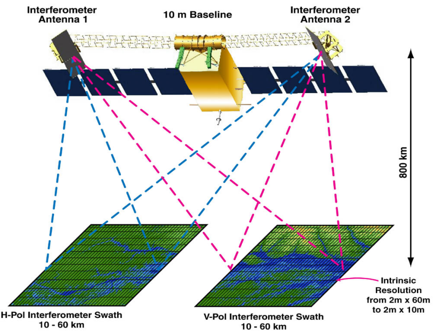
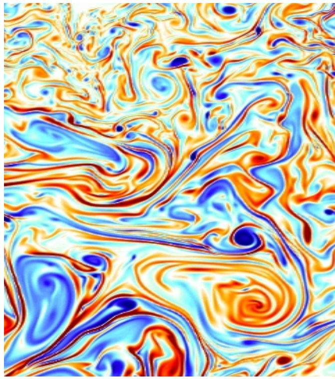
”Ocean Turbulence from SPACE”

Patrice Klein (Caltech/JPL/Ifremer)

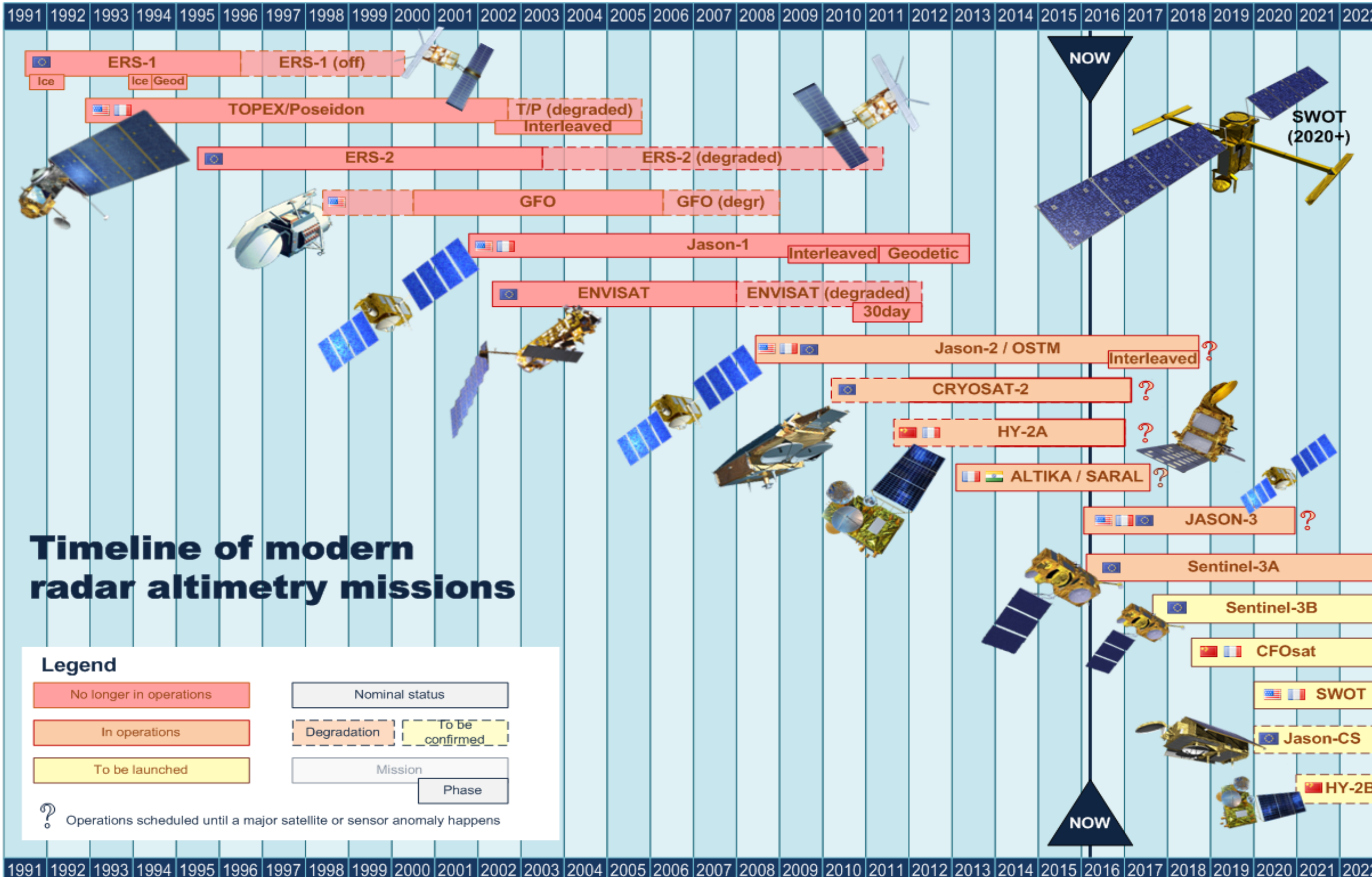
(IV) – Satellite Altimetry (b)





Satellite altimetry provides:

global coverage, all weather, real-time SSH measurements



Satellite altimetry:

1 - Major breakthroughs and existing limitations.
2 - Expectations from future altimeter missions and need for a better dynamical framework.

Some relevant papers:

- Morrow R. and P.Y. Le Traon (2012): Recent advances in observing mesoscale ocean dynamics with satellite altimetry. *Adv. in Space Res*.
- P.Y. Le Traon (2013): From satellite altimetry to Argo and operational oceanography. *Oc. Sci*.
- Chelton et al. (2011): Global observations of nonlinear eddies. *Prog.Ocean.* (50p)
- Y. Xu and L.L. Fu (2012): The effects of altimeter instrument noise on the estimation of the wavenumber spectrum of Sea Surface Height. *J.P.O.*
- Zhai et al. (2008): On the seasonal variability of eddy kinetic energy in the Gulf Stream region. *GRL*.
- Dong et al. (2014): Global heat and salt transports by eddy movements. *Nat.Comm.*
- Zhang et al. (2014): Oceanic mass transport by oceanic eddies. *Science*
- Fu L.L. and R. Ferrari (2008): Observing oceanic submesoscale processes from space. *EOS.*

Textbook: S. Martin (2014) « An introduction to Ocean Remote Sensing » C.U.P.

Satellite altimetry allows to estimate the ocean SSH variability on a global scale and in real time.

<u>Some major results (see previous class):</u>

(1) Spatial SSH variability is dominated by nonlinear mesoscale eddies with scales > 100 km
(2) Oceans are crowded with a large number of nonlinear eddies
(3) EKE > 10 . MKE
(4) Eddy tracking technics allow to monitor their propagation pathways and bring into light the meridional divergence of cyclones and anticyclones.

Some limitations:

(1) Present satellite altimetry only captures large eddies (>100 km)

(2) Results do not indicate the existence of a universal wavenumber spectrum and therefore of a universal dynamics

(3) Diagnosis of eddy impact on global heat and salt transports using Argo float data is promising but still suffers some uncertainties because of the data resolution.

(4) Seasonality is observed in the EKE but data do not allow to understand the mechanisms involved.

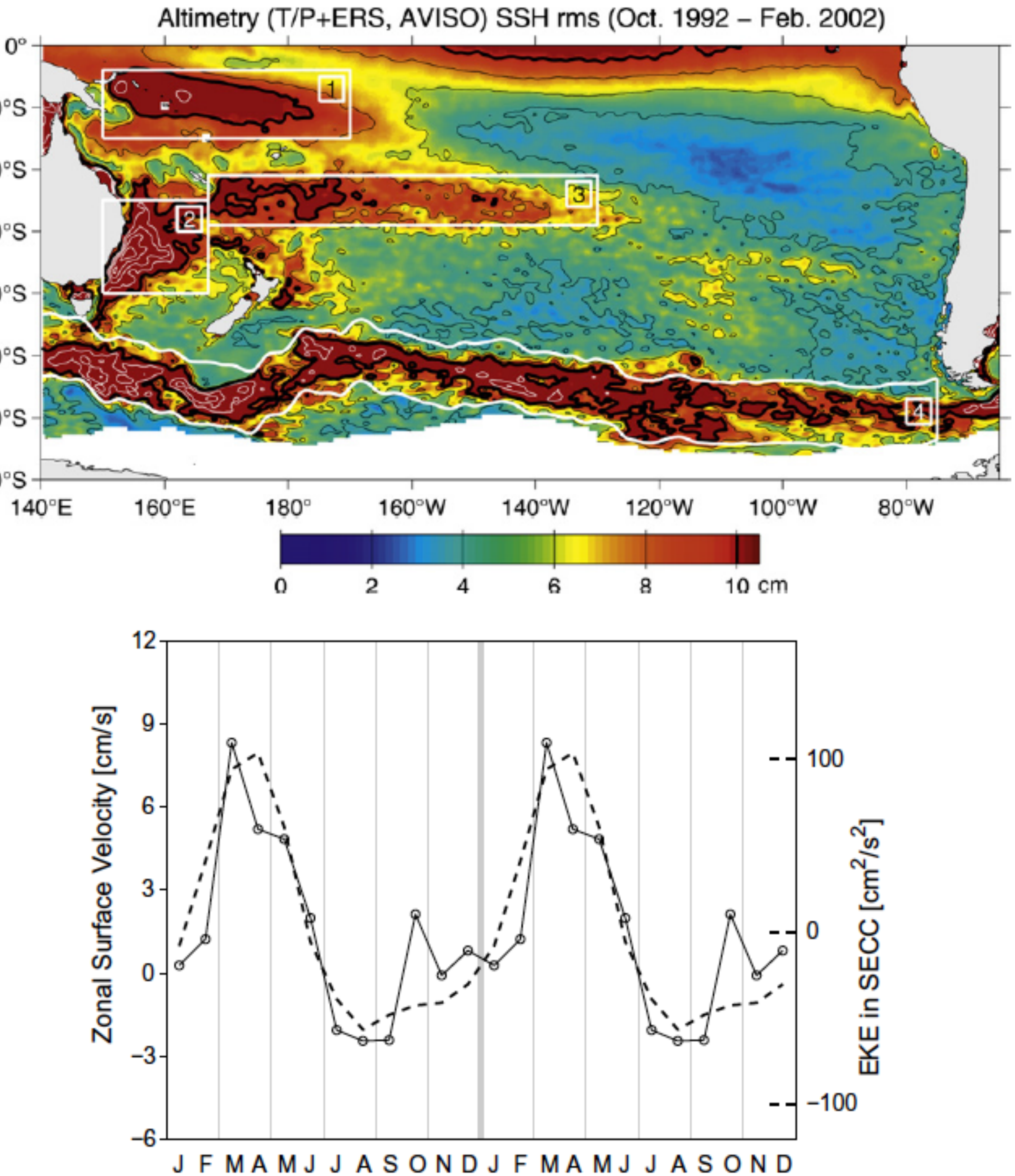


Fig. 3. (a) Map of the rms sea surface height variability from T/P + ERS data in the South Pacific Ocean. Box 1 highlights the SECC variability, Box 3 the STCC variability. (b) Zonal velocity shear between 0 and 600 m for the STCC-SEC from monthly climatological data (solid line) compared to altimeter EKE (dashed line) (after Qiu and Chen, 2004 © American Meteorological Society).

Yongsen Xu and Lee L. Fu JPO 2012: SSH spectrum slope from Jason 1

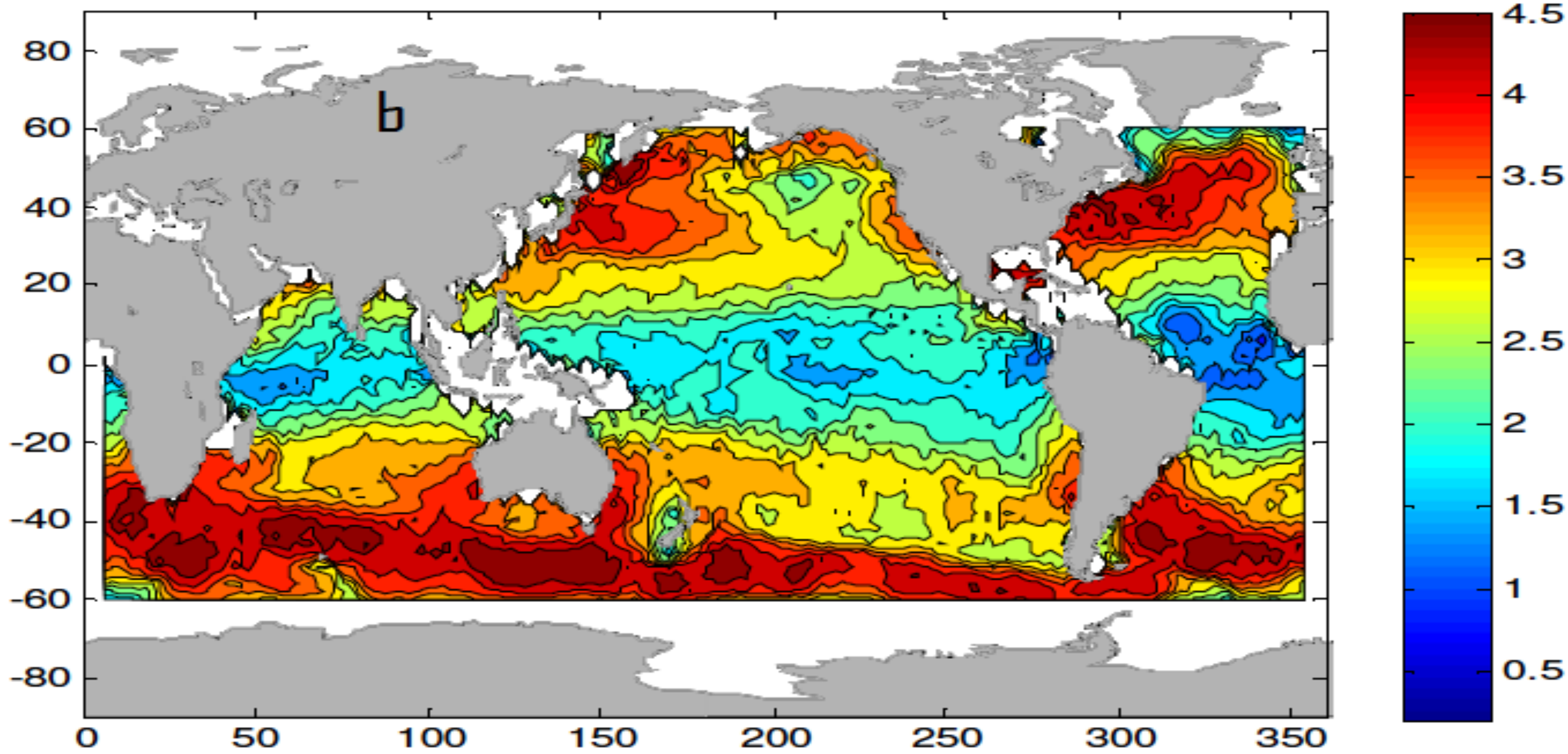


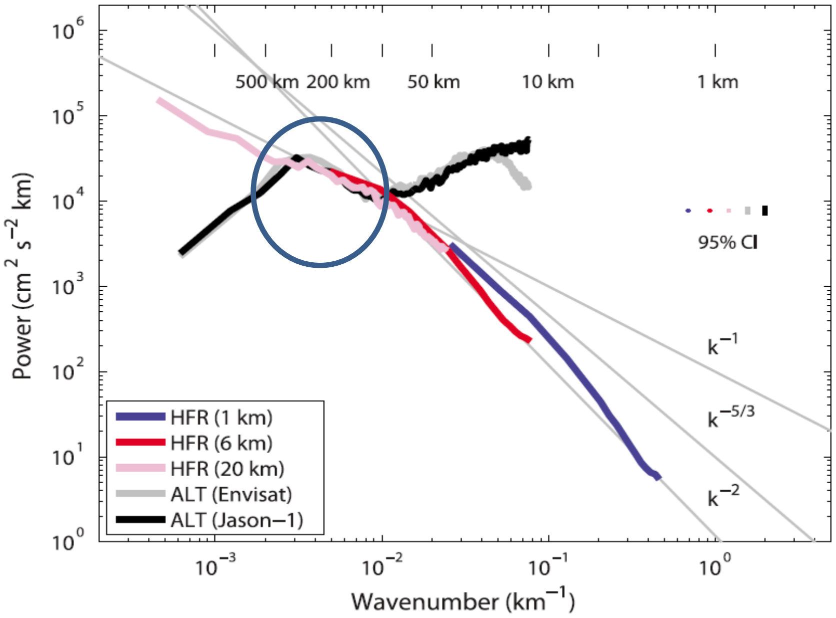
Fig. 3. The global distribution of the spectral slopes of SSH wavenumber spectrum in the wavelength band of 70–250 km estimated from the Jason-1 altimeter

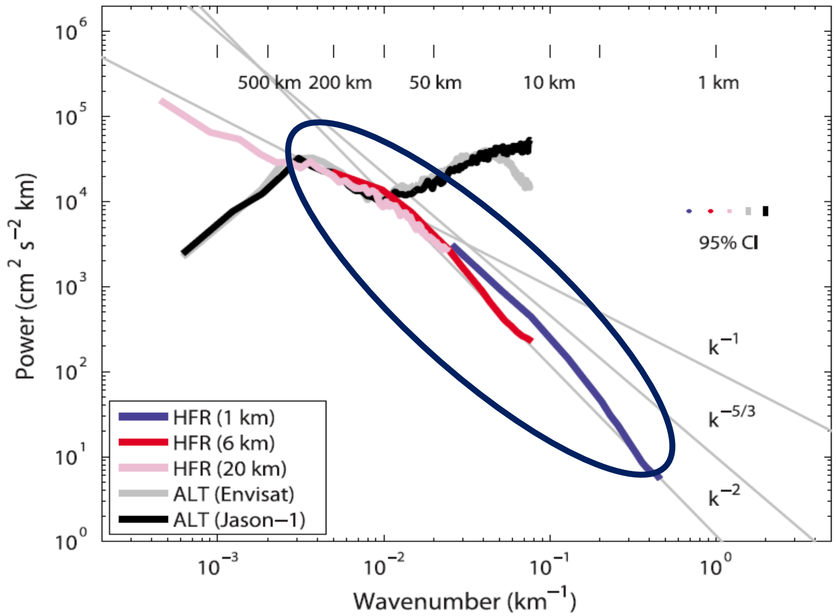
These results do not indicate the existence of a universal wavenumber spectrum and therefore of a universal dynamical regime in the world ocean

Comparisons of satellite data with high resolution numerical models:

- further emphasize the limitations of satellite altimetry
- point to the **important impact of smaller scales** (not resolved by present satellite altimetry)
- This impact requires **a dynamical framework that involves the nonlinear interactions between small and large scales.**

Kim et al.,'11, using HF radar observations





These high-resolution observations reveal that submesoscales are more energetic than previously thought: velocity and density spectra have a shallower slope (**k^{-2} instead of k^{-3}** near the surface)

Comparison of satellite data
with high resolution numerical models:

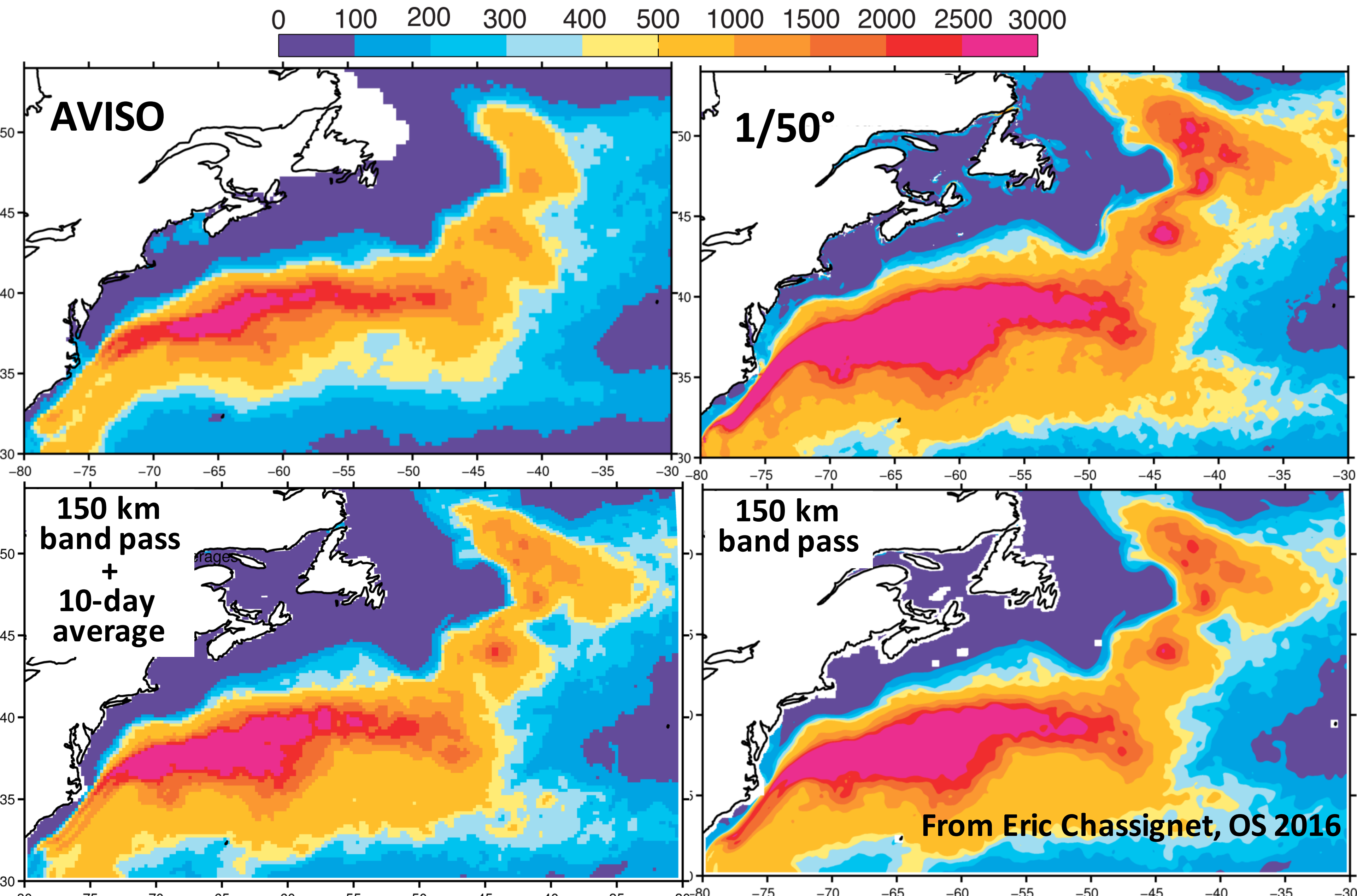
Impact of scales < 100-150 km

- **(1) Eddy kinetic energy**
- **(2) Cyclogeostrophic motions [Rossby number O(1)]**
- **(3) Dispersion of tracers (direct cascade of tracers)**
- **(4) Inverse cascade of kinetic energy**

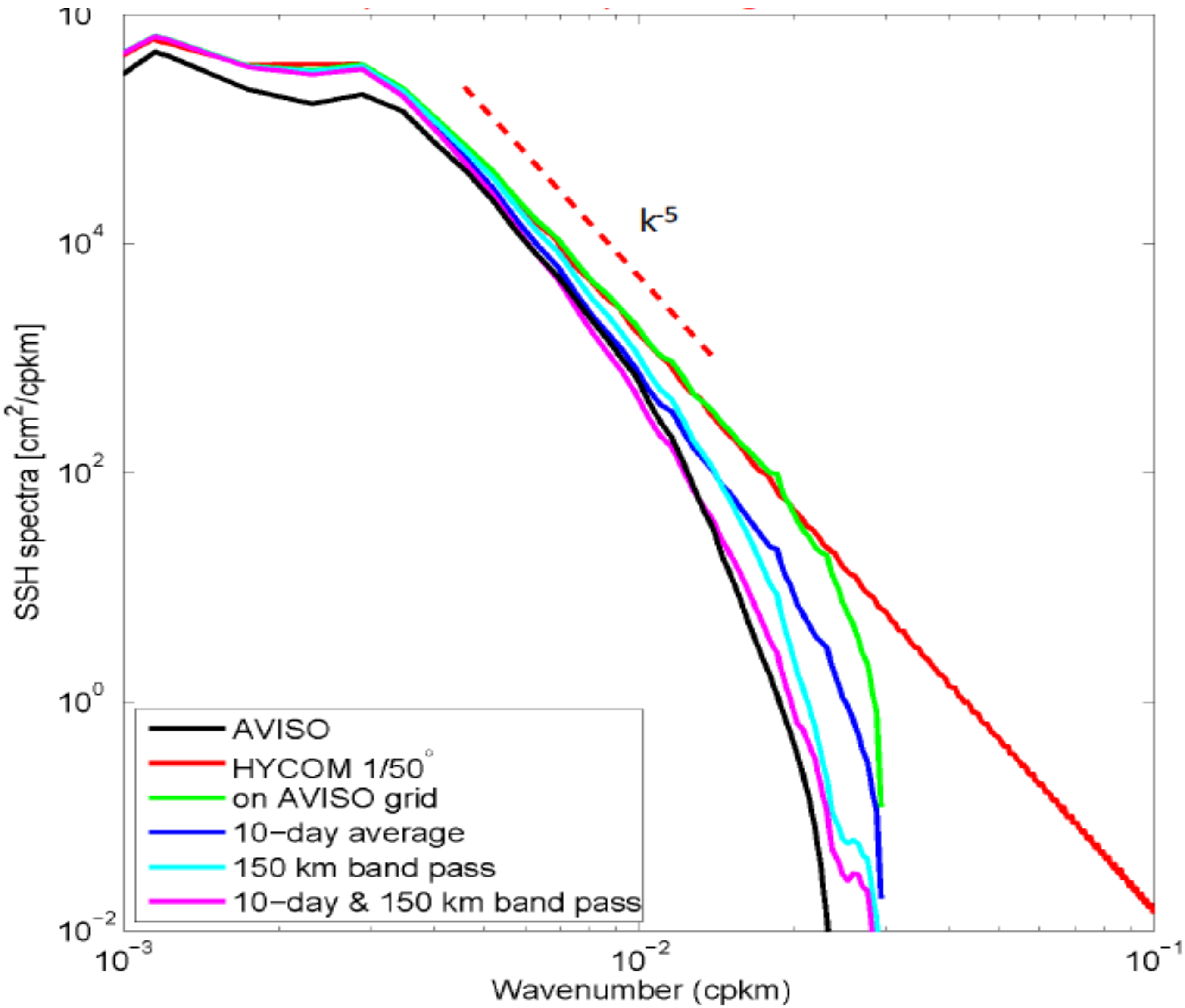
(1) EKE is LARGER in numerical models than from altimetry data

This is explained by smaller scales (not resolved by satellite altimetry)

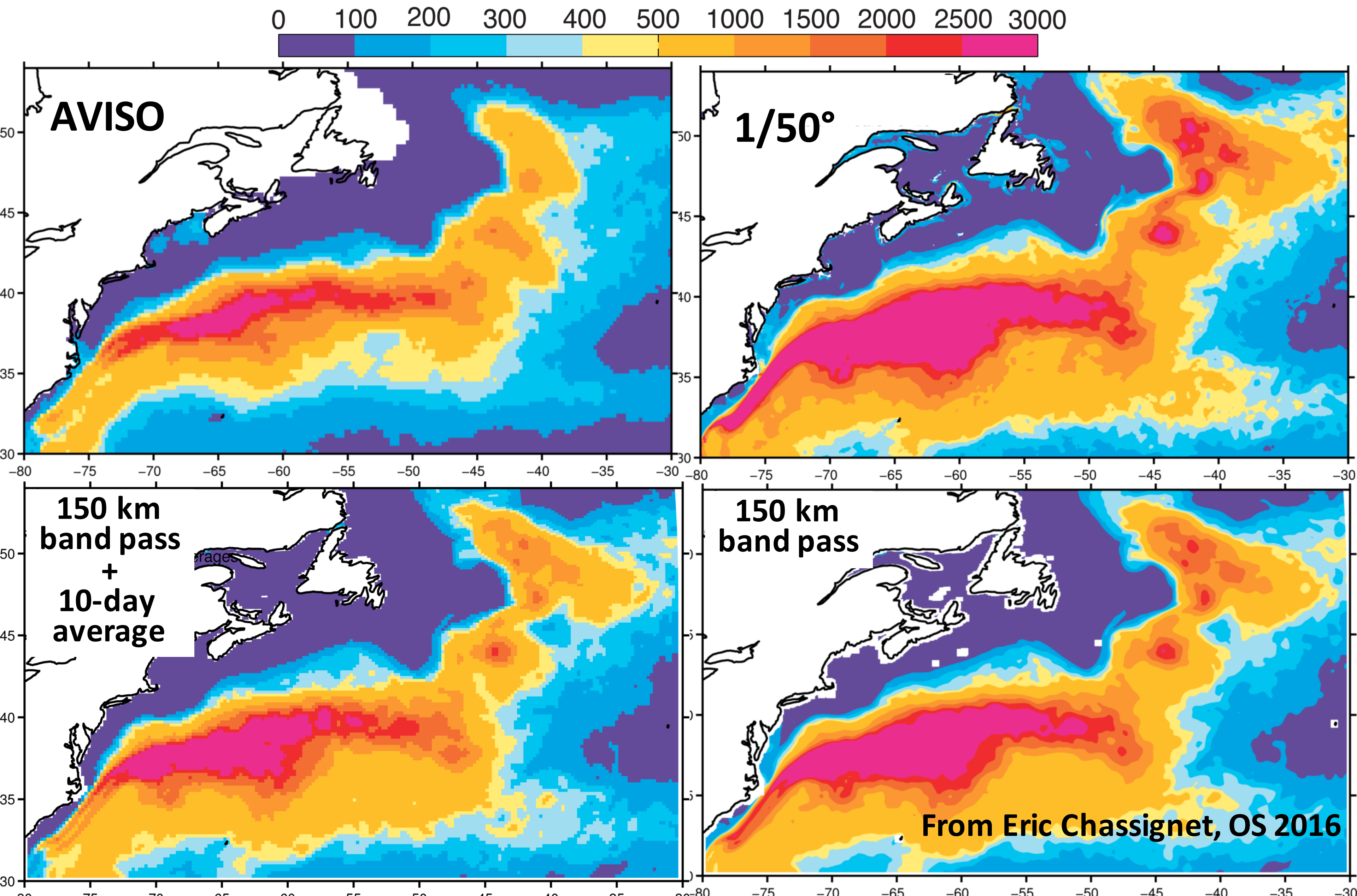
Impact of scales < 150 km on EKE



Satellite altimetry only resolves scales larger than 150 km (from E. Chassignet, Ocean Sciences, 2016)



Impact of scales < 150 km on EKE



A related point: AVISO spectra are also impacted by smoothing (Arbic et al. 2014); SWOT data will be better! (But will still be aliased in time)

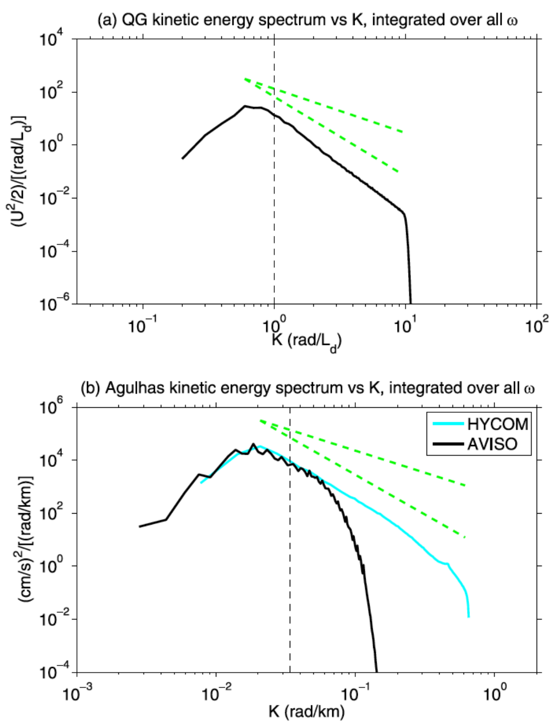


FIG. 6. Wavenumber domain kinetic energy spectra $\mathrm{EKE}_1(K)$, integrated over all ω. (a) Upper-layer kinetic energy spectra in idealized two-layer QG simulation. Dashed vertical line denotes the deformation wavenumber 1 rad/L_d. (b) Ocean surface kinetic energy spectra in HYCOM and AVISO Agulhas region output. Dashed vertical line denotes the deformation wavenumber 1 rad/L_d for the Agulhas region (see text). Dashed slanted green lines indicate slopes of $-5/3$ and -3.

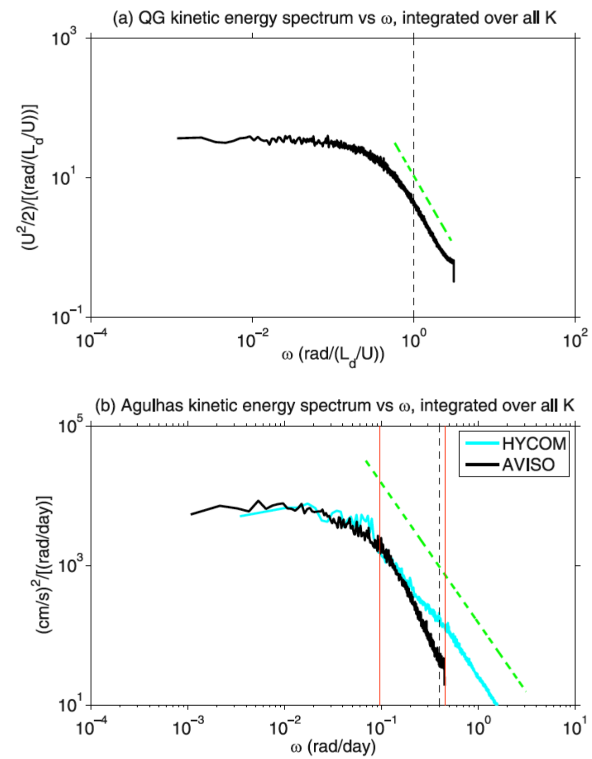


FIG. 7. Frequency domain kinetic energy spectra $\mathrm{EKE}_1(\omega)$ integrated over all K. (a) Upper-layer kinetic energy spectra in idealized two-layer QG simulation. Dashed vertical line denotes the frequency 1 rad/(L_d/U), where U is the imposed mean shear $\overline{u}_1 - \overline{u}_2$. (b) Ocean surface kinetic energy spectra in HYCOM and AVISO Agulhas region output. Dashed vertical black line denotes the frequency 1 rad/(L_d/U), where L_d is the deformation radius, and U is the roughly estimated mean shear for the Agulhas region (see text). Red vertical lines in (b) indicate periods of 14 and 68 days. Slopes of the HYCOM frequency spectra computed over this band are discussed in the text. Dashed slanted green lines indicate slope of -2.

(2) Impact of cyclogeostrophic motions (again)

Gradient wind balance (includes nonlinear terms)

$$\boldsymbol{u}.\nabla\boldsymbol{u}+f\boldsymbol{k}\times\boldsymbol{u}=-g\nabla\eta$$

cyclogeostrophic motions [O(Ro)]

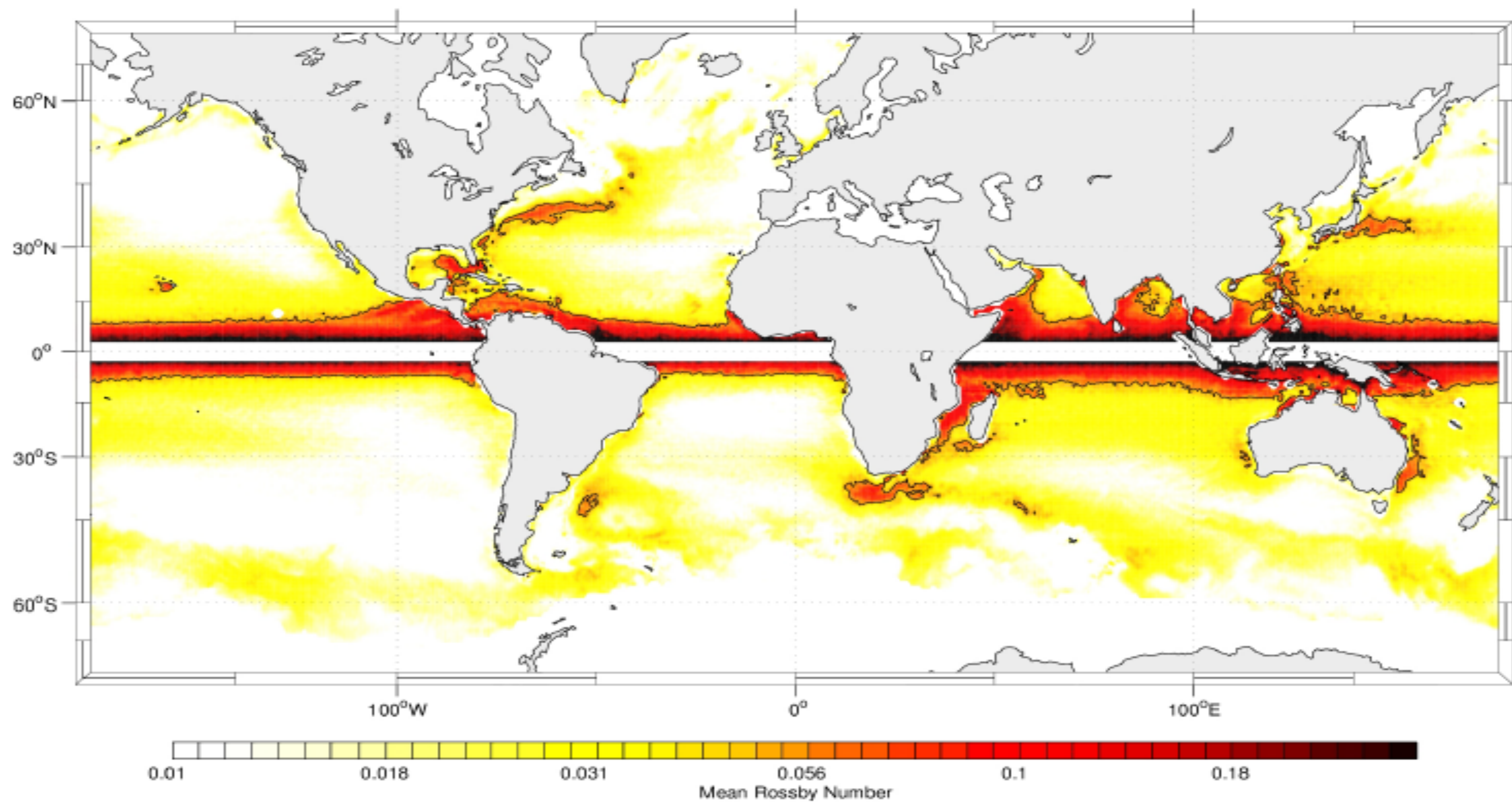
Coriolis term [O(1)]

pressure term [O(1)]

Cyclogeostrophic motions from AVISO

Application at global scale

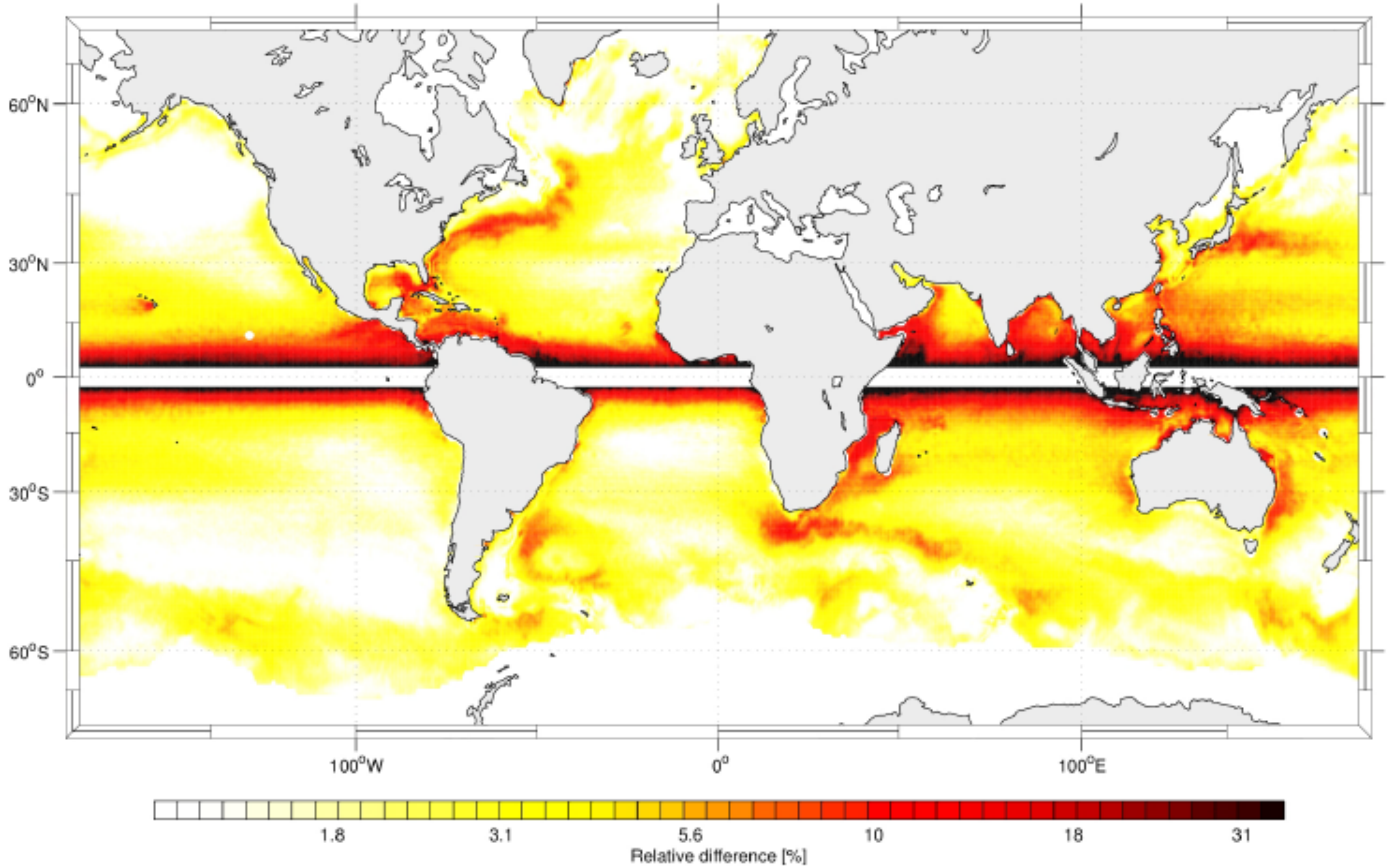
Mean Gradient Wind Rossby number (i.e. using R from AVISO as length scale):



Regions above 0.05: low latitudes and western boundary currents

From Penven et al. Ocean Sciences 2016

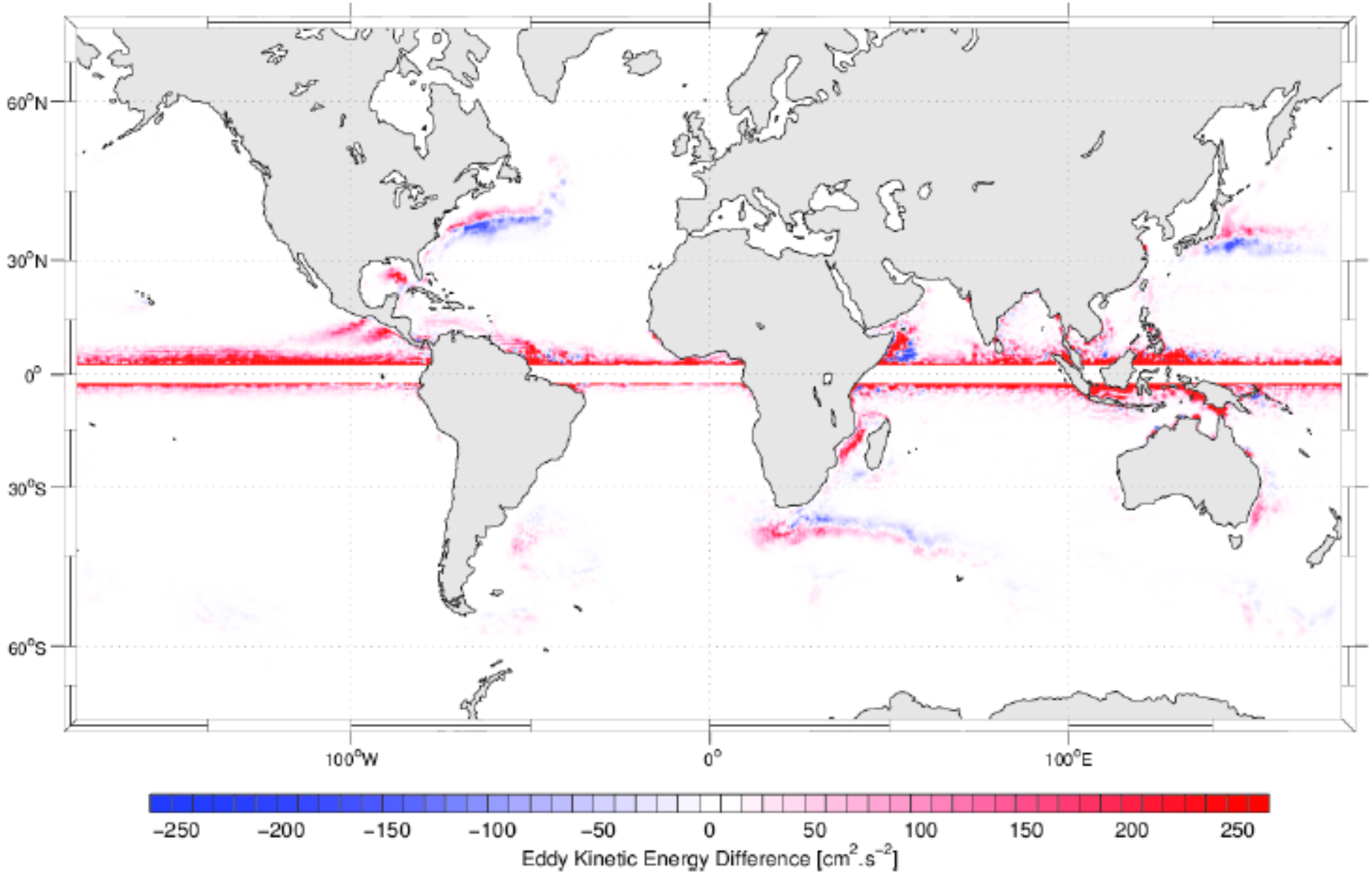
Mean relative difference between cyclogeostrophic and geostrophic speeds



Attains 10 to 20 % of the currents

From Penven et al. Ocean Sciences 2016

Differences between cyclogeostrophic and geostrophic EKE

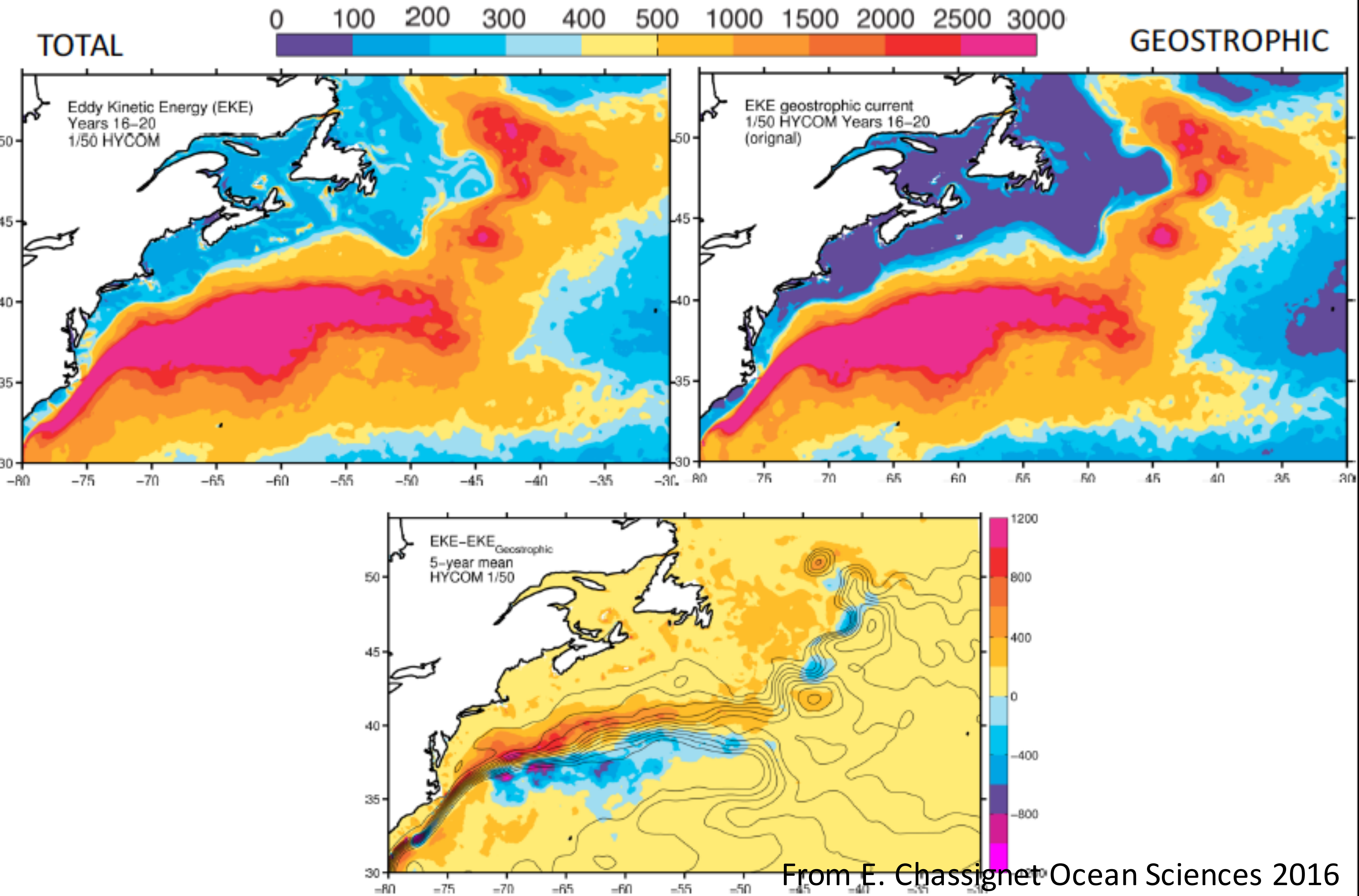


Typical negative/positive patterns in western boundary extensions currents

Signature of regions dominated by anticyclones.

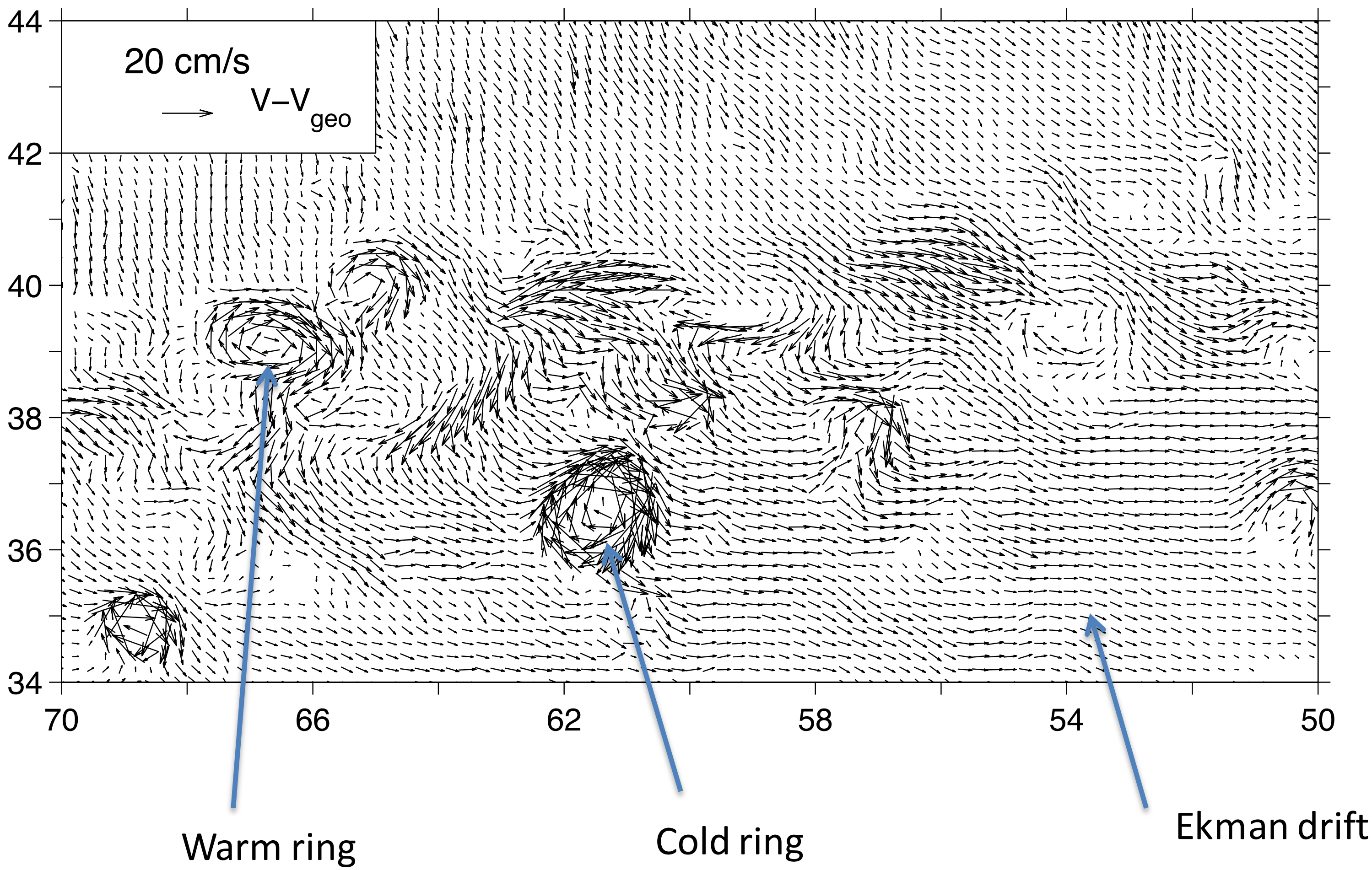
From Penven et al. Ocean Sciences 2016

EKE geostrophic difference (1/50°)



From E. Chassignet Ocean Sciences 2016

Nonlinear terms are important !



From Eric Chassignet: Ocean Sciences 2016

Rossby number in numerical models is LARGER than that from altimetry data

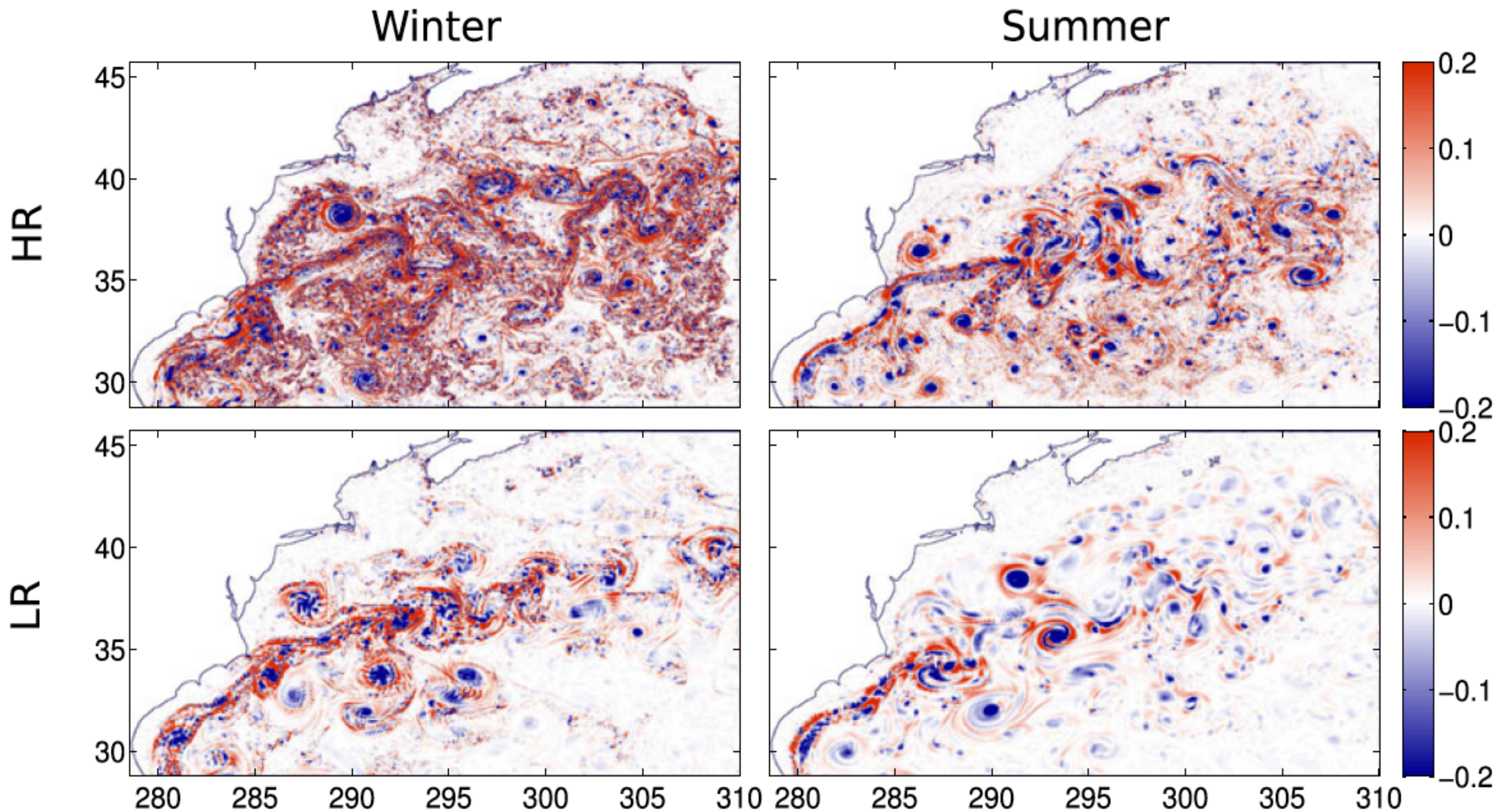


Fig. 14 Okubo–Weiss parameter normalized by f_0^2 computed at the surface (5 m) for winter (*left column*), summer (*right column*), HR (*top row*), and LR (*bottom row*)

From numerical simulations [Mensa et al., OD 2013]

(3) Dispersion of tracers (direct cascade) using satellite altimetry

Transfer of tracer variance from large to small scales

$$\frac{\partial U}{\partial t} + U\cdot\nabla U + f\cdot\vec{k}\times U = -\frac{\nabla p}{\rho_0}$$

$$\Rightarrow \boxed{\nabla\cdot(U\cdot\nabla U) - f\zeta = -\frac{\Delta p}{\rho_0}}$$

$O(R_o)$ $\qquad$ $O(1)$ $\qquad$ $O(1)$.

$\nabla\cdot(U\cdot\nabla U)$ is the Okubo-Weiss quantity

$$\Rightarrow \boxed{\nabla\cdot(U\cdot\nabla U) = \frac{1}{2}\left[S_1^2 + S_2^2 - \zeta^2\right]}$$

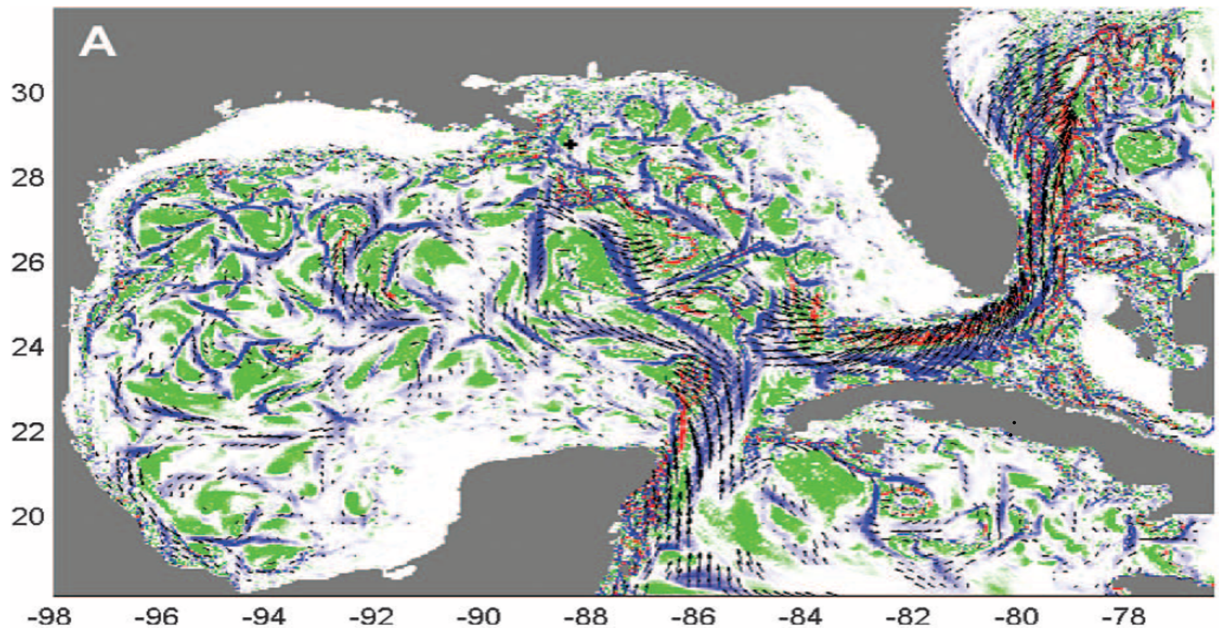
$$S_1 = \left[\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right],\quad S_2 = \left[\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right],\quad \zeta = \left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right]$$

O.W. <0 in vorticity regions. $\rightarrow$ Eddy tracking

O.W. >0 in strain regions. $\rightarrow$ **Dispersion of tracers**
(Lyapounov exponents)

Satellite altimetry data are often used to estimate the impact of surface currents on the dispersion of pollutants and oil spills.

This figure compares the forecast (blue and red colors) of the dispersion of oil spill with what was observed (in black) after the Deep Water Horizon accident in the Gulf of Mexico. This forecast is based on altimeter data.



Forecast of oil spill dispersion in the Gulf of Mexico on 25 june 2010 (red and blue show regions of strong oil dispersion within 3 days), based on altimetric data. This diagnosis compared well with what was observed (Mezic et al, Science, 2010).

However …

Impact of scales < 100 km in terms of the dispersion of pollutants or floats by the surface currents (Finite Size Lyapunov Exponents) [Haza et al. '12]

No submesoscale

With submesoscales

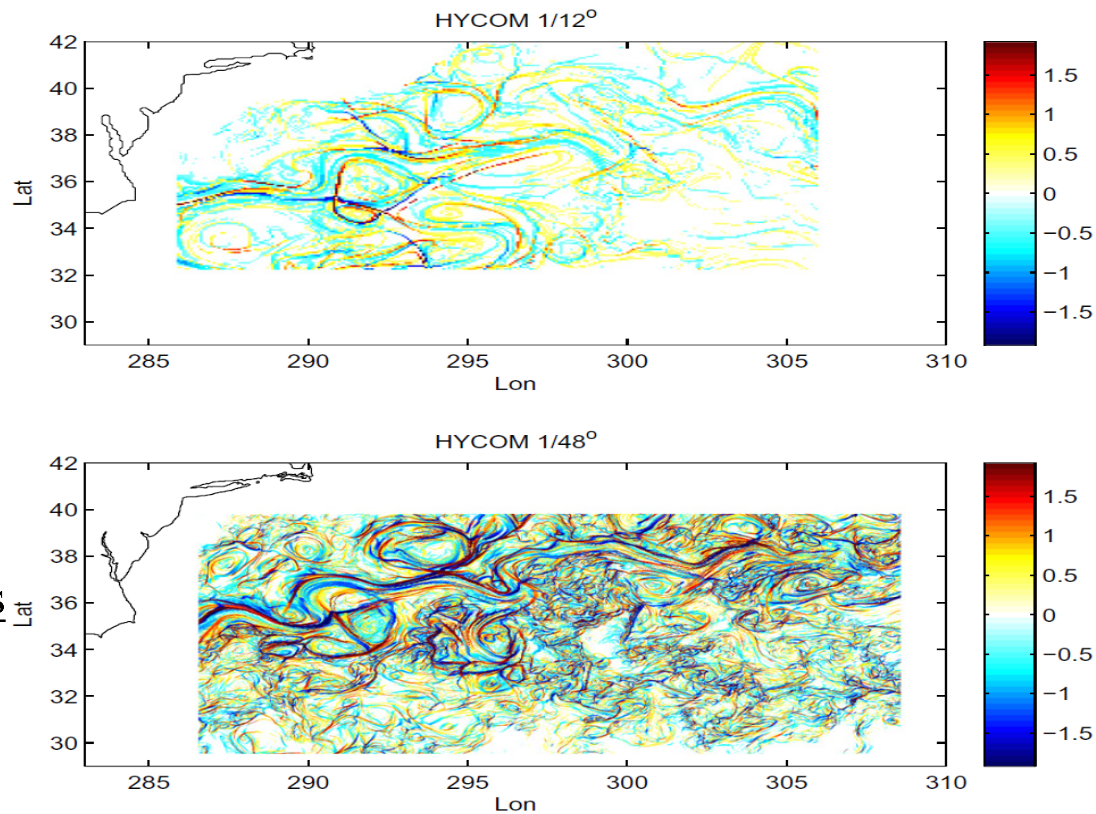


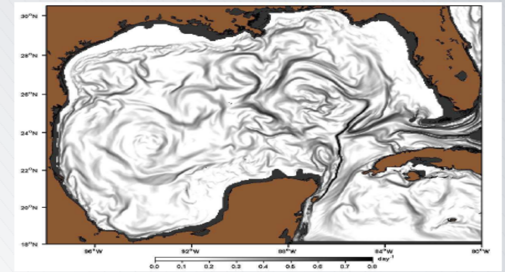
Fig. 1. FSLE branches from 1/12° (upper panel) and 1/48° (lower panel) HYCOM simulations in the Gulf Stream region. Note the rich submesoscale field in the higher resolution case. The color panels indicate FSLE in 1/days. Blue colors show inflowing/stable LCS from forward in time, and red colors out-flowing/unstable LCS from backward in time particle advection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

When scales < 100 km are present FSLE have a larger magnitude and involve smaller scales

=> Dispersion by scales < 100 km is significant.

These ideas are presently tested in the Gulf of Mexico where a very large number of surface drifters have been deployed.

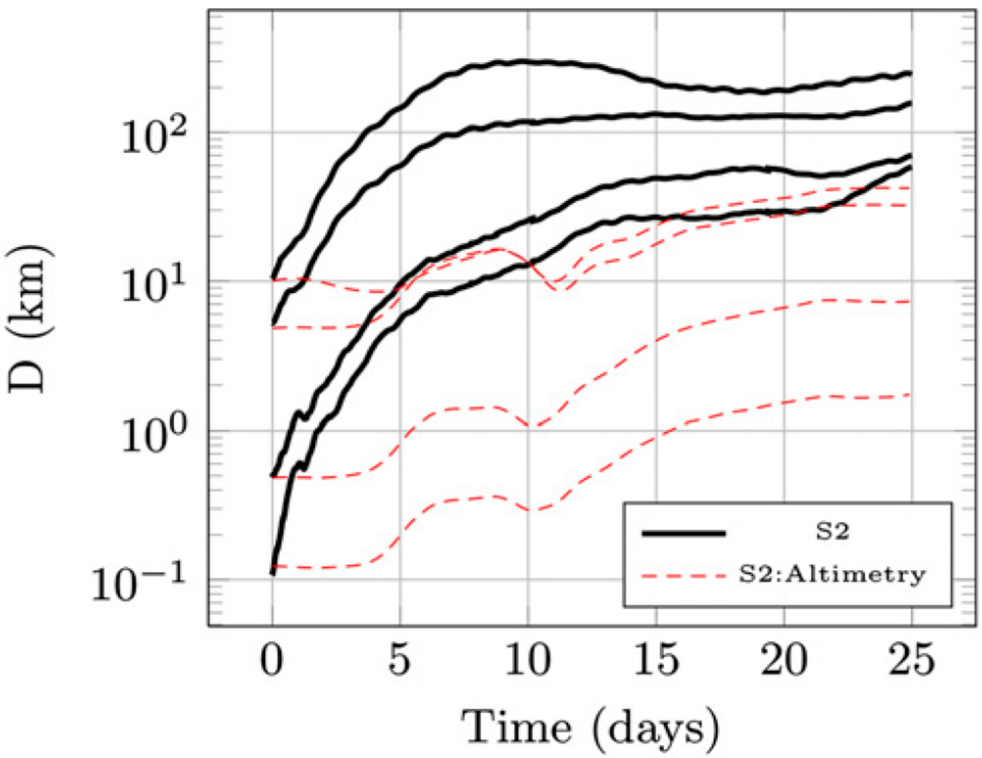
Dispersion by submesoscales in the Gulf of Mexico



Lyapunov exponent

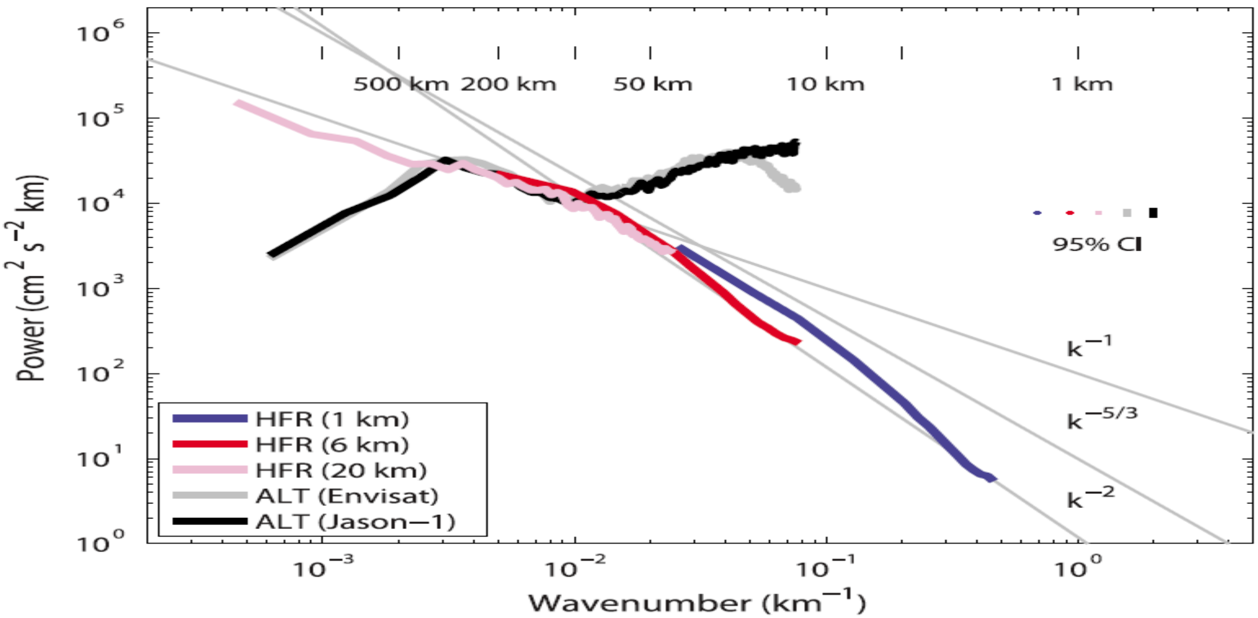
Separation distance of a particle pair, D(t), estimated

- using HR data from 300 drifters (**black curves**): submesoscales are taken into account;
- using LR AVISO data (**red**): submesoscales are **NOT** taken into account.



Dispersion is <u>10-100 times LARGER</u> when submesoscales are taken into account !

(from Poje et al.'14)



Impact of scales < 100 km on the ocean dynamics can be significant and consequently these scales have to be considered in numerical models.

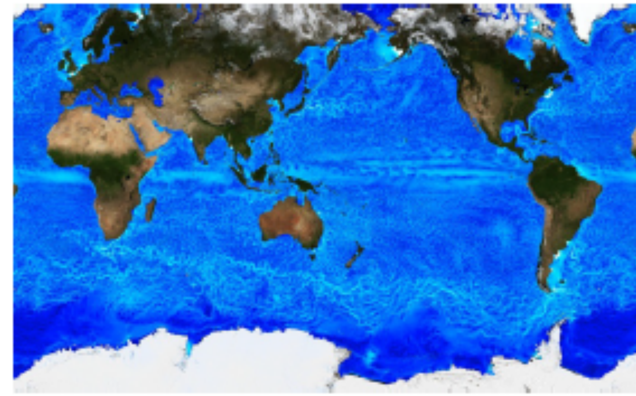
But they need to be observed!

The future satellite SWOT altimeter should be able to sample these scales.

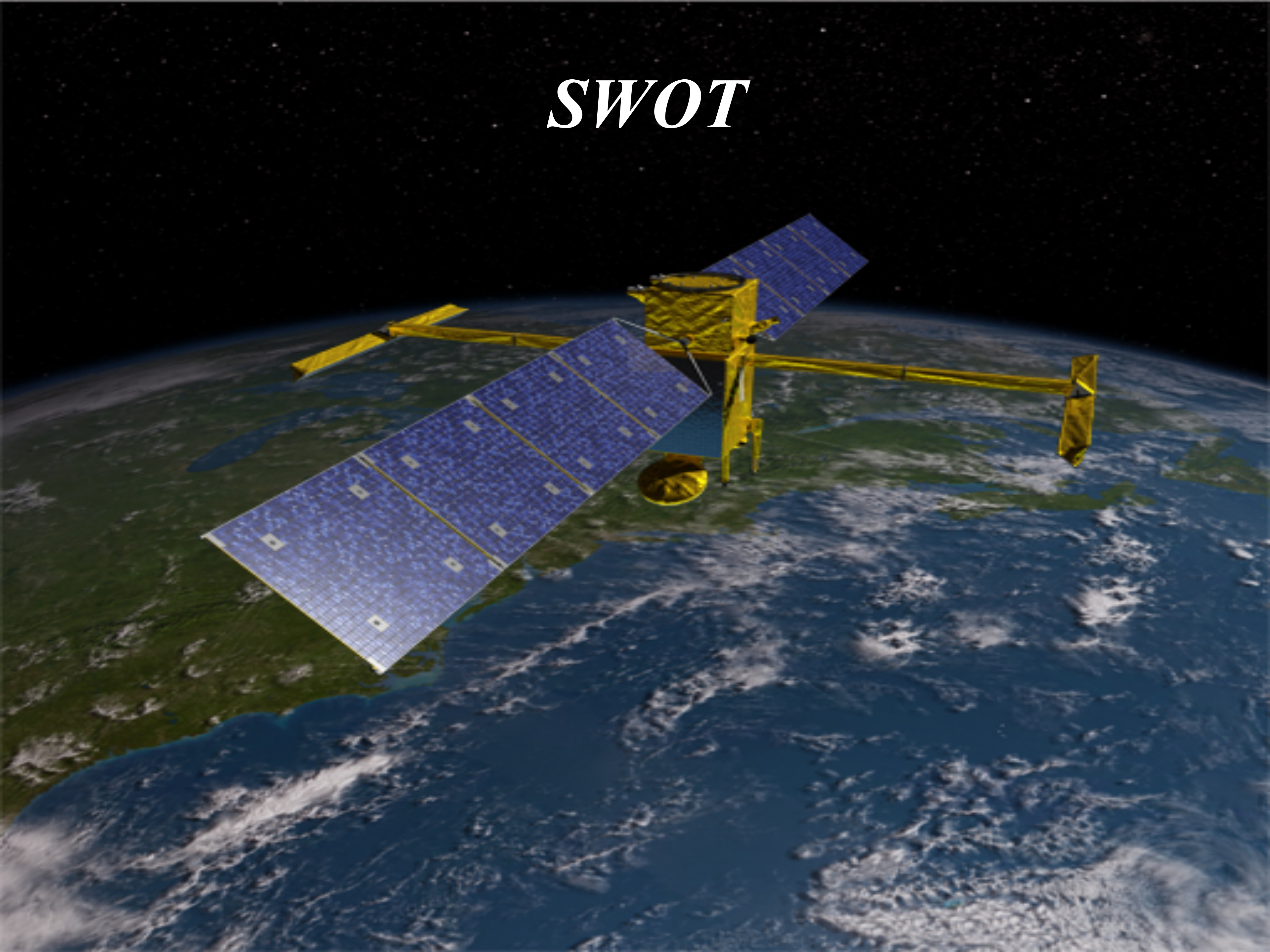
Overview

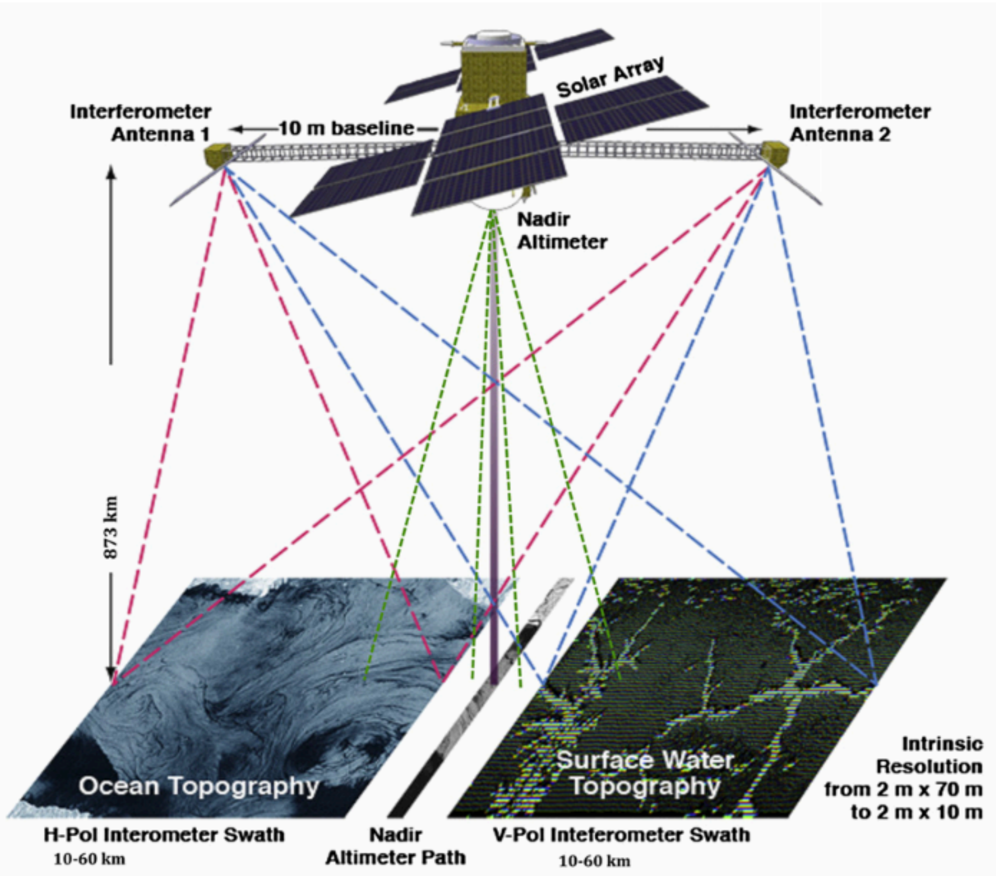
« Increased resolution in ocean models needs to be accompanied by higher resolution observations. »

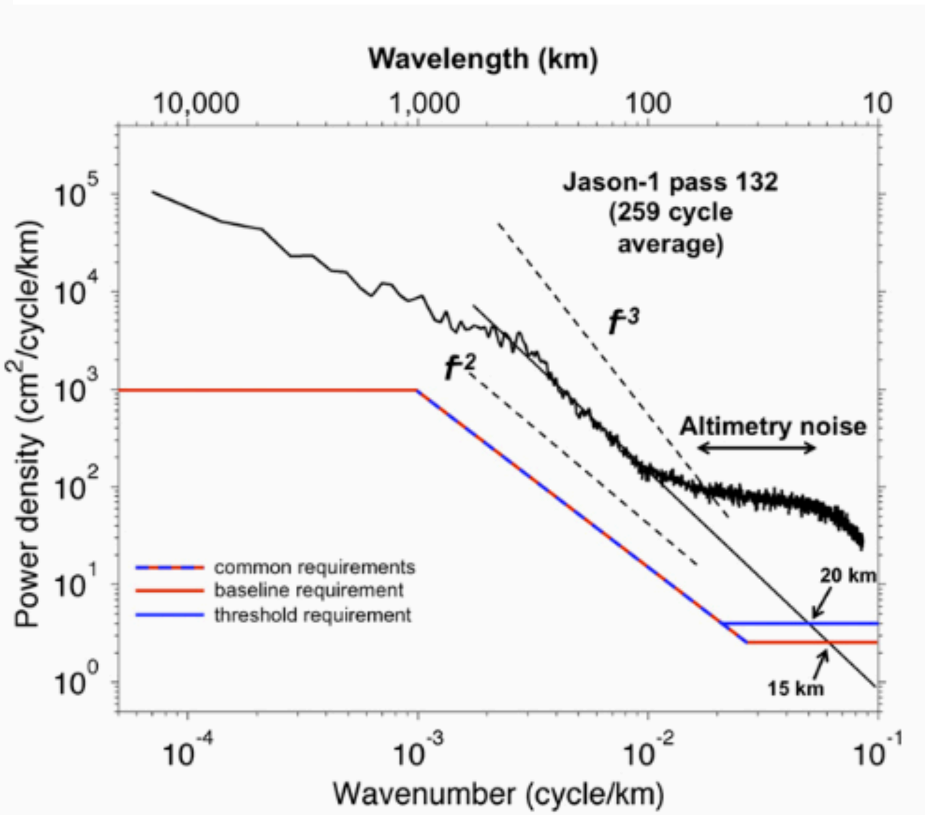
Carl Wunsch, Lisbon 2010



- **Opportunities in observing the ocean SSH from 10-100 km wavelength & validating ocean models at these scales**
  - New altimetric technology
  - Dynamical contributions from mean sea surface/geoid, tides, internal waves, sea-state effects
- **How to address the different spatial-temporal sampling of models, in-situ data, compared to alongtrack / SWOT SSH observations?**
- **Role of the HR modelling for the CalVal of SWOT/altimetry – rapid 2D « snapshots », which depths?**


SWOT

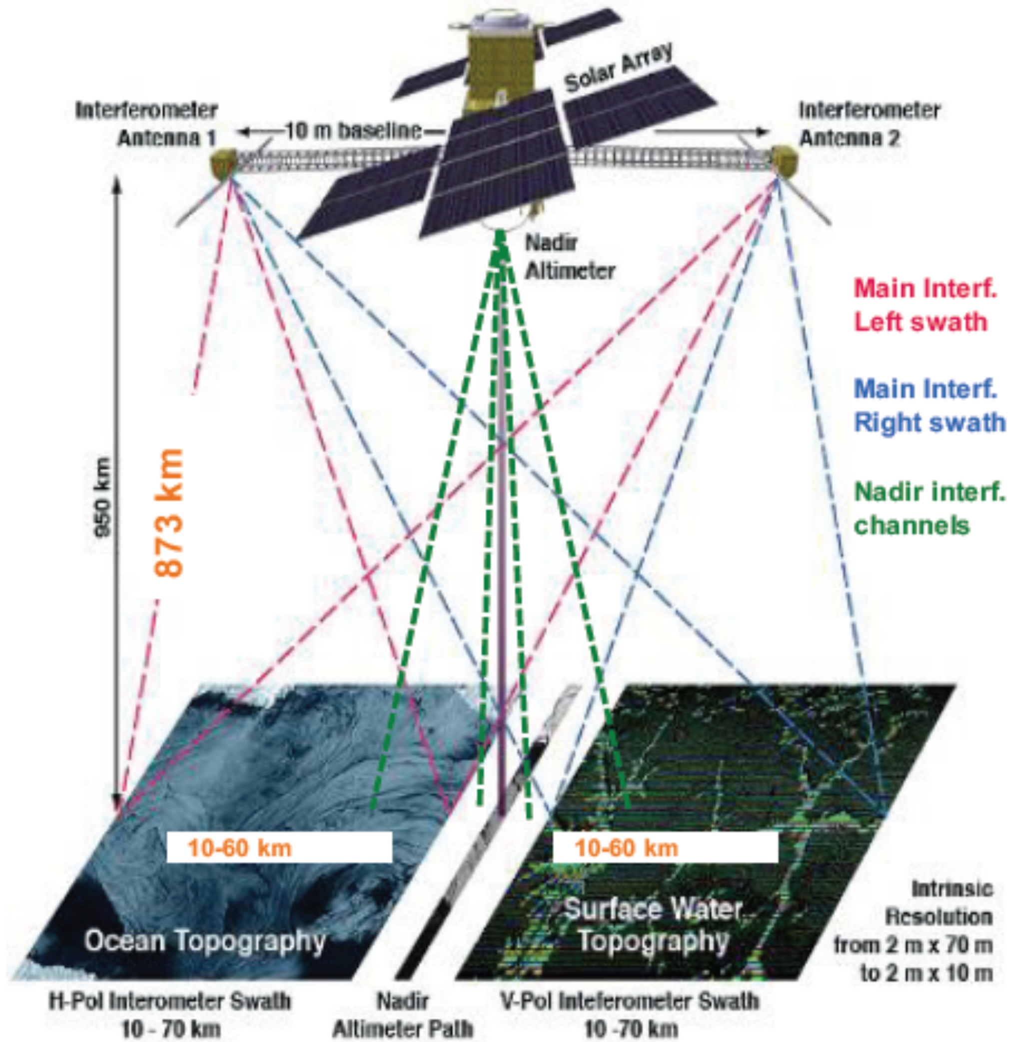

Solar Array
Interferometer Antenna 1
10 m baseline
Interferometer Antenna 2
Nadir Altimeter
873 km
Ocean Topography
Surface Water Topography
Intrinsic Resolution from 2 m x 70 m to 2 m x 10 m
H-Pol Interometer Swath
10-60 km
Nadir Altimeter Path
V-Pol Inteferometer Swath
10-60 km


Wavelength (km)
10,000
1,000
100
10
Jason-1 pass 132 (259 cycle average)
f^{-3}
f^{-2}
Altimetry noise
Power density (cm^2/cycle/km)
common requirements
baseline requirement
threshold requirement
20 km
15 km
Wavenumber (cycle/km)

SWOT (Surface Water Ocean Topography) Mission

Mission Architecture

- Ka-band SAR interferometric (KaRIn) system with 2 swaths, 60 km wide
- Produces heights and co-registered all-weather SAR imagery
- Intrinsic resolution 2 m x 10-70 m grid
- **Onboard processor gives 250 m^2 grid over oceans**
- **Interferometry will reduce noise by 1 order of magnitude : 2.4 cm^2/cycle/km^2**
- Use conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/Doris/Laser ranging for orbit determination.



- Partnered mission NASA, CNES & CSA & UKSA
- Mission life of 3.5 years
- 890 km Orbit, 78° Inclination, 21 day repeat
- **Launch: 2020**