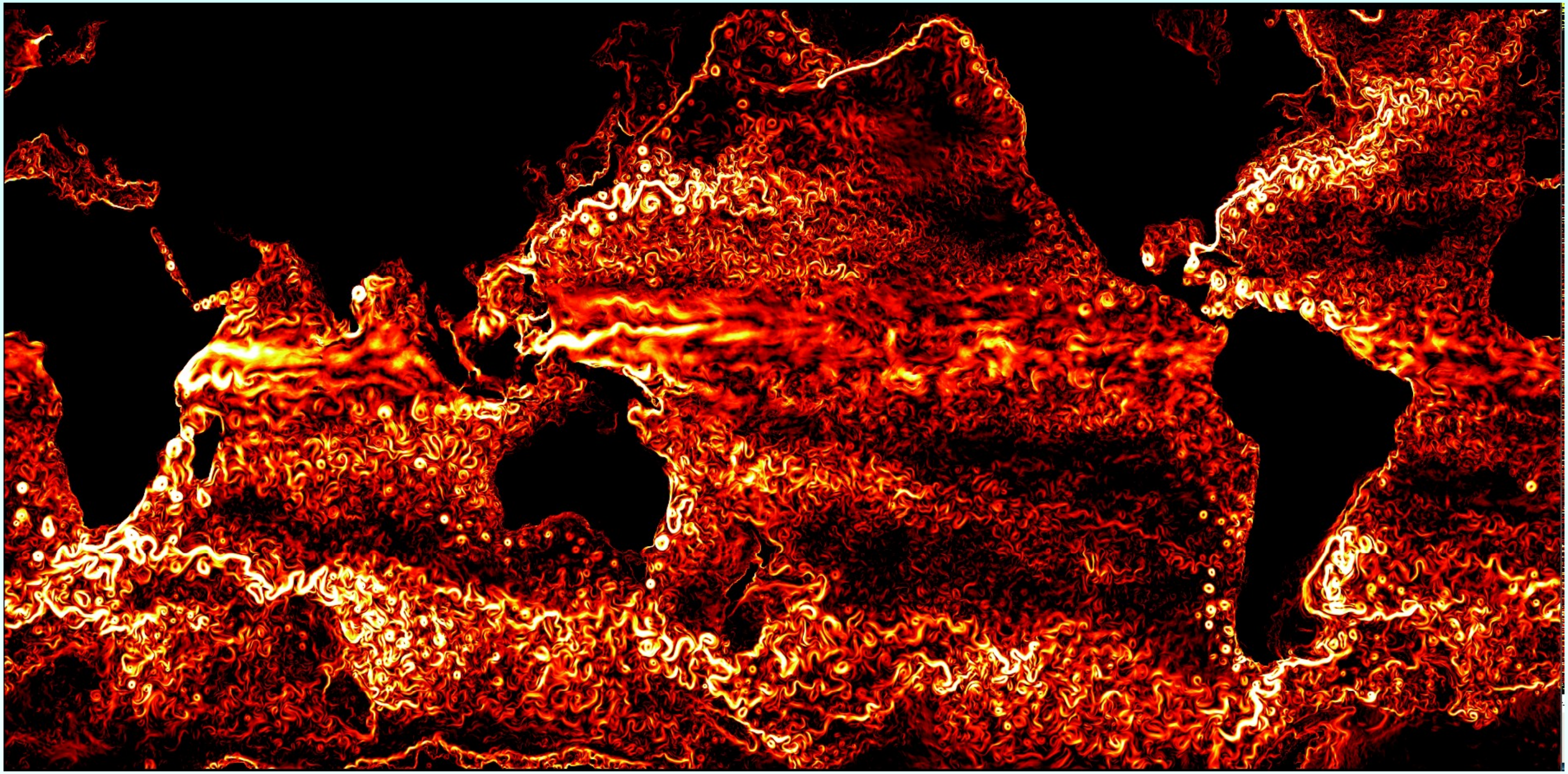
Impact of submesoscales on the ocean dynamics

P. Klein, G Lapeyre,
X. Capet, G. Roullet, B.L. Hua, (Ifremer, Brest)
and H. Sasaki (Earth Simulator Center, Japan)

A fully turbulent ocean !

Observations and modelling studies of the last 10 years have strengthened the vision of an upper ocean **crowded with a large number of mesoscale eddies (GS, Kur., ACC)**



Mesoscale eddies (with 100km scales) are in all the oceans (Courtesy Raf Ferrari)

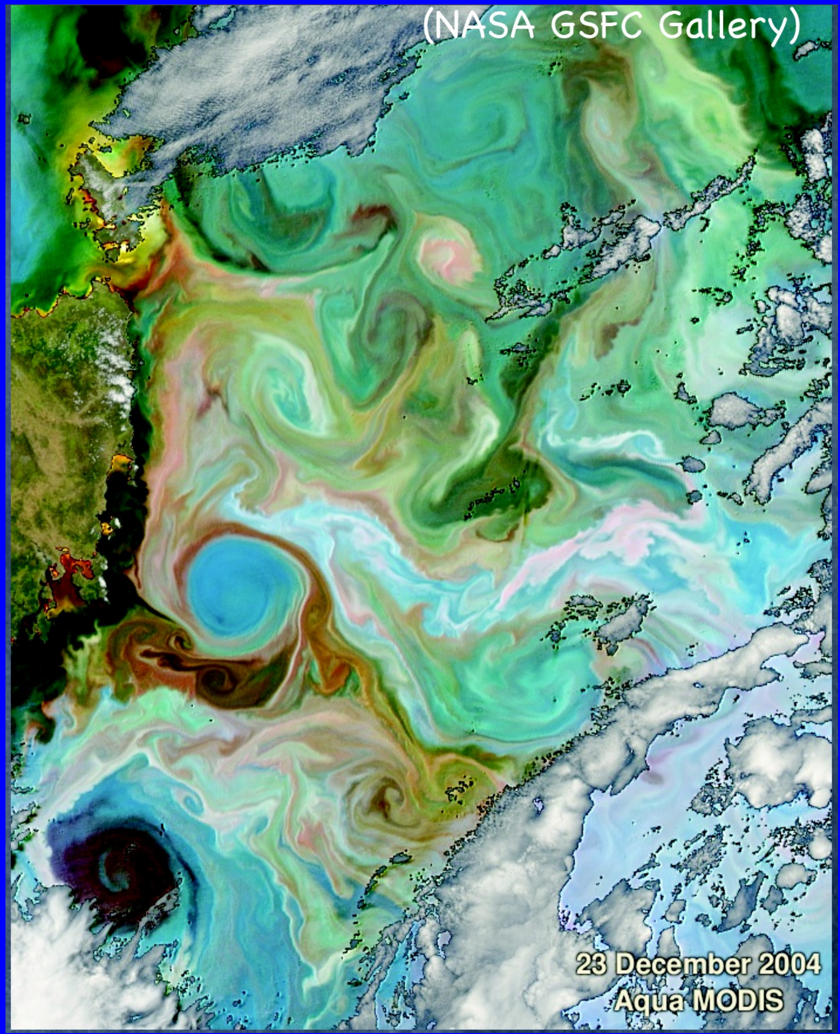
[well captured by conventional altimetry and reproduced by recent OGCM]

Important property:

Mesoscale eddies strongly interact:

SST and biogeochemical tracers are stirred leading to a large number of small-scales.

This is observed on HR ocean color and SST satellite images that reveal at the surface a large number of submesoscales (filaments ~10km)



Mesoscale eddies and submesoscale structures ubiquitous on satellite data

@ ***Submesoscale structures*** (10-30km elongated filaments)

These structures were <u>considered</u> (until a few years) to be very weakly energetic <u>with NO impact on the ocean properties.</u>

@ ***Mesoscale eddies*** (100-300km)

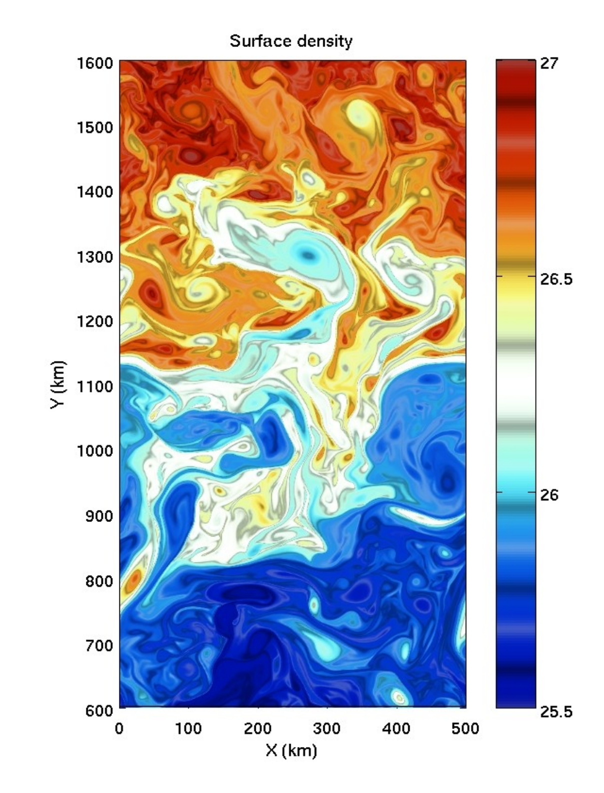
capture most of 3D dynamics :

Velocity spectrum : slope in k^{-3} (Stammer, 1997)
(property close to geostrophic turbulence)

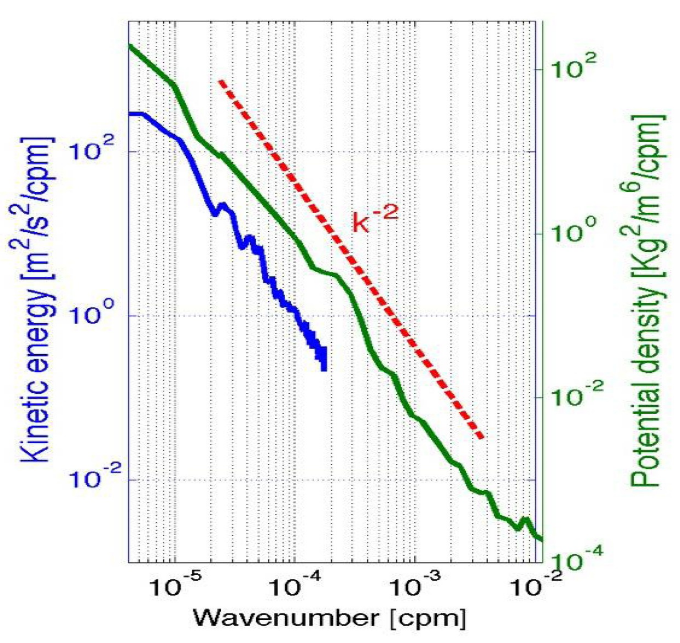
SST is usually NOT a passive tracer:

SST gradients are affected by FRONTOGENESIS !

This concerns BOTH small scales as well as large scales !



Observations: Ferrari & Rudnick, 2000
Wang et al., 2010

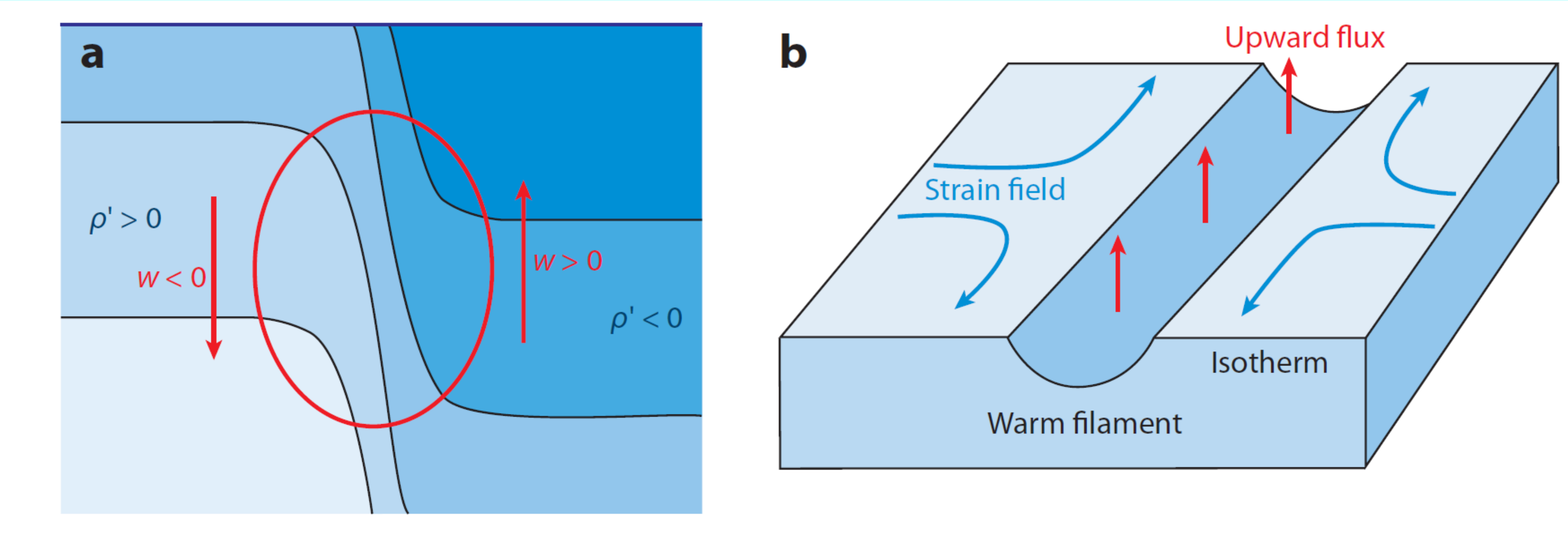


SST field involves a large number of small-scales (slope in k^{-2})

=> <u>SST gradients at small-scale are as energetic as large scales</u>

(Held et al.'95; Lapeyre & Klein'06; Tulloch & Smith'09; ...)

Frontogenesis

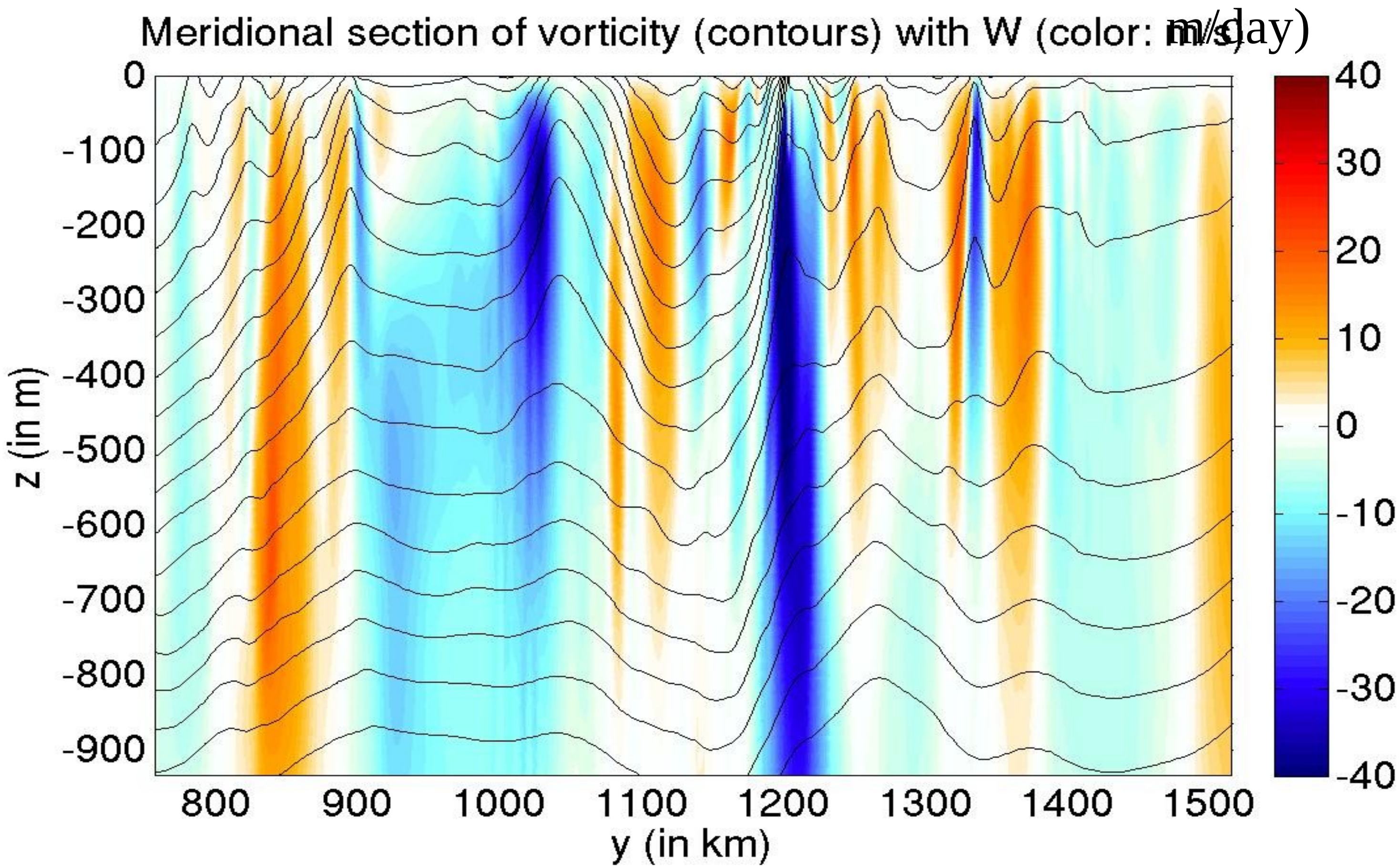


SST (density) anomalies are stirred by mesoscale eddies => SST fronts

Because of frontogenesis, ageost. circulation, including a W-field, develops. **The role of this W-field is to increase the surface current** for the front to be in thermal wind balance

=> SST fronts are associated with a significant W-field

(Hakim et al.'02; Lapeyre et al.'06; McWilliams et al.'09)



W-field (from a numerical simulation; Klein et al. 2008):
W-structures associated with SST fronts 10km wide

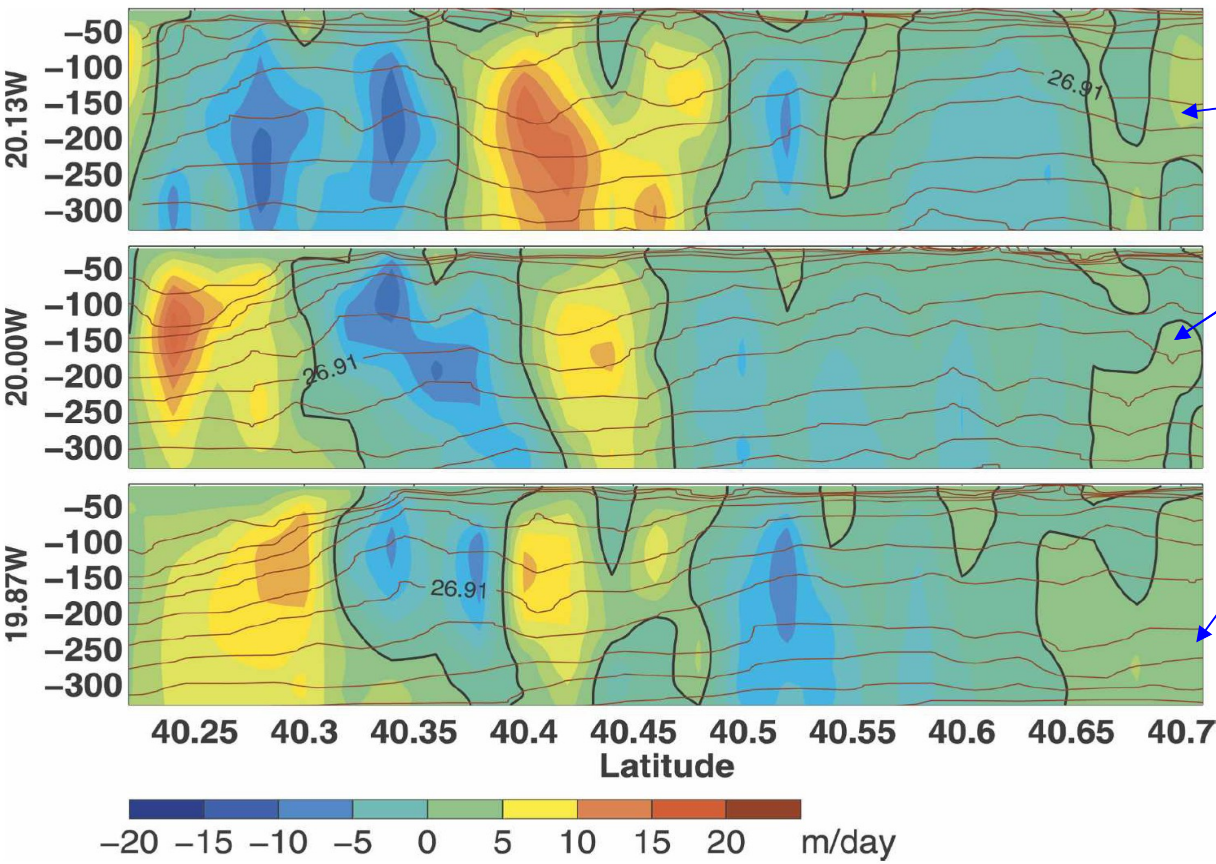


FIG. 6. Vertical velocity field estimated from the SeaSoar and SOPRANE data (in color). Thin lines are density isocontours, and the thick line is the *w*-zero contour.

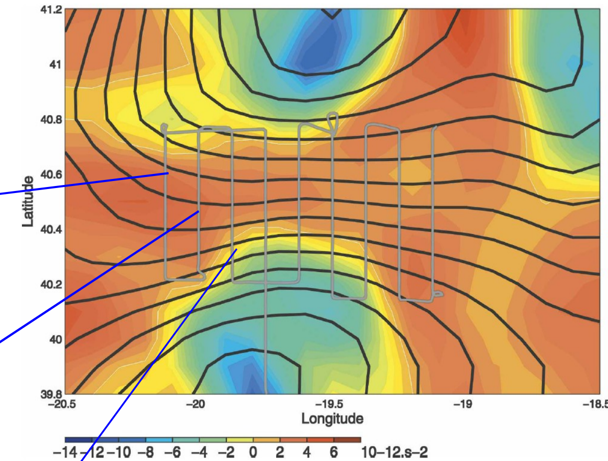
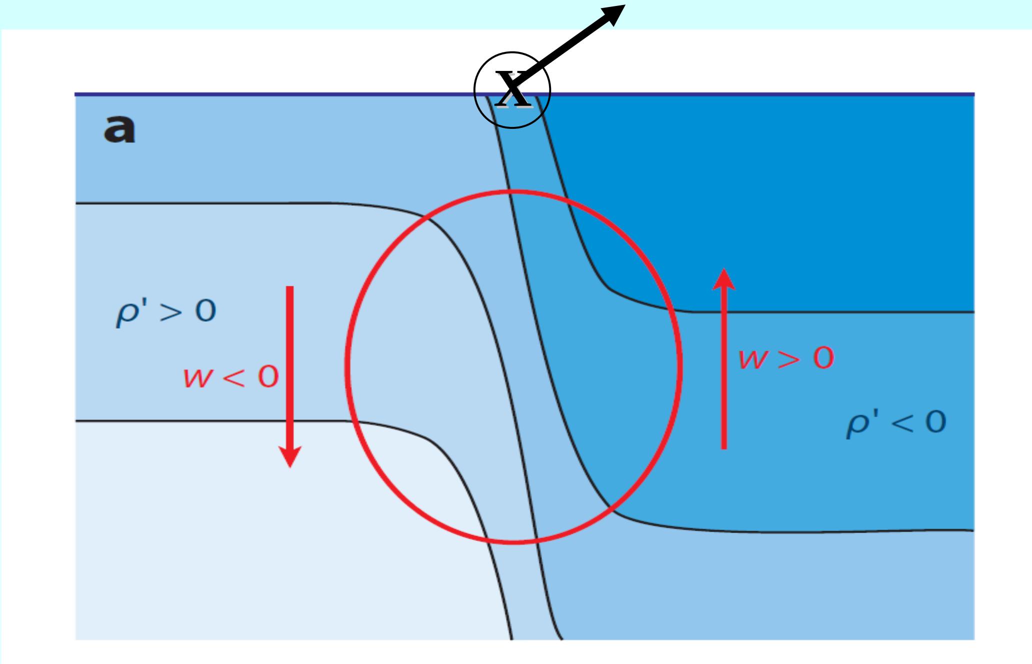


FIG. 2. Streamfunction (18 Apr 2001) from the SOPRANE data (black contours), Okubo–Weiss quantity (color), and ship trajectory (gray lines).

W-field (from field experiment: LeGal et al, 2007):
W-structures associated with SST fronts 10km wide

Surface frontal dynamics



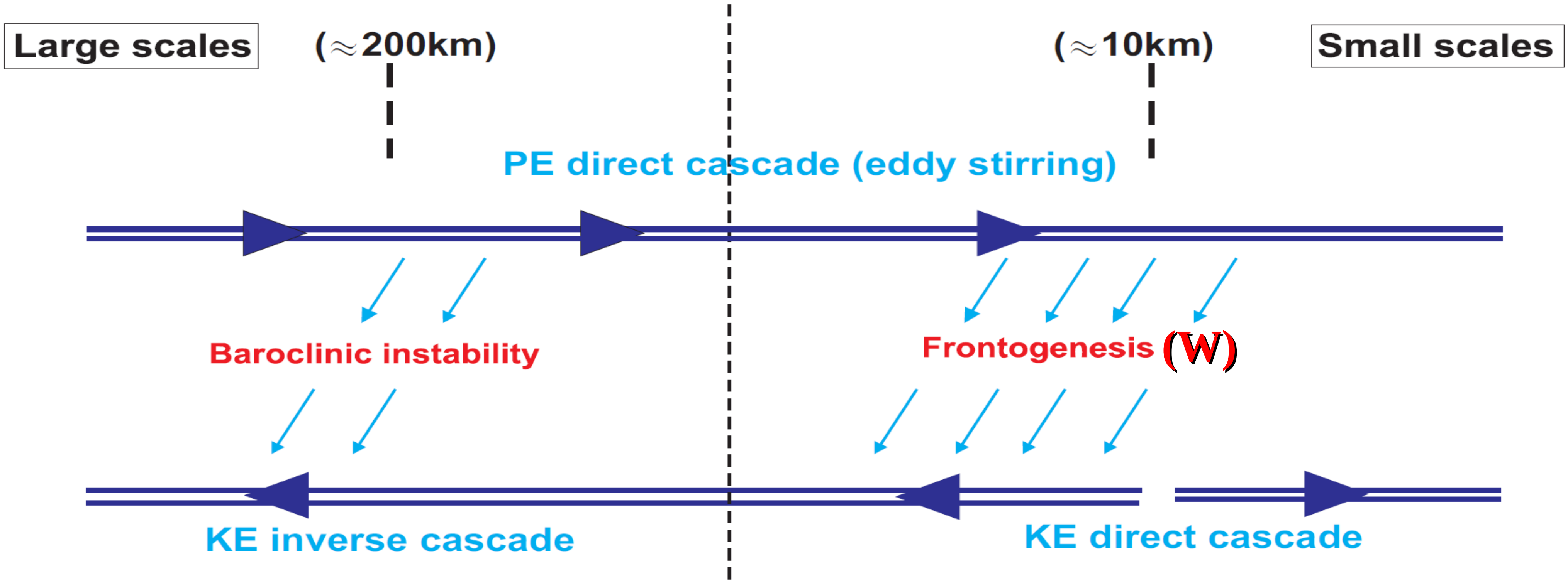
PE => KE:

$$\overline{w'\rho'} < 0$$

- Eddy stirring produces SST gradients at all scales
- Frontogenesis produces W that increases surface currents
- Frontogenesis corresponds to a

transformation of PE into KE that occurs at <u>meso and small-scale</u>.

The surface frontal dynamics modifies the nonlinear interactions on a large spectral range



Submesoscales efficiently feed up mesoscale eddies and larger scales

(Capet et al.'08; Klein et al.'08;Tulloch & Smith'09)

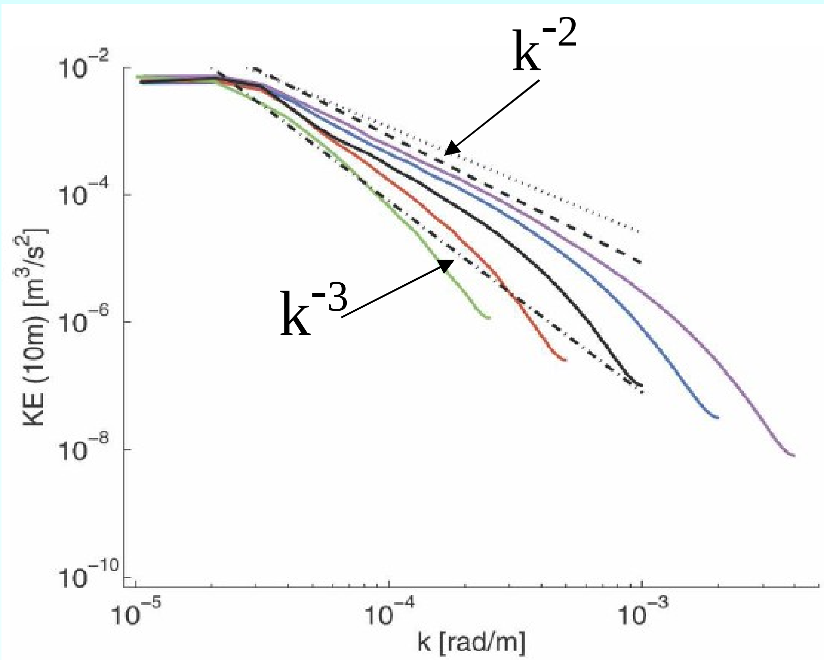
=> **Velocity spectrum (SSH) has a slope in k^{-2}** and NOT a slope in k^{-3}

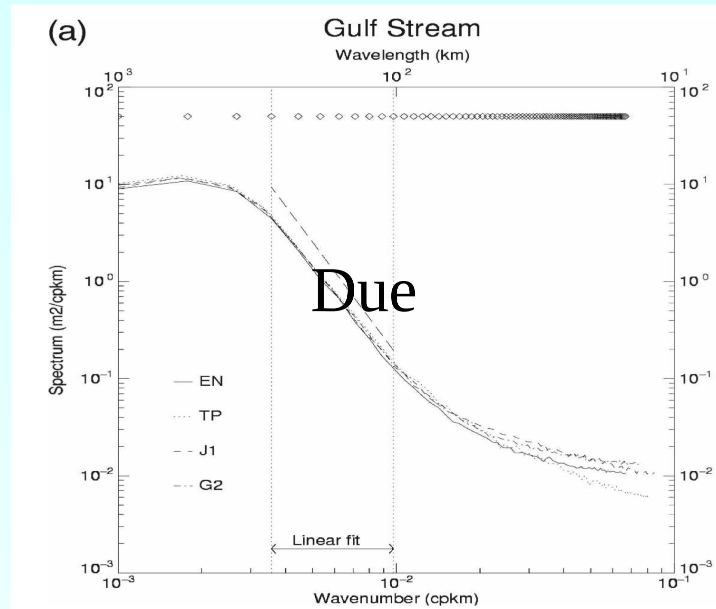
=> **Total EKE is larger** when submesoscales are taken into account

Evidence that submesoscales are more energetic: velocity has a shallower slope (k^{-2} instead of k^{-3} in the interior)

Models: Capet et al. 2008;Klein et al., 2008

Observations: Le Traon et al., 2008
Xu and Fu, 2010

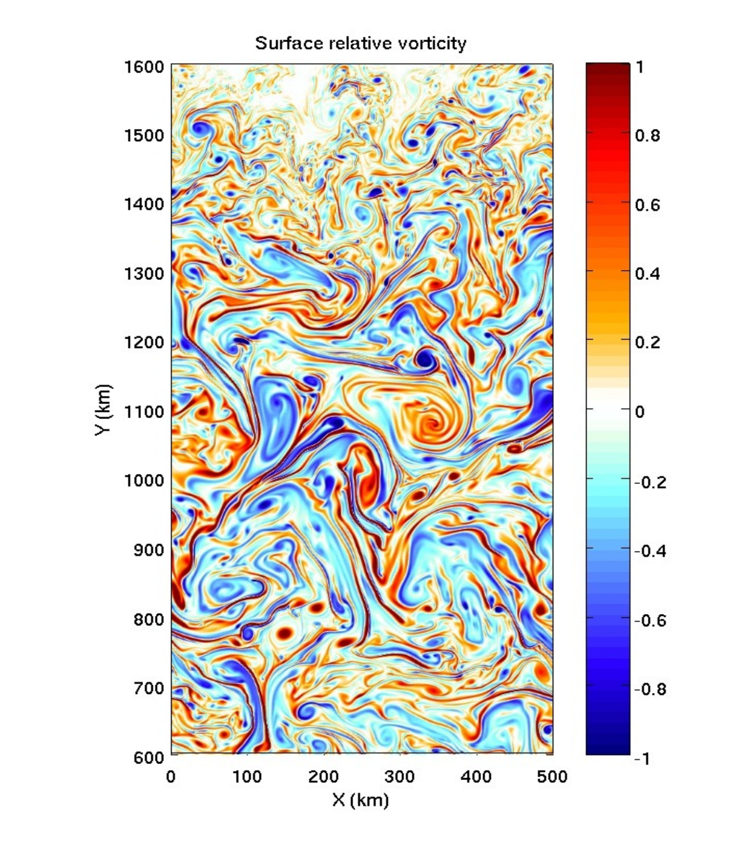


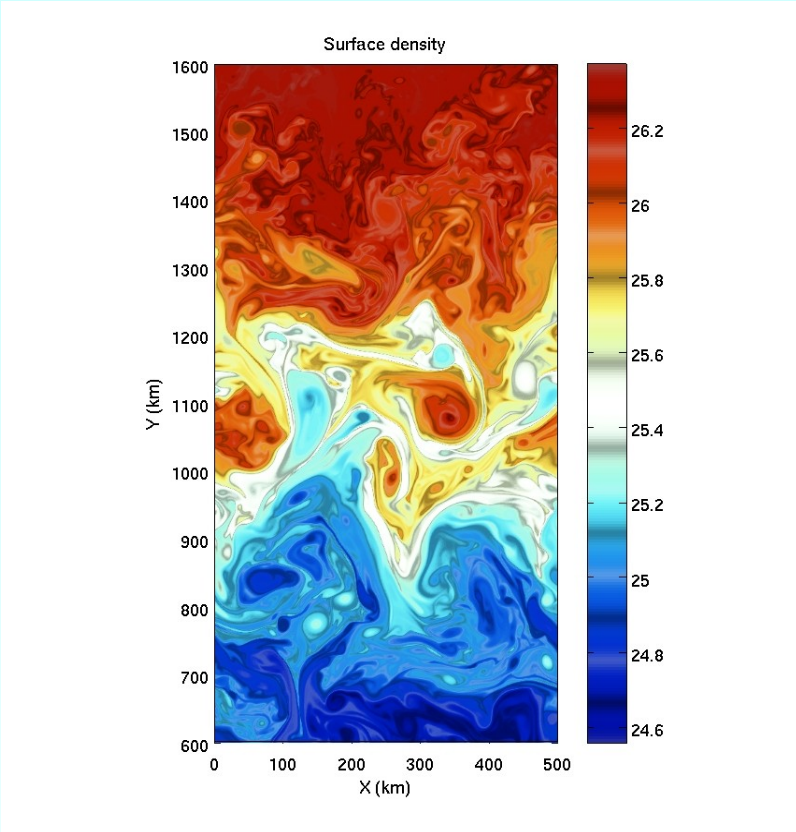


Such spectral slope over a large spectral range is due to

=> <u>the dynamical impact of the W-field at small-scales</u>

(I) HR numerical simulation ~ Gulf Stream



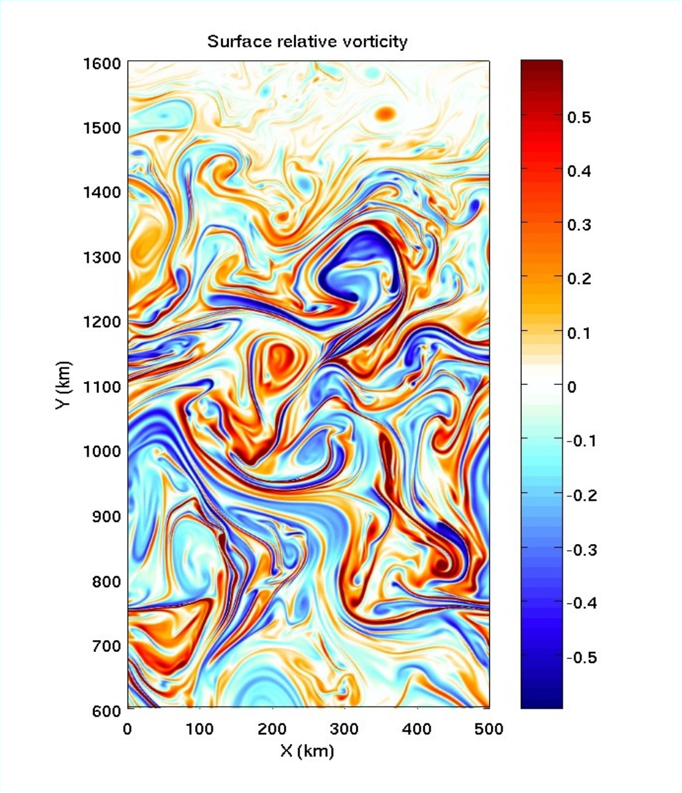


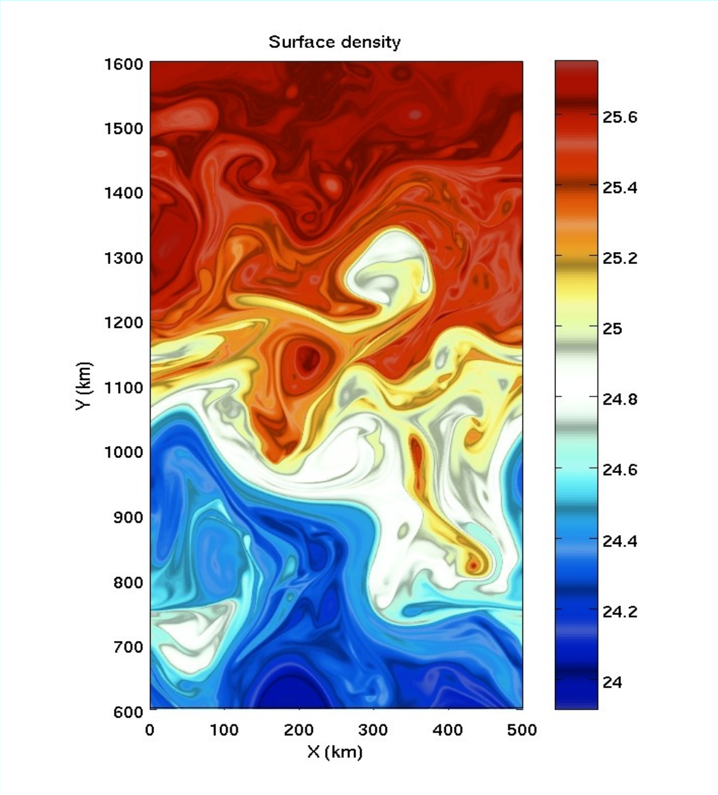
@ **strong cyclone/anticyclone asymmetry**

@ **significant W-field triggered by surface frontogenesis (moderate stratification)**

=> **Velocity spectrum has a slope in k^{-2}**

(II) HR numerical simulation: same as (I) but with stronger stratification



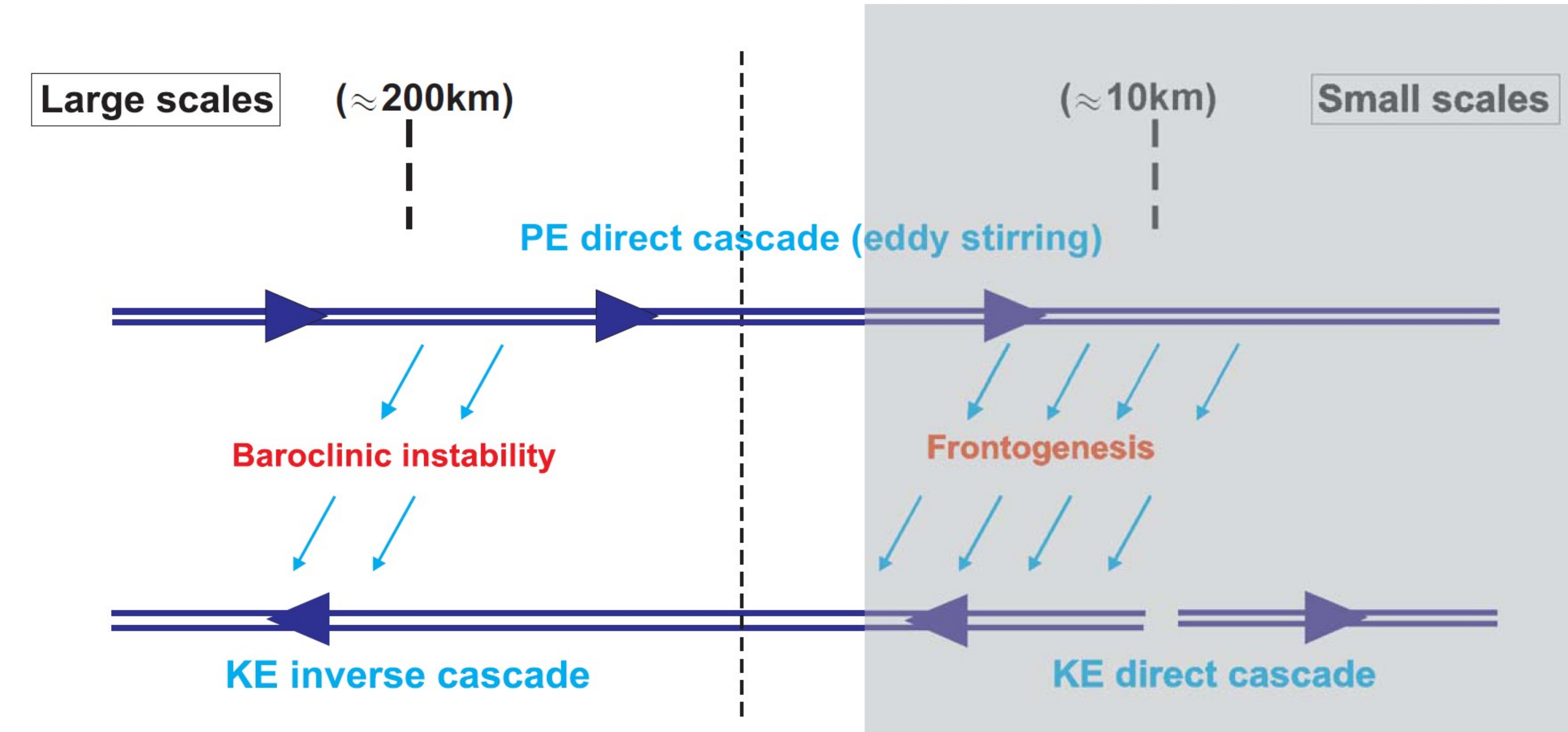


@ cyclone/anticyclone symmetry

@ weak W-field triggered by surface frontogenesis (rms value 3 times smaller)

=> Velocity spectrum has a slope in $k^{-3.5}$!

=> Total KE is almost 1.5 smaller !



@ strong nonlinear interactions

@ weak W-field triggered by surface frontogenesis (strong stratification)

=> Velocity spectrum has a slope in $k^{-3.5}$!

=> Close to geostrophic turbulence !

Summary

Surface submesoscales have a strong dynamical impact

through the energetic W-field triggered by frontogenesis

They increase the total KE through the PE => KE increase

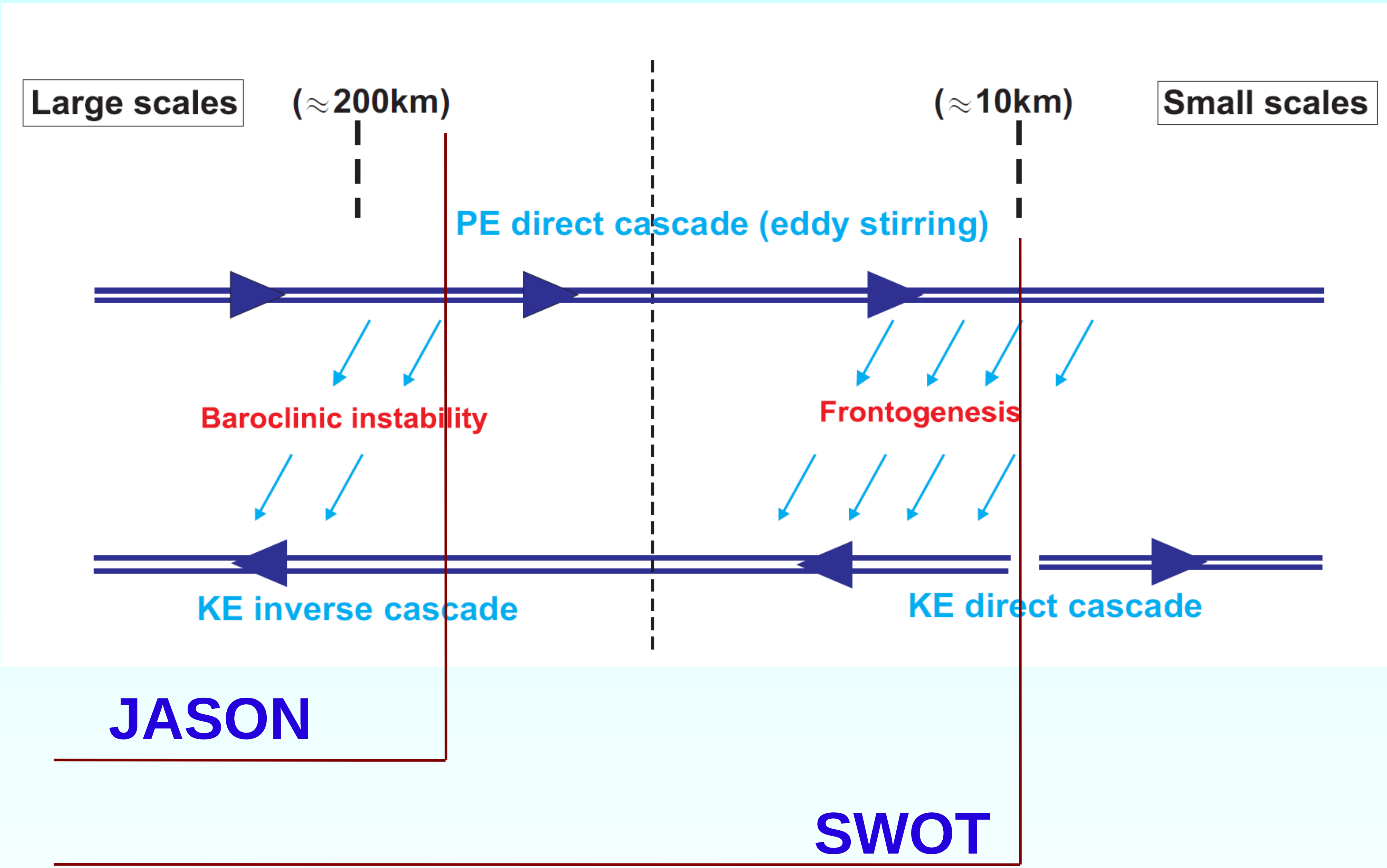
They lead to a velocity (SSH) spectrum slope in k^{-2} instead of k^{-3}

They drive a large part of the vertical fluxes of any tracers in the first 300m

They are captured by SQG dynamics instead of QG dynamics
=> 3D dynamics in the first 300-800m can be recovered from HR SSH and climatological stratification

(Lapeyre & Klein'06; Klein et al'09)

SWOT/ conventional altimetry



SWOT should allow:

to better estimate the ocean kinetic energy
to estimate the vertical fluxes in the first 300-800m

Discrepancies between velocity spectrum deduced from SSH and surface currents ?

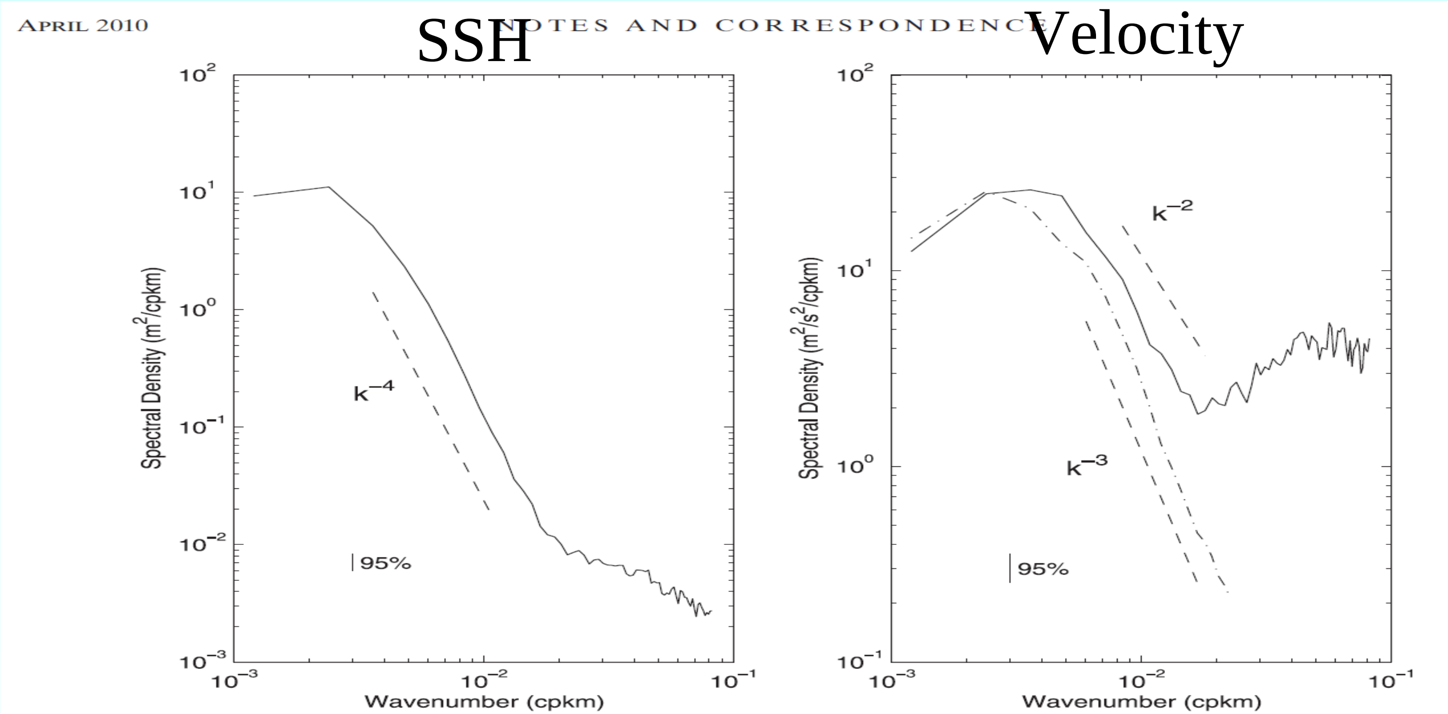


FIG. 3. (left) SSH and (right) geostrophic velocity spectra from altimetry measurements, superimposed with kinetic energy spectrum (dashed–dotted) from *Oleander* observations. Dashed lines indicate slopes of −4, −3, and −2, respectively. The 95% confidence interval is marked.

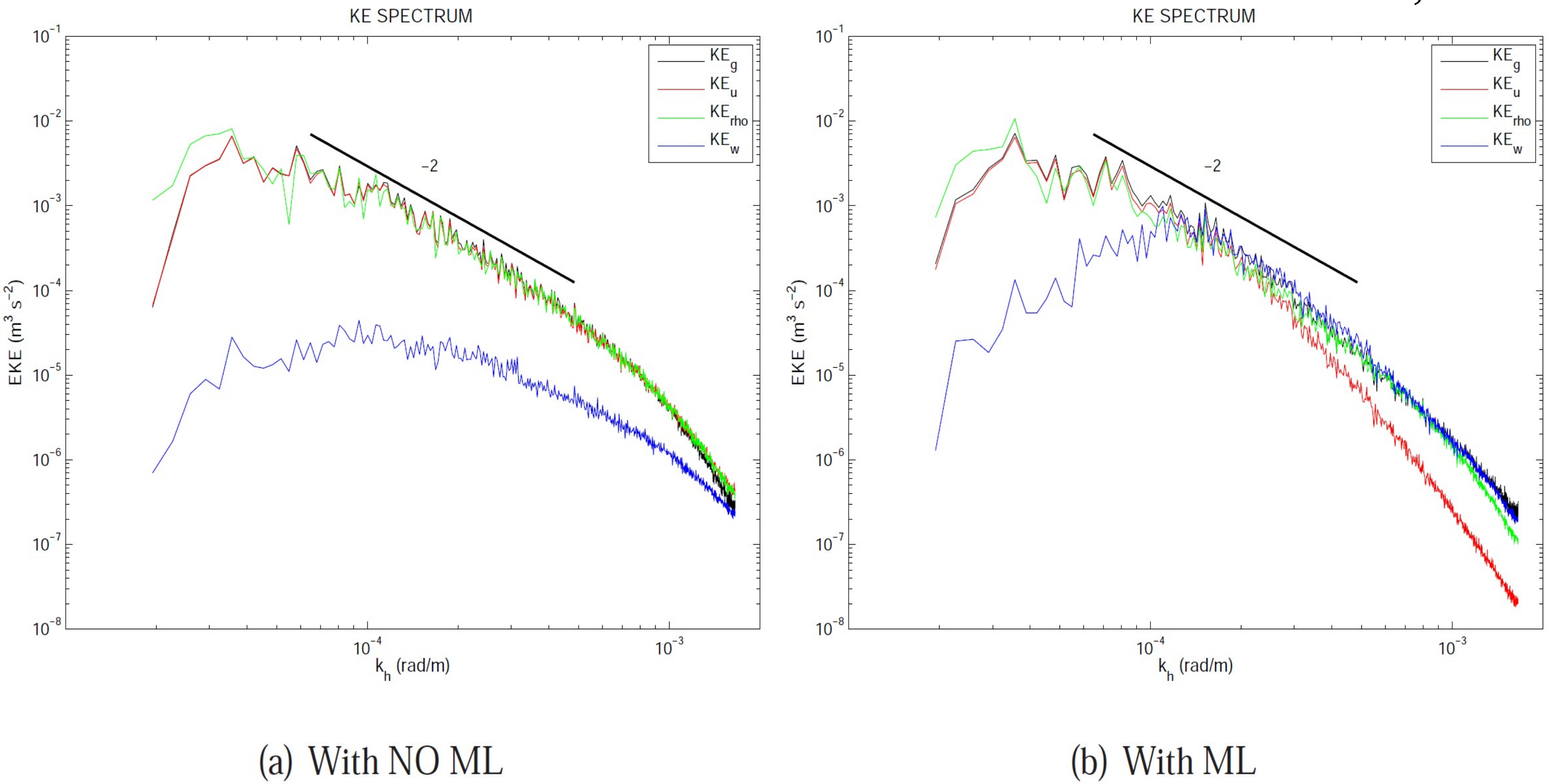
Wang et al., JPO 2010

<u>Velocity spectrum</u>: k^{-2} from SSH but k^{-3} from ADCP data (*Oleander* dataset)
<u>Kinetic energy</u>: smaller energy level with ADCP data than altimetry data
<u>Temperature spectrum</u>: $k^{-2.3}$ (closer to velocity spectrum from SSH)

Wang et al. suggest that these discrepancies question the accuracy of altimetry data. They think that these data may be contaminated by noise even for scales larger than 70km !

<u>Other reasons can explain these discrepancies ...</u>

Klein et al., JPO 2010



With no ML: * velocity spectrum from surface U,V (red) resembles that from SSH (black)
* surface density spectrum close to velocity spectrum from SSH (green)

With ML: * velocity spectrum from surface U,V (red) steeper that from SSH (black)

* surface density spectrum still close to velocity spectrum from SSH (green)

Results from high resolution simulations with ML: similar to those from Wang et al.,2010

Explanation: * in presence of a strong mixing, **ageostrophic currents** develop in order to decrease the vertical shear such that

$$\nu(\frac{\partial \boldsymbol{u_g}}{\partial z} + \frac{\partial \boldsymbol{u_{ag}}}{\partial z}) \approx 0$$

* these ageostrophic currents counterac ents and are larger for smaller scales (since the vertical shear is larger for smaller scales)

* ML mixing further boosts frontogenesis and increases surface density gradients (which compensates for their decrease by mixing)

--> surface density spectrum is still close to velocity spectrum from SSH

==> Results close to those from Wang et al. 2010

Analytical argument

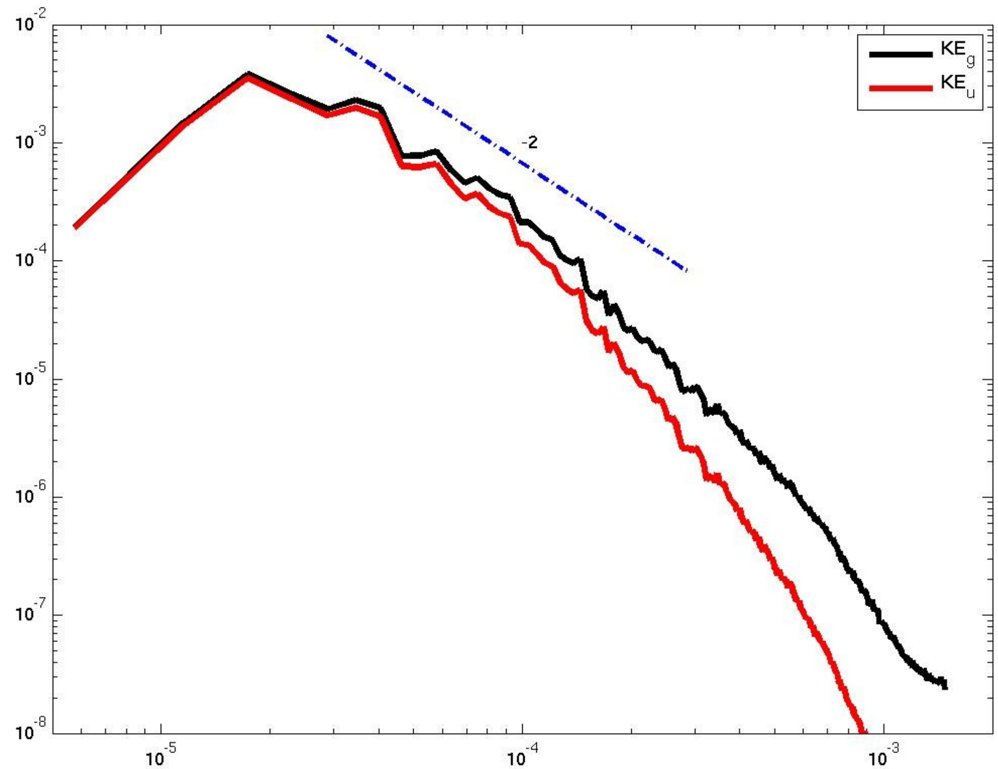
Black curve: spectrum from SSH(Ug,Vg)

Geostrophic currents at depth can be deduced from

$$\widehat{\psi}(\mathbf{k}, z) = g f_0^{-1} \widehat{\eta}(\mathbf{k}) \exp(N_0 f_0^{-1} k z)$$

Red rents assuming that Ug and Vg (from SSH and SQG relations) are well mixed over a ML of depth H:

$$|\widehat{\boldsymbol{u_s}}(k)|^2 = |\widehat{\boldsymbol{u_g}}(k)|^2 \frac{f^2}{k^2 N^2 H^2} [1 - exp(\frac{-kNH}{f}]^2$$

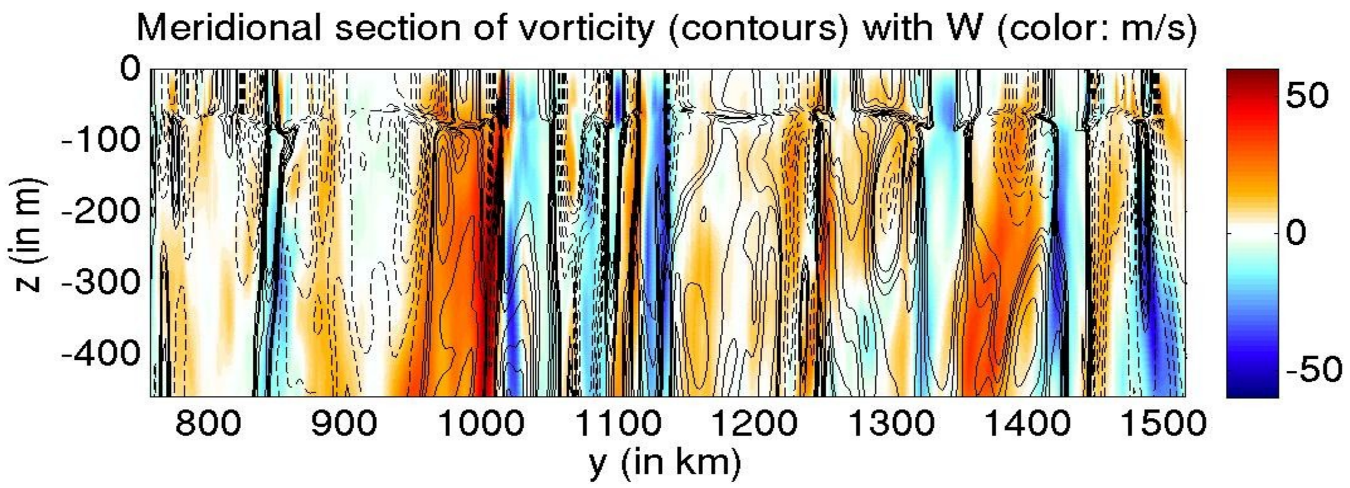


These **ageostrophic motions** induced by mixing are just **confined within the ML**.

They are in part generated by the geostrophic currents since they act to reduce the vertical shear of these currents.

This is what is observed (see also Nagai et al., JGR, 2006).

SSH is still **a good proxy to get the 3D circulation below the ML.**



High resolution altimetry data ***combined with results from theoretical***

studies should allow to diagnose the 3D motions (including W)

in the first 500m below the surface.

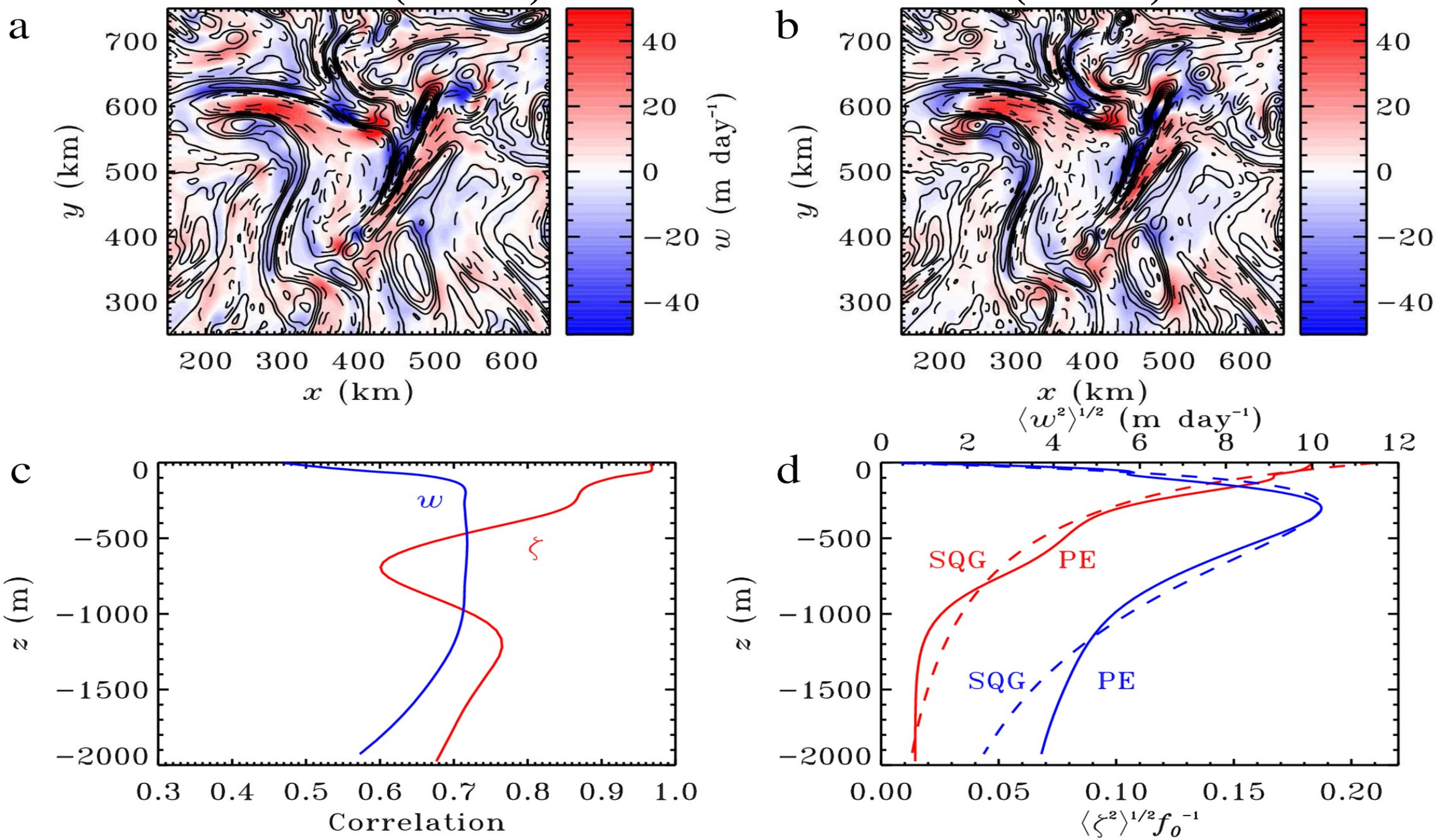
=> A HR instantaneous snapshot of SSH should give access to the horizontal and vertical fluxes of any tracers that vary slowly in time

The method to diagnose the 3D dynamics from the SSH based on the SQG dynamics (Held et al, 1995):

$$\widehat{\psi}(\mathbf{k}, z) = g f_0^{-1} \widehat{\eta}(\mathbf{k}) \exp(N_0 f_0^{-1} k z)$$

Observed W and RV (at 200m)

Reconstructed W and (at 200m)



* Differences between the KE from SSH and that from surface currents is understandable in terms of ageostrophic motions that act to reduce the vertical shear of geostrophic motions within the ML.

* Ageostrophic motions within the ML are driven by both the geostrophic currents (SSH) and the wind forcing.

* **HR SSH a good proxy to get the 3D circulation below the ML at submesoscales**

* **Surface pressure gradients (through the SSH) drive the ocean circulation within the first 500m including a part of the ageostrophic motions within the ML**

Reconstruction of 3D dynamics in the North Pacific using outputs of realistic high-resolution ocean simulations

Hideharu Sasaki[1*], Patrice Klein[2], Bunmei Taguchi[1], Nobumasa Komori[1], and Guillaume Lapeyre[3]

1: Earth Simulator Center, Japan Agency for Marine-Earth Sience and Technology,Yokohama, Japan

2: Labratoire de Physique des Océans, IFREMER, Plouzané, France

3: Laboratoire de Météorologie Dynamique/IPSL, Paris, France.

**E-mail: sasaki@jamstec.go.jp*

SSH and Mixed Layer Depth (OFES, 01/01/15th yr)

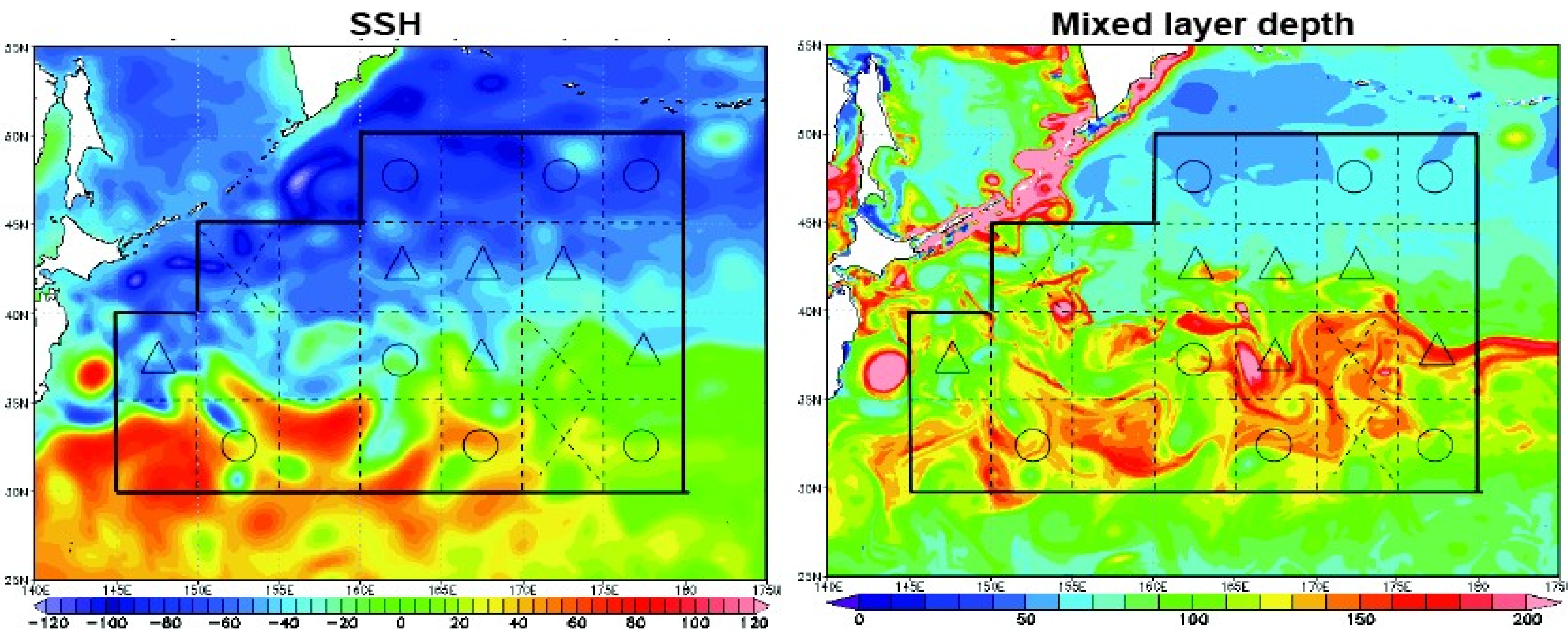
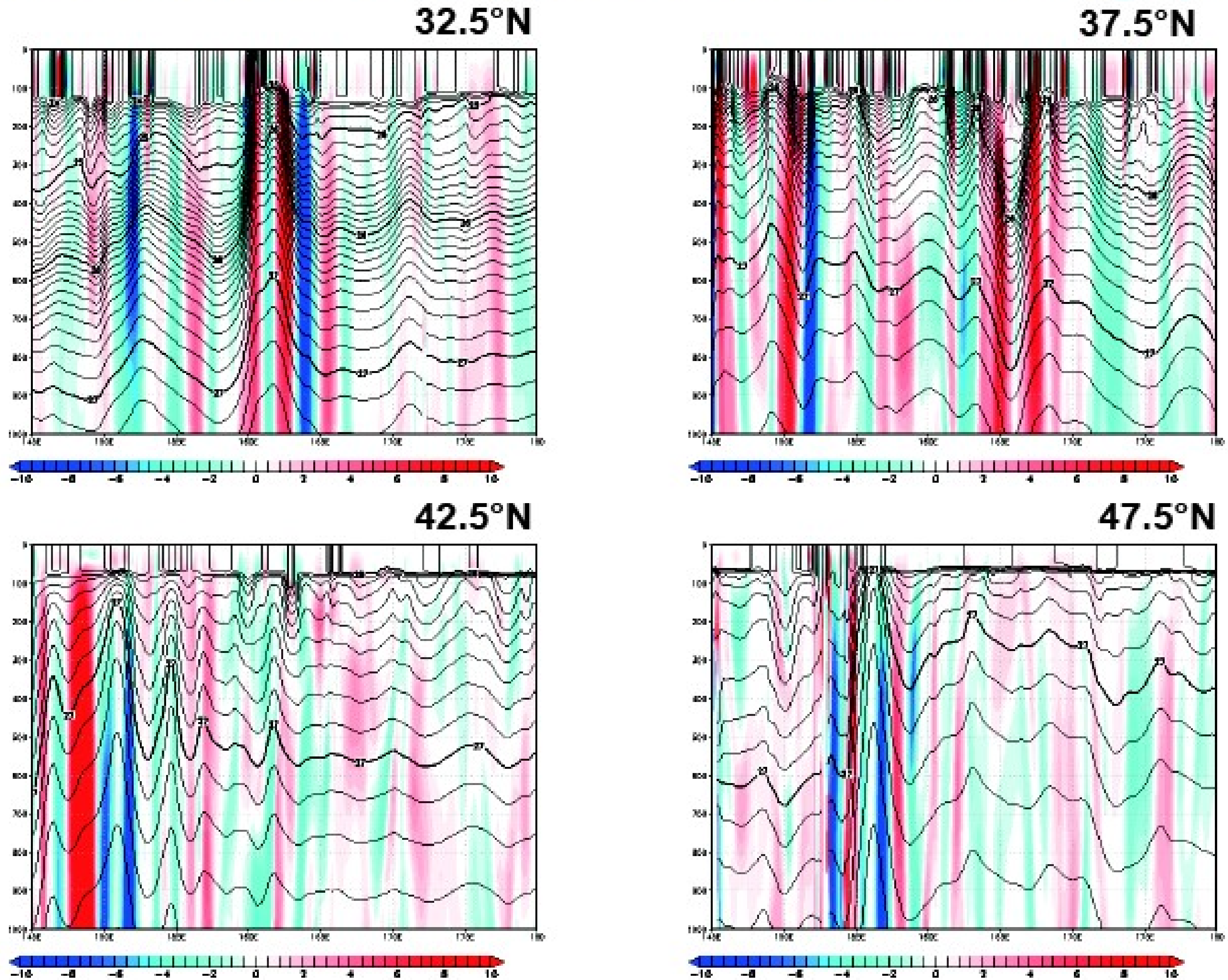


Fig. 1. (Left) Sea surface height (cm), (Right) mixed layer depth (m) of OFES daily mean on Jan. 1st, 15th model year. The eSQG reconstruction is conducted for each 5deg. x 5deg. domain. Correlation maximum of RMS of vertical motions between the eSQG reconstruction and OFES: ○: > 0.4, △: > 0.2. Reconstruction cannot be adapted due to sea mount in regions "X".

Fig. 2

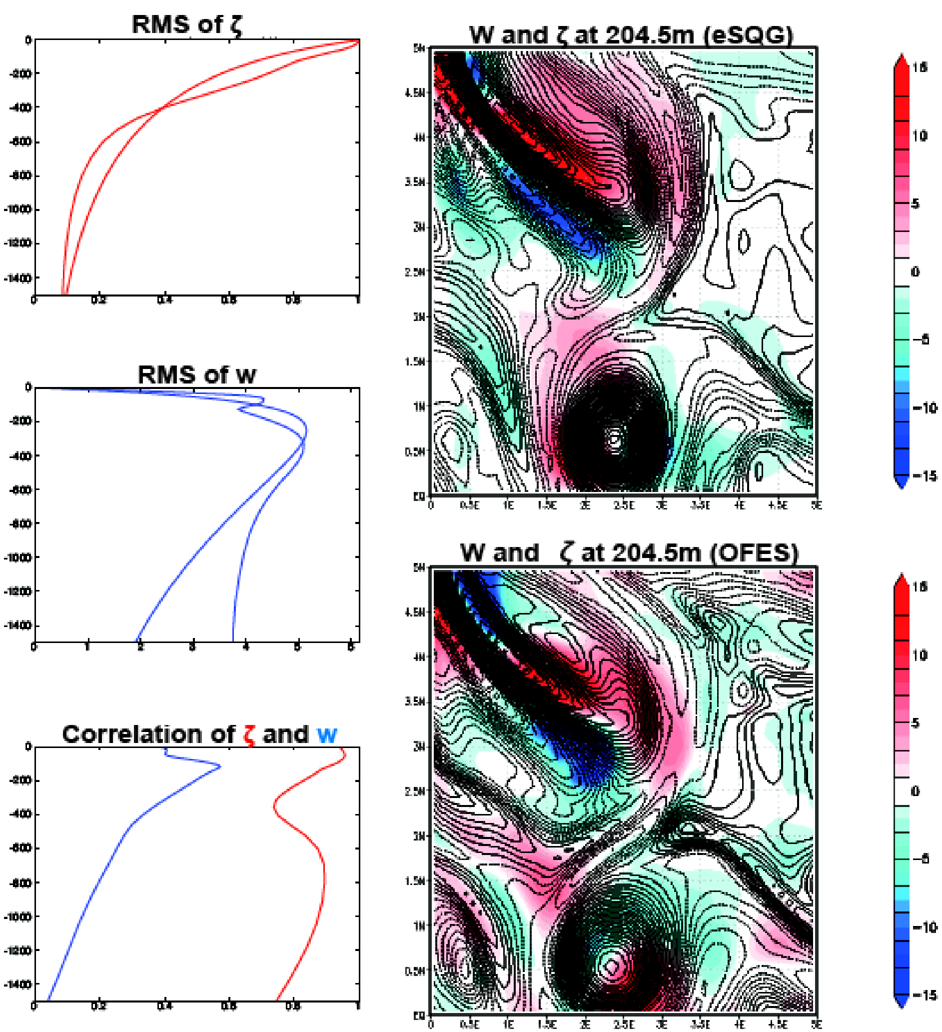
Vertical Motion and Potential Density (OFES)



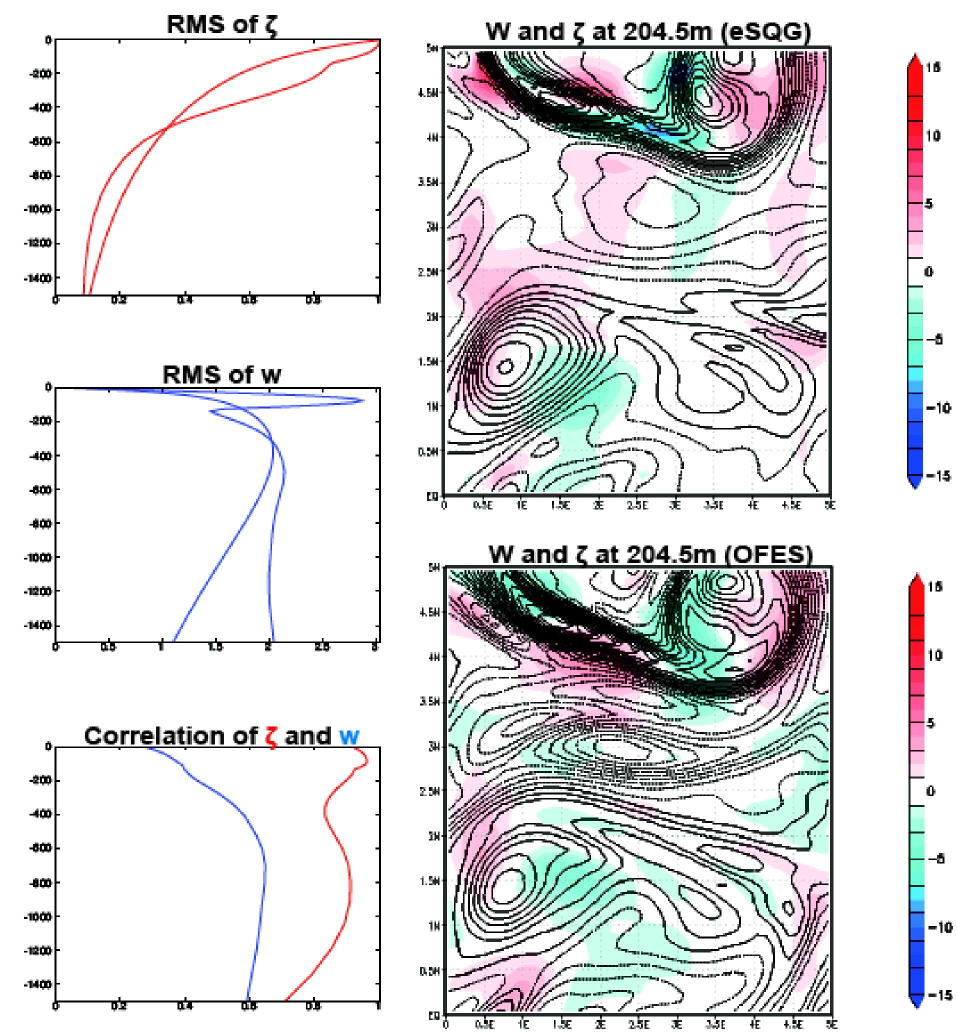
2. Longitude–vertical section of vertical velocity (color, m/day) and potential density(contour, $\sigma\theta$).

Relative Vorticity and Vertical Motions (eSQG Reconstruction vs OFES)

150–155°E, 30–35°N



165–170°E, 30–35°N



Conclusions

First results are promising

@ H.R. SSH should allow to diagnose the 3D motions (including the W field) in the upper ocean;

=> access to the horizontal and vertical fluxes

Some work has still to be done:

@ Further tests in diferent oceanic regions using OFES simulations and improvement of the method used

@ We need a better knowledge of the climatological stratification (No) (comparison of SST and SSH fields, use of Argo floats ?)

@ We need to better assess the mixed-layer dynamics (combination of SSH, SST and SAR data ?)

Assessment of the potentiality of HR SSH:

Use of simulations (as testbeds) of eddy turbulence forced by realistic HF winds

PE model 1/100e degree, 200 levels
*[3000km*2000km*4000m]*

@ Eddy turbulent field :

*** surface kinetic energy (300km) with a k^{-2} spectrum slope**

*** thin (<10km) submesoscales with large vorticity values (-f to 3f) quickly evolving (=>large W)**

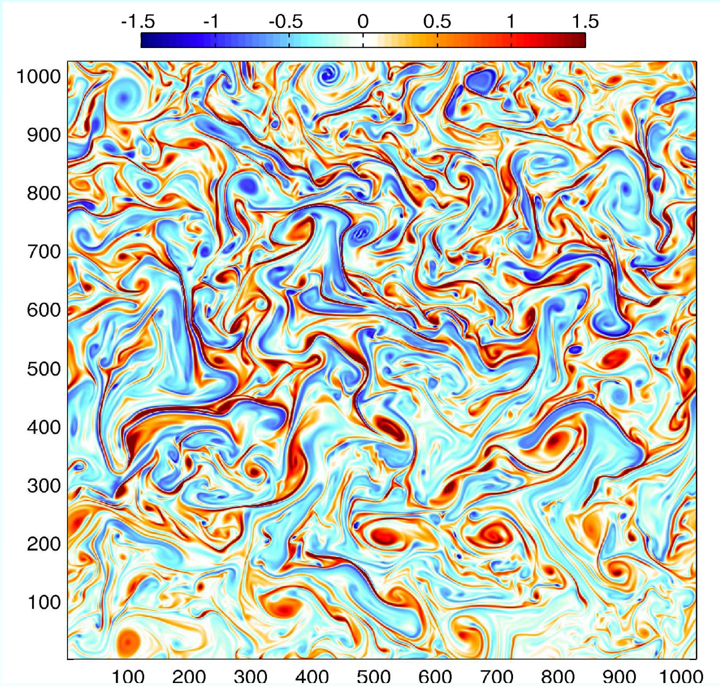
(Klein et al, JPO, 2008, Capet et al.,2008)

@ No mixed-layer (ML) AND

active ML forced by HF (3h) winds:

- 80m deep
- energetic near-inertial motions

Surface relative vorticity field

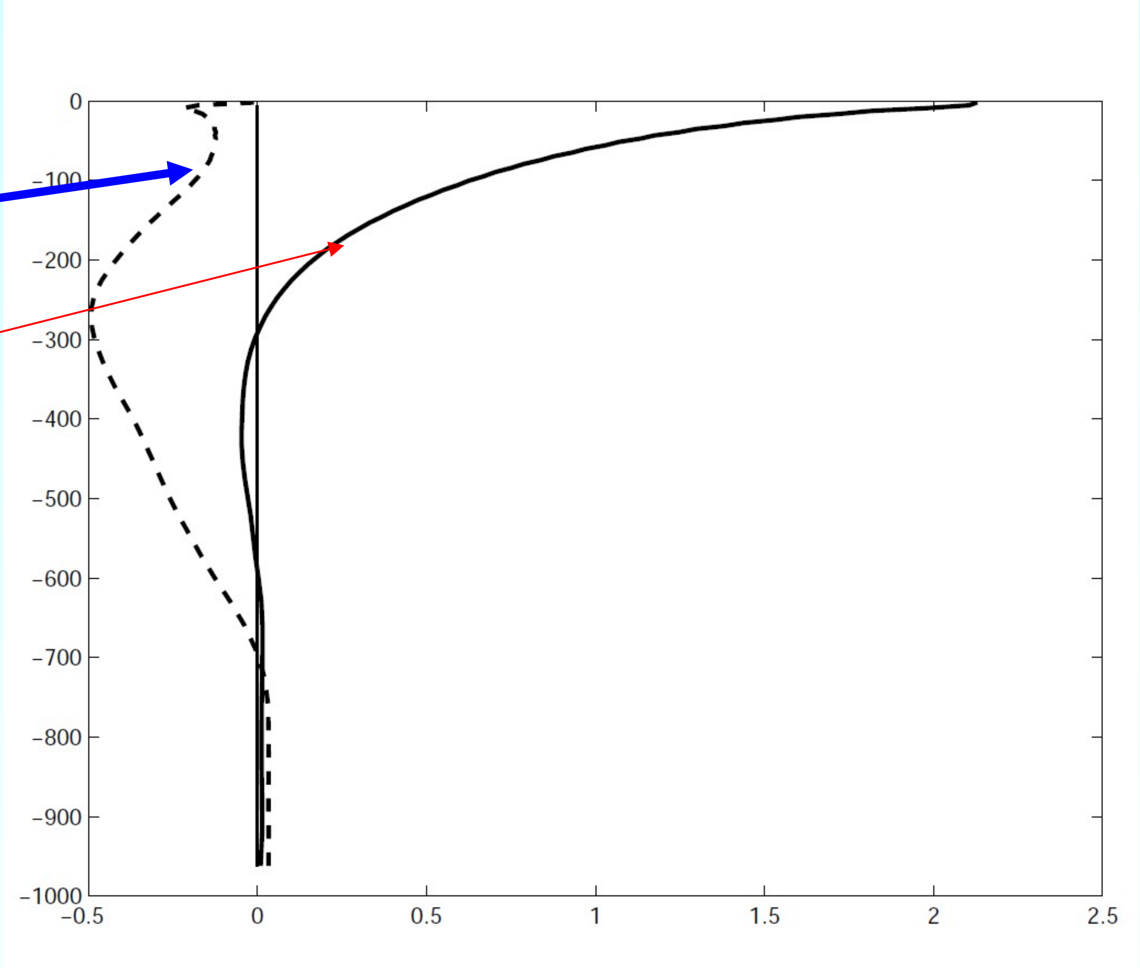


$$\frac{\partial \langle \rho \rangle}{\partial t} = -\frac{1}{f_0}\left(\frac{\partial \langle \rho\zeta \rangle}{\partial t} + \langle w\mathcal{Q} \rangle\right)$$

(Lapeyre, Klein, Hua, JPO'06)

$$\int_{-H}^{0} \frac{\partial \langle \rho\zeta \rangle}{\partial t} dz + \int_{-H}^{0} \langle w\mathcal{Q} \rangle dz = 0$$

$$\langle w_z \rho \rangle \qquad \langle w \rho_z \rangle$$



(II) Significant cyclone/anticyclone asymmetry

skewness

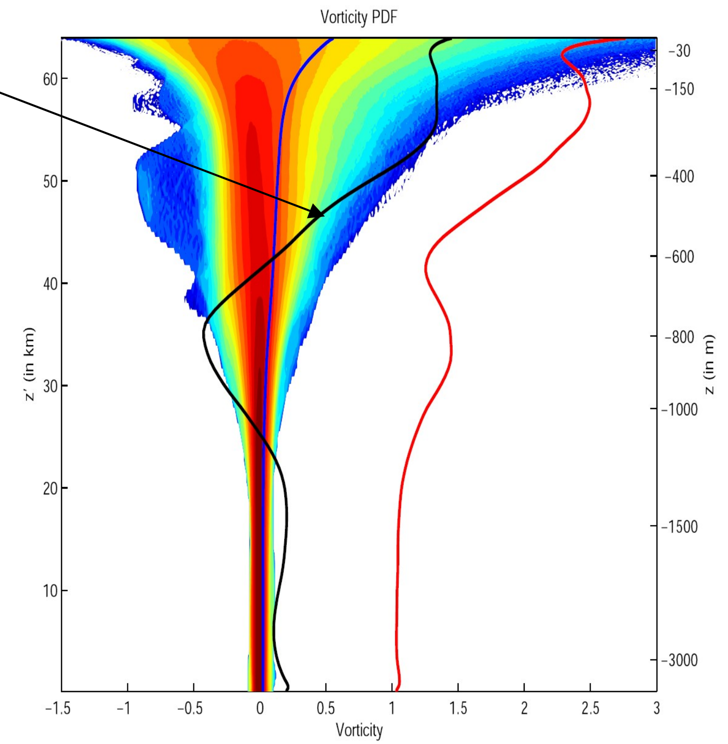


FIG. 6. Pdf of ζ/f_0 (in log scale) as a function of the stretched coordinate z' (left axis) and z (right axis). Superimposed are rms (blue), skewness (black) and kurtosis/3 (red).

(Roullet and Klein, PRL 2010)

Ro=0.6 at surface (due to submesoscales) and 0.06 at 800m

Regime of surface turbulence:
Cyclonic structures dominate
(Hakim et al., JAS 2002,
McWilliams et al., 2009)

Regime of interior turbulence:
Anticyclonic structures dominate
(Polvani et al., Chaos 1994)

Departure from QG flow is due to surface submesoscales
=> suggests a connection between upper and deeper layers

Conclusions

@ Submesoscales are energetic near the surface and are driven by frontogenesis

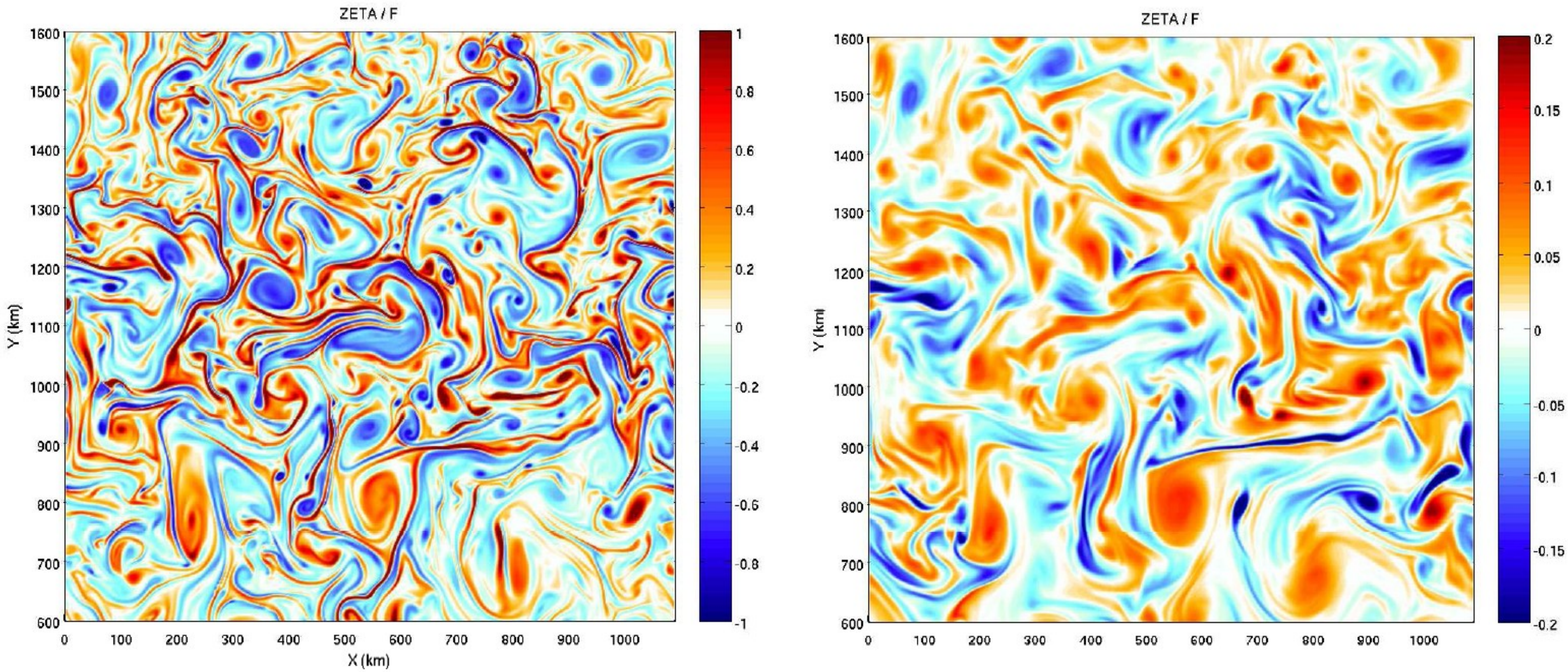
@ they are associated with an energetic vertical velocity field (W)

@ through W, submesoscales not only feed up mesoscale eddies but they also force the vortex stretching in the interior

@ as such submesoscales affect the larger ocean circulation in both the upper and deeper layers

=> they need to be taken into account in simulations and to be observed

They are not accessible from satellite data at the present time. However new altimeters should provide HR SSH, which combined with dynamical properties may allow to diagnose submesoscale dynamics.



(a) Surface relative vorticity

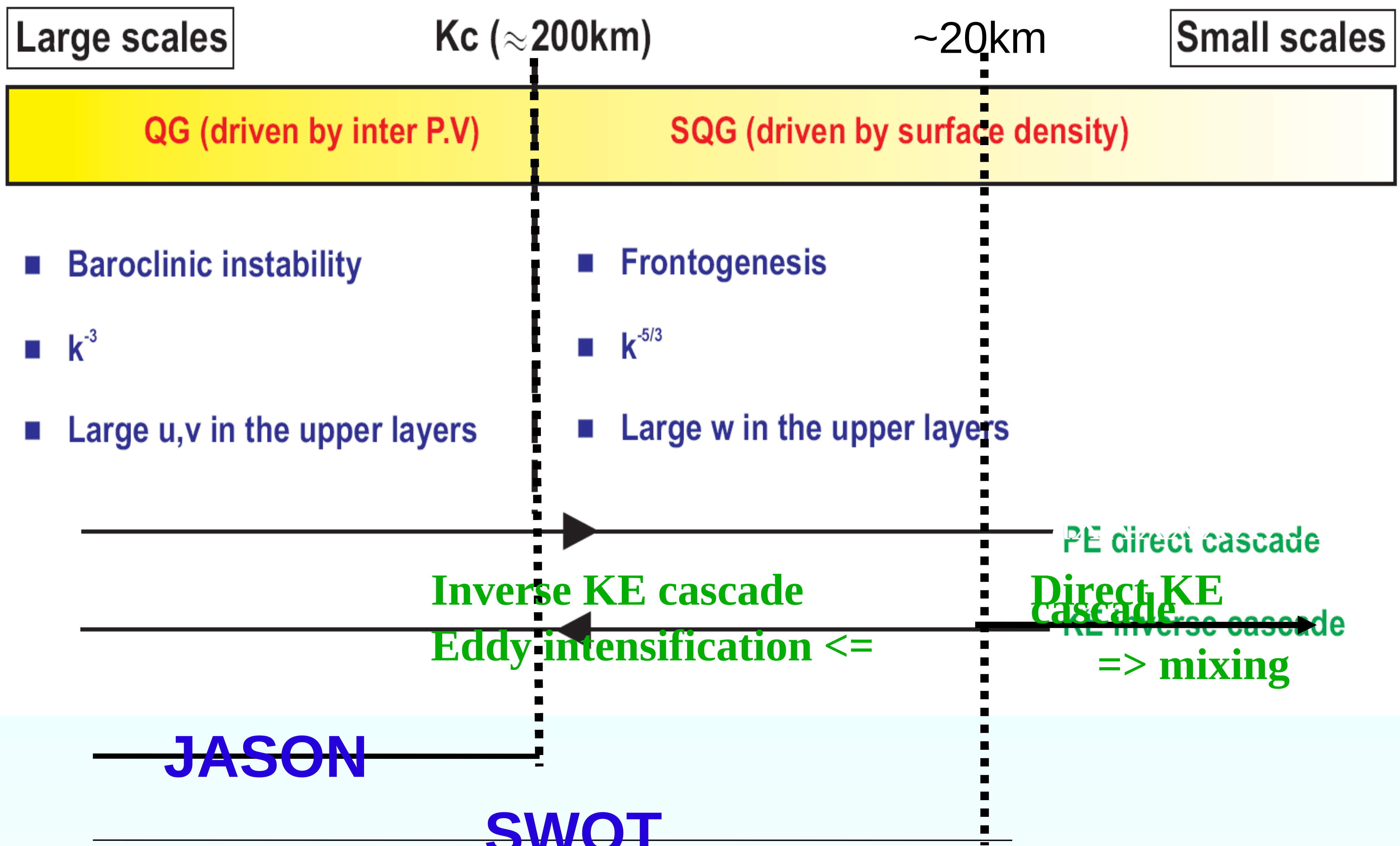
(b) Relative vorticity at 800m

Submesoscales are energetic in the surface oceanic layers (300m)
(k^{-2} surface velocity and density spectra)
=> driven by frontogenesis

Submesoscales are much weaker at depth (k$^{-3.5}$ velocity spectrum)

Existence of a surface dynamical mode (Charney mode) that captures most of the 3D dynamics of the upper oceanic layers.

=> leads to propose a conceptual framework to reconstruct the 3D dynamics in the first 500m from HR SSH/SST using climatological stratification.



Large scales
Kc (≈200km)
~20km
Small scales
QG (driven by inter P.V)
SQG (driven by surface density)
Baroclinic instability
k-3
Large u,v in the upper layers
Frontogenesis
k-5/3
Large w in the upper layers
PE direct cascade
Inverse KE cascade
Eddy intensification <=
Direct KE cascade
KE inverse cascade
=> mixing
JASON
SWOT

Lapeyre and Klein (JPO 2006):

PV anomalies in the ocean interior (driven by baroclinic instability) are correlated to the surface PV anomalies (driven by surface frontogenesis) [*see also Isern et al.,JGR 2008; Klein et al., GRL 2009; Sasaki et al., in preparation]*.

This leads to propose a method to diagnose the 3D dynamics from either the SSH or the surface buoyancy.

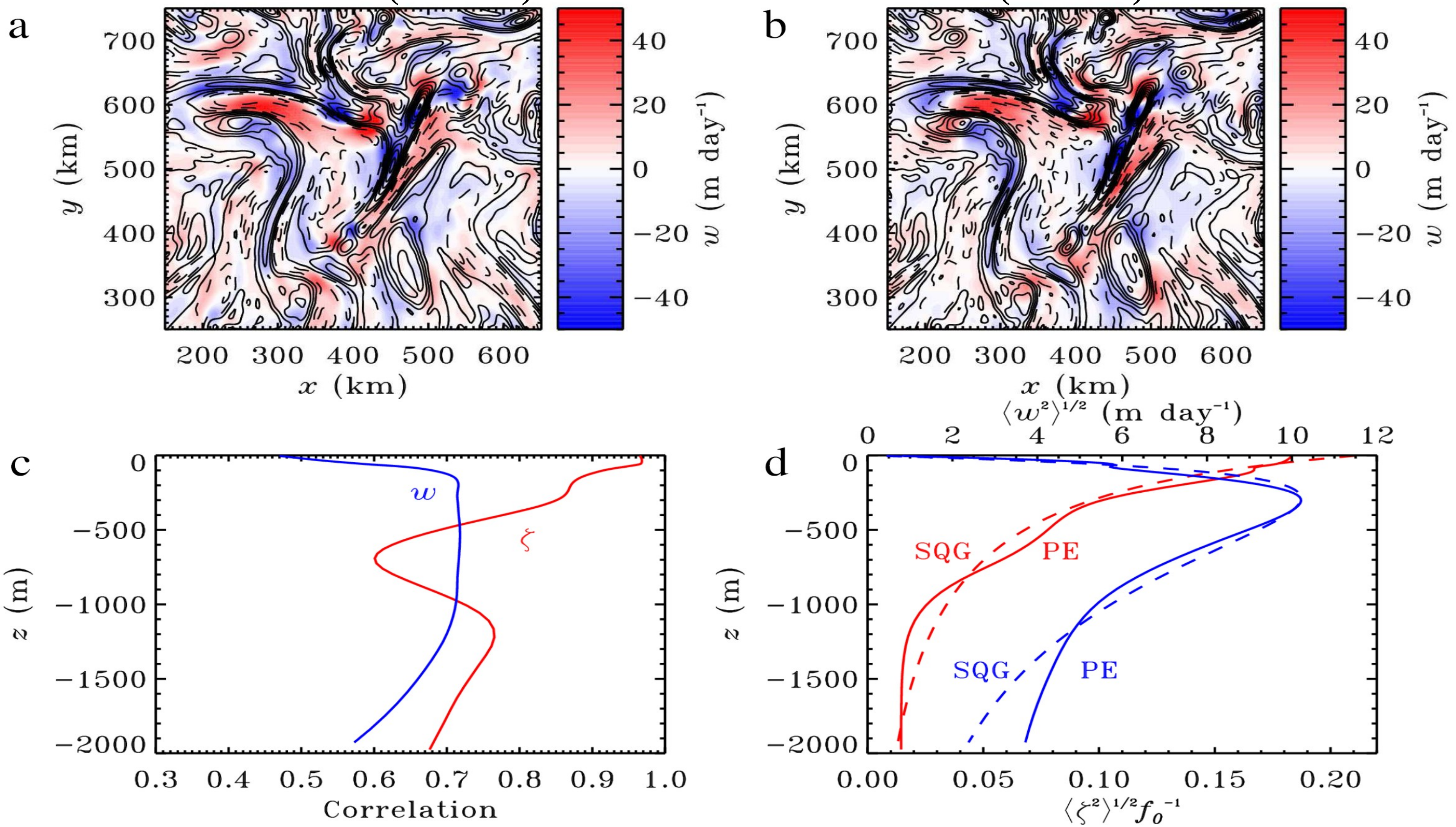
This diagnosis method is based on the SQG dynamics (Held et al, 1995):

$$\widehat{\psi}(\mathbf{k}, z) = g f_0^{-1} \widehat{\eta}(\mathbf{k}) \exp(N_0 f_0^{-1} k z)$$

No/fo takes into account the contribution of the interior dynamics

Observed W and RV
(at 200m)

Reconstructed W and
(at 200m)



Reconstruction of 3D dynamics in the North Pacific using outputs of realistic high-resolution ocean simulations

Hideharu Sasaki[1*], Patrice Klein[2], Bunmei Taguchi[1], Nobumasa Komori[1], and Guillaume Lapeyre[3]

1: Earth Simulator Center, Japan Agency for Marine-Earth Sience and Technology,Yokohama, Japan

2: Labratoire de Physique des Océans, IFREMER, Plouzané, France

3: Laboratoire de Météorologie Dynamique/IPSL, Paris, France.

**E-mail: sasaki@jamstec.go.jp*

SSH and Mixed Layer Depth (OFES, 01/01/15th yr)

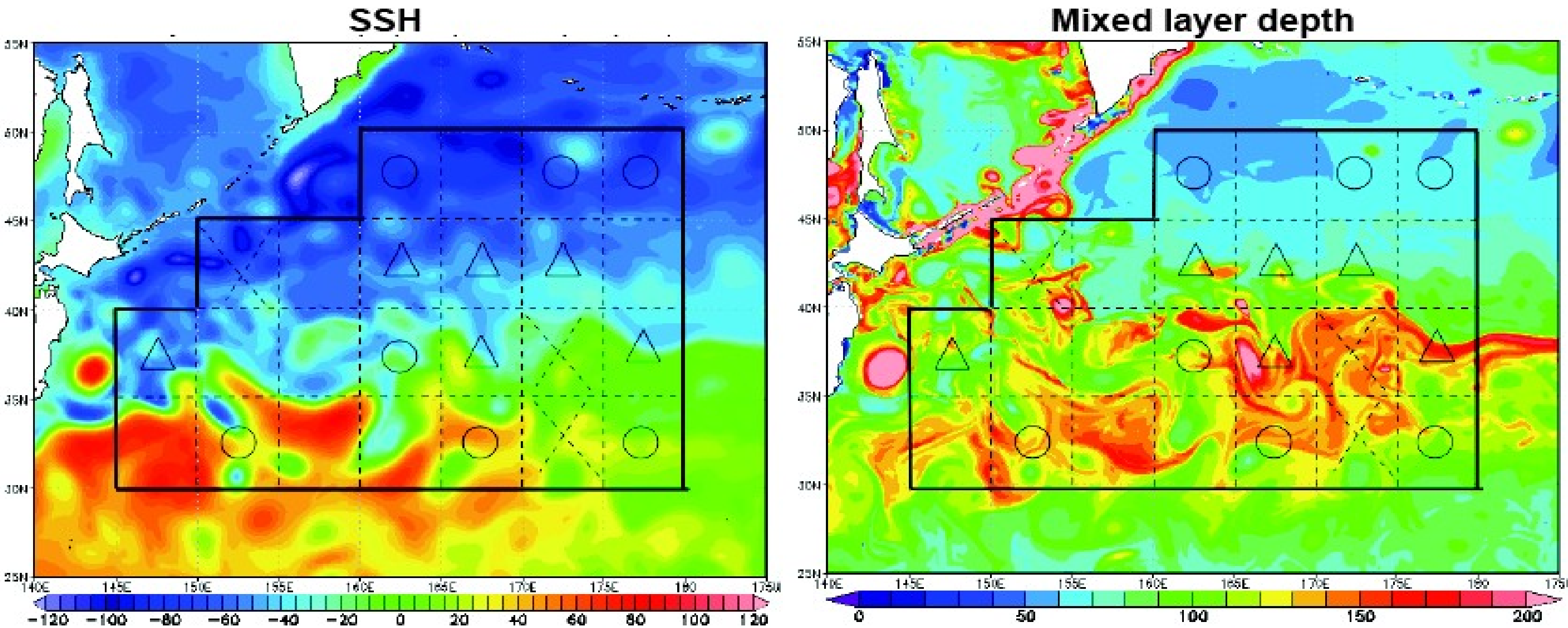
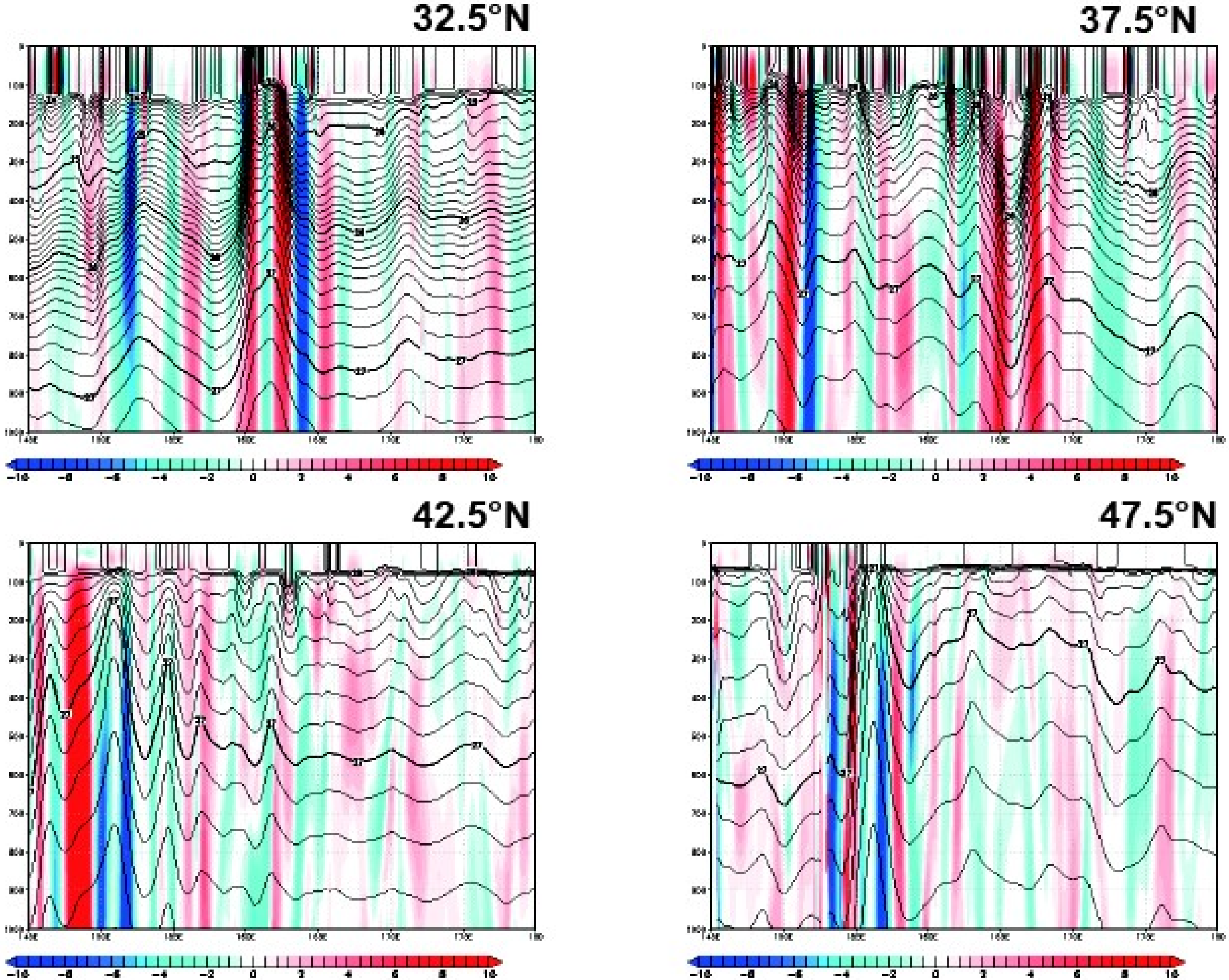


Fig. 1. (Left) Sea surface height (cm), (Right) mixed layer depth (m) of OFES daily mean on Jan. 1st, 15th model year. The eSQG reconstruction is conducted for each 5deg. x 5deg. domain. Correlation maximum of RMS of vertical motions between the eSQG reconstruction and OFES: ○: > 0.4, △: > 0.2. Reconstruction cannot be adapted due to sea mount in regions "X".

Fig. 2

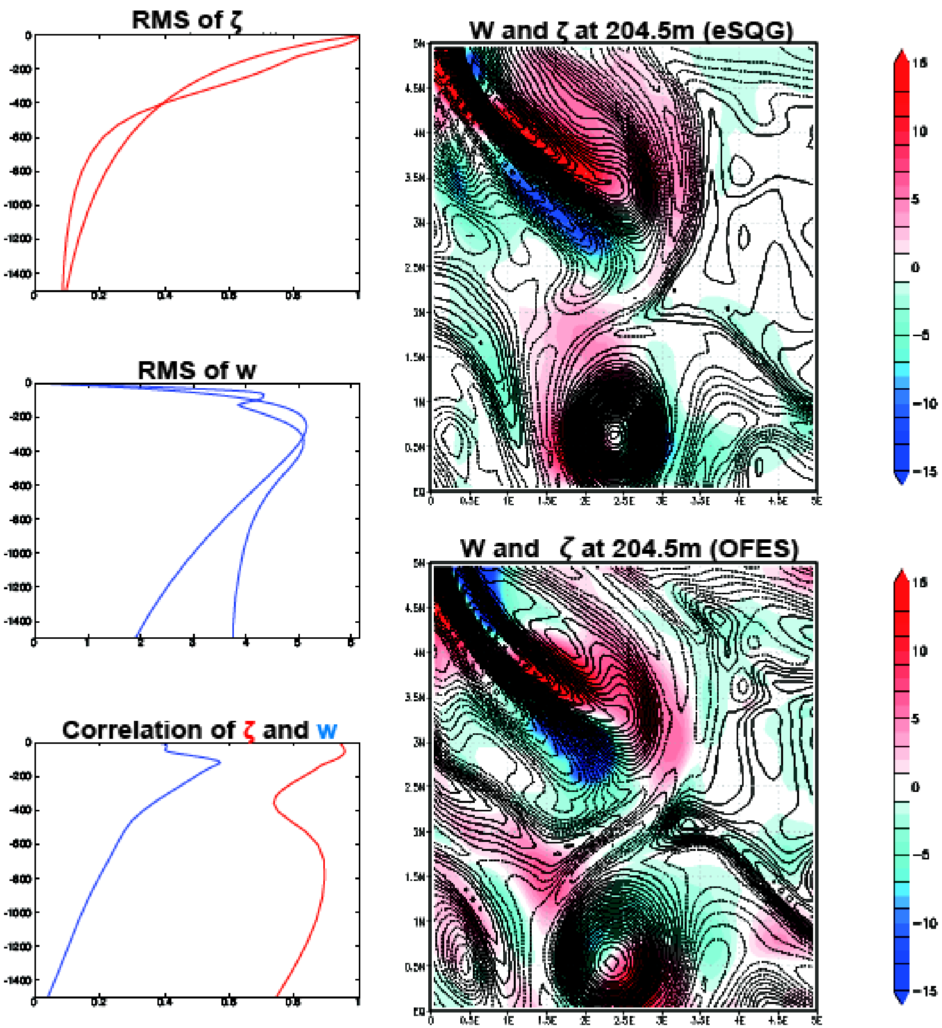
Vertical Motion and Potential Density (OFES)



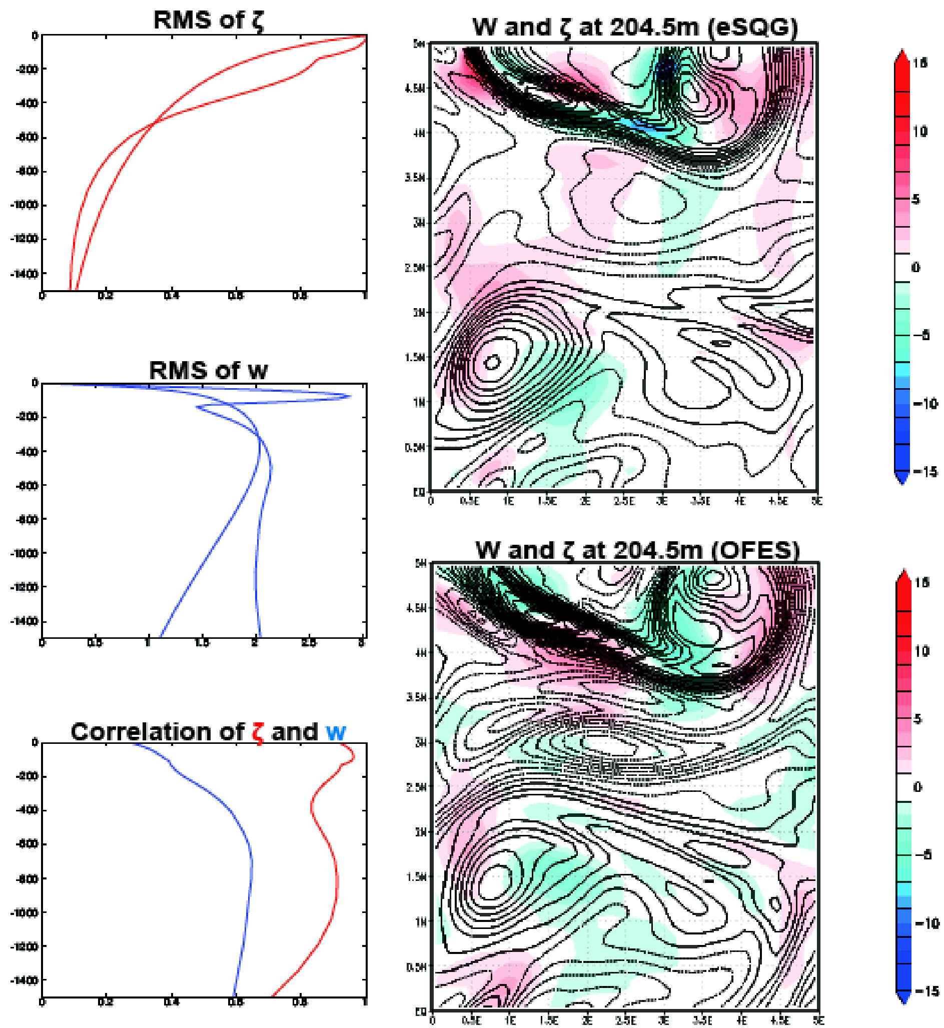
2. Longitude–vertical section of vertical velocity (color, m/day) and potential density(contour, $\sigma\,\theta$).

Relative Vorticity and Vertical Motions (eSQG Reconstruction vs OFES)

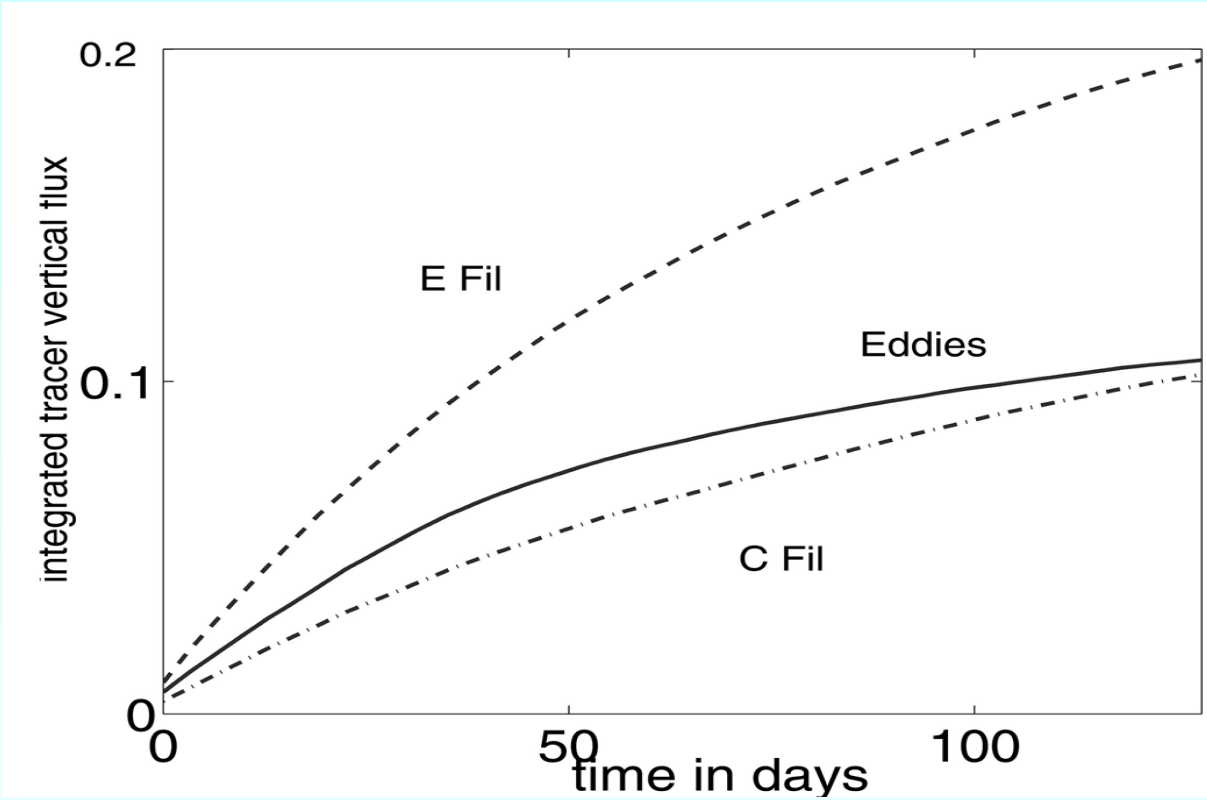
150–155°E, 30–35°N



165–170°E, 30–35°N



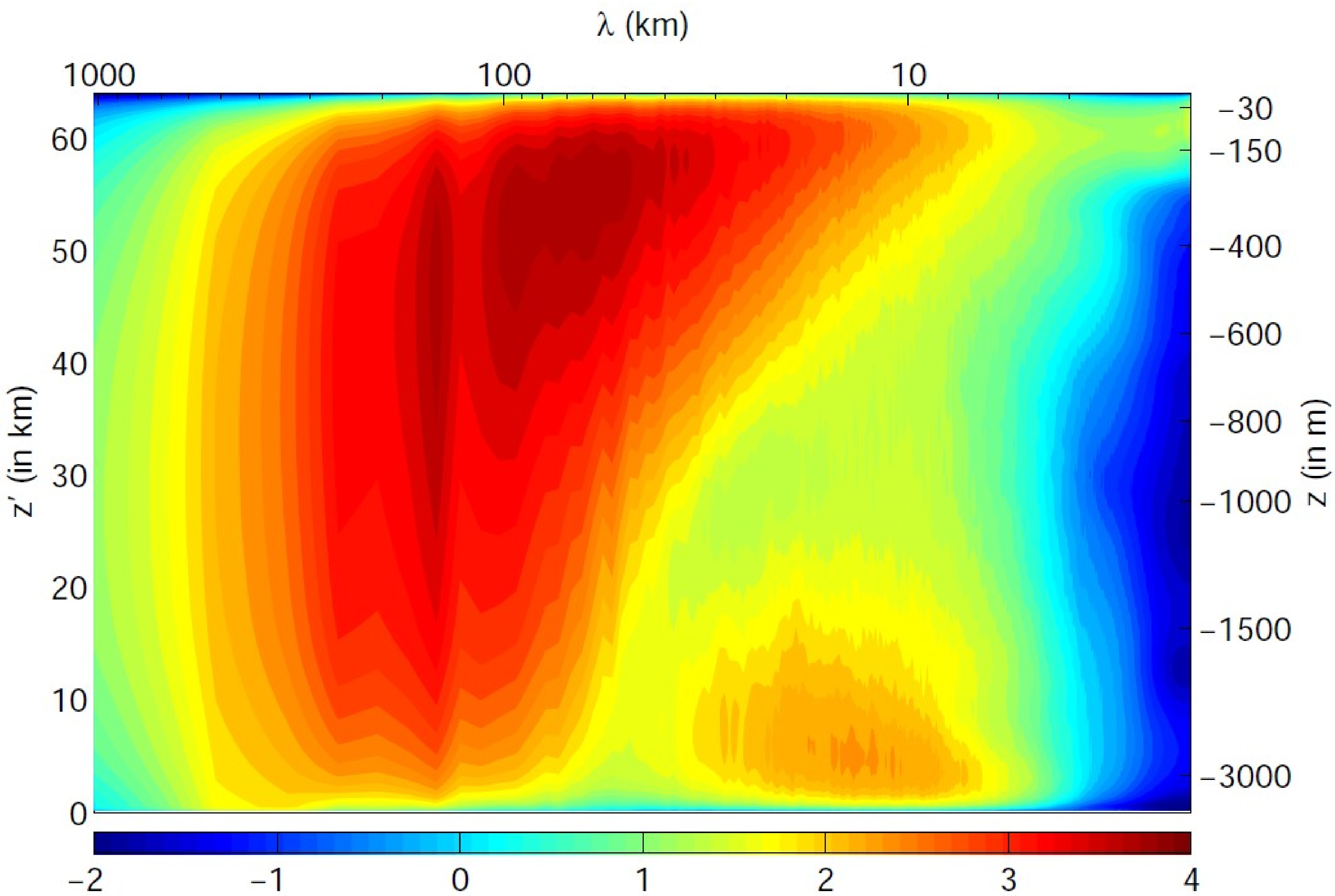
Because of the frontogenesis, submesoscales are associated with an <u>energetic vertical velocity field</u> in the first 300m



50% of the vertical tracer fluxes at 200m occur within the elongated filaments outside the eddies

=> Strong impact on the global ocean dynamics...

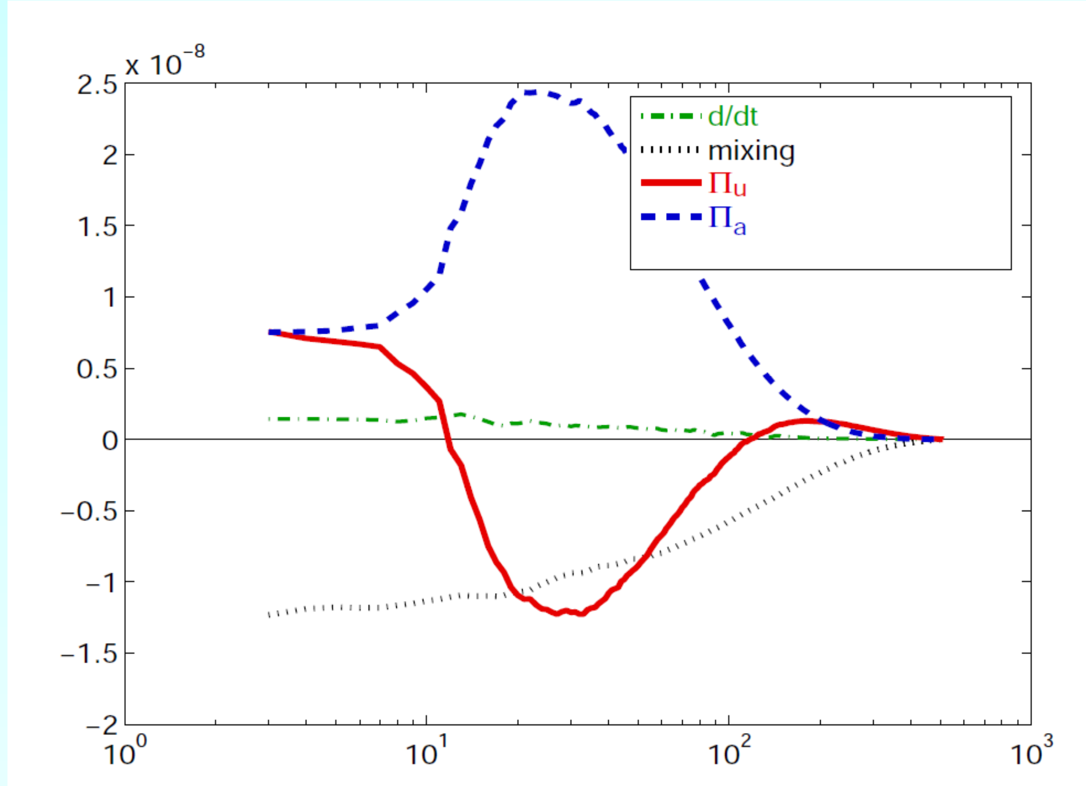
Three results...



(b) Wavenumber spectrum of the vertical velocity

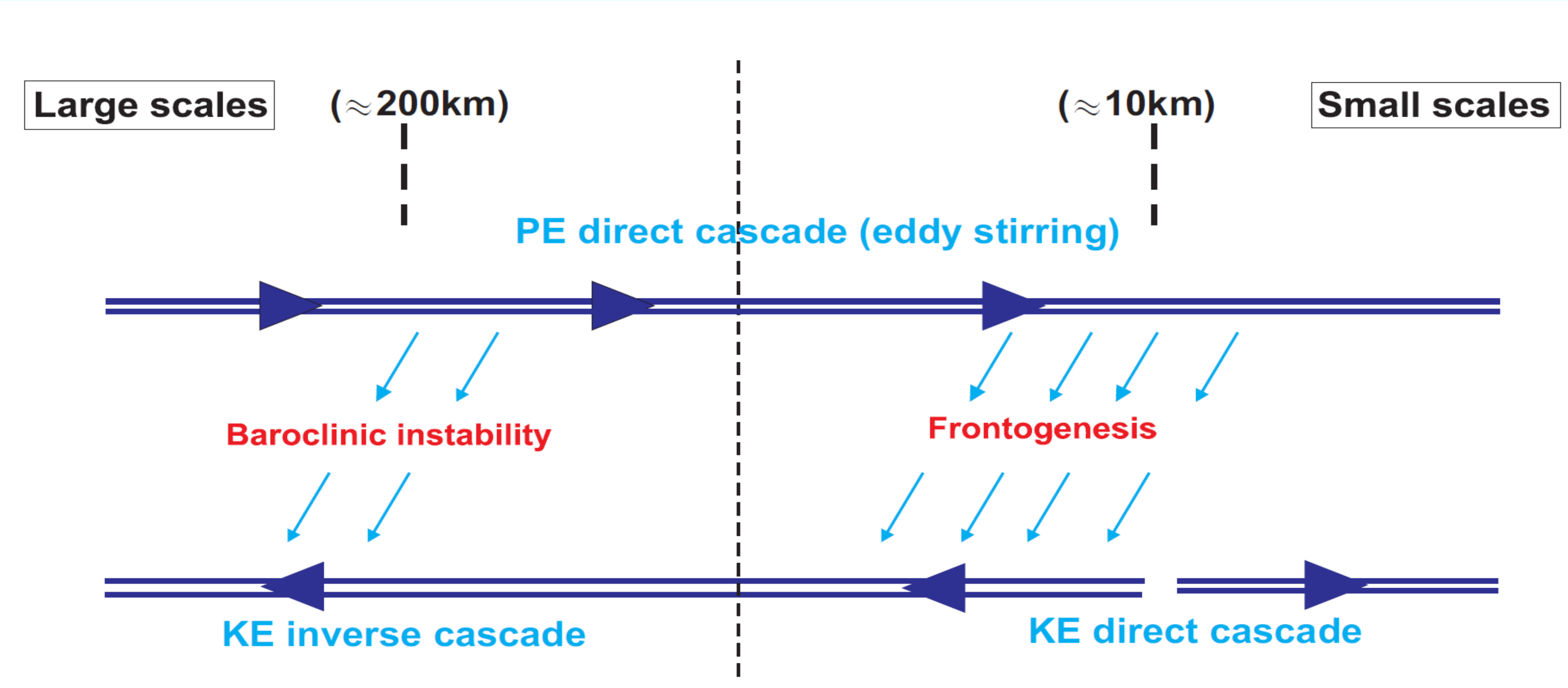
Impact of frontogenesis on the KE budget:

The dashed blue curve
(APE to KE transfer through W)
and solid red curve
(inverse KE cascade)
well ***extend in the small scales region*** *(Klein et al., 2008, Capet et al., 2008)*



Divergent motions strongly increase the APE transformation into KE at small scales which feeds up the inverse KE cascade => a total kinetic energy increase by a factor 2

Submesoscales efficiently feed up mesoscale eddies and larger scales



Direct PE cascade at surface through eddy stirring processes
Frontogenesis at all scales

Inverse KE cascade through nonlinear interactions

=> **Velocity spectrum (SSH) has a slope in k^{-2}** and NOT a slope in k^{-3}

=> **Total EKE is multiplied by 2** when submesoscales are taken into account