Part 2

Submesoscale dynamics

Dynamics at the ocean submesoscales

Characteristic scales:

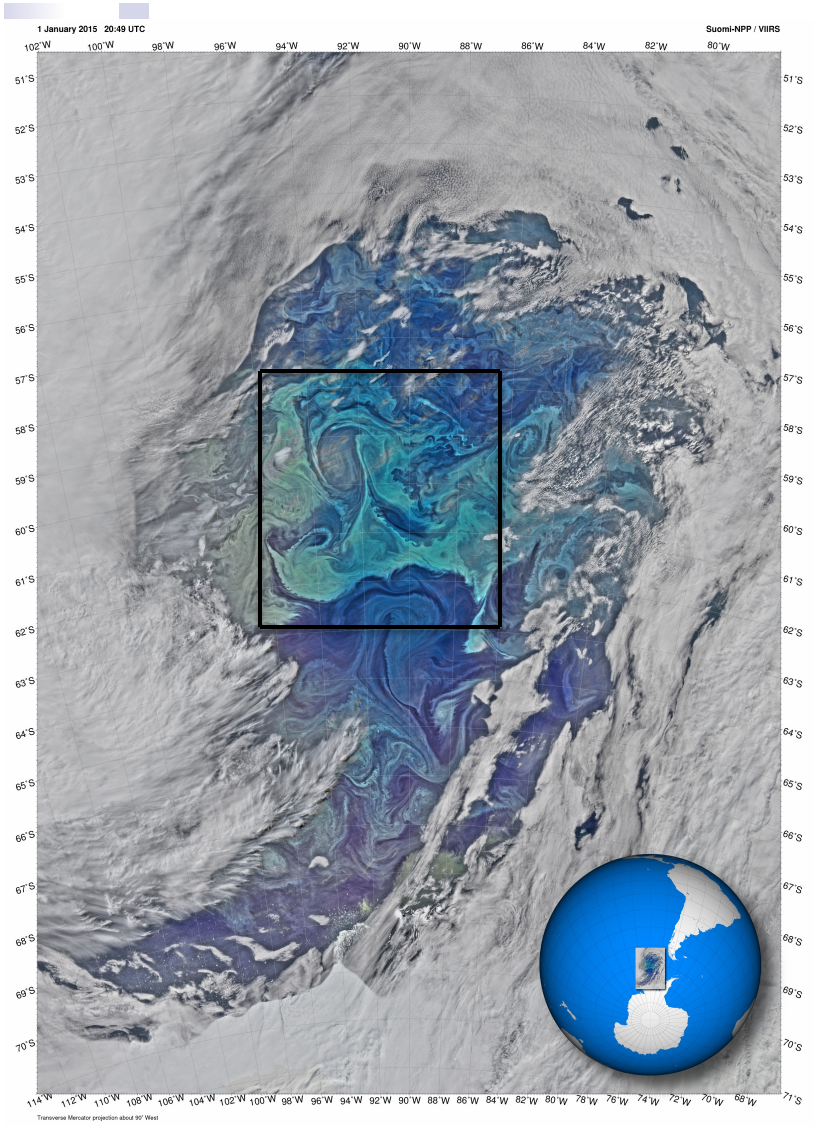
- L ~ 100 m - 10 km (here ≥ 1 km)
- H ~ 10 - 100 m
- t ~ hours – few weeks (here ≥ 1 day)

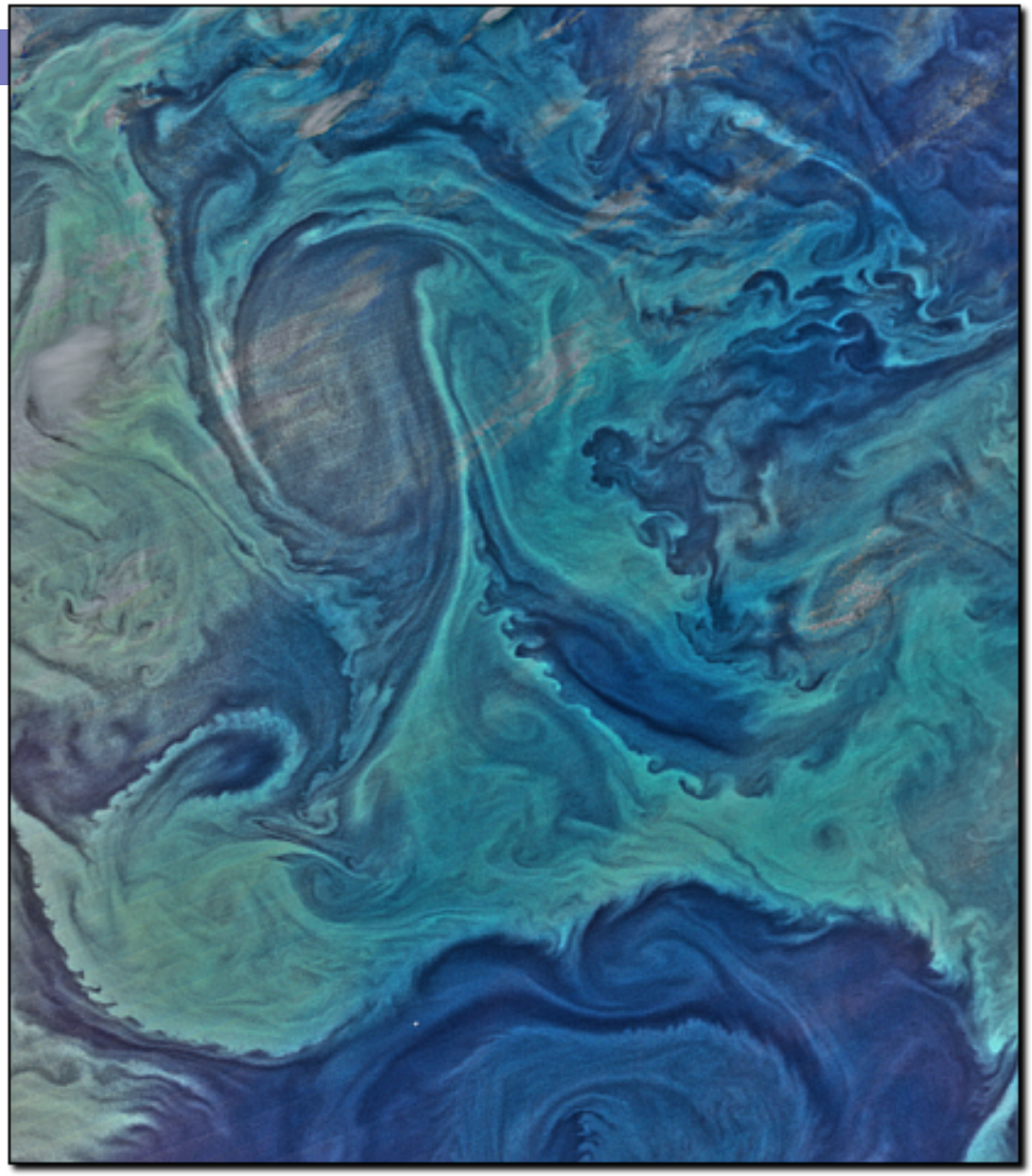
- Rotation and stratification are still important but are not asymptotically overwhelming
- Ageostrophic motions cannot be neglected

Dynamics at the ocean submesoscales

- Arise from **mesoscale eddies** and boundary currents (or interactions with **bottom topography**) in the form of surface-layer fronts, vorticity filaments, small coherent vortices.
- Associated with large APE->EKE transfers through **mixed-layer instabilities and frontogenesis**
- Dynamics are mostly advective and only partly "balanced" with $R_o = V/fL \sim 1$
- Strong surface convergences and vertical velocity, hence vertical fluxes

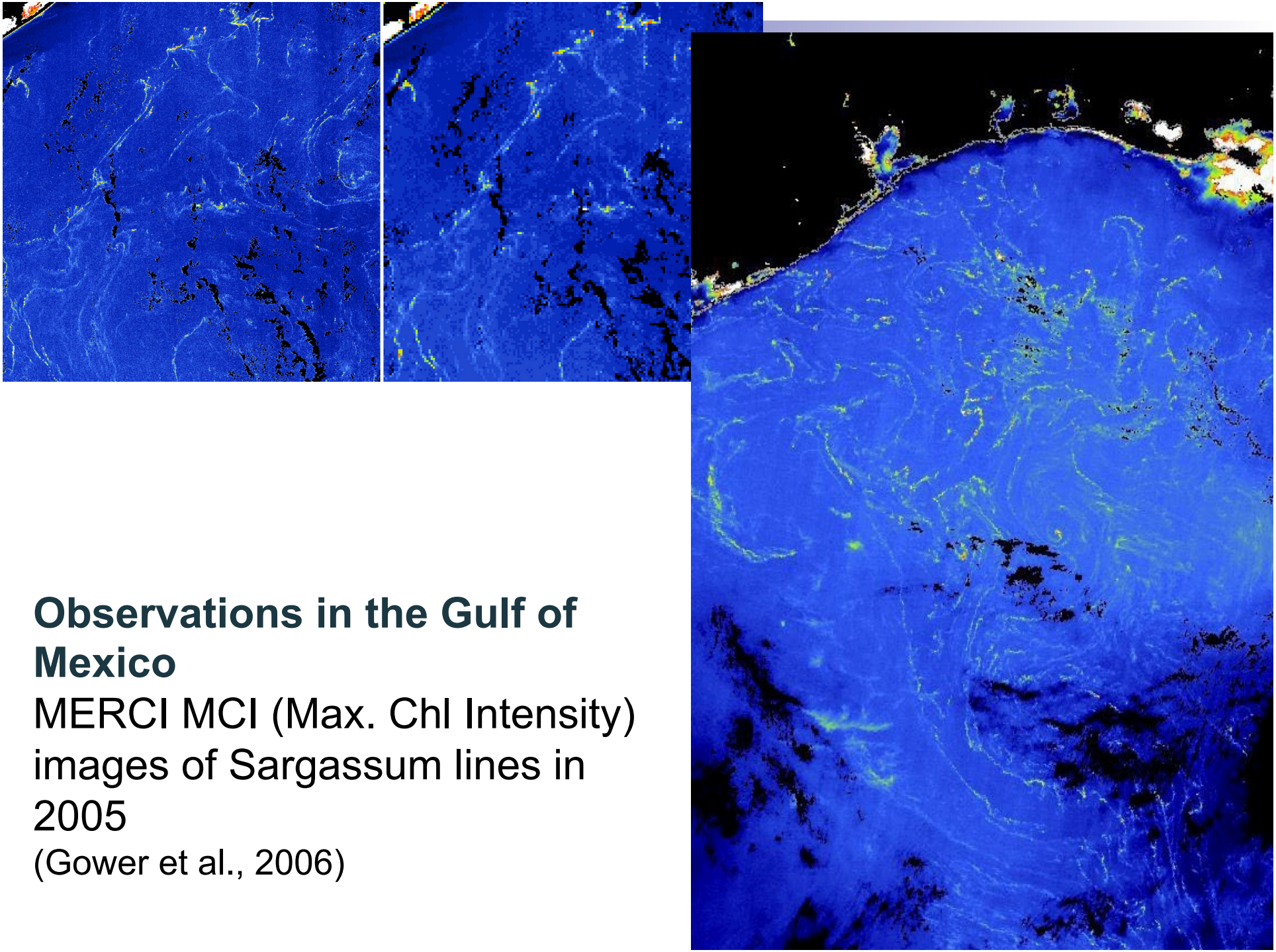
- Limited measurements
- Most progress in our understanding through modeling using nested techniques to investigate finer and finer scales
- Approaching the limits of hydrostatic models





Observations: Phytoplankton bloom around Antarctica

January 15, 2015. Modis AQUA



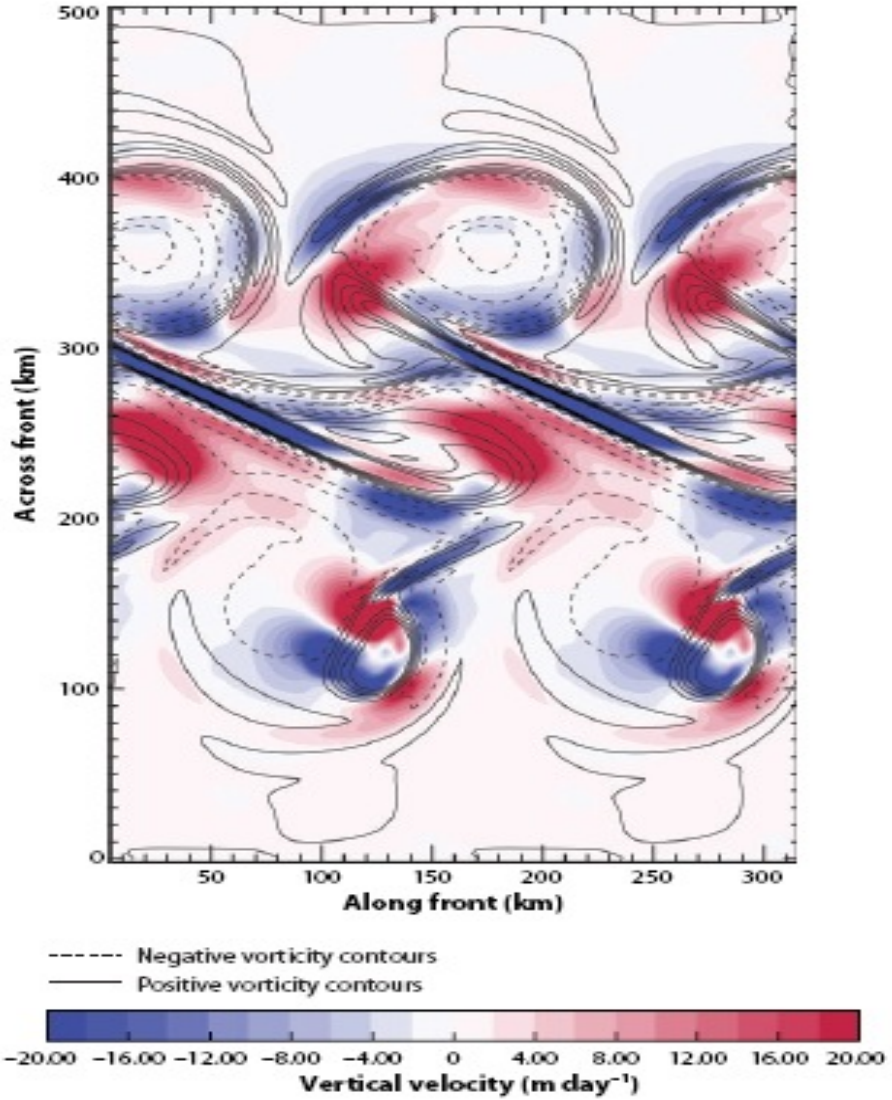
Observations in the Gulf of Mexico

MERCI MCI (Max. Chl Intensity) images of Sargassum lines in 2005

(Gower et al., 2006)

Ageostrophic (unbalanced) motions cannot be neglected

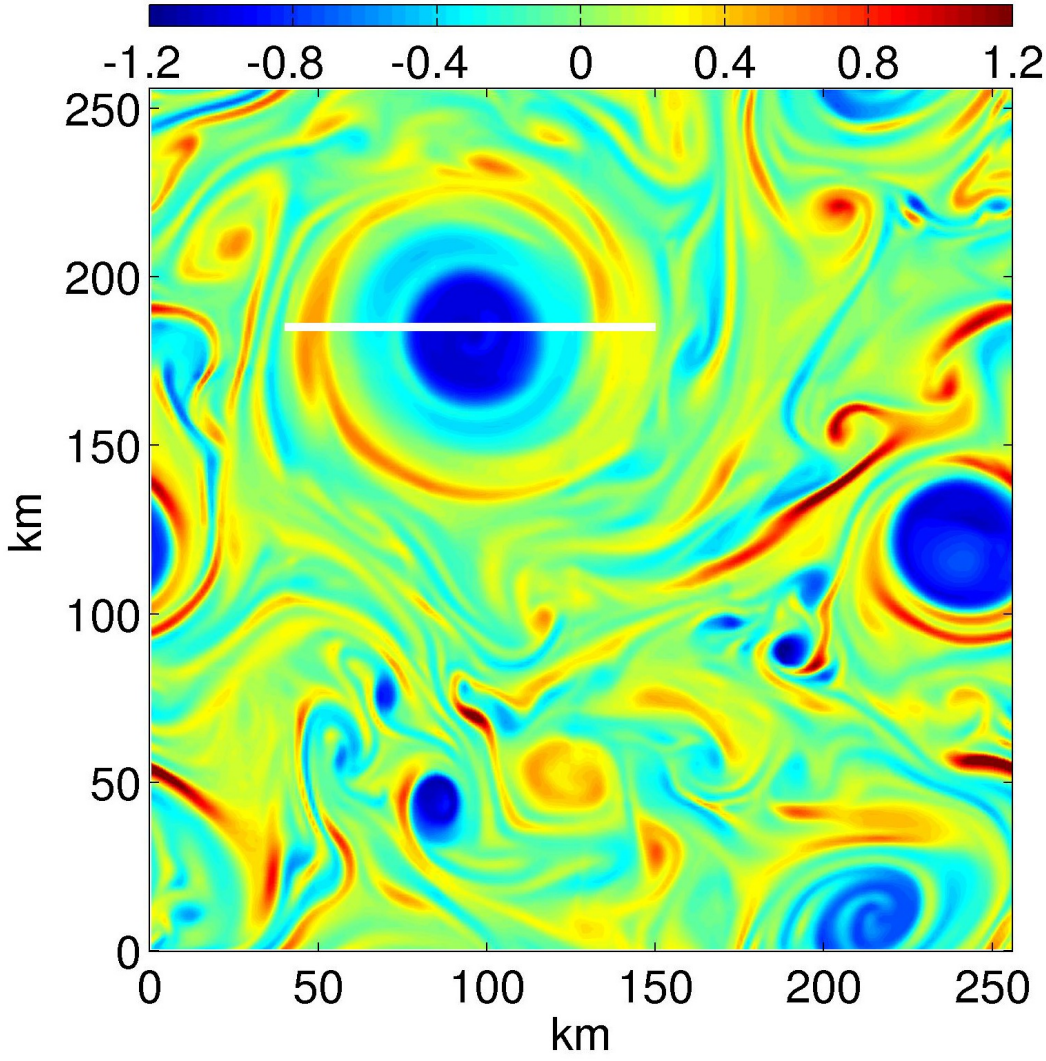
Klein and Lapyere, Ann. Rev. Marine Science, 2009



Vertical velocities at 90 m (*red for upward and blue for downward*) around a front.

Vorticity Field, ζ/f

Koszalka et al, JGR 2009

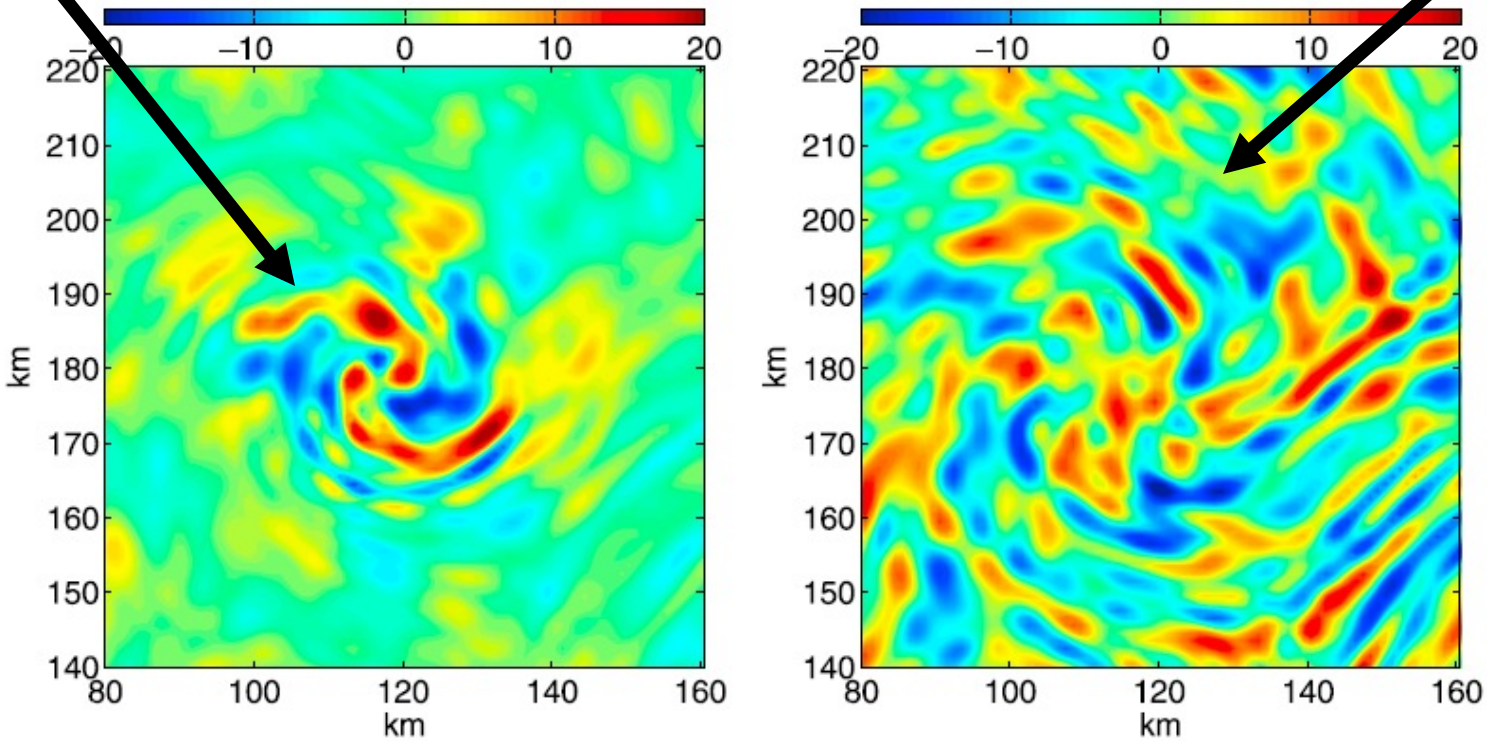


Looks even more complicated if we do not average over one day…

Vortex Rossby waves
VRW

again 78 and 350m, in m/day

near-inertial oscillations
NIO



VERTICAL TRANSPORT: Eddies and internal waves

Kunze (1985) shows that eddies 'polarize' near inertial waves. Anticyclones trap them and reflect the energy downward, while cyclones expel them.

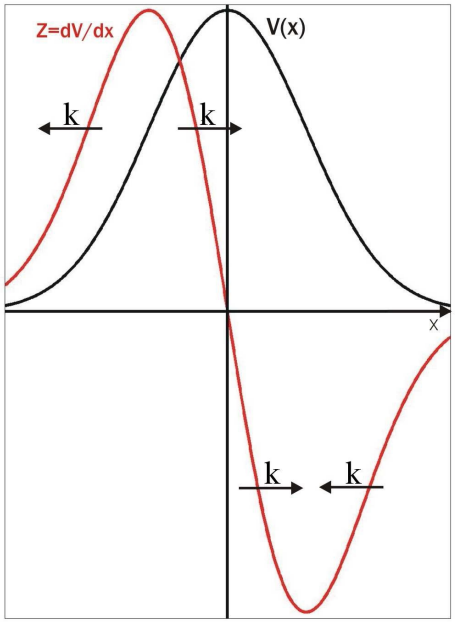
$$u(\vec{x},t) \approx u_o \sin(ft + \frac{Z}{2}t) \approx u_o \sin(ft + \frac{Z_o}{2}t - \vec{k}\cdot\vec{x})$$

Mechanism: Winds with energy in the f band excite inertial waves at the ocean surface. The frequency of the excited oceanic wave depends on f corrected by Z/2 (near inertial).

Cyclones end up with $f_{eff} > f$ and the waves can propagate outside. In anticyclones $f_{eff} < f$ and NIW are trapped.

Refraction by relative vorticity causes a decrease in NIW scale accelerating their vertical propagation.

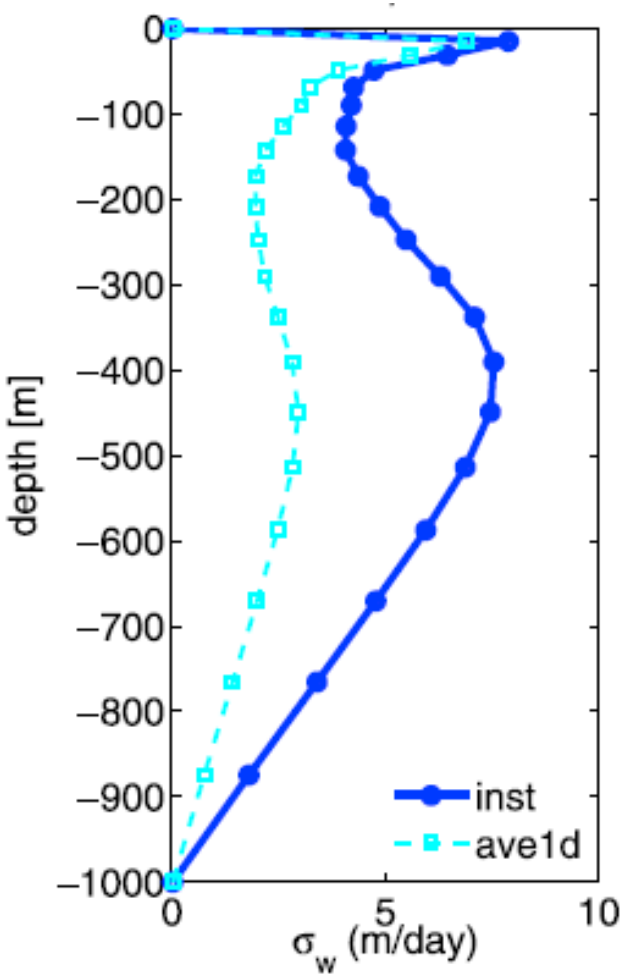
(Danioux and Klein, 2008; Danioux et al. 2008, 2011)



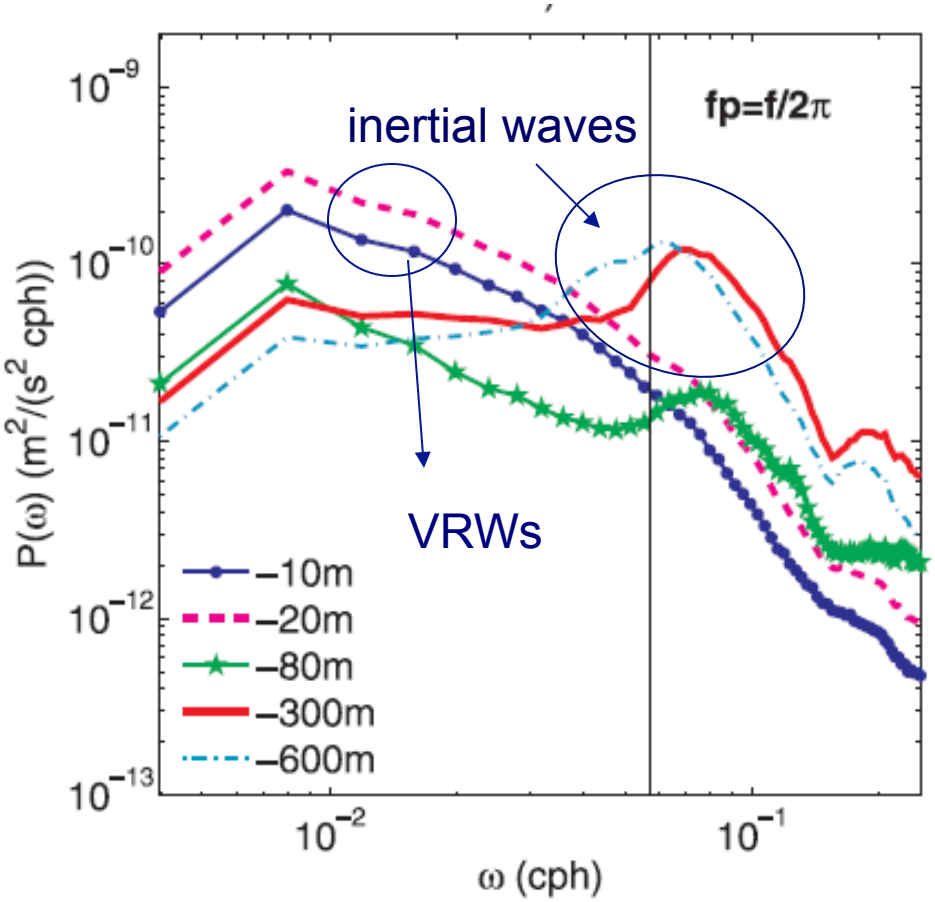
$$k = -\frac{\partial Z}{\partial x}\frac{t}{2}$$

schematic by P. Klein

standard deviation
vertical velocity field



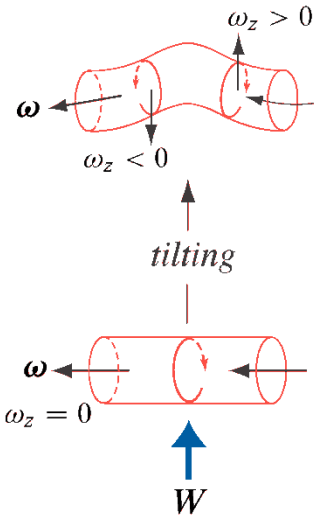
frequency spectra



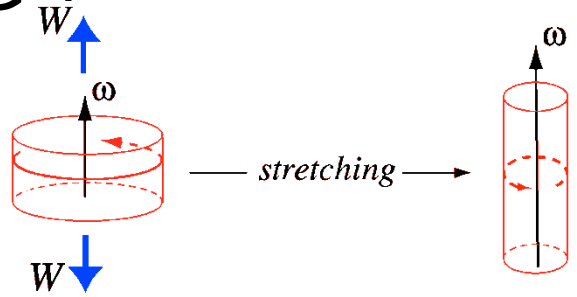
Diagnosing the vertical velocity field

w = FREE SURFACE +

ADVECTION (AGEOSTROPHIC) +



STRETCHING + TILTING +



EKMAN +

HORIZONTAL MIXING +

VERTICAL MIXING

FREE SURFACE

$$w(x,y,z) = \frac{D\eta}{Dt}$$

ADVECTIVE

$$-\int_z^\eta \alpha_1 \left[\frac{\partial \zeta_1}{\partial t} + u\frac{\partial \zeta_1}{\partial x} + v\frac{\partial \zeta_1}{\partial y} + w\frac{\partial \zeta_1}{\partial z}\right] dz$$

ADVECTIVE

$$-\int_z^\eta \alpha_2 \left[\frac{\partial \zeta_2}{\partial t} + u\frac{\partial \zeta_2}{\partial x} + v\frac{\partial \zeta_2}{\partial y} + w\frac{\partial \zeta_2}{\partial z}\right] dz$$

STRETCHING

$$-\int_z^\eta \alpha_1 [\chi_2 \zeta_1]\, dz - \int_z^\eta \alpha_2 [\chi_1 \zeta_2]\, dz$$

TILTING

$$-\int_z^\eta \alpha_1 [\frac{\partial w}{\partial x}\frac{\partial v}{\partial z}]\, dz + \int_z^\eta \alpha_2 [\frac{\partial w}{\partial y}\frac{\partial u}{\partial z}]\, dz$$

WIND STRESS

$$+\int_z^\eta \frac{\alpha_2}{\rho_o}\left[-\frac{\partial}{\partial y}\frac{\partial \tau_x}{\partial z}\right] dz$$

HORIZONTAL MIXING

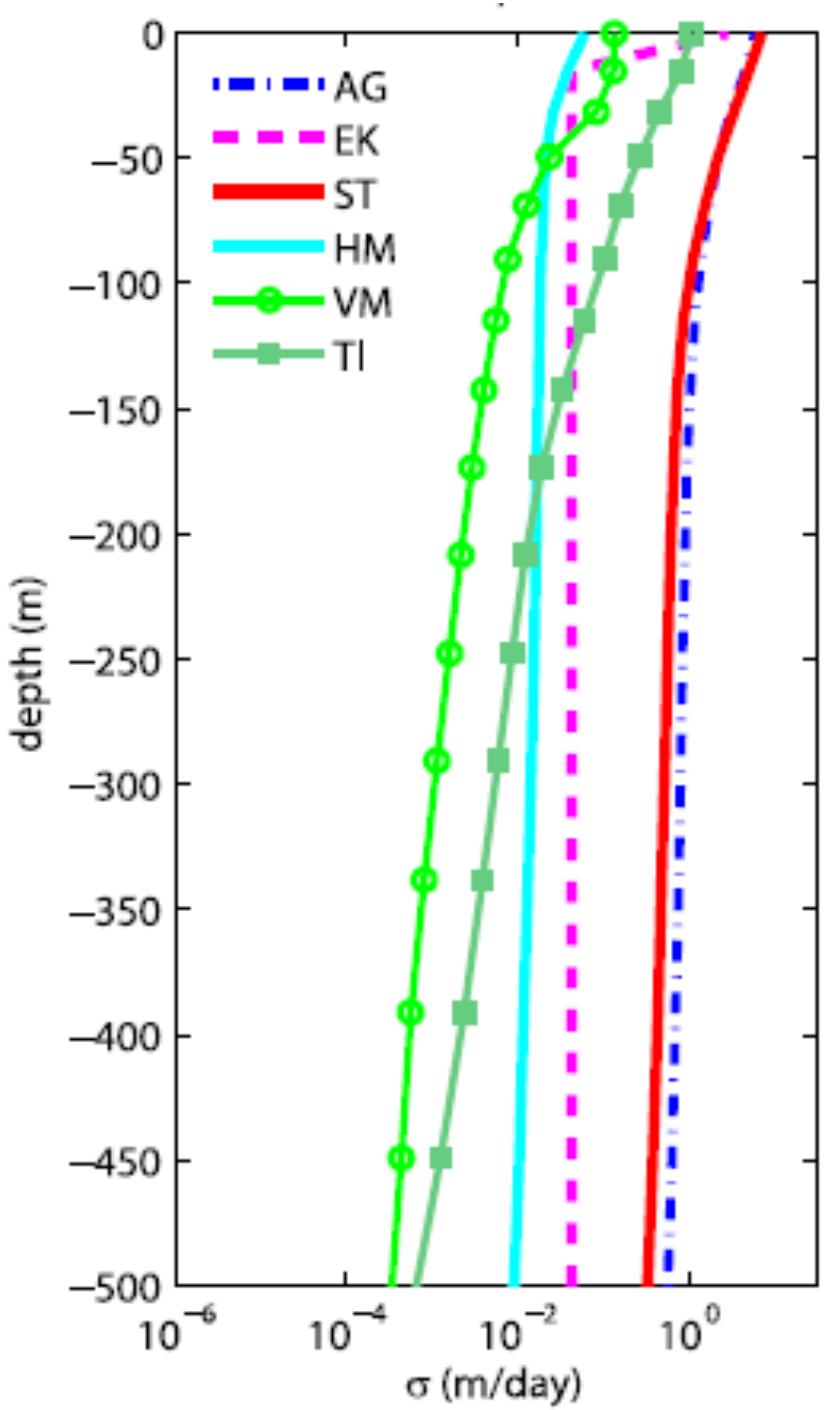
$$+\sum_{i=1,2}\int_z^\eta \alpha_i A_H (\frac{\partial^4 \zeta_i}{\partial x^4} + \frac{\partial^4 \zeta_i}{\partial y^4})\, dz$$

VERTICAL MIXING

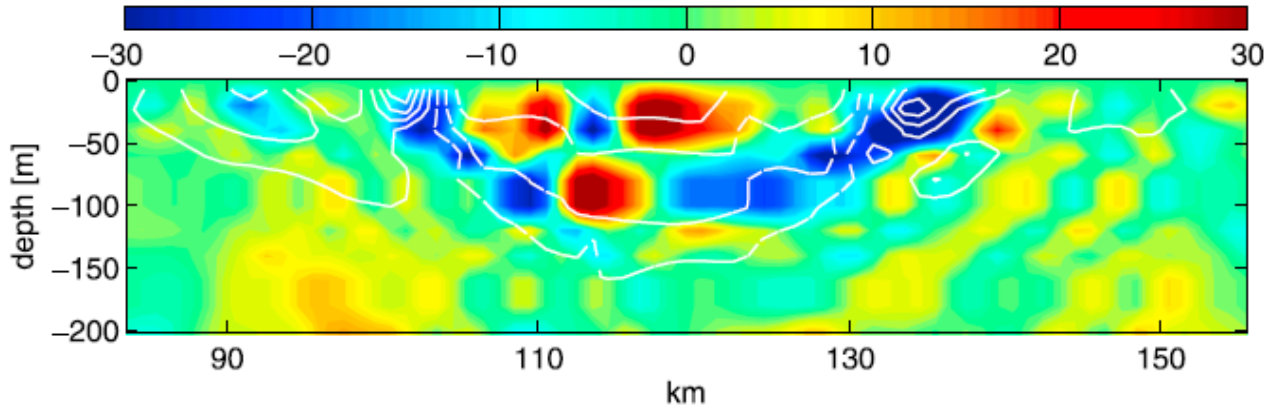
$$+\int_z^\eta \alpha_1 \frac{\partial}{\partial x}\frac{\partial}{\partial z}(K_v \frac{\partial v}{\partial z})\, dz - \int_z^\eta \alpha_2 \frac{\partial}{\partial y}\frac{\partial}{\partial z}(K_v \frac{\partial u}{\partial z})\, dz$$

$$\zeta_1 = \frac{\partial v}{\partial x};\quad \zeta_2 = -\frac{\partial u}{\partial y};\quad \chi_1 = \frac{\partial u}{\partial x};\quad \chi_2 = \frac{\partial v}{\partial y}$$

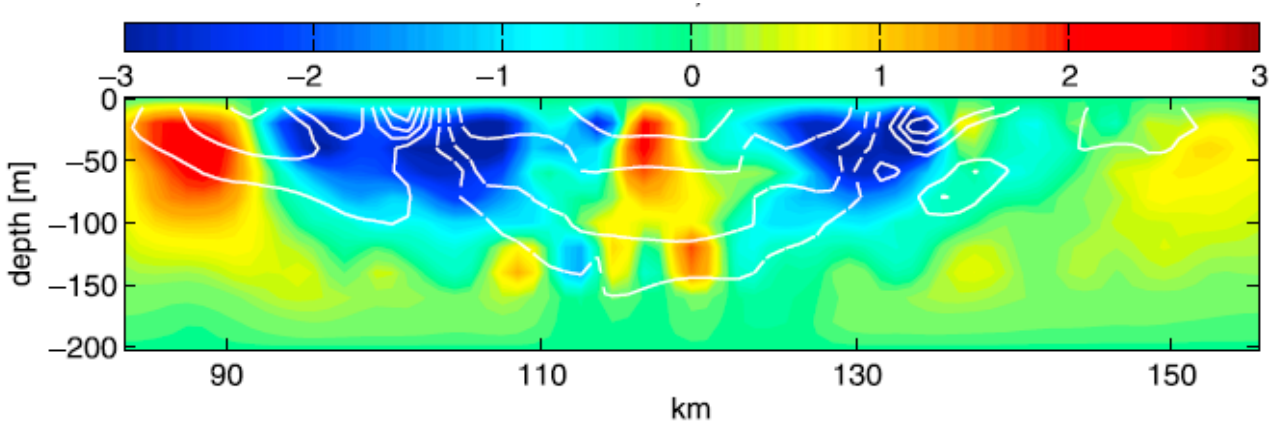
$$\alpha_1 = \left(f + \zeta_1\right)^{-1};\quad \alpha_2 = \left(f + \zeta_2\right)^{-1}$$



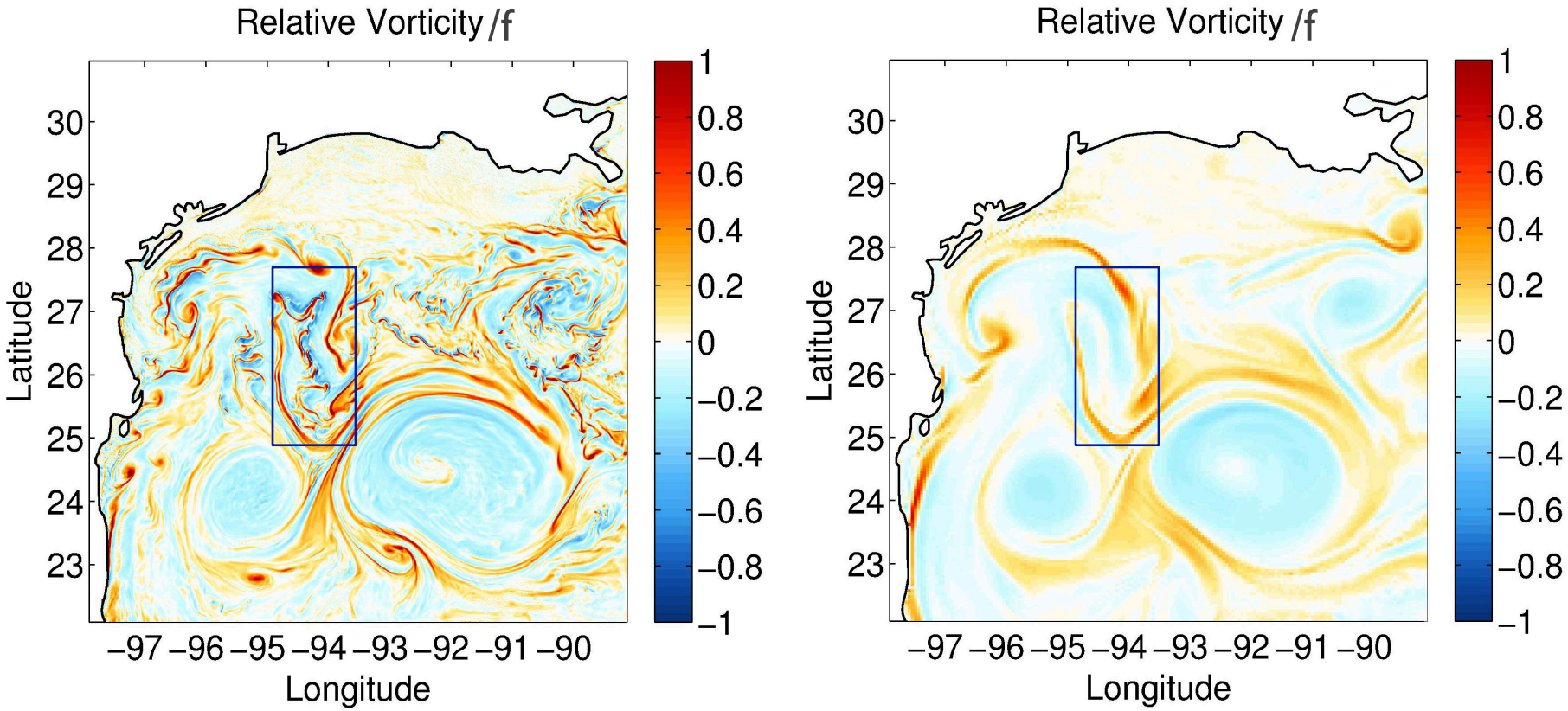
with primitive equations (ROMS)



with the omega-equation

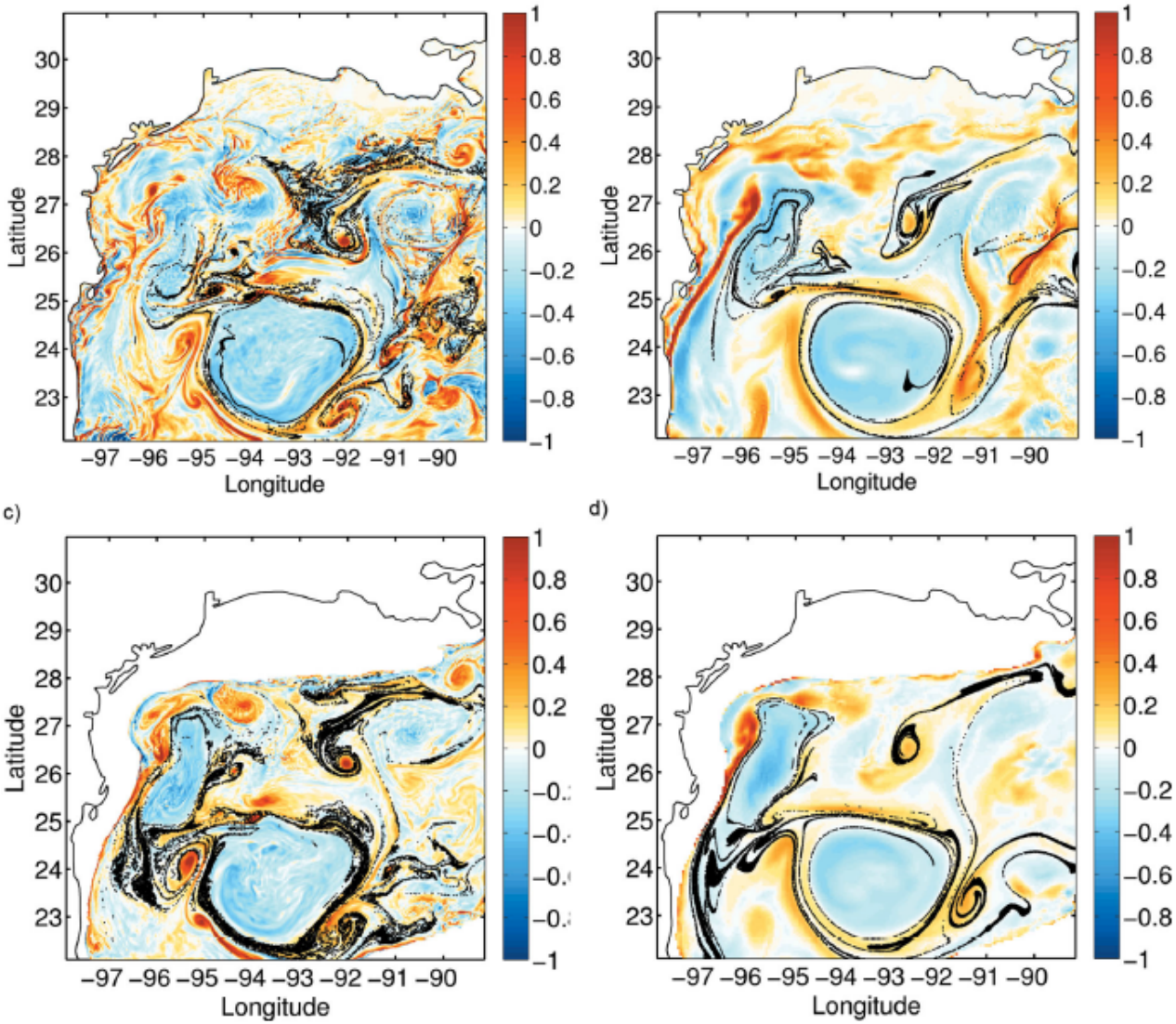


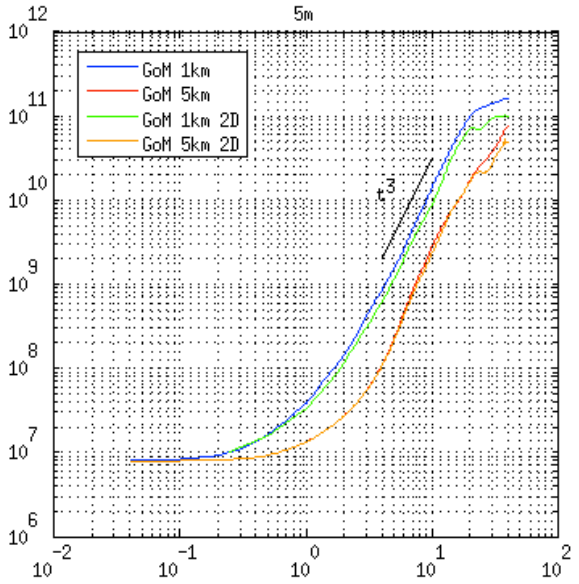
And in a realistic set-up (Gulf of Mexico)



Zhong and Bracco, 2013

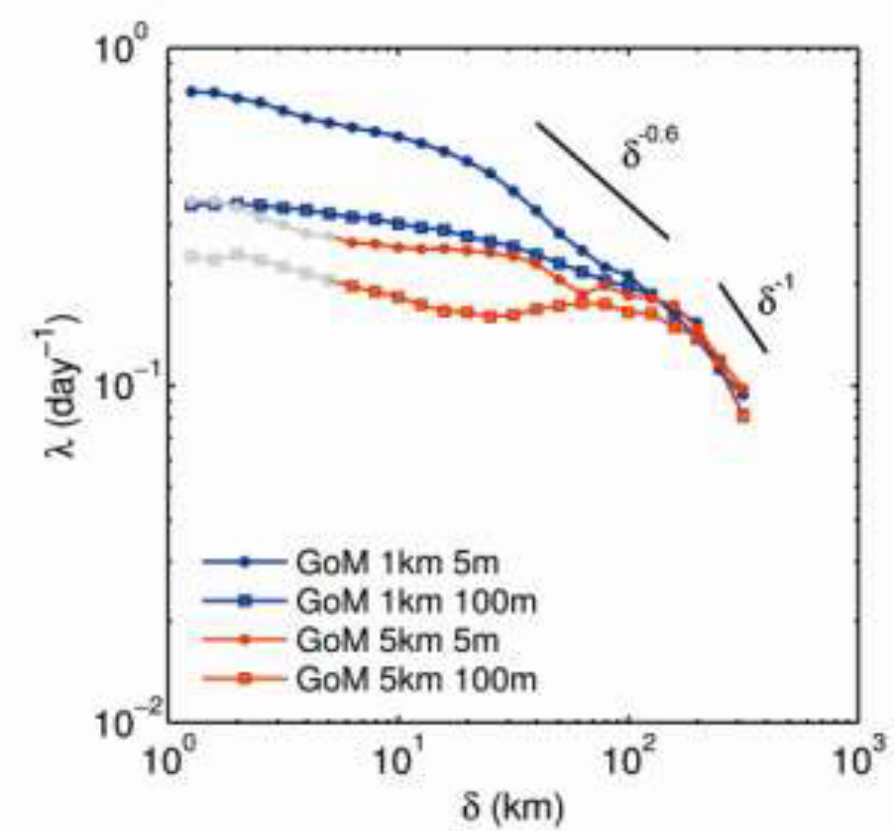
HORIZONTAL TRANSPORT:
Relative dispersion



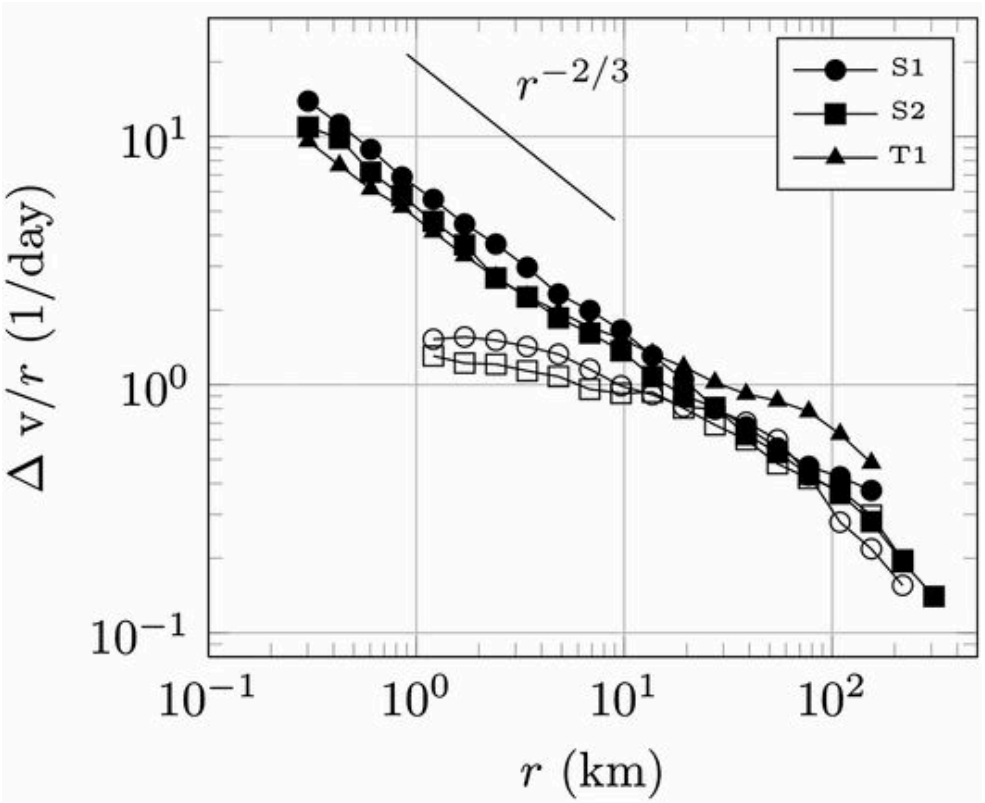


Relative dispersion for 2d and 3d particles deployed at 5m depth

FSLE: scale-dependent pair separation rate as function of separation distance

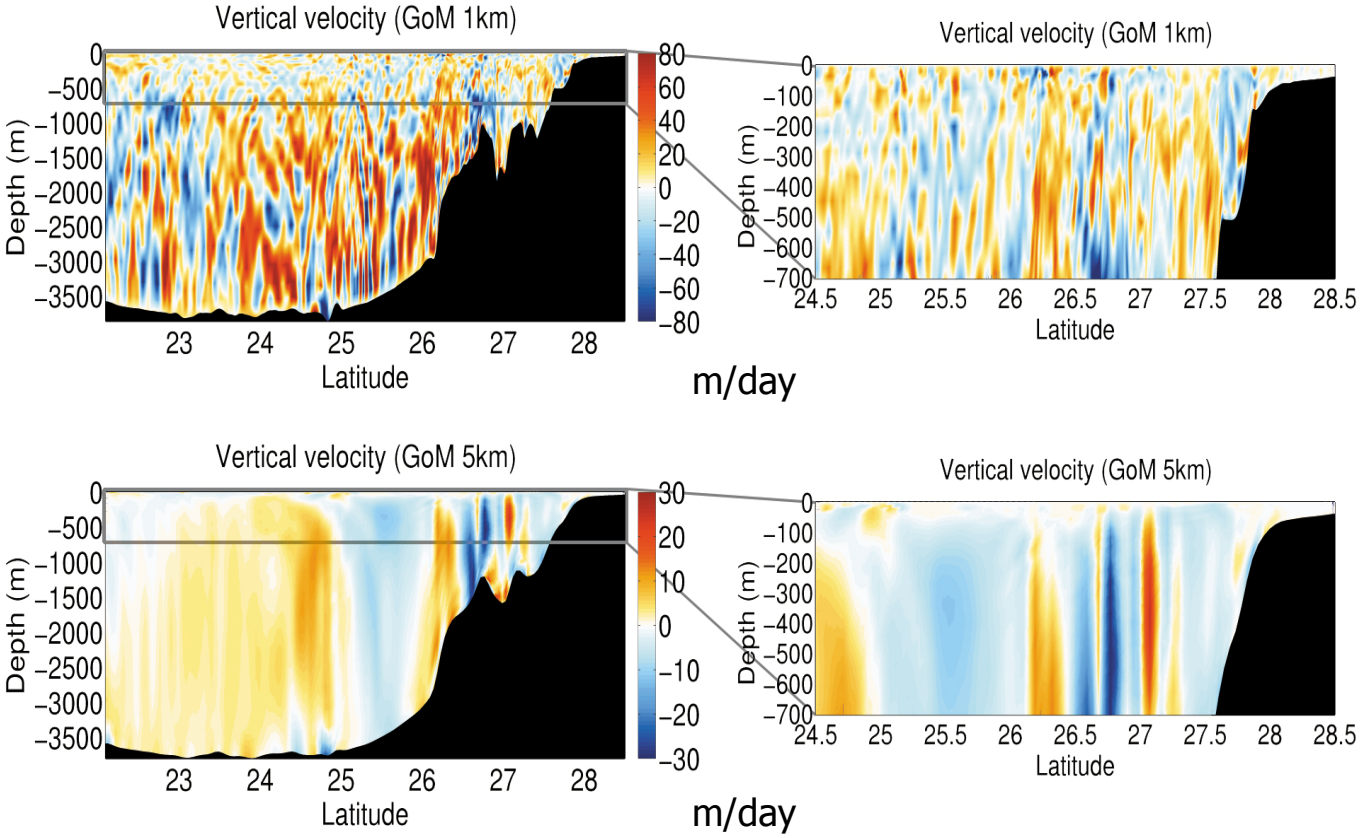


ROMS

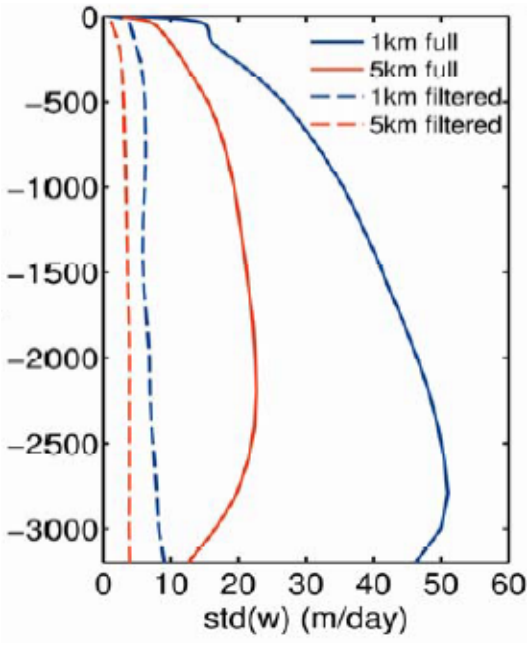


GLAD observations, Northern Gulf, summer 2012 and NCOM 3km model (Poje et al., PNAS 2014)

VERTICAL TRANSPORT: Vertical velocities

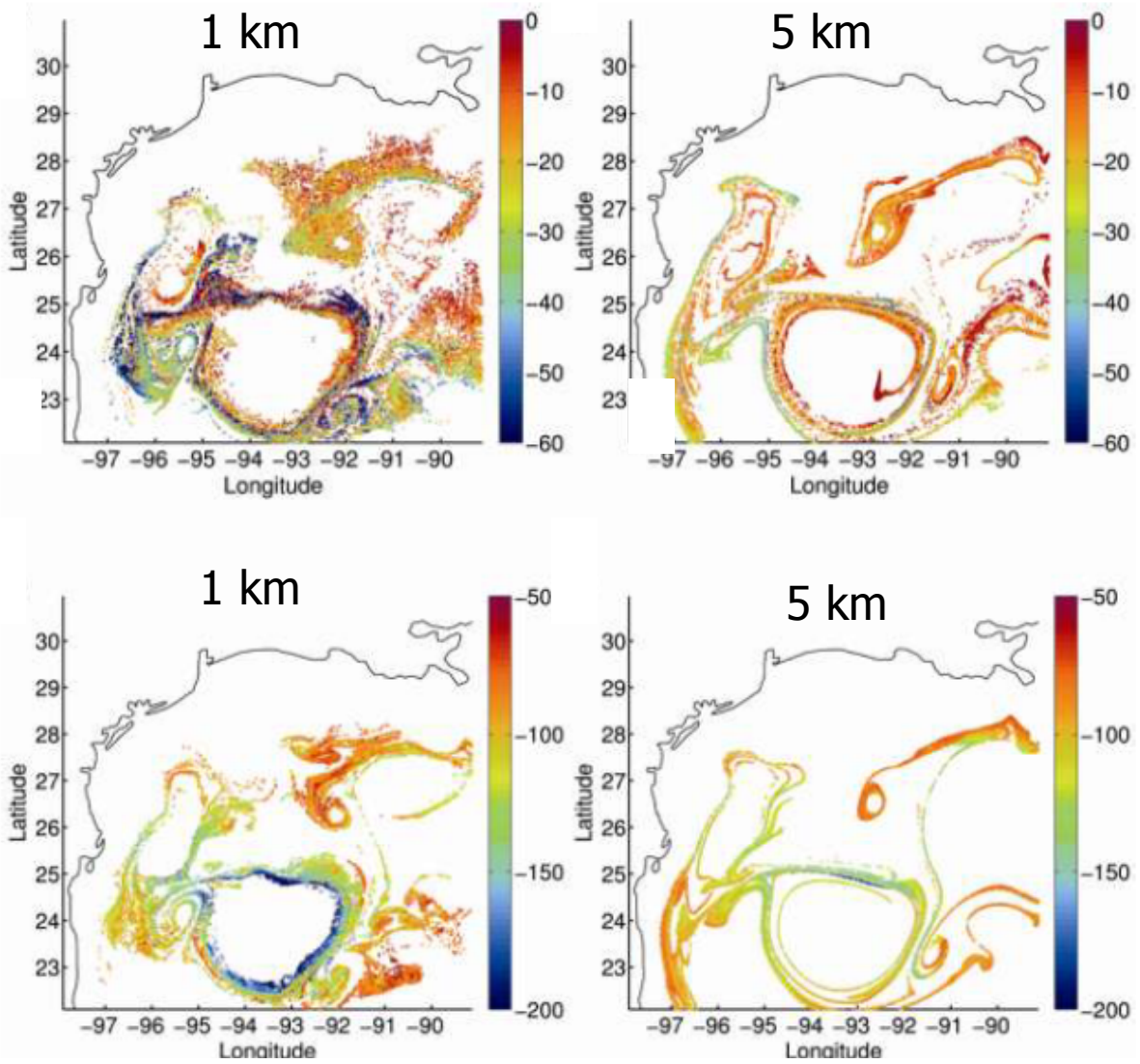


Vertical transects of vertical velocity



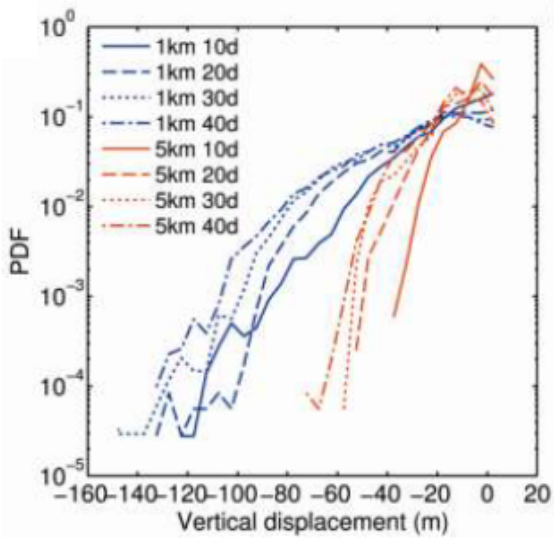
w standard deviation also shown after filtering frequencies larger than f

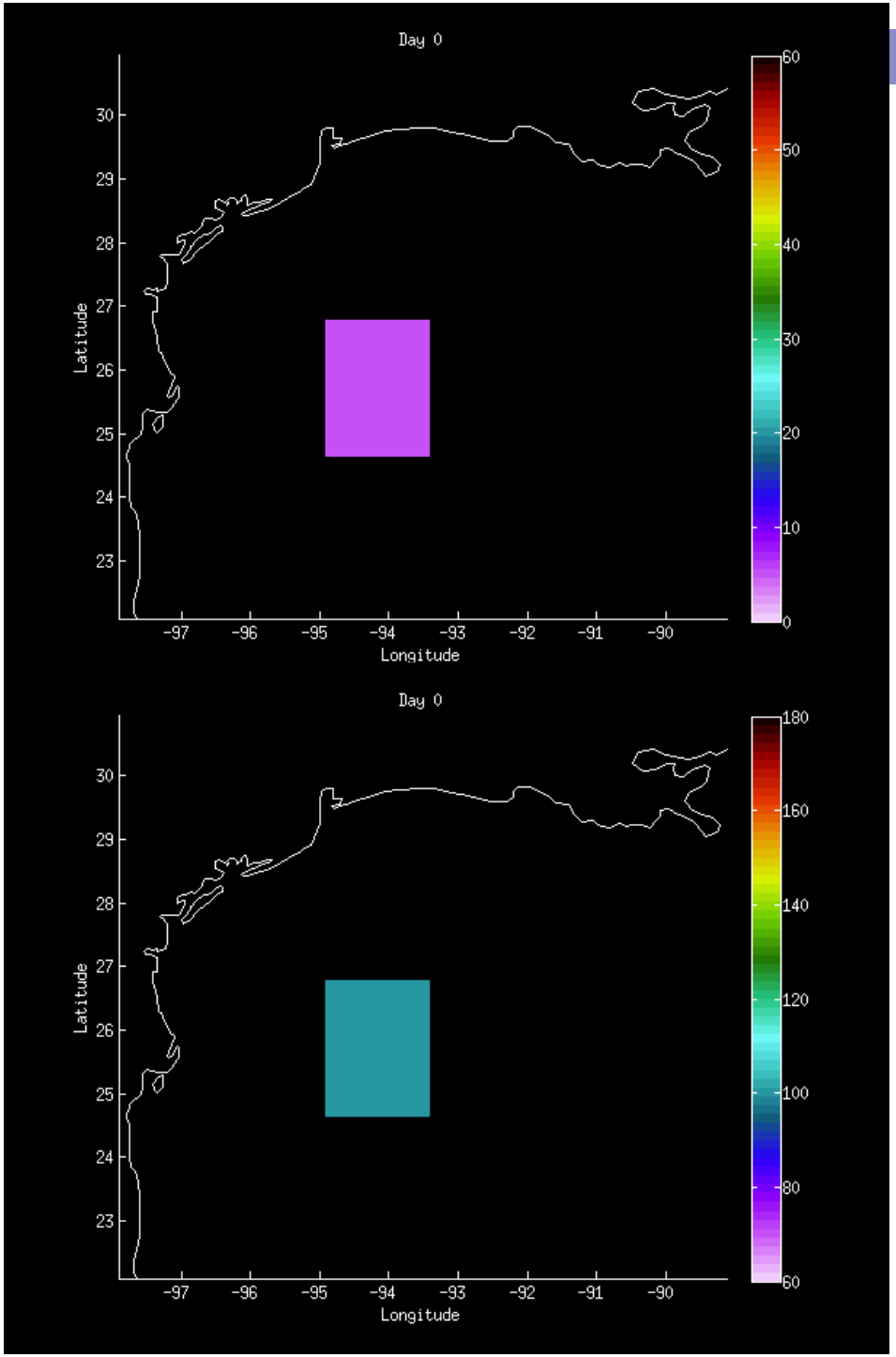
VERTICAL TRANSPORT: Displacement

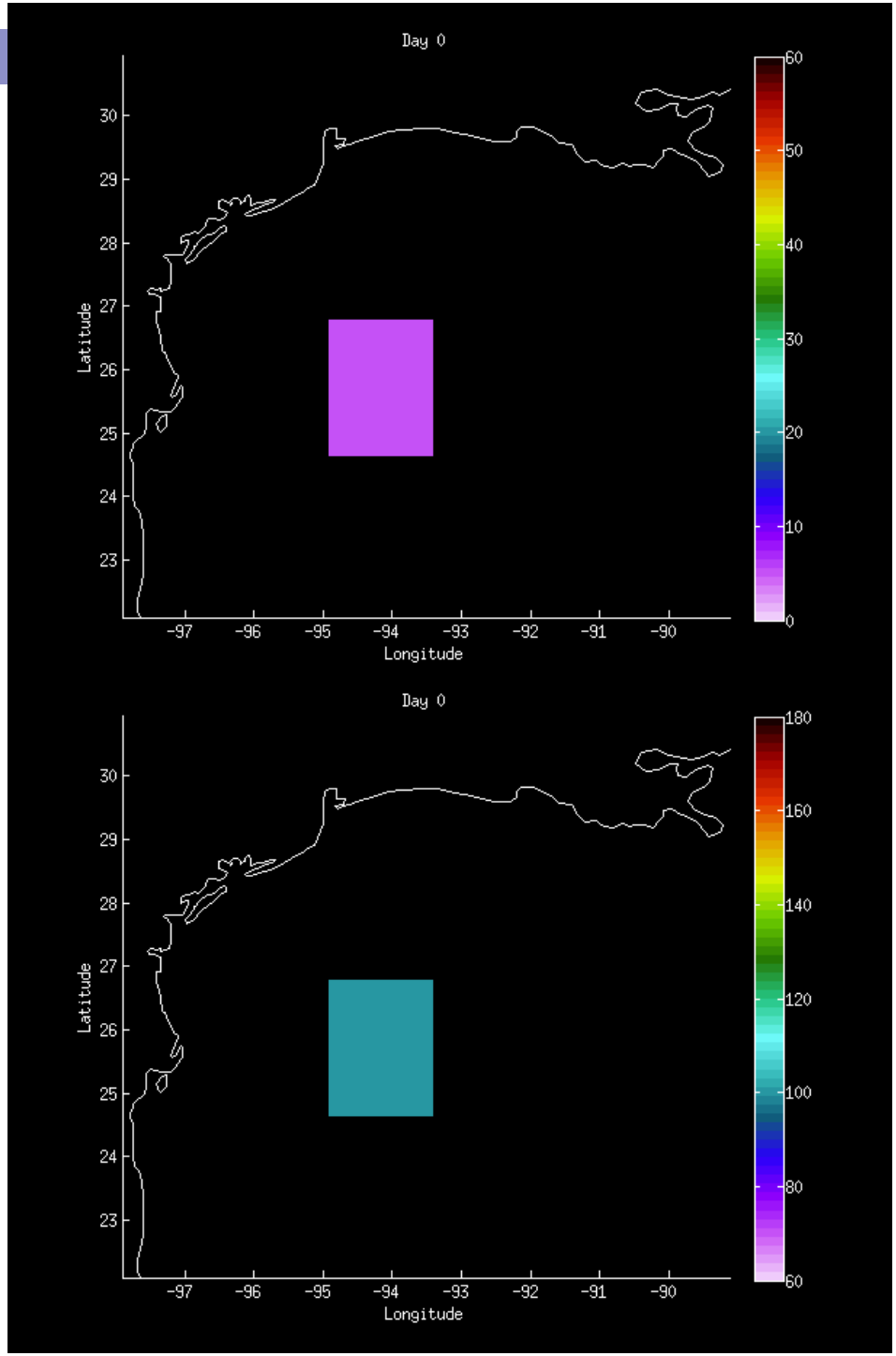


Vertical distribution of 3D particles deployed a 5m (top) and 100m (bottom) 40 days after deployment. Color indicates depth

Bottom figure: PDF of displacements for particles deployed at 5m




Day 0
Latitude
Longitude
30
29
28
27
26
25
24
23
-97
-96
-95
-94
-93
-92
-91
-90
60
50
40
30
20
10
0


Day 0
Latitude
Longitude
30
29
28
27
26
25
24
23
-97
-96
-95
-94
-93
-92
-91
-90
60
50
40
30
20
10
0

Day 0
Latitude
Longitude
30
29
28
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24
23
-97
-96
-95
-94
-93
-92
-91
-90
180
160
140
120
100
80
60

Day 0
Latitude
Longitude
30
29
28
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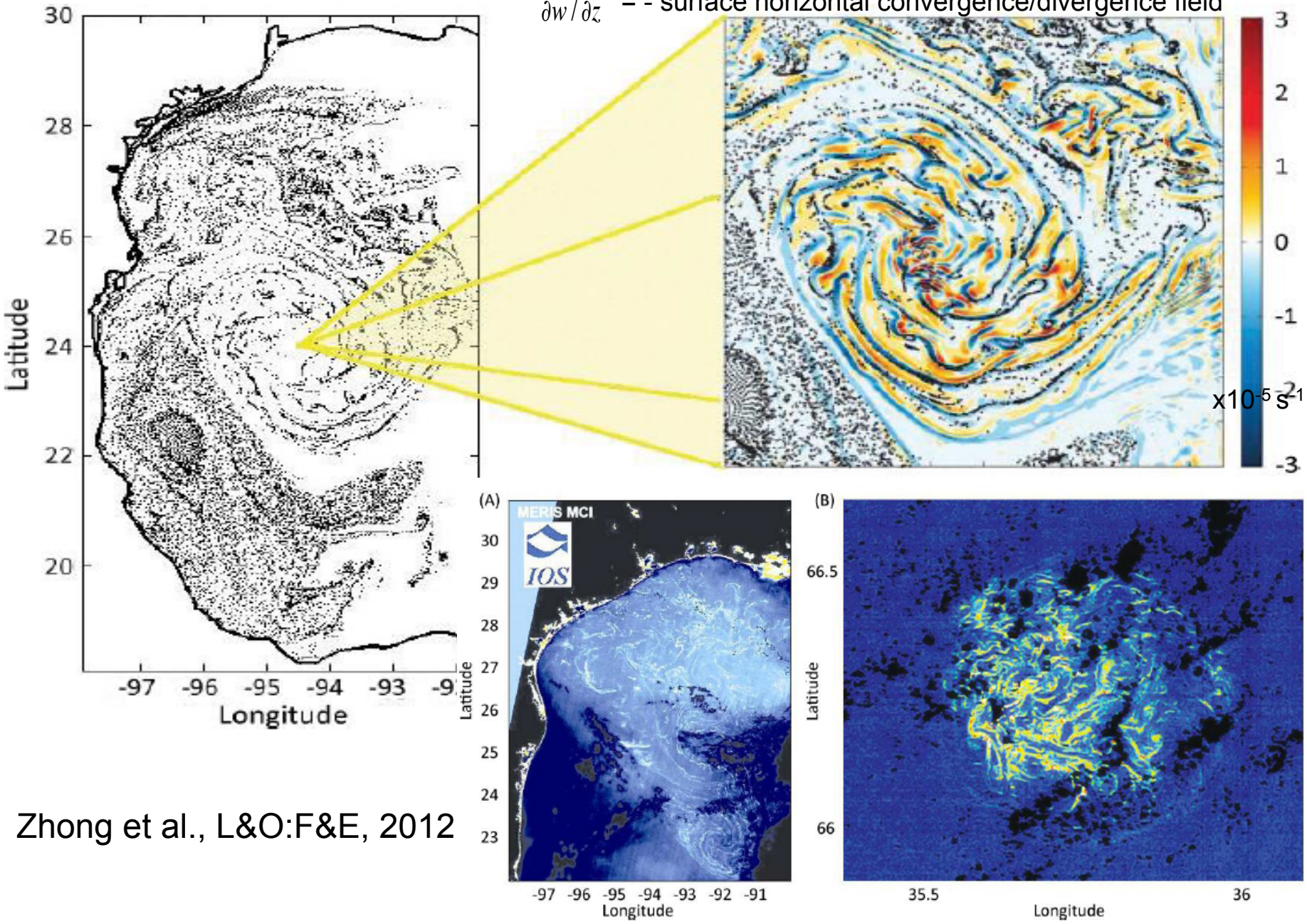
25
24
23
-97
-96
-95
-94
-93
-92
-91
-90
180
160
140
120
100
80
60

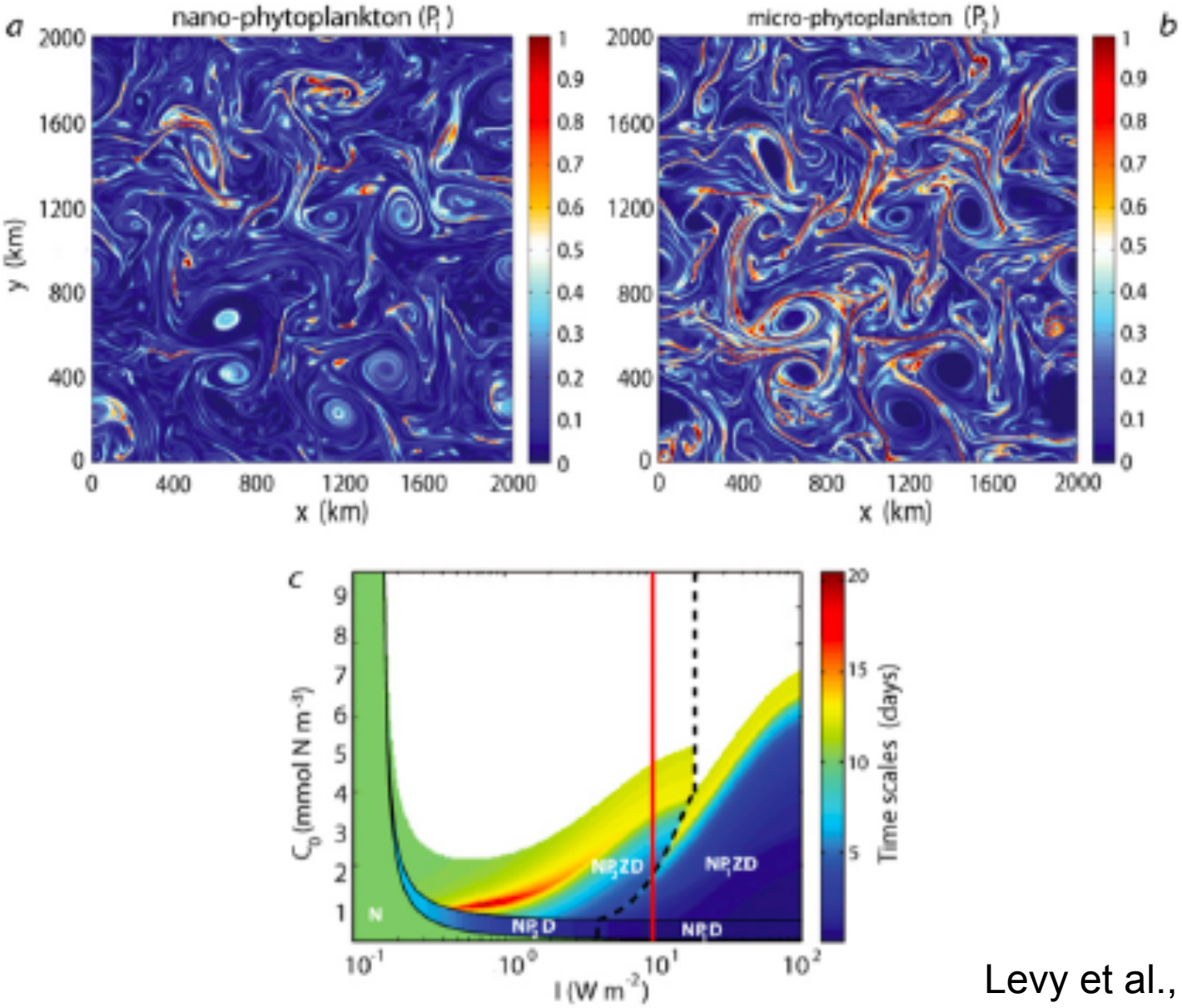
impact on surface patterns

$\partial w / \partial z$ = - surface horizontal convergence/divergence field



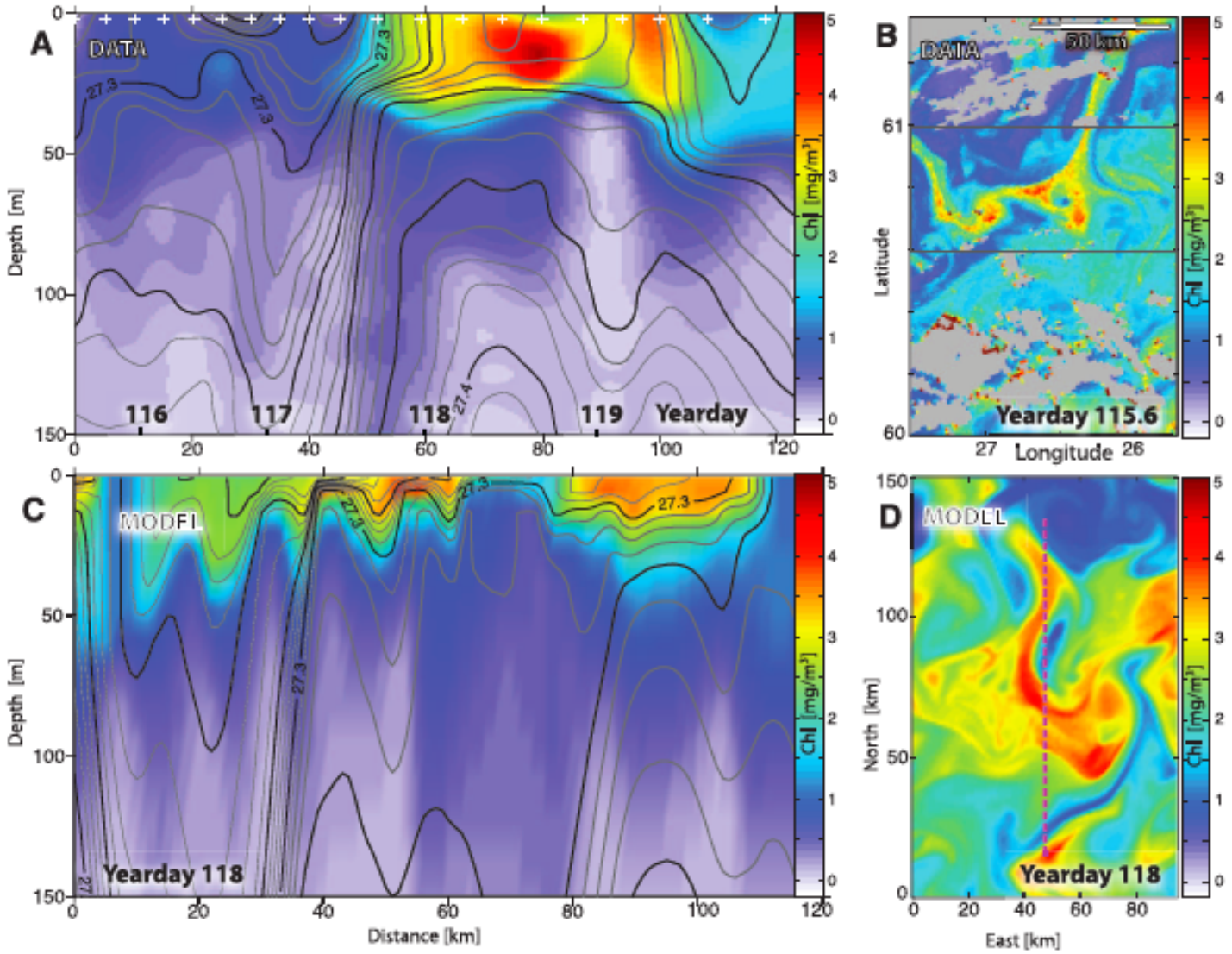
Zhong et al., L&O:F&E, 2012

impacts on plankton size-classes distributions



Levy et al., GRL 2012

Impact on bloom initiation



Spring bloom initiation is not due to surface warming but to eddy-driven slumping of N-S density gradients, and it happens 20-30 days earlier than by warming

Mahadevan et al., Science, 2012

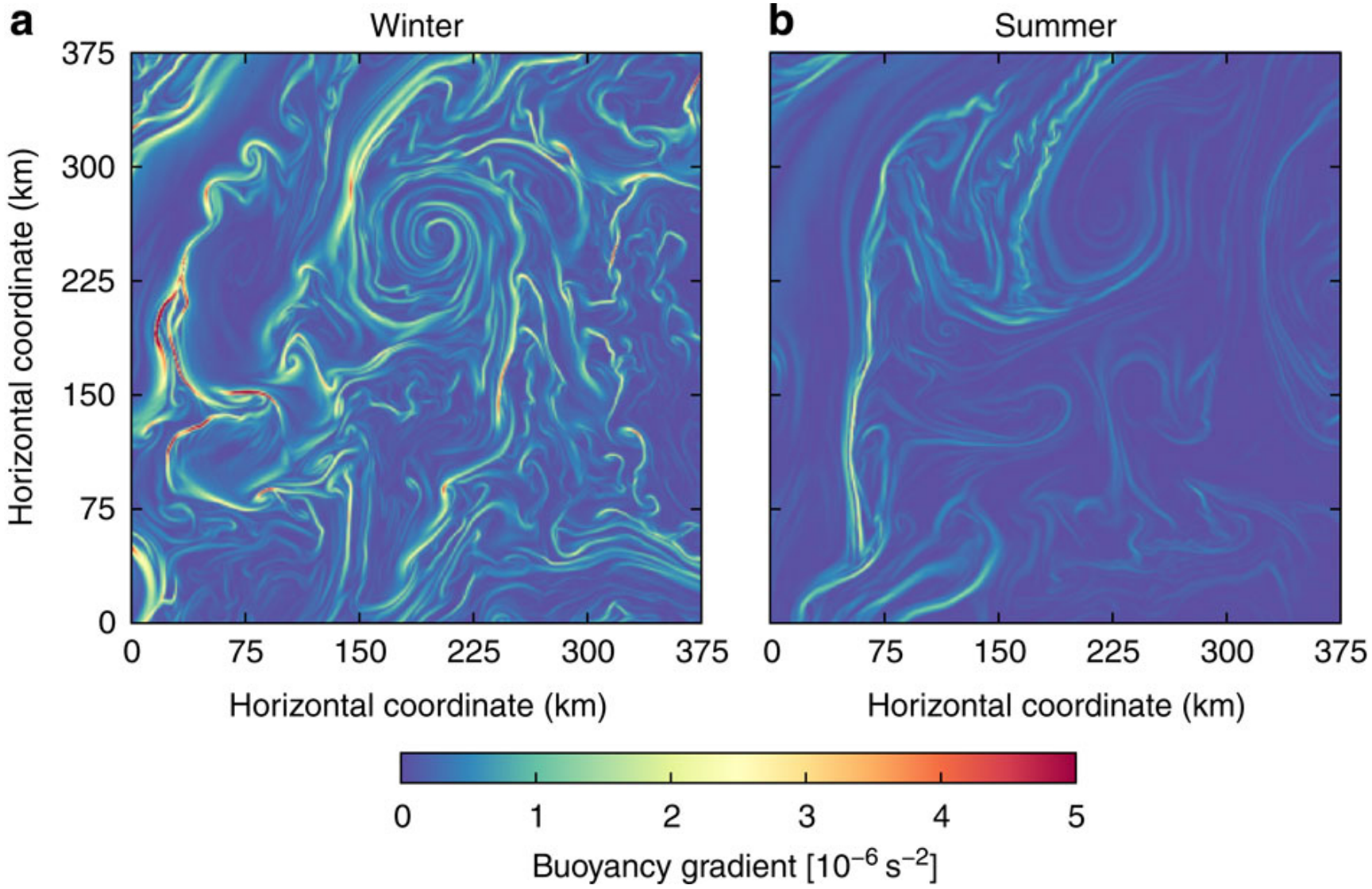
Seasonality of submesoscale processes

- APE availability depends on mixed layer depth and lateral density gradients. In general, is higher in winter, when the MLD is deeper (Mensa et al., 2013; Callies et al., 2015)

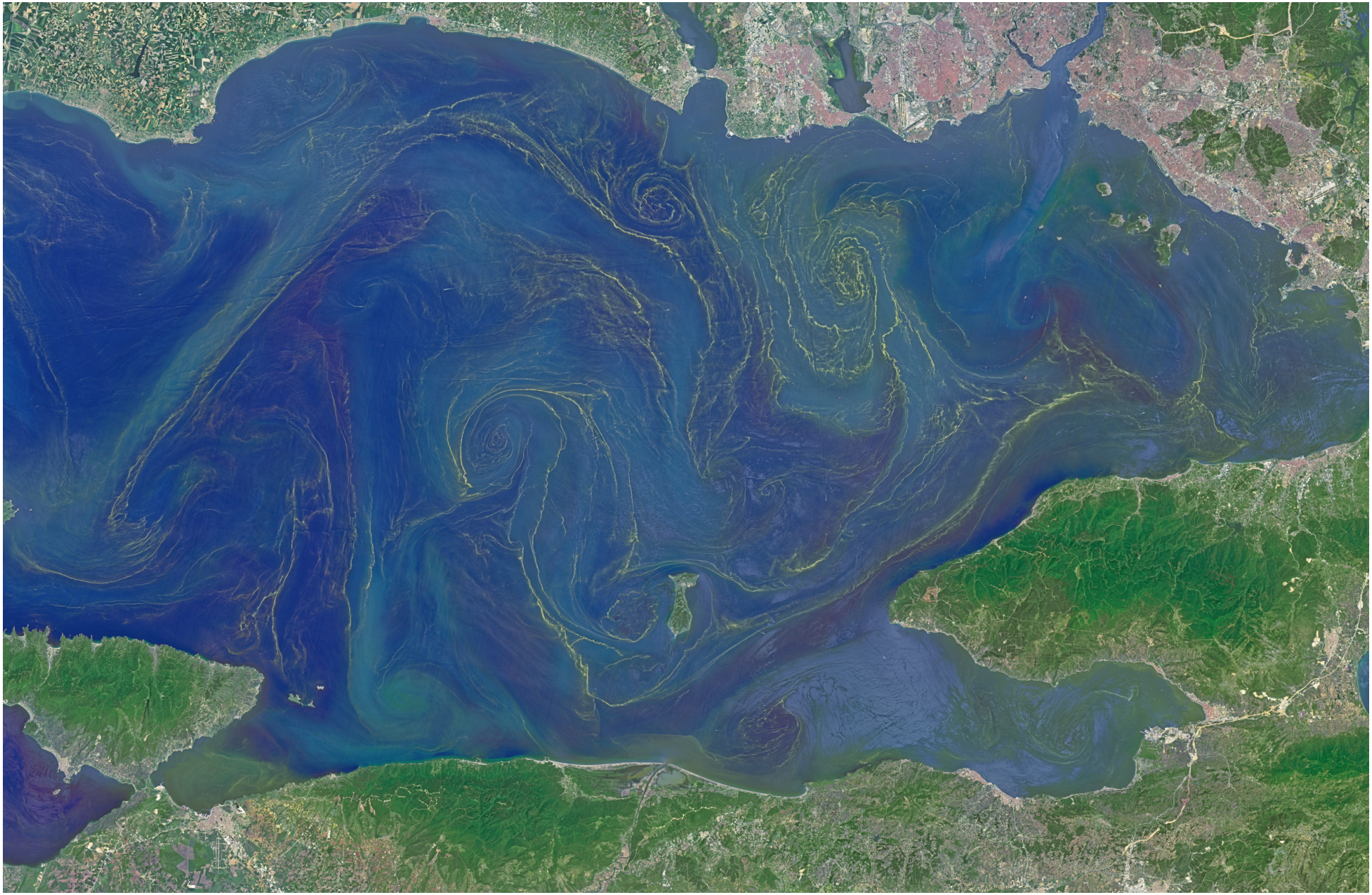
- “However, frontogenetical processes increase horizontal buoyancy gradients when the mixed layer is shallow (i.e. in summer)

- and overturning instabilities weaken the horizontal buoyancy gradients as the mixed layer deepens (i.e. in winter)” Brannigam et al., 2015

Seasonality of submesoscale processes

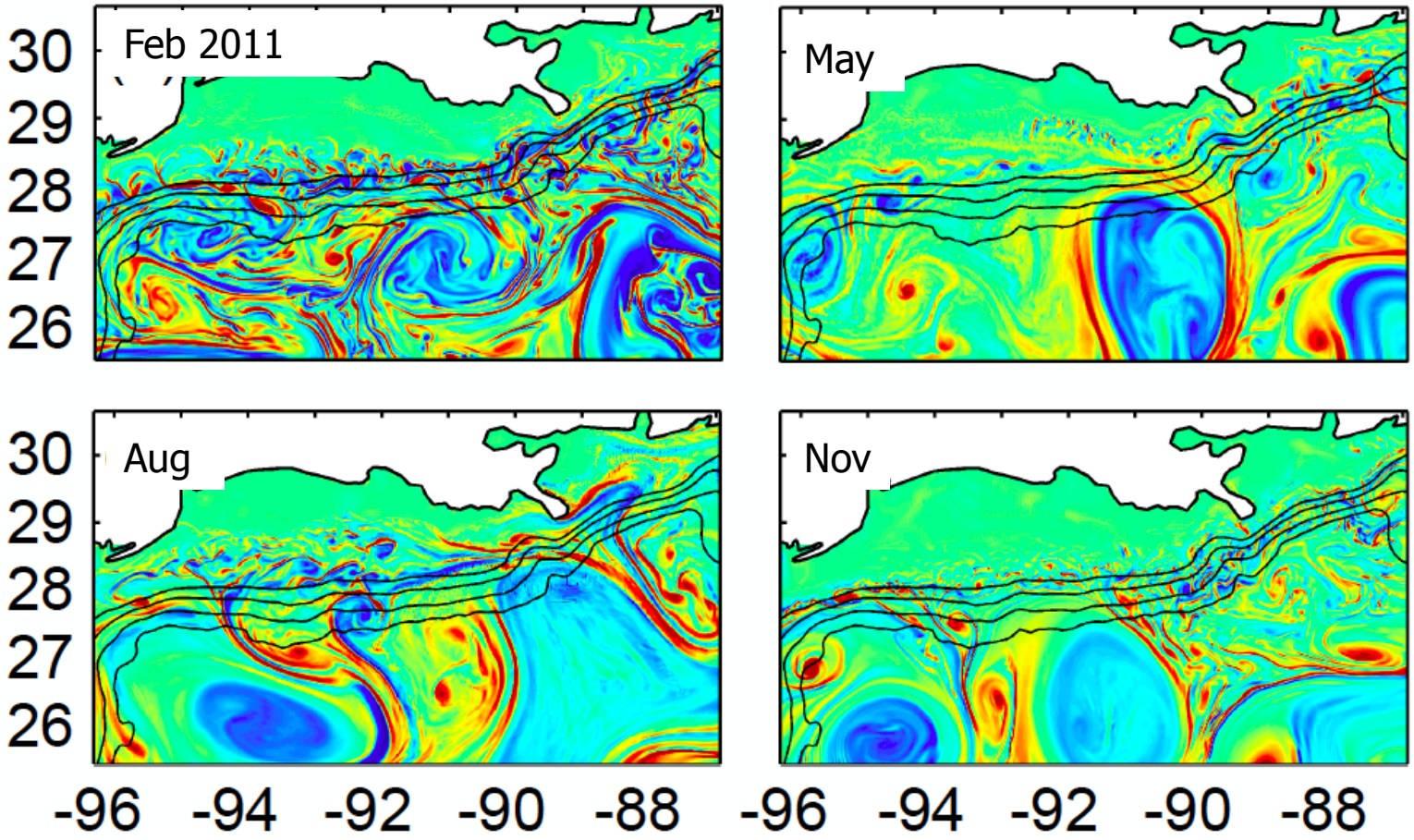


Is this true everywhere?

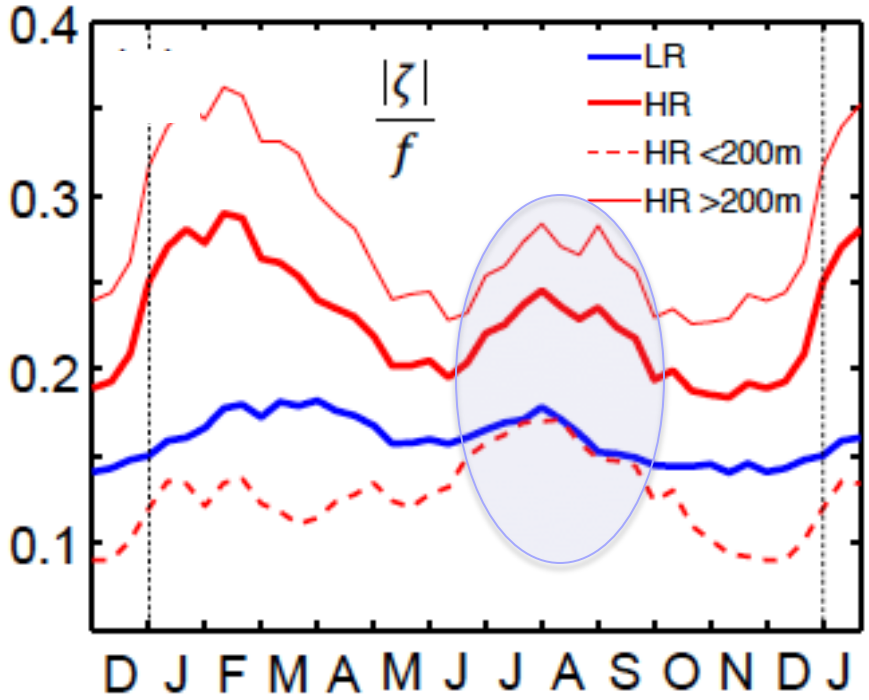


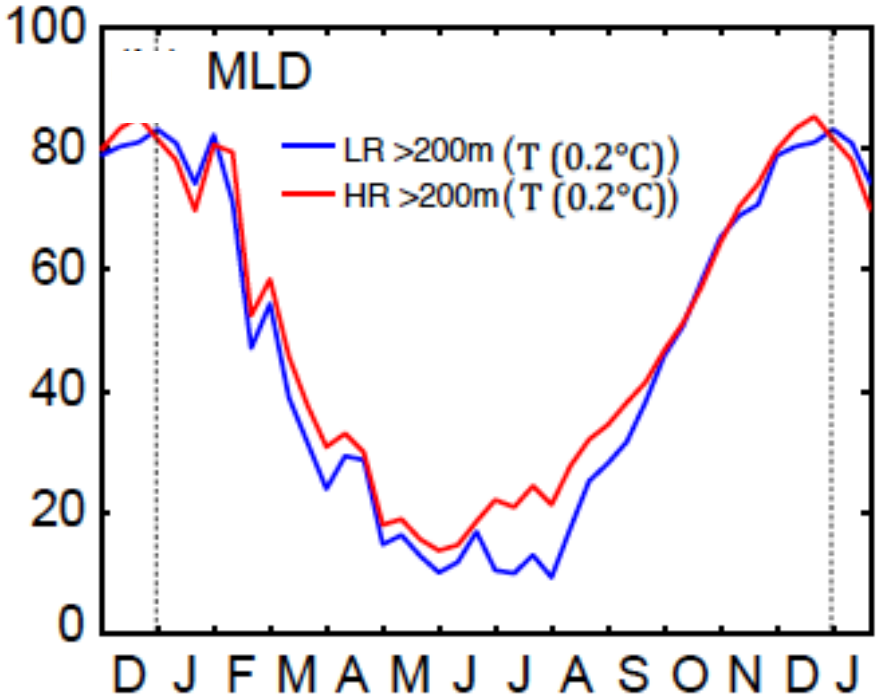
Sea of Marmara Operational Land Imager on the Landsat 8 satellite image of a phytoplankton bloom on May 17, 2015

SEASONALITY OF THE VORTICITY FIELD

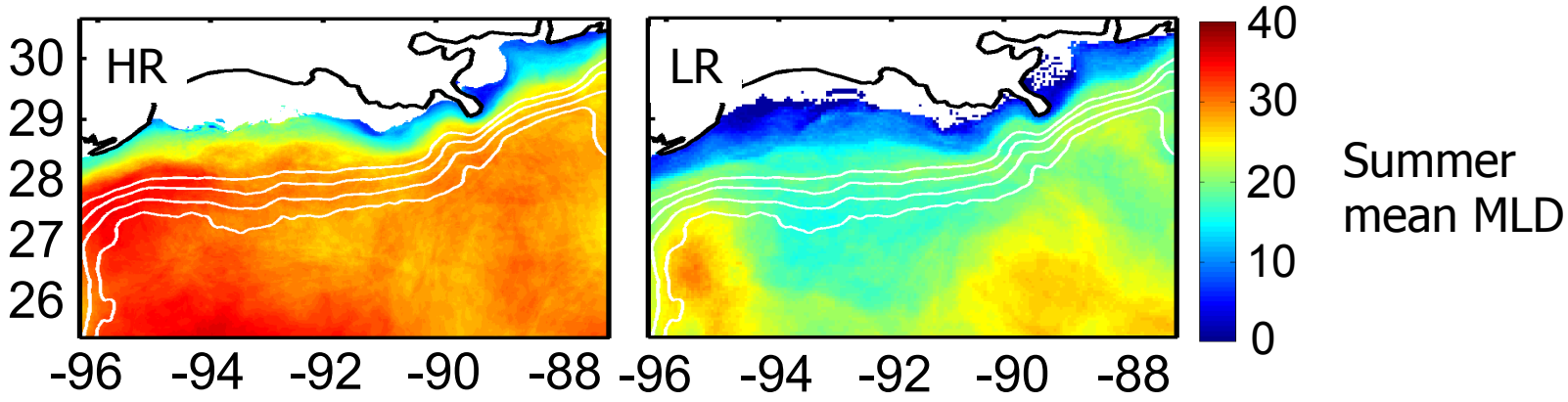


- Stronger around the Loop Current and the Rings.
- Enhanced over the slope, weaker on the shelf (especially in winter and fall).
- Wintertime maxima associated with deeper mixed layer





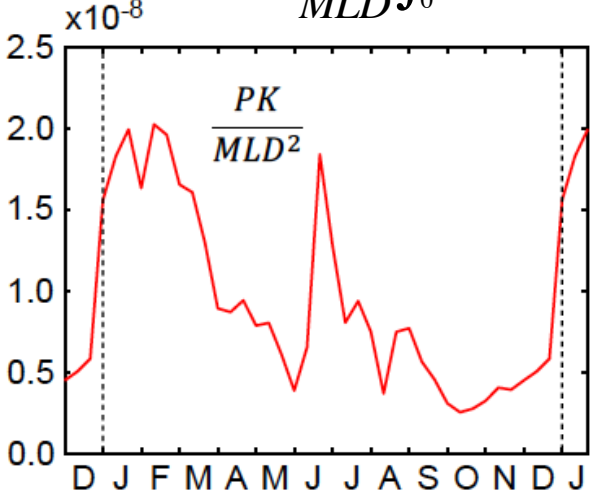
Annual cycle of vorticity and mixed layer depth



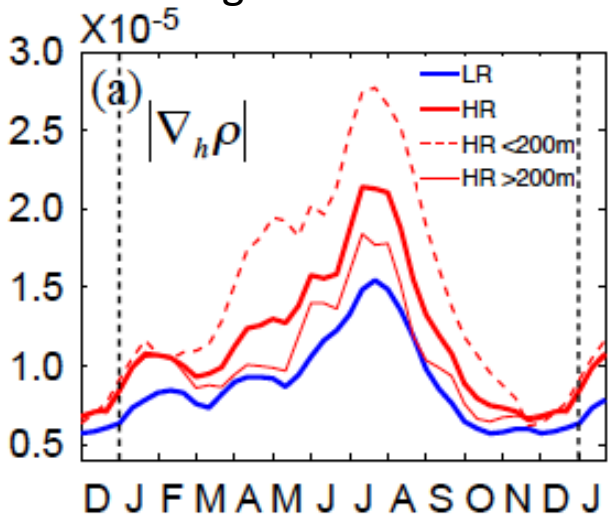
Summer mean MLD

Other submesoscale variables

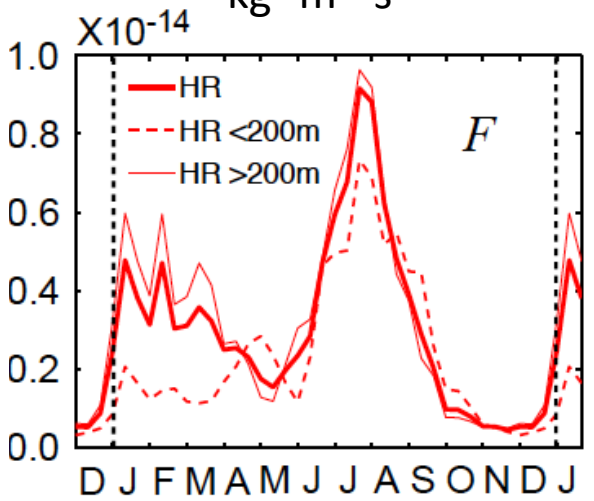
m s^{-3} $PK = \frac{1}{MLD}\int_0^{-MLD} \langle w'b' \rangle dz$



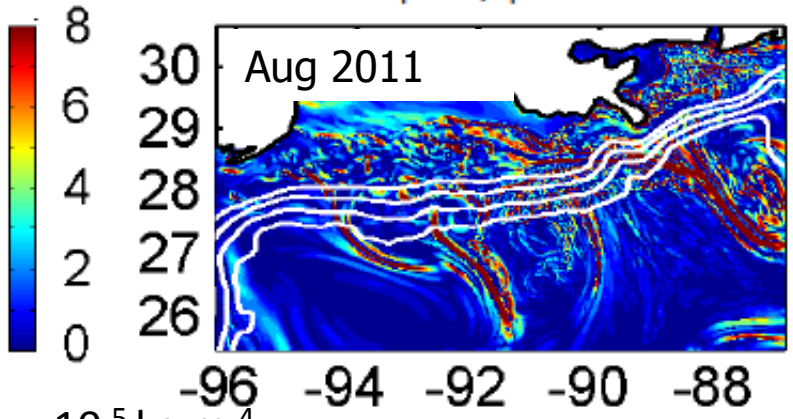
kg m^{-4}



kg^2 m^{-8} s^{-1}

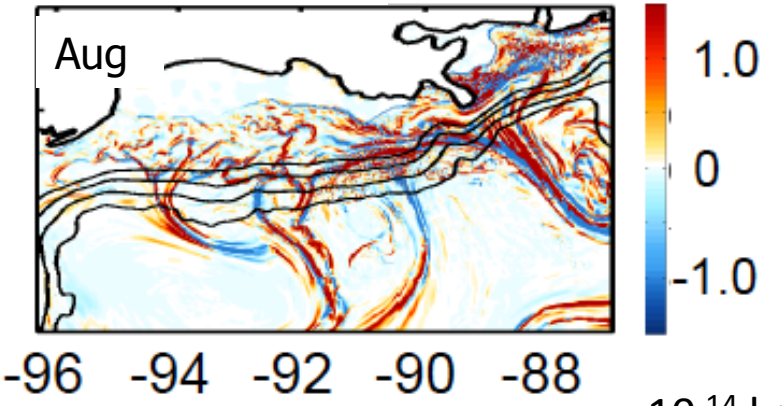


$|\Delta_h \rho|$



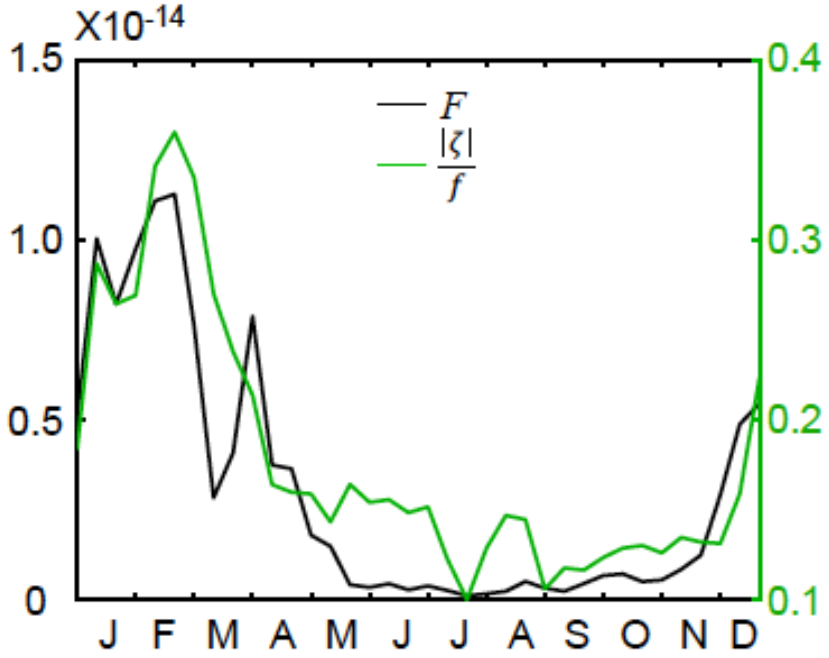
10^{-5} kg m^{-4}

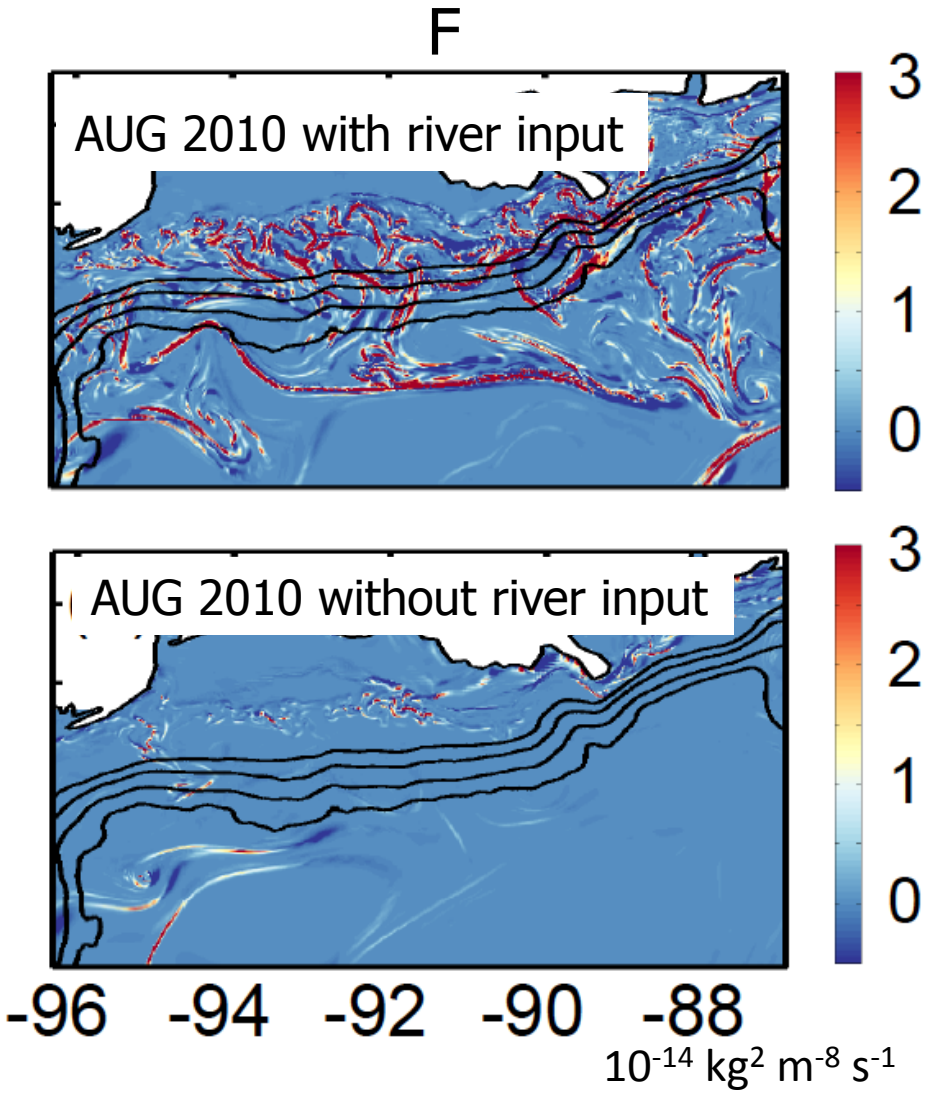
$F = \frac{D|\nabla_h \rho|^2}{Dt} = \mathrm{Q} \cdot \nabla_h \rho \quad \mathrm{Q} = (Q_1, Q_2) = -\left(\frac{\partial u}{\partial x}\frac{\partial \rho}{\partial x} + \frac{\partial v}{\partial x}\frac{\partial \rho}{\partial y}, \frac{\partial u}{\partial y}\frac{\partial \rho}{\partial x} + \frac{\partial v}{\partial y}\frac{\partial \rho}{\partial y} \right)$



10^{-14} kg^2 m^{-8} s^{-1}

In the absence of river input





Summary and relevance

- Submesoscale expressions (patterns) vary with season and basins. The energy required by submesoscale instabilities to grow is directly proportional to the mixed layer depth but can be supplied through externally driven density anomalies.
- River outflows drive frontogenesis in summer. Given the depth of the mixed layer, summer instabilities are mostly in the shape of elongated fronts
- Any other oceanic regions where river inputs and/or precipitation or ice-freezing and melting are submesoscale hot-spots ⇒ Coastal/estuarine areas and of climatic interest the Amazon, Congo, Mekong plume regions, ocean areas affected by monsoonal rain, Antarctica shelves, Greenland shelves, Arctic

Is this all?

Operational Land Imager on Landsat 8 of large bloom of cyanobacteria in the Baltic Sea

11 August 2015