Meso-submesoscale dynamics and their impact on sea level: Overview of recent studies and perspectives

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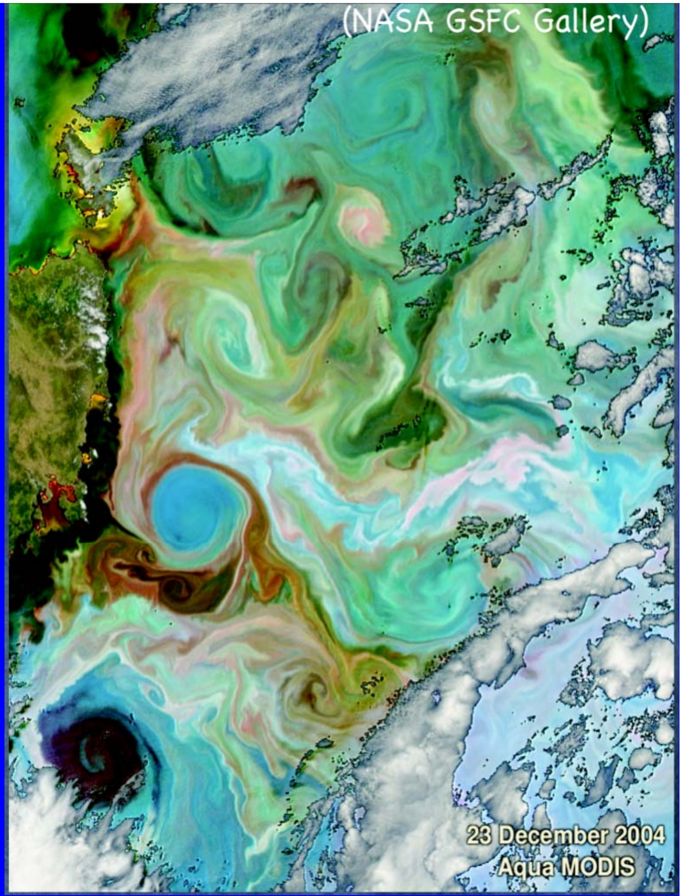
High resolution satellite images, such as SST, SAR and color images, reveal not only <u>mesoscale eddies</u> (100-200km) - 80 % of the ocean KE - but also smaller scales (1 km-40 km) called <u>submesoscales</u>.



These HR satellite images (or conventional altimeters) do not provide much dynamical information on the <u>submesoscales.</u> This explains that in 1/10th models (that only resolve mesoscale eddies) submesoscale impact is usually parameterized as a <u>dissipation of kinetic energy</u>.

However ...

<u>recent studies</u>, both experimental and numerical, have emphasized that the dynamical impact of submesoscales is <u>NOT DISSIPATIVE</u> and affects much the ocean circulation and the biodiversity (because of their W-field).

Just to summarize ...

@ Classical vision of the upper ocean dynamics: driven by mesoscale eddies (induced by the baroclinic instability in the ocean interior (~ 800-1000m)) with, as a result,

- **Surface properties close to QG turbulence** (with surface velocity spectrum with a **k^{-3} slope**)
- **W field is mostly located within mesoscale eddies**

@ New vision of the upper ocean dynamics (from studies resolving submesoscales as small as 5 km): driven not only by mesoscale eddies but also by **frontal instabilities at submesoscale**, with the resulting properties:

- **(1) Total kinetic energy can larger** by a **factor 1.5 to 2**;
- **(2) Surface velocity spectrum with a k^{-2} slope (instead of a k^{-3} slope)** which suggests that submesoscale impact the larger scales
- **(3) More than 50% of the W-field (in the first 500m) is within submesoscales with its rms magnitude increased by a factor 5!**

Consequences: these properties make submesoscales to impact the basin-scale ocean dynamics and the physical-biological interactions

to detail this vision …

A brief review of what we have learnt, in the last 10 years, on the impact of submesoscales on the larger scales ...

@ Results from observations strongly suggest that the submesoscale field in the upper layers is driven by frontogenesis (k^{-2} slope) and also that most of the W-field is within submesoscales (Le Traon et al., '08 ; Xu and Fu, '12 ; Lumpkin and Elipot, '10 ; Le Gal et al., '07)

@ High resolution numerical simulations performed in large domains have revealed that **(a)** the eddy kinetic energy is increased when submesoscales are present (submesoscale impact is NOT DISSIPATIVE) and **(b)** that these scales involve <u>energetic frontal instabilities and mixed-layer instabilities</u>, that are a <u>source of kinetic energy</u> *(Klein et al., '08; Capet et al., '08; Levy et al.'10, '12; Haza et al. '12; Sasaki and Klein, '12, '13; Ponte et al., 2013 ...)*

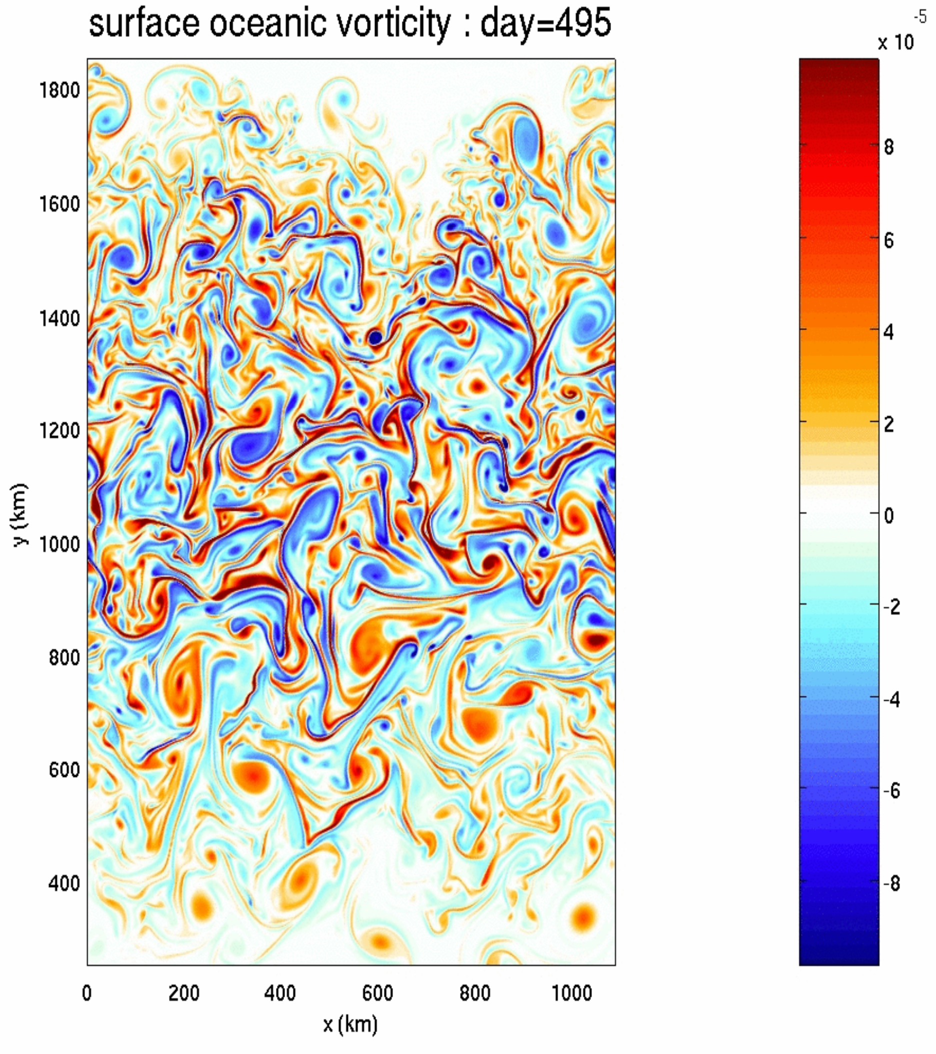
Quickly illustrate some of these results and in particular the interactions between mesoscale eddies and submesoscale structures (using two movies) ...

Submesoscales involve <u>energetic frontal (sheared) instabilities (this movie)</u> <u>and frontal (winter mixed-layer) instabilities (next movie)</u>,

- **Submesoscales mostly involve unstable fronts, which produces small-scales eddies.**

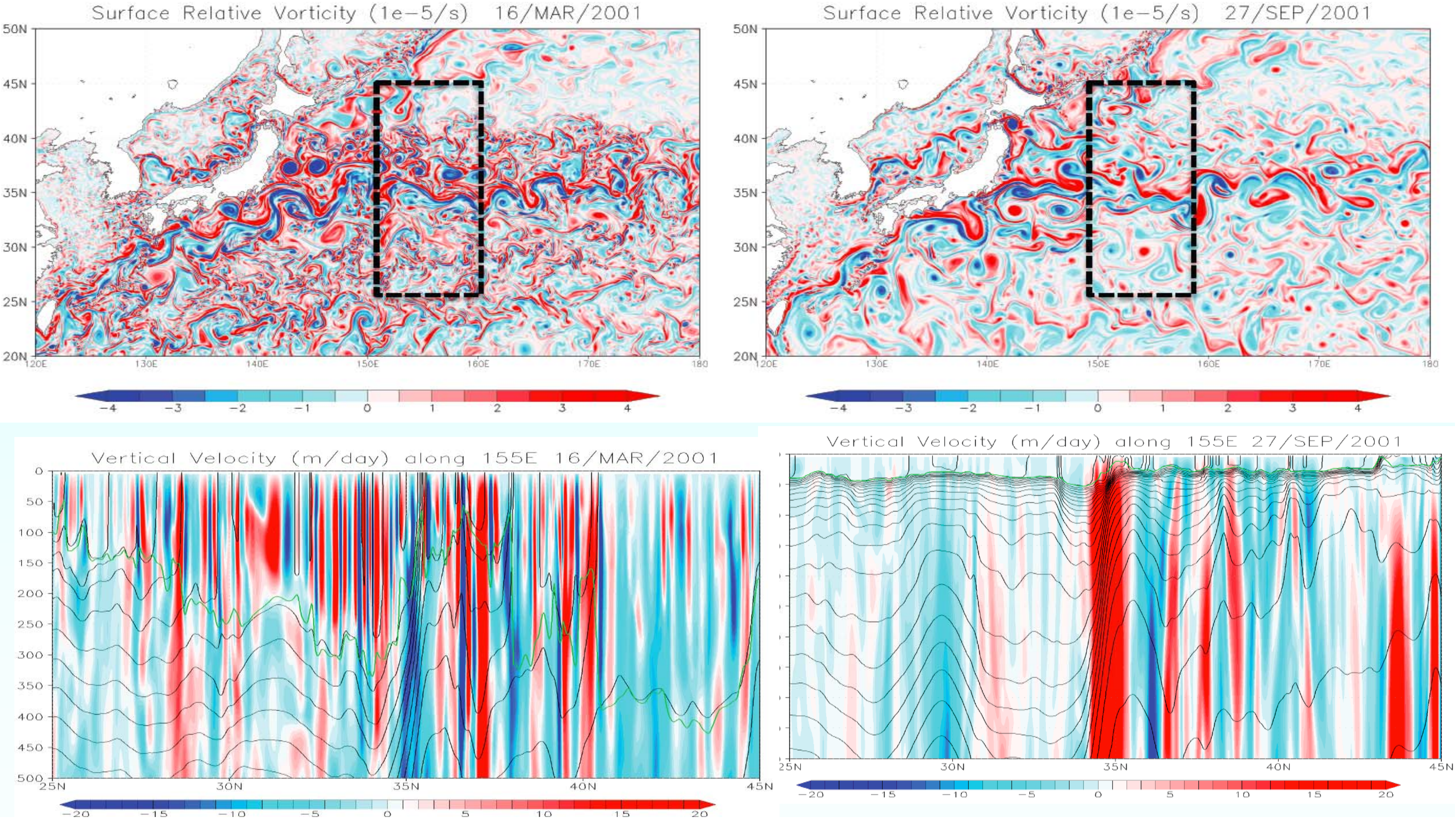
- **These small-scale eddies subsequently merge leading to larger-scale eddies.**

(Klein, Hua et al, '08; Capet et al.,'08; Levy et al., 2010,2012; Sasaki and Klein,'12)



North Pacific simulation (1/36th 100 vertical levels) (Sasaki et al.,'13.) :

Impact of submesoscale mixed-layer instabilities on larger scales



A brief review of what we have learnt on submesoscales in the last 10 years...

First : results from high resolution PE models (using two movies)

Submesoscales do impact the larger scales

What are the mechanisms through which ...

submesoscales impact the large-scale ocean dynamics ?

(Tulloch and Smith, '09; Capet et al.'08; Klein et al.'08,10; Levy et al.'10; Roullet et al. '12; Haza et al. '12; Ponte et al., '13; Sasaki et al., '12,'13...):

It is important to identify these mechanisms in order to be able to simply diagnose them from observations (satellite and in-situ) and parameterize them in climate model

What are the ...

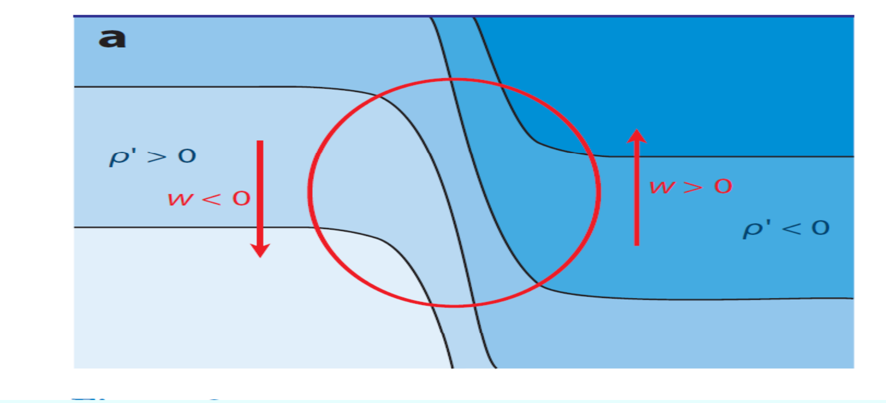
opened questions and new challenges to meet

One way to understand the impact of the submesoscale instabilities is to focus on SST ...

Sea Surface Temperature (SST) is NOT a passive tracer:

SST gradients are affected by FRONTOGENESIS !

Then, because of frontogenesis, an ageost. circulation, including a W field, develops for the SST front to be in thermal wind balance, involving **|W| ~ |ΔSST|**



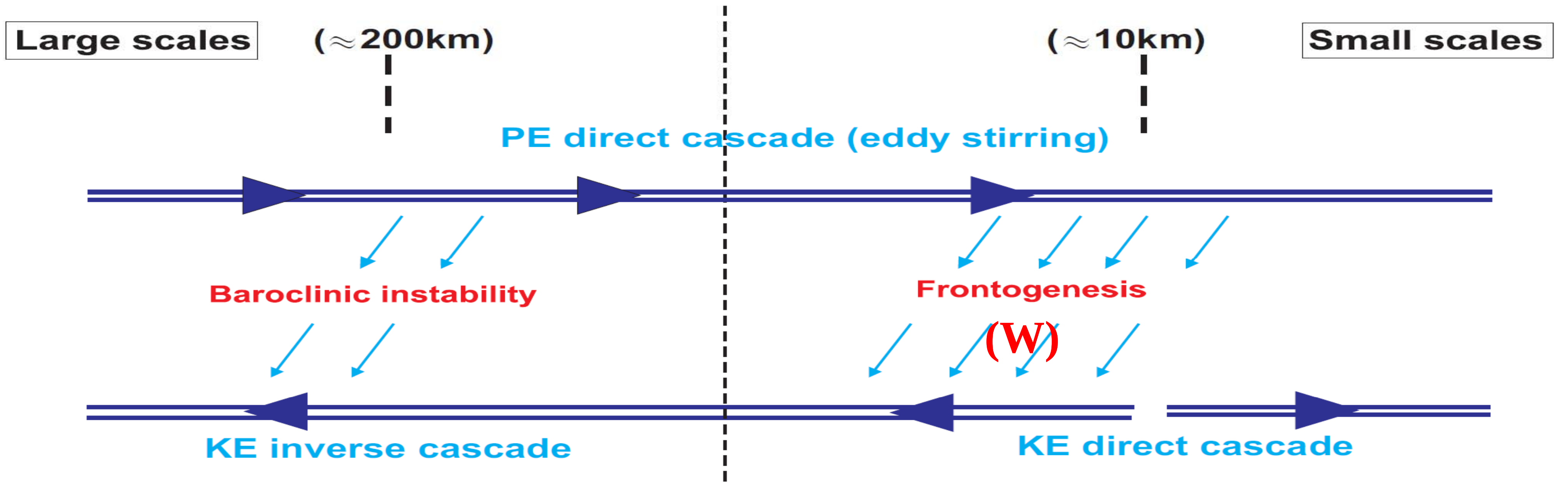
=> Since SST spectrum slope is in k^{-2} (**=> ΔSST ~ k^2**), this explains that the W-field is mostly within submesoscales and its rms value is multiplied by a factor 5 !

=> Strong consequences on the physical-biological interactions ;

=> Consequences on the larger scales and explain that submesoscale impact is **NOT DISSIPATIVE :** Indeed, frontogenesis corresponds to a transformation of PE into KE since $\overline{w'\rho'} < 0$

As a result ...

… the unstable frontal dynamics at small scale modifies the nonlinear interactions over a large spectral range



Submesoscales efficiently feed up the KE of mesoscale eddies and of the larger scales through **W at small scales**

=> **Total EKE is larger (by a factor 1.5 – 2)**; submesoscale impact is not dissipative ;

=> Submesoscales significantly impact the large-scale dynamics principally through their contribution to the horizontal and vertical heat and momentum fluxes (up to 50 % of the total fluxes (Levy et al.'10; Waugh et al.'12 ; Keating et al.'12)!

These results mostly come from H.R. Models, which leads to the question :

How to observe these submesoscale impacts on a global scale? ***=> New challenge !***

Future altimeter data combined with recent diagnosis methods should allow to meet this challenge.

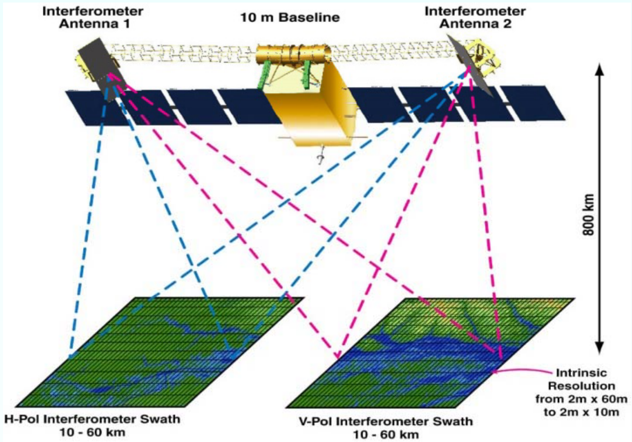
Analytical methods based on the H.R. modelling results indicate that H.R. altimeter data combined with Argo float data should allow to diagnose not only the surface currents but also the 3D motions (including the W velocity) in the first 500m.

(Lapeyre and Klein,'06; Lascace and Mahadevan,'06; Klein et al.,'09; Scott and Furnival,'12; Ponte and Klein,'13; Ponte et al.,'13; Wang et al., '13)

These diagnosis are based on the potential vorticity (PV) inversion ! In this context, H.R. SSH data are used to estimate the H.R. surface PV and Argo float data the correlation between the surface and interior PV; which allows to get the 3D PV field.

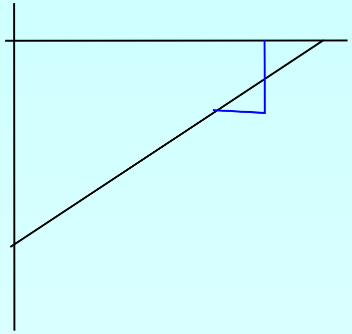
=>

These diagnosis methods highlight **the strong potential of** the new class of wide-swath altimeters such as **SWOT and COMPIRA** to meet this challenge since they should capture wavelengths down to 10 km to 20 km...

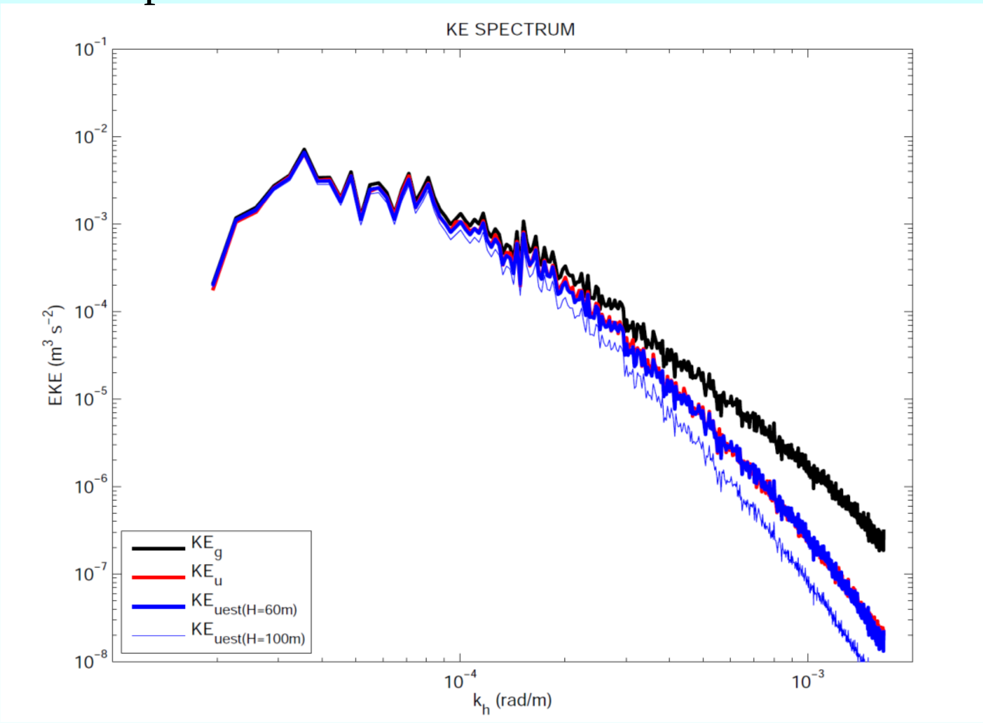


This new potential has been successfully tested, in particular for …

Diagnosis of the 3D dynamics in the first 500m including within the ML (Ponte et al.,'13)



spectrum of ML horizontal motions



Black curve: velocity spectrum from SSH (Ug,Vg)

Red curve: velocity spectrum from surface currents observed in the model

Thick blue curve: velocity spectrum diagnosed from SSH using an additional mixing argument related to the mixed-layer dynamics

=> Mixing argument explains the differences between the black and red curves.
The resulting analytical solution only requires the knowledge of

high resolution SSH and climatological value of the ML depth

In the same way ...

the W field within the ML is diagnosed by considering that it involves a SQG contribution <u>and a mixing contribution</u> (derived from Garrett and Loder,81) :
[Ponte et al.'13]

Simulated W by an OGCM ***Diagnosed W from SSH, SST and Kv***

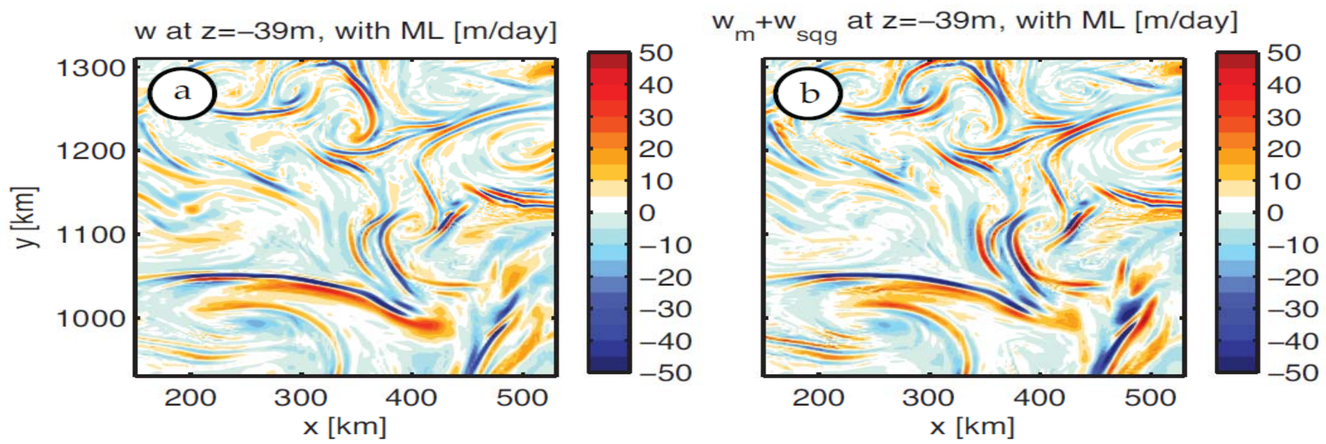


FIG. 6. Snapshots of the vertical velocity field at 40 m with ML (a) and reconstructed field $w_{sqg} + w_m$ (b). Units are m/day.

=> W diagnosis requires the knowledge of, **both**, **HR SSH, HR SST and order of magnitude of the vertical mixing (from Argo floats)**

These first diagnosis results seem promising and point out the strong potential of the wide-swath altimeters

Open questions still to address ...

before SWOT and COMPIRA launching in order to fully take advantages of the new data when they become available at the beginning of the next decade ...

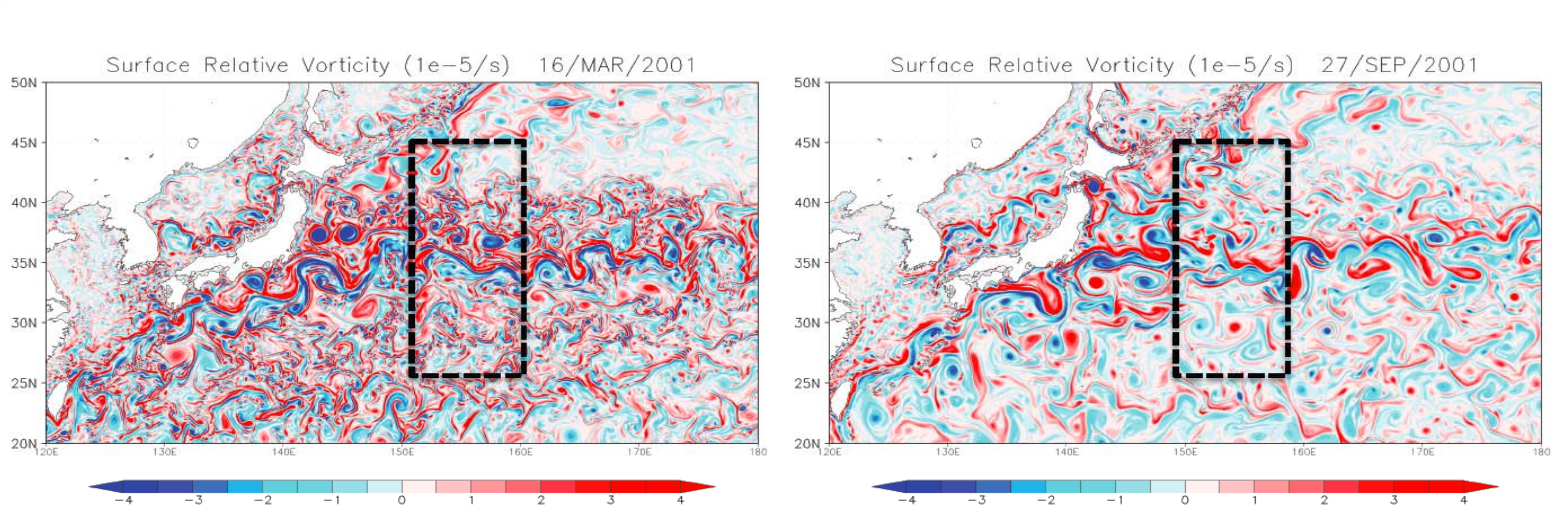
@ In the real ocean, upper layer dynamics (where submesoscale are energetic) can be intermittent and compete with the interior dynamic. This intermittency and competition may differ in the western and eastern parts of the ocean basins. We need to better identify and understand these differences and their signatures on the SSH.

@ Submesoscales do interact with internal waves (near-inertial and tidal) but how and how does this impact SSH ?

@ Will the new SSH data allow to exploit the potential synergy between all other satellite data ?

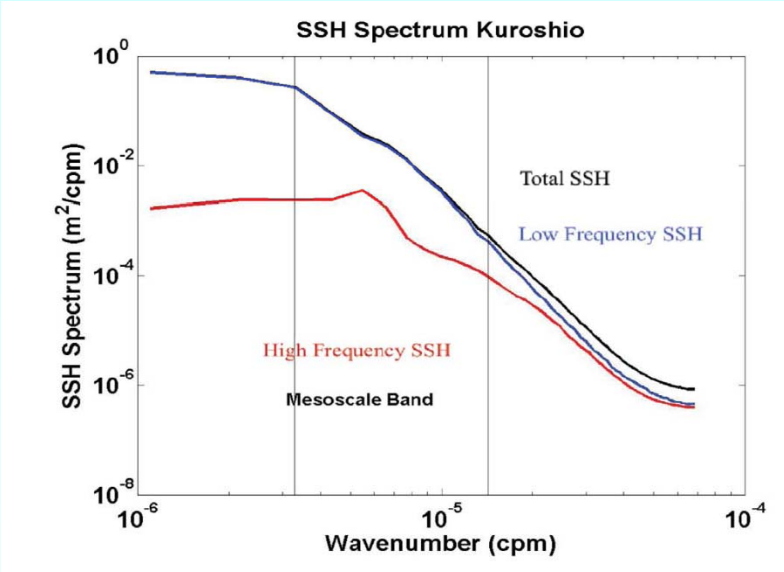
@ In the real ocean, upper layer dynamics involving submesoscales can be intermittent and compete with the interior dynamic. This intermittency and competition may differ in the western and eastern parts of the oceanic basins. How to better identify and understand these differences and their signatures on the SSH? How available in-situ data (Argo floats) can help to identify these differences and help to use appropriately the new SSH data .

North Pacific simulation (1/36th 100 vertical levels) (Sasaki et al.,'13)



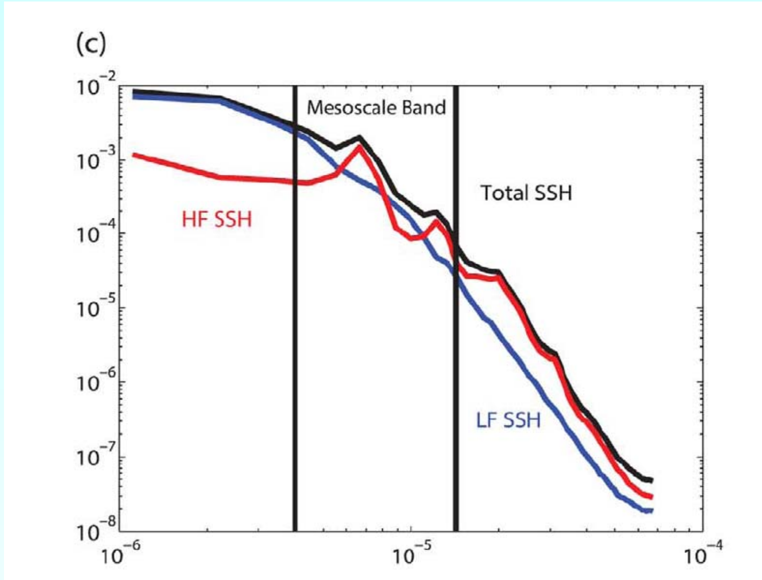
@ **Submesoscales do interact with internal waves (near-inertial and tidal) but how and how does this impact SSH ?**

Western North Pacific



(from Jim Richman et al.'12)

Eastern North Pacific



Internal tides have spatial and temporal scales not far from those of submesoscales. How do both interact in regions where HF KE is as large as LF KE ?

What are the consequences on the SSH and the diagnosis of 3D dynamics related to LF motions (how to discriminate internal tides from meso/submesoscale turbulence) ?

@ How to exploit the synergy between the new SSH data and existing satellite data ?

Existing and future satellite data have different resolutions and therefore different spectral gaps, for example :

SSH (SWOT) : 1 km – 3 km and 10 days – 20 days ;

SST (AMSR-E) : 25 km to 40 km and 1 day ;

Can we exploit the synergy between all these satellite data to diagnose the surface potential vorticity field with resolutions close to 1km-3km and 1 day ?

First attempts : see C. Ubelmann' talk this morning .

International working group on the physics of meso – submesoscale processes

Several teams have already started to address part of these questions independently.

We need a coordinated effort to explore these issues and to get appropriate answers in the next 10 years.

We propose to create **an international working group that includes members of the SWOT SDT and also external members.**

This group will exchange results and ideas (meeting twice a year) in support for SWOT and COMPIRA studies. This group will address long-term scientific activities.

List (provisional):

SWOT-SDT :

US : (PIs) L. Fu, B. Arbic, B. Qiu, T. Farrar, W. Kessler,
+ (Co-Is) M. Alford, D. Chelton, J. McWilliams, J. Molemaker, J. Richman, J. Shriver,
R. Samelson, A. Thompson, C. Ubelmann ;

France : (PIs) P. Klein, R. Morrow, P.Y. Le Traon, F. D'Ovidio, B. Chapron, J. Le Sommer,
+ (Co-Is) M. Levy, G. Lapeyre, X. Capet, J. Verron.

External members :

US : R. Ferrari, S. Smith, S. Keating ;
Japan : T. Suga, H. Sasaki S. Minobe.

How to address these questions:

- Development of high resolution numerical simulations, both, realistic (NP in Japan, ACC in the US) and idealized (US, Japan and France). These simulations (1/100th, 400 vertical levels) may include or not internal tides;

- Further analysis of the Argo float database (in terms of 3D eddy PV);

- Further analysis of past in-situ experiments (LatMix).

- Set up a future field campaign (GS or Kuroshio) around 2017-2018 that may includes an Airborne version of a wide-swath altimeter .

Thank you

Impact of submesoscales

@ ***Submesoscales*** *significantly impact the large-scale dynamics principally through their contribution to the horizontal and vertical heat and momentum fluxes (up to 50 % of the total fluxes (Levy et al.'10; Waugh et al.'12 ; Keating et al.'12)!*

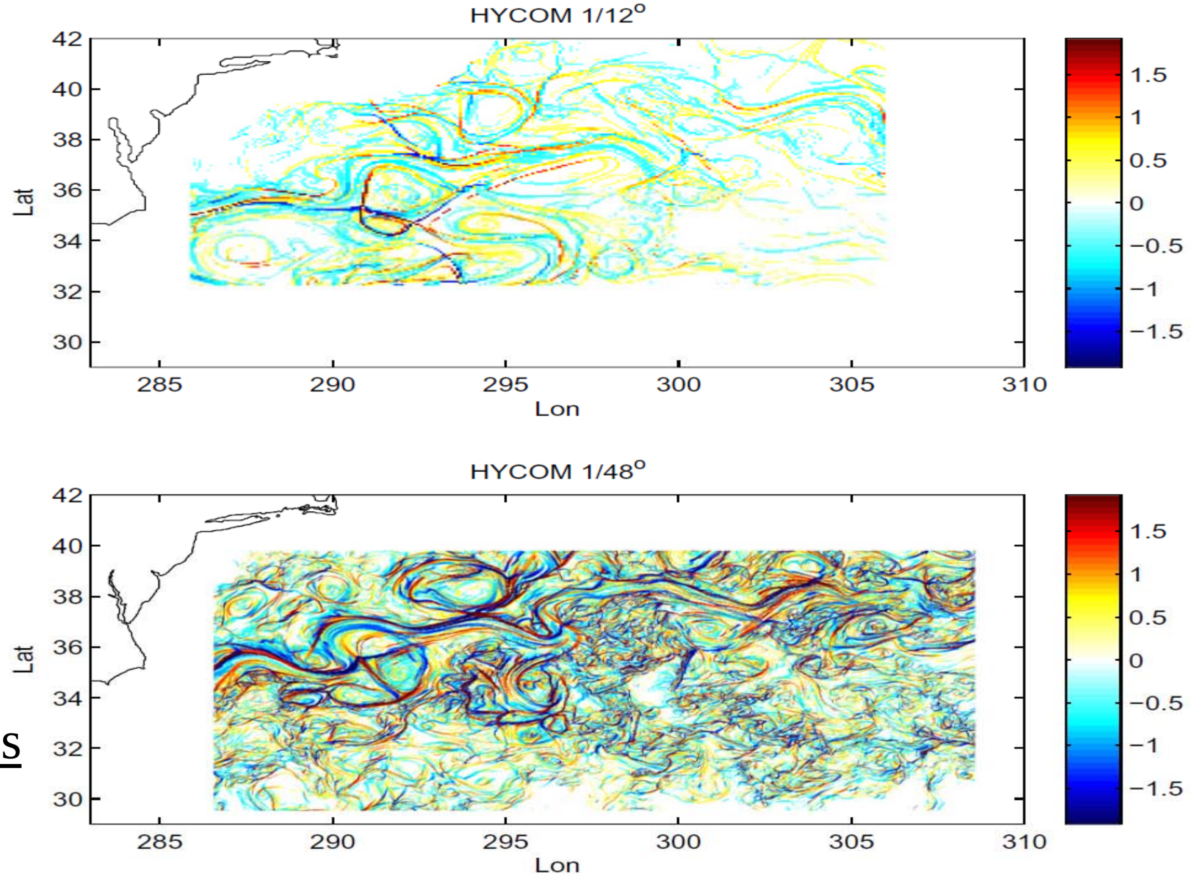
@ ***Submesoscales*** *strongly impact the physical-biological interactions and organize the biodiversity (Perruche et al.,'10 ; Levy et al., '12a,b; Harrison et al.'13))*

@ ***3-D dispersion is enhanced*** *by submesocales (Haza et al, '12; Levy et al., 2012a,b ; Keating et al.'12 ; Zhong and Bracco,'13) !*

Impact of submesoscales 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



[From Haza et al., OM 2012]

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 submesoscales are present FSLE have a larger magnitude and involve smaller scales

=> Dispersion by submesoscales is significant

Impact of submesoscales

@ Because of their aspect ratio (horizontal/vertical), ***submesoscales represent a significant part of the 3D ocean dynamics in the first 500 m***

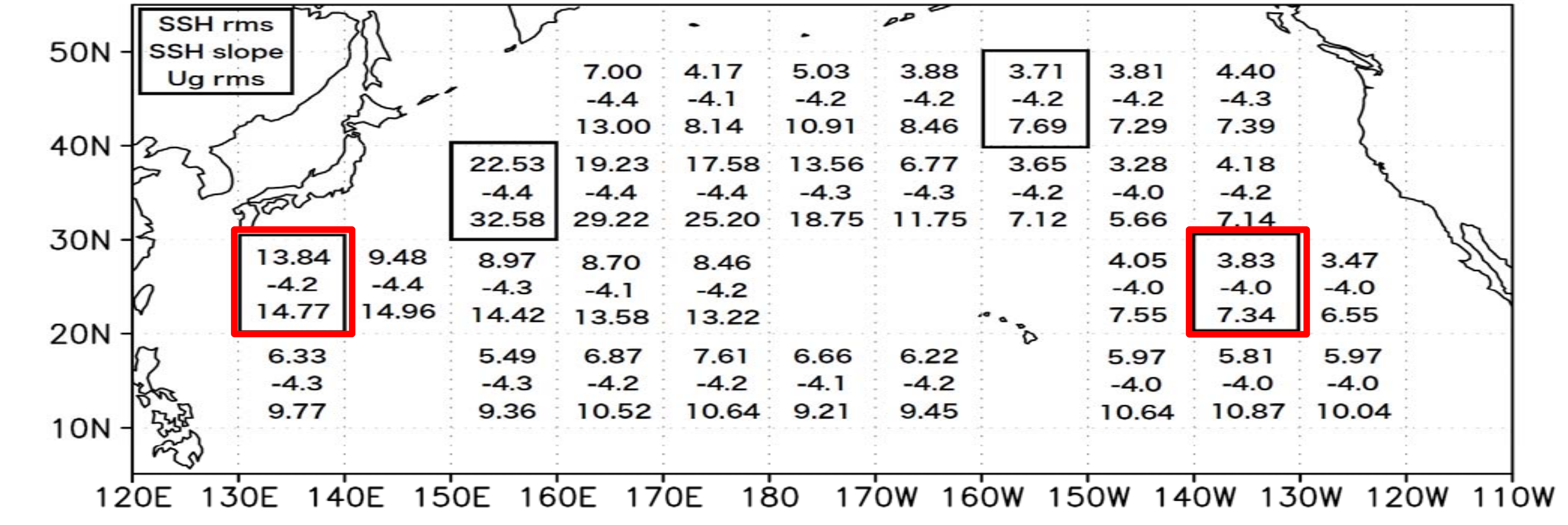
@ ***Submesoscales*** *significantly impact the large-scale dynamics principally through their contribution to the horizontal and vertical heat and momentum fluxes (up to 50 % of the total fluxes (Levy et al.'10; Waugh et al.'12 ; Keating et al.'12)!*

@ ***Submesoscales*** *strongly impact the physical-biological interactions and organize the biodiversity (Perruche et al.,'10 ; Levy et al., '12a,b; Harrison et al.'13))*

@ ***3-D dispersion is enhanced*** *by submesocales (Haza et al, '12; Levy et al., 2012a,b ; Keating et al.'12 ; Zhong and Bracco,'13) !*

@ In the real ocean, submesoscale characteristics may differ in the western and eastern parts of the ocean basins and may vary with time. We need to better identify this « dynamical » diversity.

Statistical SSH characteristics estimated in 10° x 10° boxes



SSHrms in cm (upper), **SSH spectrum slope (middle)** and Urms (lower) in cm/s.

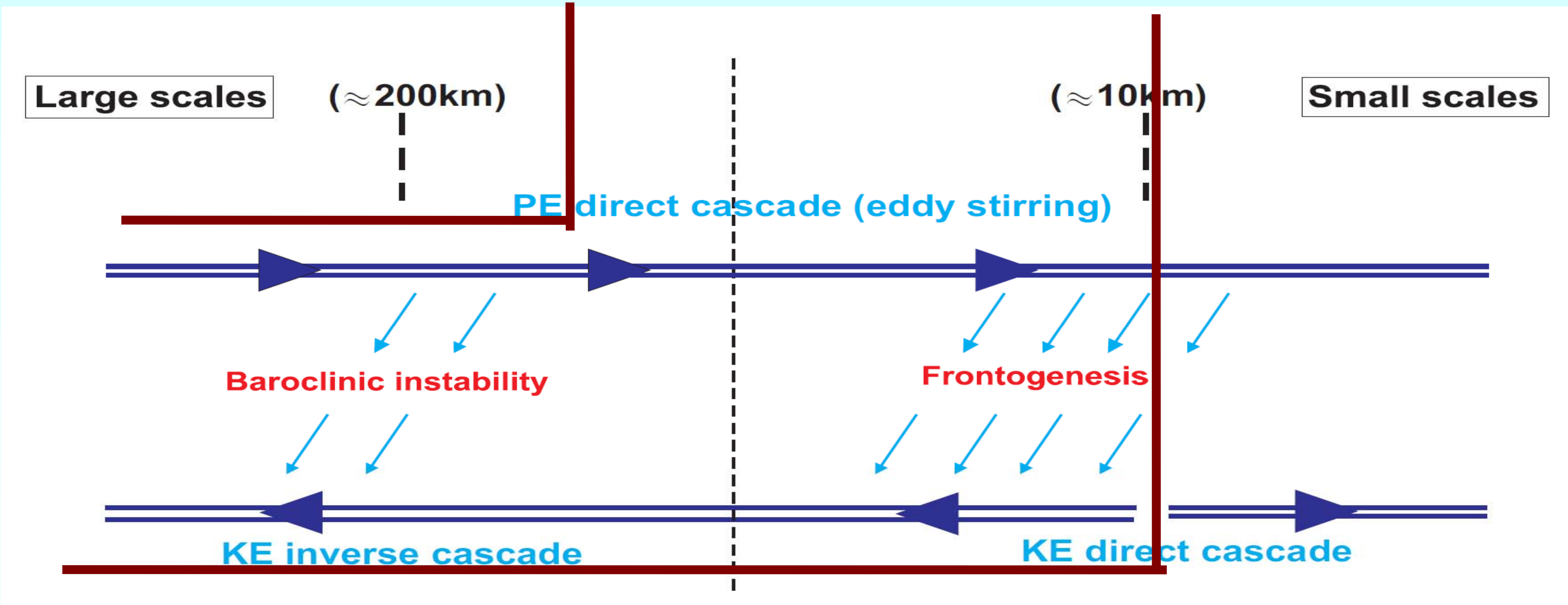
=> **~ k^{-4} SSH spectrum slope not only in high but <u>also in low EKE areas</u>**
(which emphasizes the impact of submesoscales on the larger ones)

=> however analysis of **SSH spectra reveals some important differences**

New altimetry/ conventional altimetry

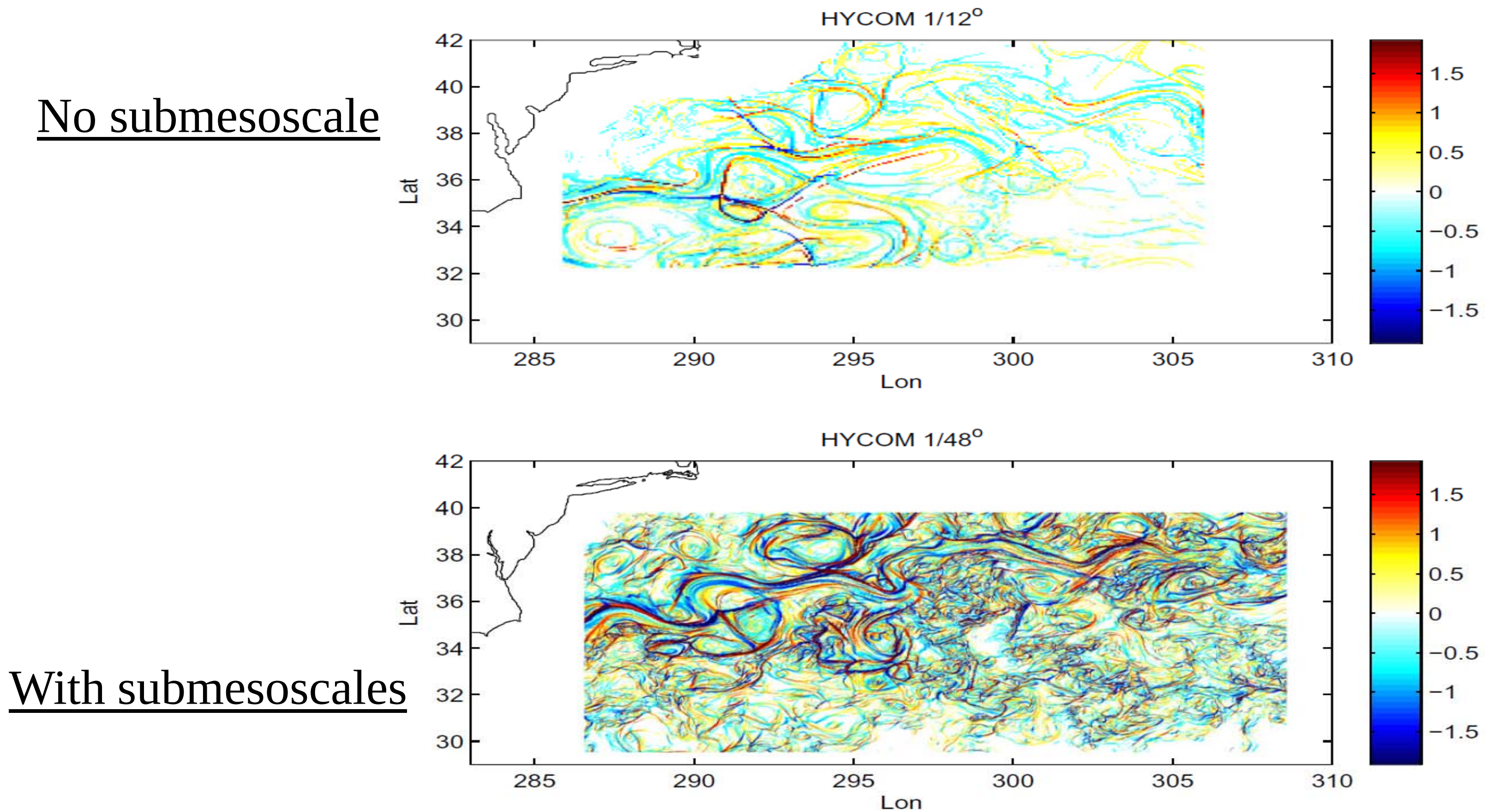
SWOT and COMPIRA should be able to capture oceanic scales smaller than 10 km !

JASON



SWOT and COMPIRA

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



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When submesoscales are present FSLE have a larger magnitude and involve smaller scales

=> Dispersion by submesoscales is significant (see also Keating et al.'12)

Conclusions

@ Submesoscales are energetic, in the first 500m, and are driven by frontogenesis;

@ They are associated with an energetic vertical velocity field (W) <u>in the first 500m</u>;

@ They have a significant impact on the large-scale ocean dynamics

@ They boost the biogeochemical system and appear to explain a part of the biodiversity

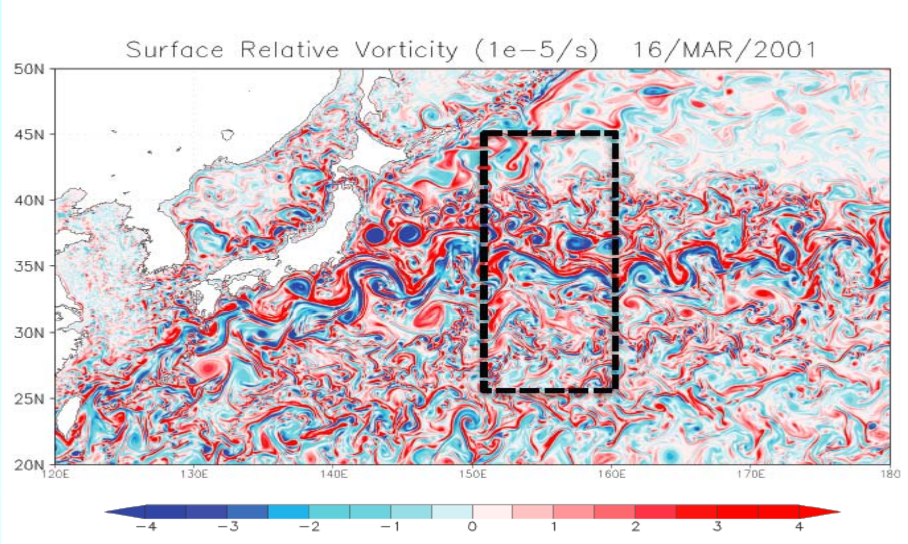
=> ***<u>They need to be taken into account in simulations and to be observed</u>***

=> ***<u>New class of altimeters combined with the Argo float dataset should allow to assess the impact of these submesoscales on global scale</u>***

Many more results from high resolution P.E. Models ...

(Klein et al., '08; Capet et al., '08; Levy et al.'10, '12; Haza et al. '12; Sasaki and Klein, '12; Ponte et al., 2013 ...)

@ **New vision of the upper ocean dynamics :** driven by both, baroclinic instability in the ocean interior and by the **surface frontogenesis** at meso/submesoscale, with the resulting properties:



- Horizontal motions are still principally captured by mesoscales, BUT:

- **(1) Surface velocity spectrum with a k^{-2} slope** (in accordance with experimental results) which suggests a dynamics different from the QG dynamics

- **(2) Wrms is multiplied by a factor up to 5 (mostly captured by submesoscales)**

Consequences of these two important properties ...

Strong numerical evidence from high resolution P.E. Models ...

These models have shown that ***submesoscales*** *do have* ***a strong impact on the larger oceanic scales,*** principally ***through their associated vertical velocity field :***

(Klein et al., '08; Capet et al., '08; Levy et al.'10, '12; Haza et al. '12; Sasaki and Klein, '12; Ponte et al., 2013 ...)

=> ***Wrms is multiplied by a factor up to 5*** *(mostly captured by submesoscales)*

=> ***Total EKE is larger*** *(~ X 1.5) when submesoscales are taken into account because of the inverse KE cascade and mesoscale eddies are more robust and coherent;*

=> ***Impact of submesoscales*** *on the large scale ocean circulation is* ***equivalent to that of mesoscales***