifremer

Ocean Low-Resolution data available globally to 78°;

also High-Resolution (10-70 m) data over land (in Red)



+ 4 patches of120x120 km^2 over ocean / sea-ice

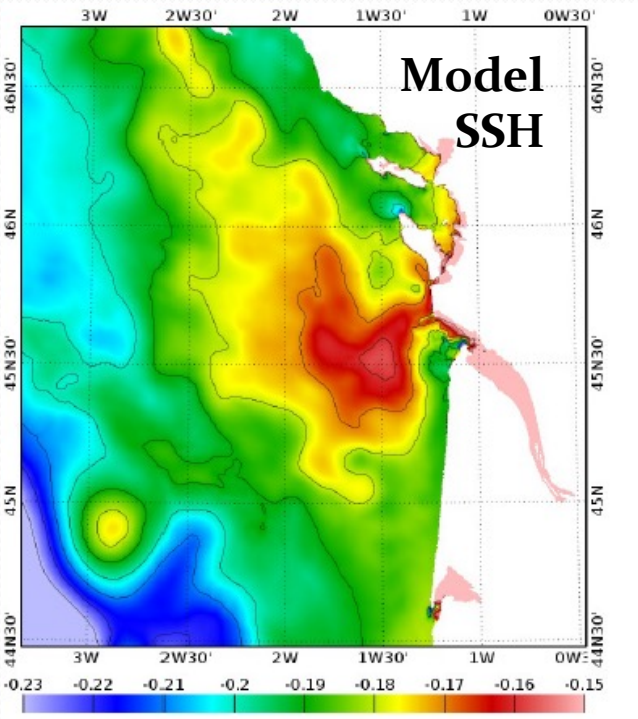
Possibility of adjusting the HR mask up to 4 times per year (ex. for seasonal variations)

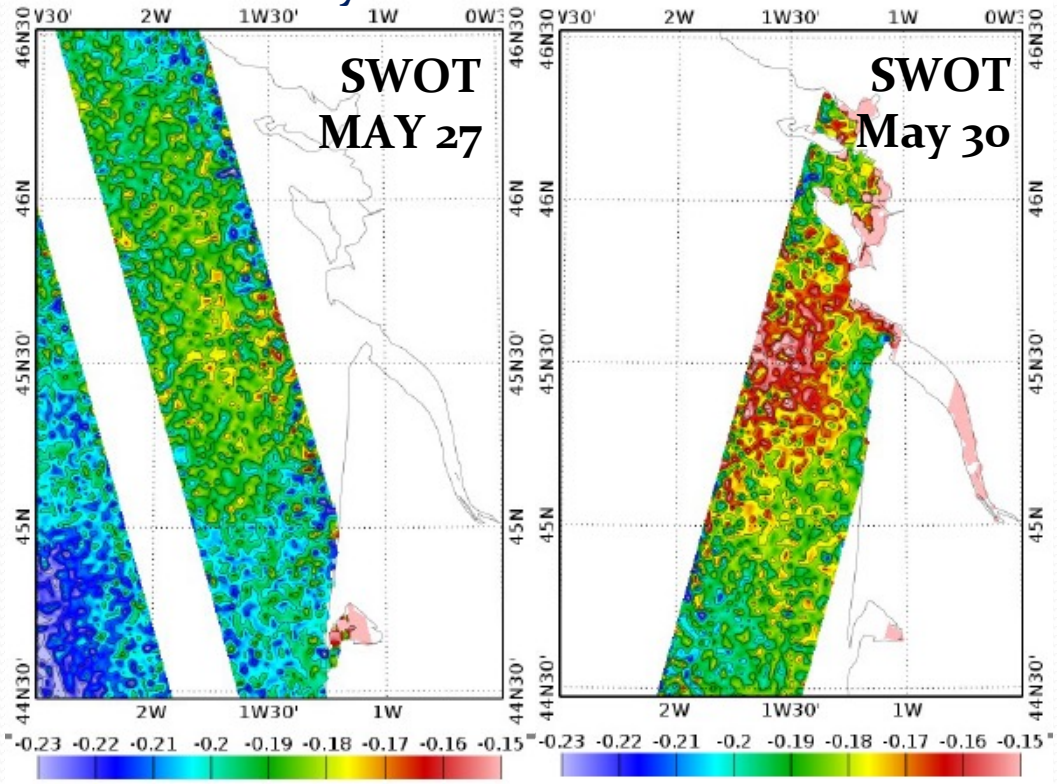
Tools : Preparing for SWOT – ocean simulator

SWOT 2D high-resolution SSH – capturing the eddy anisotropy and strain
Precise 2D horizontal gradients needed for velocity and vorticity

SWOT simulator to study successive passes over a region using your model
(open source : https://github.com/SWOTsimulator/swotsimulator.git

Eg : HR model of Bay of Biscay and Gironde Estuary … with SWOT swath and noise





Toublanc et al. (in prep)

Observability of ocean SSH

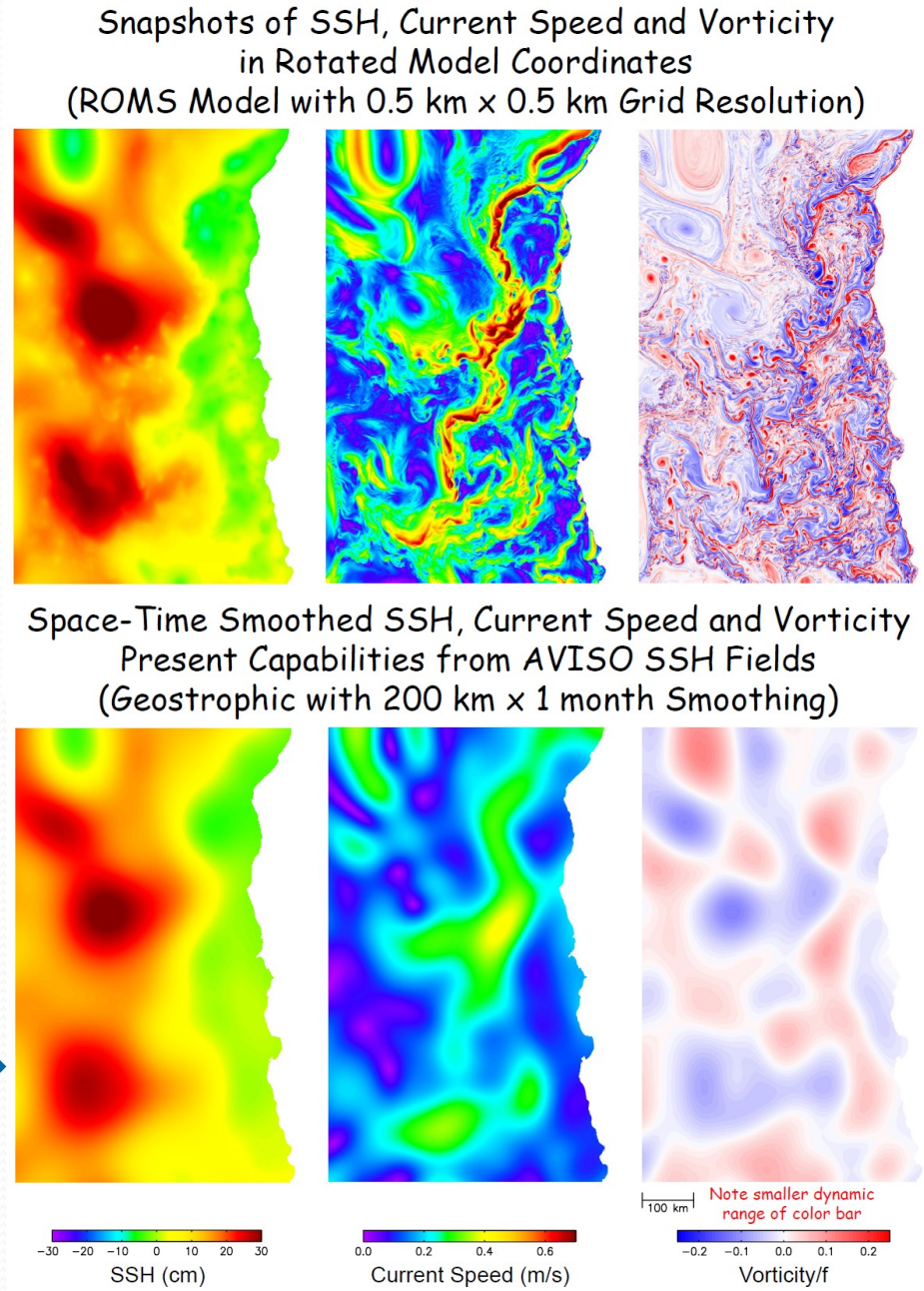
SWOT- from SSH gradients to currents & vorticity

More precise 2D SSH strucure (amplitude, gradients, anisotropy) leads to greatly improved geostrophic velocity & vorticity fields.

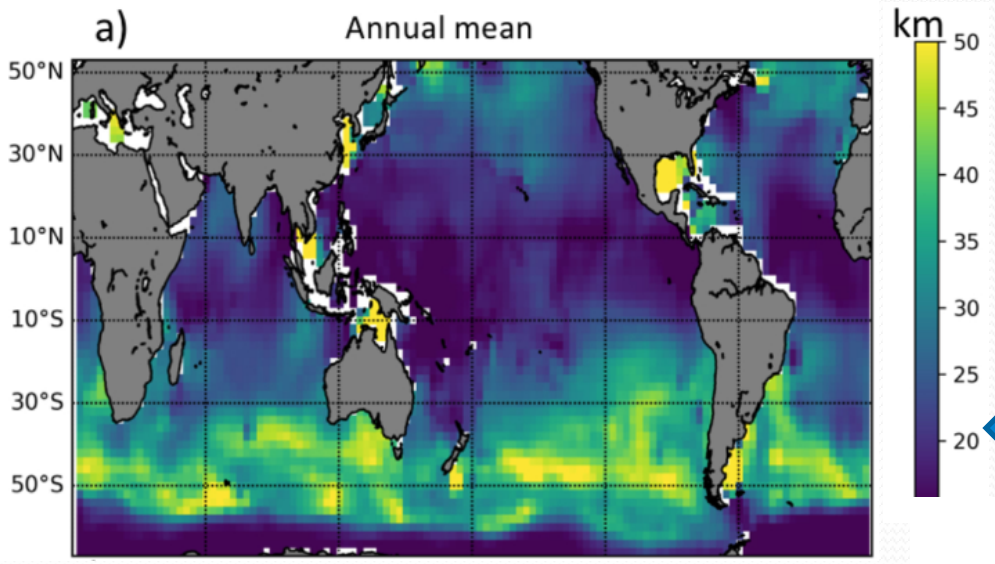
Mapping of SWOT-like observations of SSH, currents, vorticity

Mapping of AVISO-like observations of SSH, currents, vorticity

Chelton et al, PO, 2019



But at fine scales, altimetry/SWOT's SSH is limited by 2 main factors



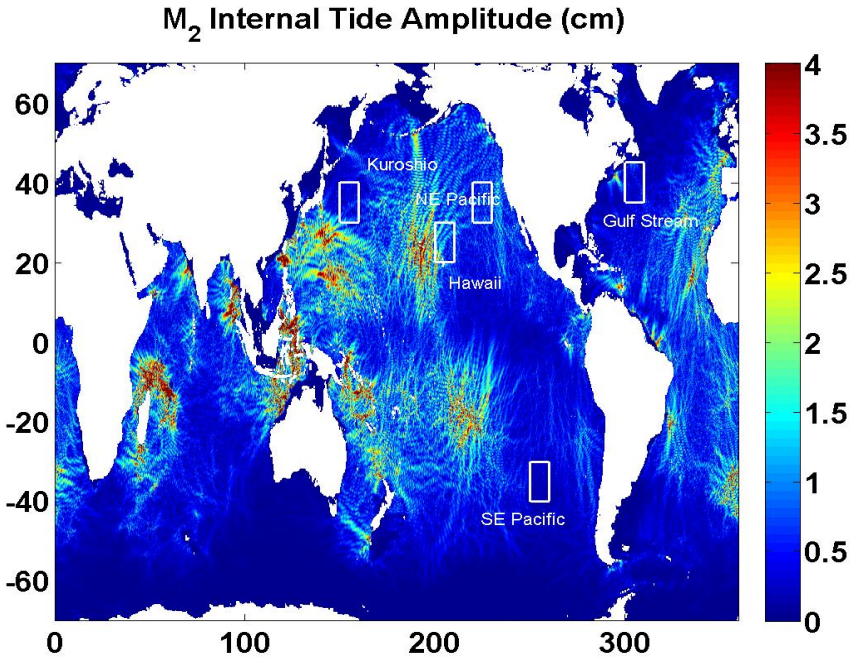
SWOT's noise is 1 order of magnitude lower than Jason-class altimeters

But still has geographical structure : **SWOT's effective spatial resolution** depends on sea-state (signal > noise)

Wang & Fu, JPO, 2018

Deriving geostrophic currents from altimetric SSH depends on a **good separation of tides & internal tides** from SSH observations ....

And internal tides can have similar space scales to mesoscale eddy processes

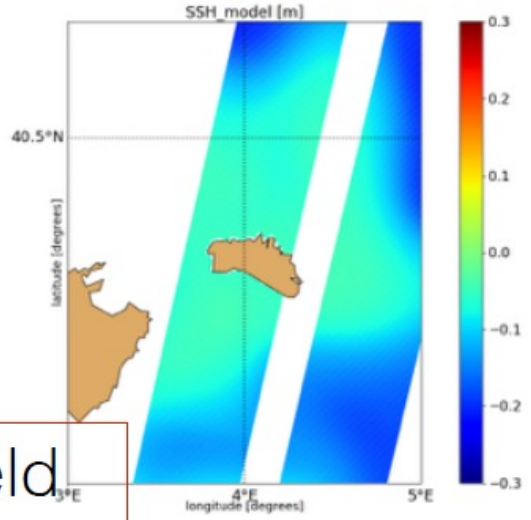


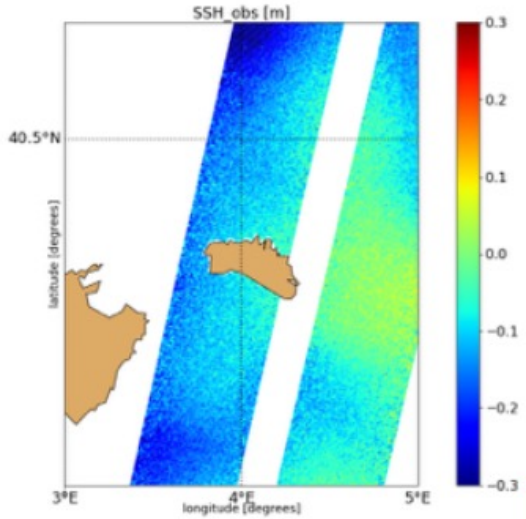
Model : HYCOM 1/12° *Arbic et al., 2012*

SWOT Noise reduction and 2D reconstruction

Different SWOT-ST groups exploring techniques to reduce noise in 2D SSH images, and for fine-scale 2D reconstruction

Without noise



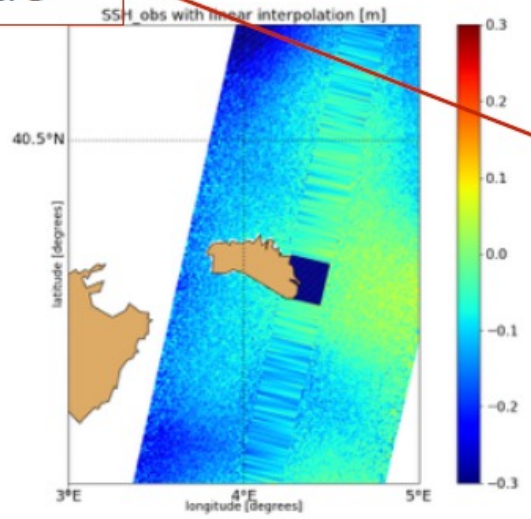


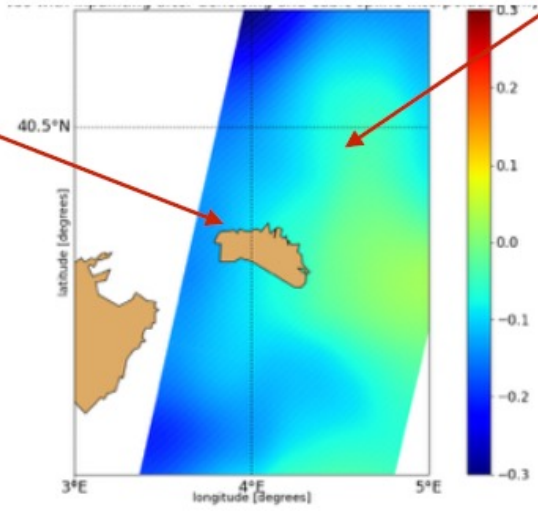
With noise

Smooth field near islands

Fill the gap

With noise, linear interpolation in the gap





With noise, after denoising and inpainting

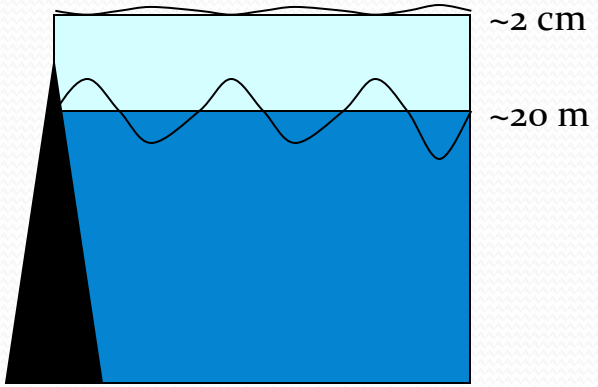
E. Cosme

Barotropic tides (Coastal, high-latitude) and internal tides
- a Challenge and Opportunity

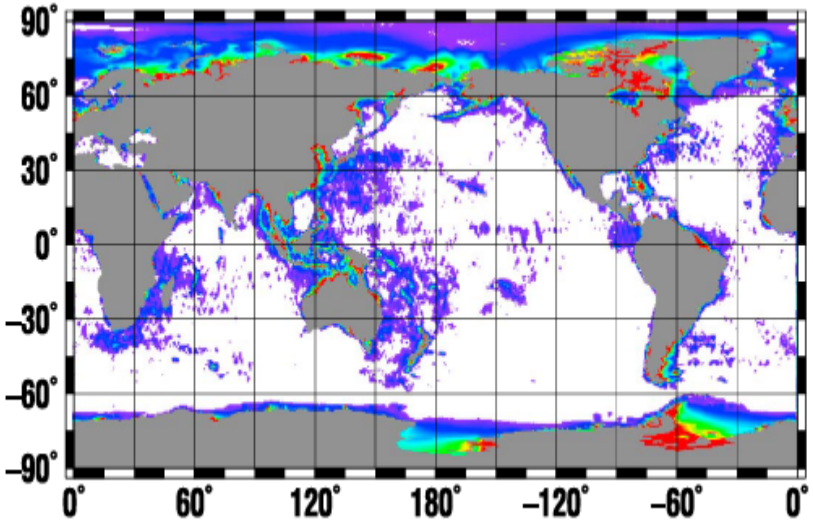
SWOT orbit chosen to resolve tides –

1) 3 years of SWOT data will resolve the finer-scale 2D tides at 250 m resolution, up to the coasts

2) 2D Internal tides observed by SWOT – important for ocean mixing & energy dissipation

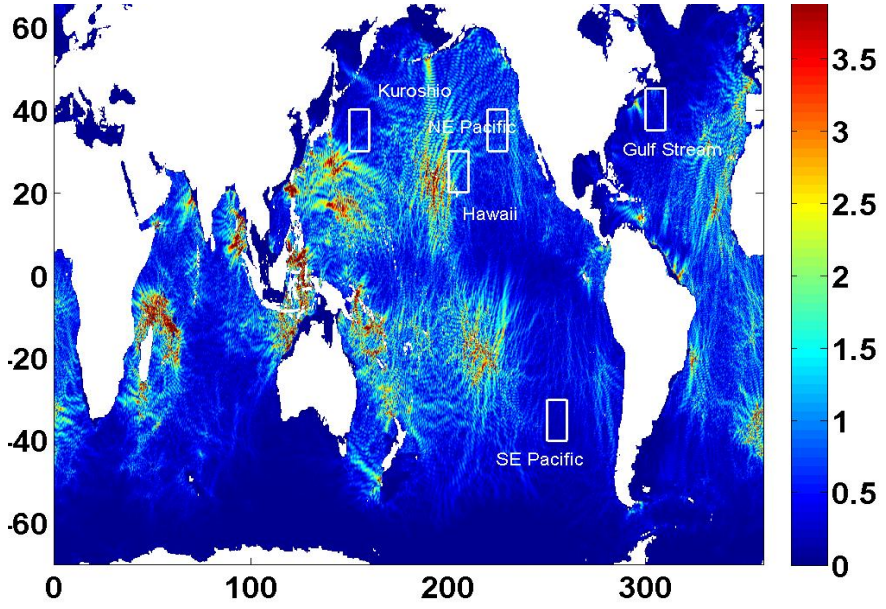


Barotropic Tide model comparison :
Today's errors are where we expect largest improvement



St. Dev of 7 global tide models, M2
Stammer et al., 2014

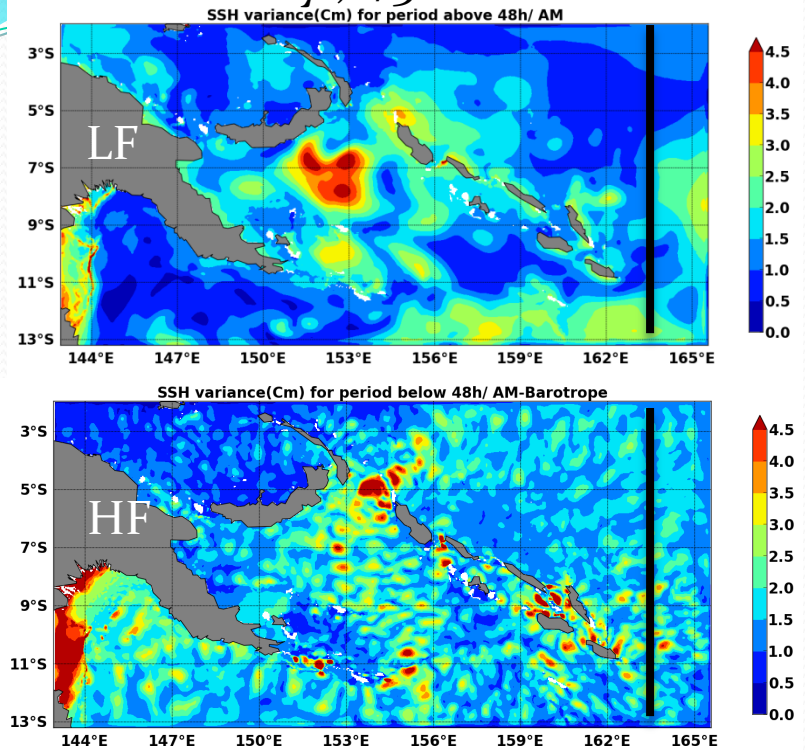
Modelled coherent (predictable)
internal M2 tide amplitude



Model : HYCOM 1/12° *Arbic et al., 2012*

Altimetric SSH Wavenumber Spectra modified by internal tides

SSH variability ; 1/36° model :



Need models with internal tides to explain flat altimetry k-spectra in Soloman Sea :

- Model with no tides : steep k-spectra
- Coherent BC modes : match altimeter k-spectra from 70-250 km
- Incoherent internal tides dominate < 70 km

Altimeter obs : AL & J2 (- BT tide)

Model spectra cases :

No Tide : 1/36° - 5d average

No Tide : 1/36° - 1h snapshots

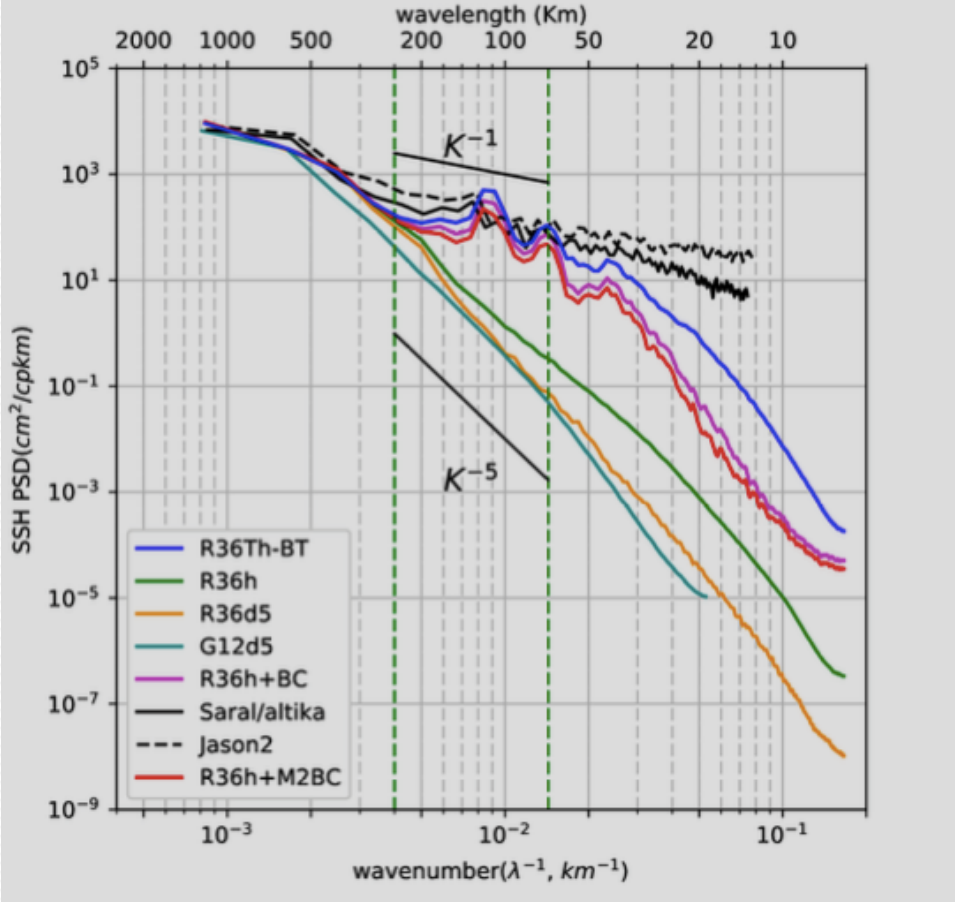
With Tides (but BT tide removed) :

Full internal Tide : 1/36° - 1h

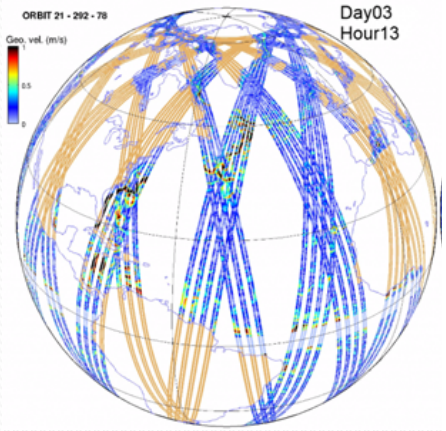
Coherent BC modes (M2 only)

Tchilibou et al., 2019

SSH wavenumber spectra altimetry & models



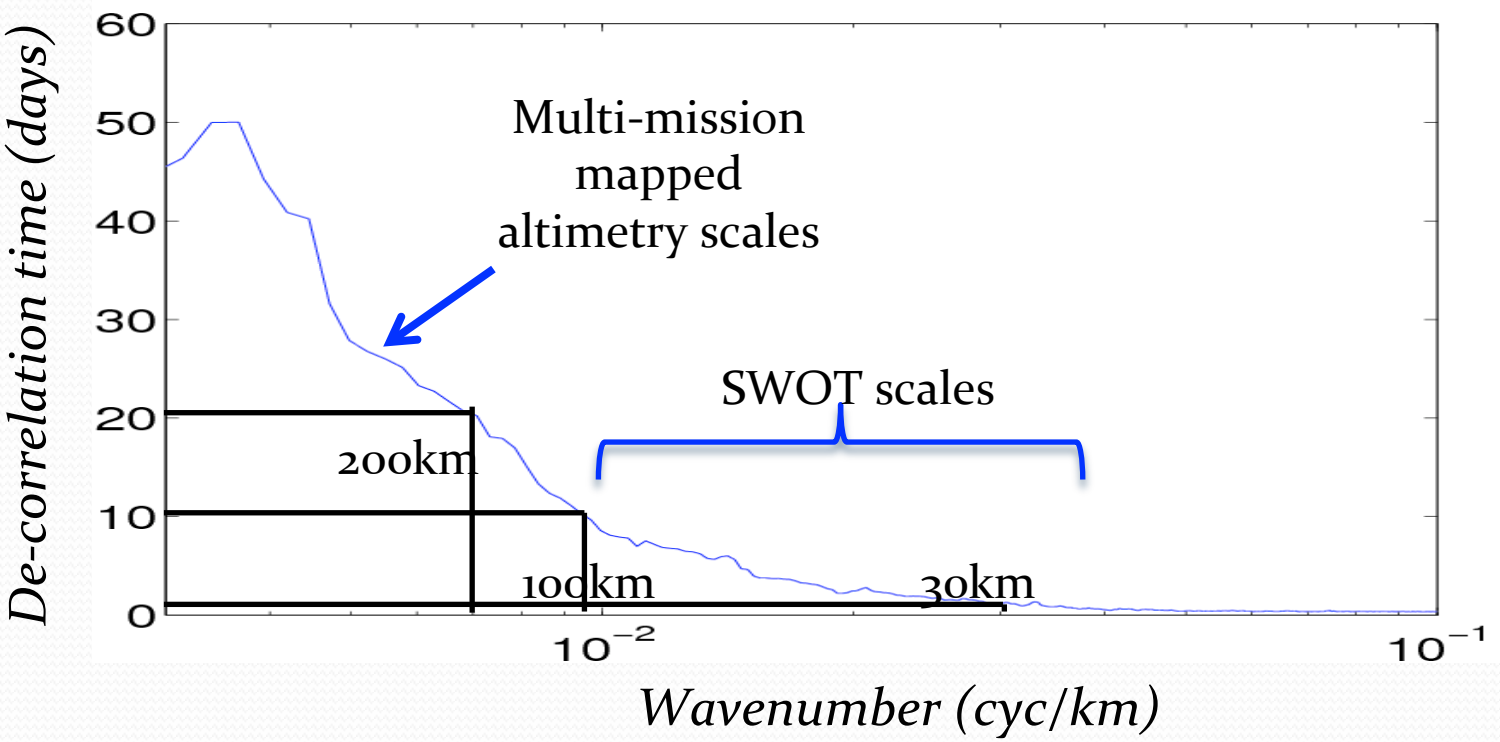
Challenge : 2D/3D reconstruction of upper ocean SSH and currents



How to maintain small scales and reconstruct global 2D SSH or 3D upper ocean fields ?

- 2D DUACS-HR SSH maps – new « dynamical » interpolation (Ubelmann & Fu, 2015; Rogé et al., 2018)
- 3D *u,v,w* currents reconstructed using :
  - omega equation,
  - sQG projection,
  - assimilation

Time scales of ocean variability decrease with spatial scales

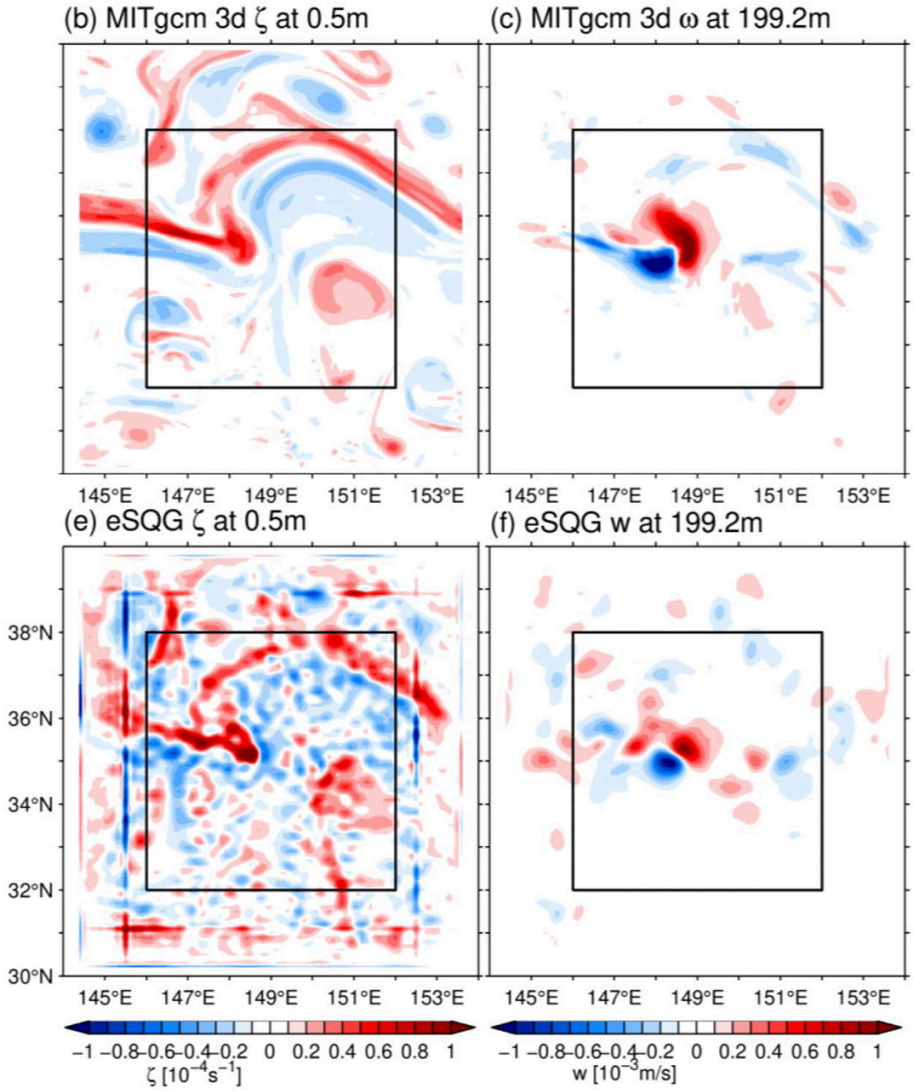


Credit : C. Ubelmann

Surface Vorticity and Vertical Velocity

A Grand Challenge for Ocean Remote Sensing

Surface vorticity 200 m Vertical velocity

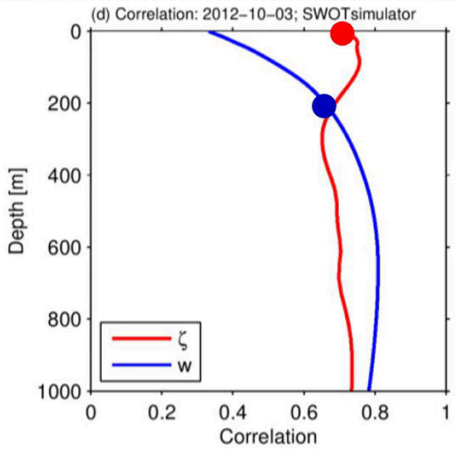


target ζ & w field

eSQG reconstruct using SWOT-measured η

(Qiu et al, 2018)

Reconstruction via Effective sQG theory :
3D reconstruction of vorticity, ζ, and vertical velocity, w, from mapped SWOT SSH data using effective sQG
Below : vertical correlations of ζ, w
Region : N Pacific (32°–38°N ; 144°–150°E)



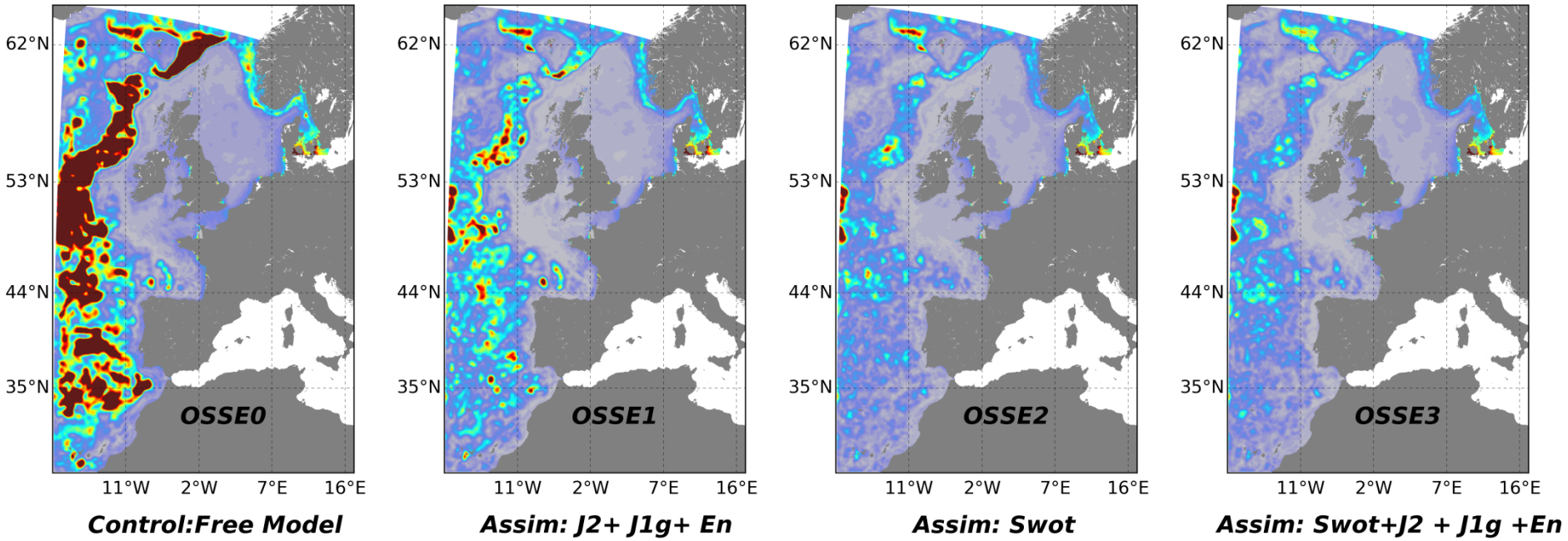
2D/3D reconstruction : Filling the observational gaps

Assimilation : Mercator Ocean are currently performings OSSEs to

- Prepare the Mercator Ocean data assimilation to ingest SWOT data
- Estimate how SWOT data will constrain the system (physical processes, analyses, forecasts)

Input OSSE Data from IBI1/36° with tides, filtered at 25h; output 1/12° filtered at 25h

Ssh Error Variance (Error= NatRun – OSSEs; IBI12; 2009)



Le Traon/Remy/Benkiran

SWOT – Calibration - Validation

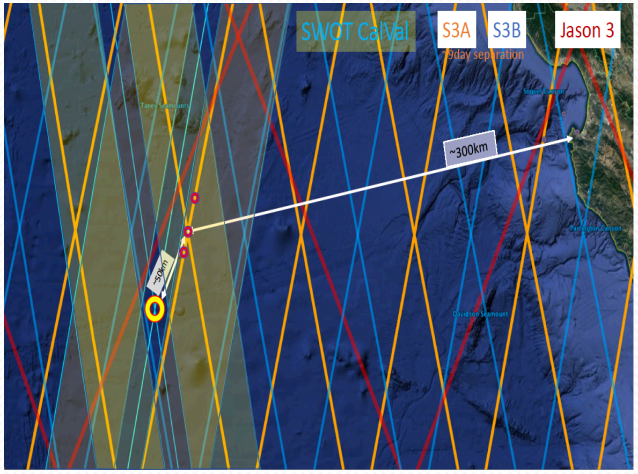
- *Global statistical CalVal from intercomparisons of SWOT-Karin-Nadir and SWOT with alongtrack SAR S3 J-CS*

- *Challenge of in-situ validation of rapid, 15-100 km SSH dynamics*

(Satellites fly at 7 km/s; cover 420 km in one minute)

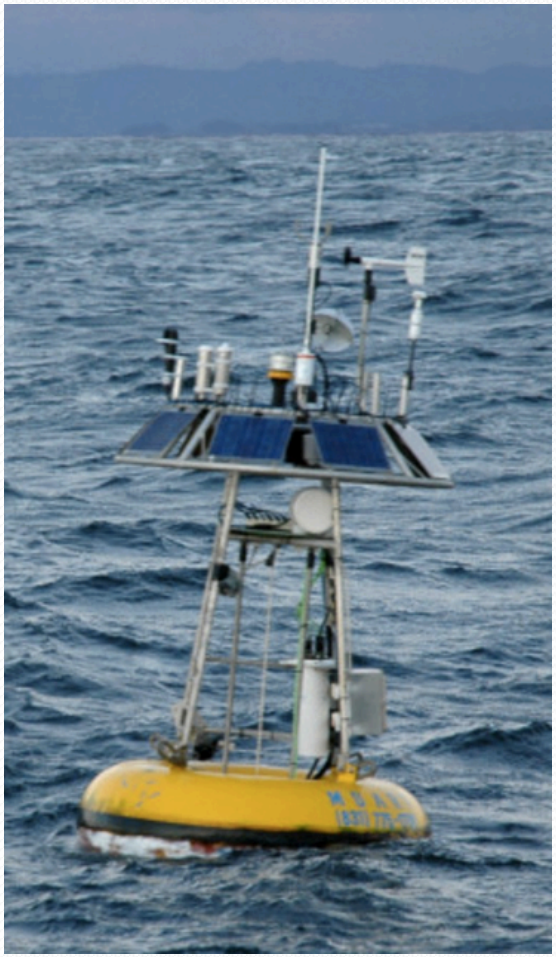
Californian SWOT Crossover campaign

Validation of spectral requirements



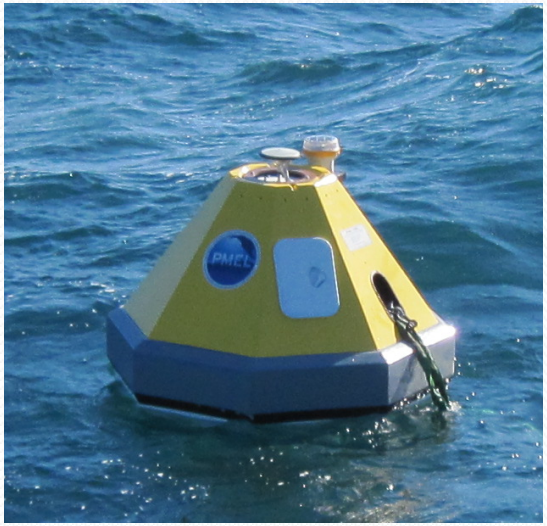
CTD Moorings &
Wirewalkers 0-500m

Lidar for SSH & SWH



Lidar & gliders/drifters
for 2D coverage

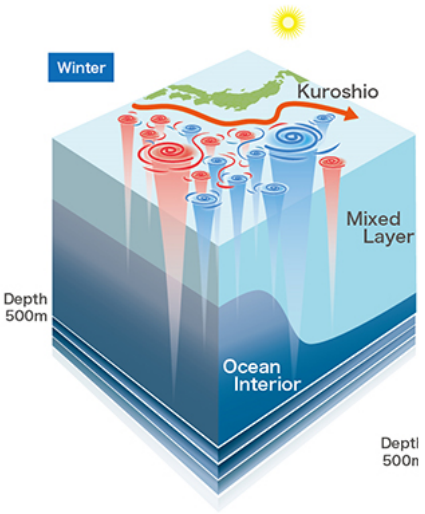
GPS buoys



Gliders

Other Applications (global : pixels at 250 m / 2 km)

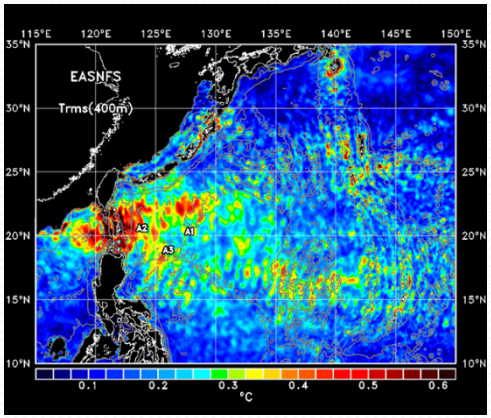
2D surface height images for …



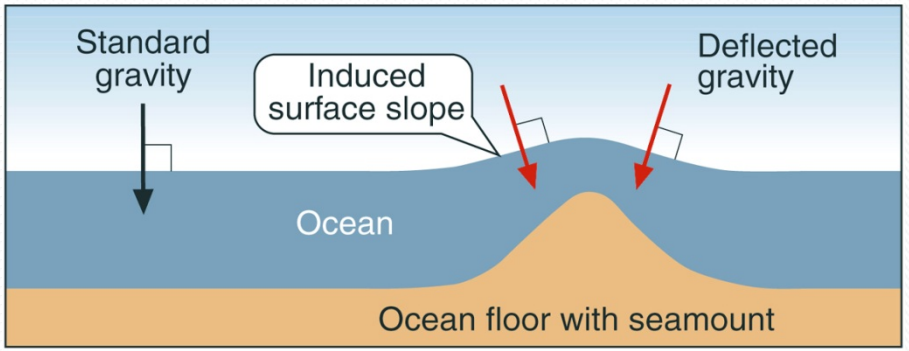
Meso & sub-mesoscale ocean SSH & currents

Coastal/estuarine SSH & currents

High-latitude Currents in leads & Sea Ice Freeboard



Coastal, high latitude Tides & Internal Tides / Internal waves



250 m open ocean geoid & Bathymetry

SWOT Ocean Final remarks

- **SWOT observes SSH and SAR images … need careful processing to remove noise, and separate coherent & incoherent internal tides**
- **Expecting good observations of anisotropic 2D structure of small mesoscales, and derived balanced currents, vorticity and strain**
- **SWOT will provide unique observations of the interactions between balanced flow and internal gravity waves (incl internal tides)**
- **Mapping the fine-scale SWOT SSH swath data onto regular 2D fields presents many challenges, explored using dynamical interpolation techniques, different vertical projection schemes, full assimilation techniques, and synergy with other satellite observations.**
- **Altimetric mesoscale era was accompanied by a global Argo program. The question of how to collocate the rapidly evolving fine-scales observed by SWOT data with in-situ data poses new challenges.**

Info : Mission, orbits, data products :
http://swot.jpl.nasa.gov & www.aviso.altimetry.fr => swot

SWOT Ocean Simulator (orbits & errors) :
https://github.com/SWOTsimulator

Thank you