Dynamics of wind-forced coherent anticyclones in the open ocean

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Idealized set-up to investigate the dynamics of wind-driven coherent anticyclones in the open ocean

- Double-periodic domain
- Constant depth H=1000m; lateral size L=256Km or L=128Km
- Resolution Δx=1 or 0.5 km, 18 and 80 vertical layers (6 and 27 in the first 100 meters)
- Coriolis frequency $f = 10^{-4}s^{-1}$
- Narrow band wind forcing kx = ky = 6 with an added random noise component:

  $\tau^x (x, y) = 0.1 * \sin(2\pi k_x x) \sin(2\pi k_y y) + 0.3 \ (ran[0\text{-}1] - 0.5)$ or following the power spectra in Muller & Frankigoul (1981) changing between random distributions with identical power spectrum every 5 or 20 or 40-days and linearly interpolated in between

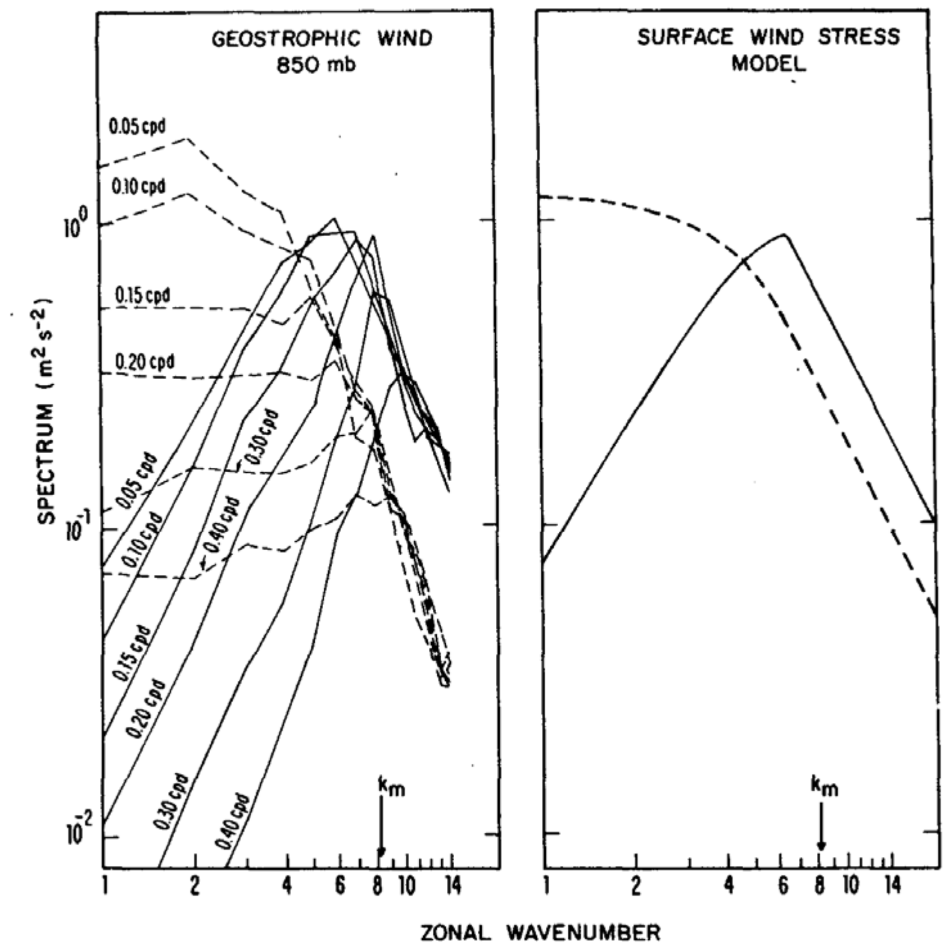


FIG. 3. Left: Zonal wavenumber spectra of zonal (dashed line) and meridional (solid line) geostrophic wind at 35°N and 850 mb for various frequencies. The spectra were computed by Pratt (1975) from four 132-day winters, after high-pass filtering to remove seasonal effects. A pointed arrow indicates the low wavenumber limit of the oceanic motion considered in this paper. Right: Model zonal wavenumber spectra of the wind stress components at low frequencies, based on the model (3.3). The ordinate has arbitrary log units.

from Muller and Frankignoul, JPO 1981

- temperature profile $T(z) = 10+12\exp(0.017\ z)\ {}^oC$ and salinity $S(z) = 35+2.0\ \exp(0.024\ z)$ PSU (Conkright et al., 2002) below a 20m mixed-layer
- constant solar shortwave radiation: QT = 150 Wm^{-2} (mid-latitudes in April)
- Lagrangian tracers: released after the system had achieved a statistically stationary state in 3 sets of 4096 floats at -1, 78 and 204m on a regular grid
- The system, under the assumption of being equivalent barotropic, is characterized by the following Rossby, Froude number and Rossby deformation radius:

$$R_o = \frac{U}{fL} \sim 0.06$$

$$Fr = \frac{U}{\sqrt{g'h}} \sim 0.1$$

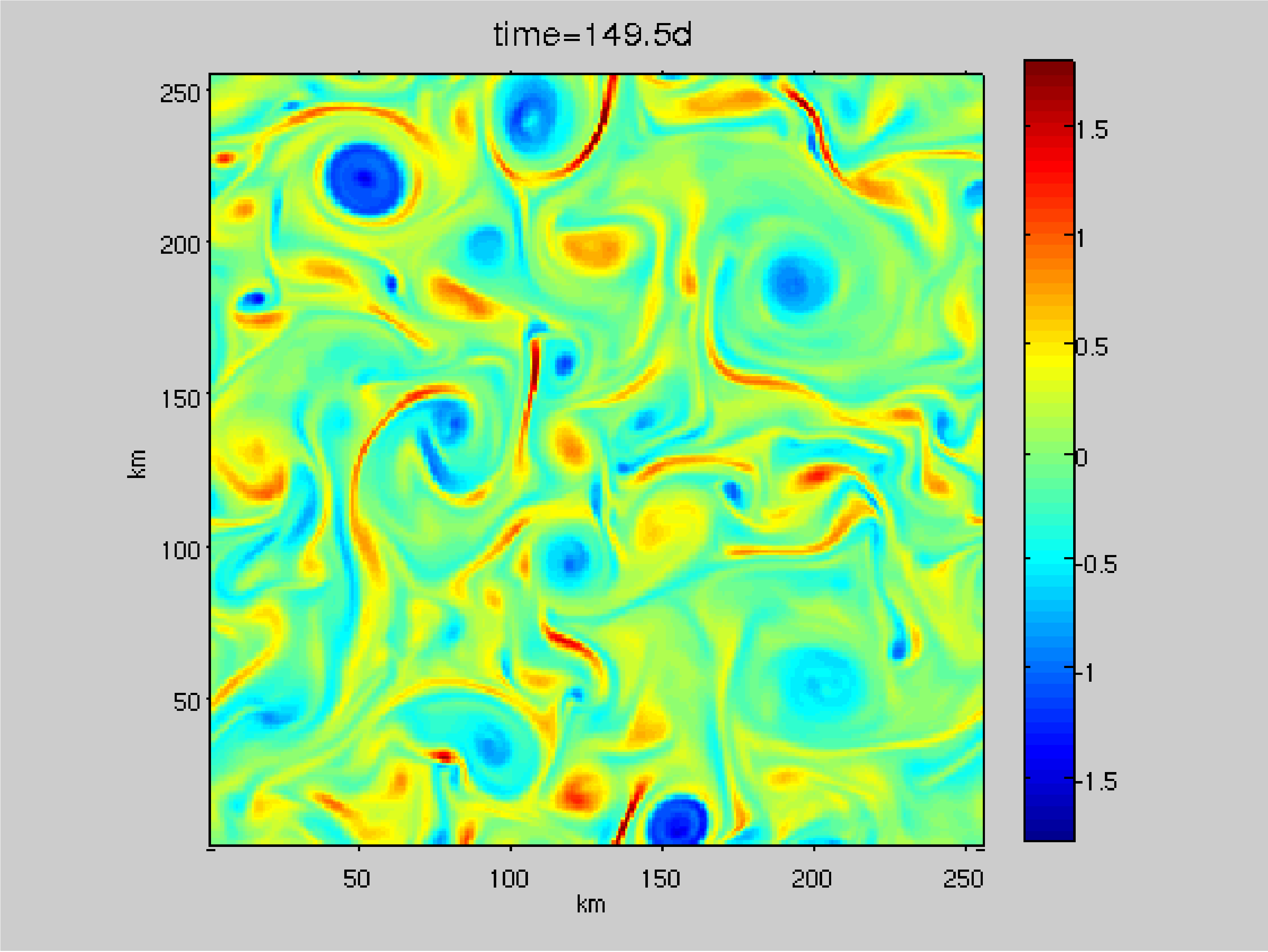
$$L_d = \frac{\sqrt{g'h}}{f} \sim 15km$$

- Around ~ day 25 the vortices form, which is of the order of the characteristic spin-up time for the system defined as (Pedlosky, 1987)

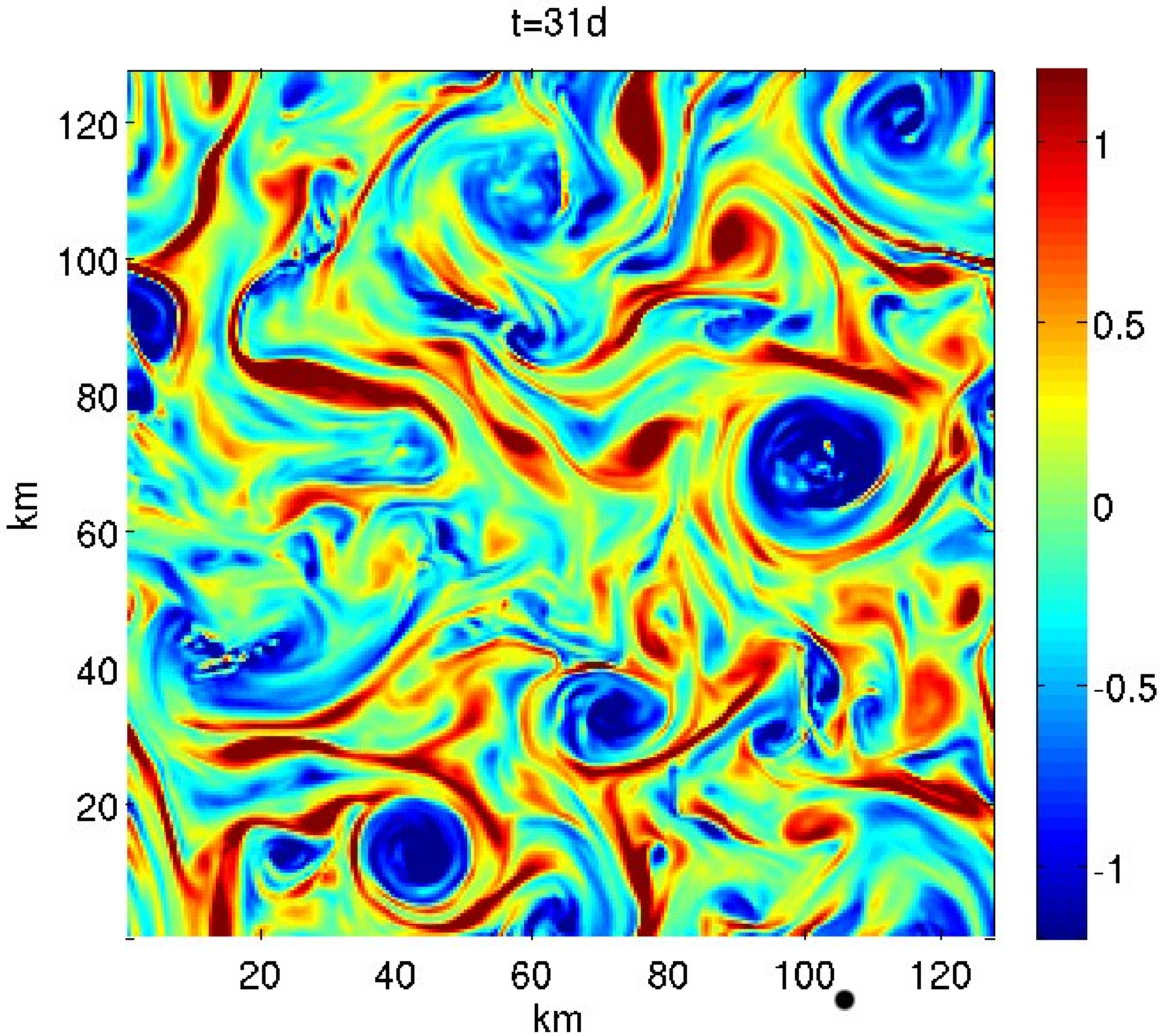
$$\tau = H / \sqrt{Kv * f} \sim 1000 / \sqrt{5 * 10^{-3} * 10^{-4}} \sim 20 days$$

- From this time on, the system is characterized by the presence of coherent structures of different scales (of the size of initial circulation cells or smaller). Predominantly anticyclones, shielded by rings of positive undergoing continuous formation, decay and merging

- The nudging to the temperature and salinity profiles prevents the system from barotropization


time=149.5d
250
200
150
100
50
km
50
100
150
200
250
km
1.5
1
0.5
0
-0.5
-1
-1.5

with 0.5 km resolution



Cyclones/anticyclones asymmetry

Cushman-Rosin & Tang 1990: stability argument: on a f - plane with free surface, axis-symmetric vortices are solutions that optimize the kinetic energy, but while the anticyclonic vortices are stable, cyclones are not

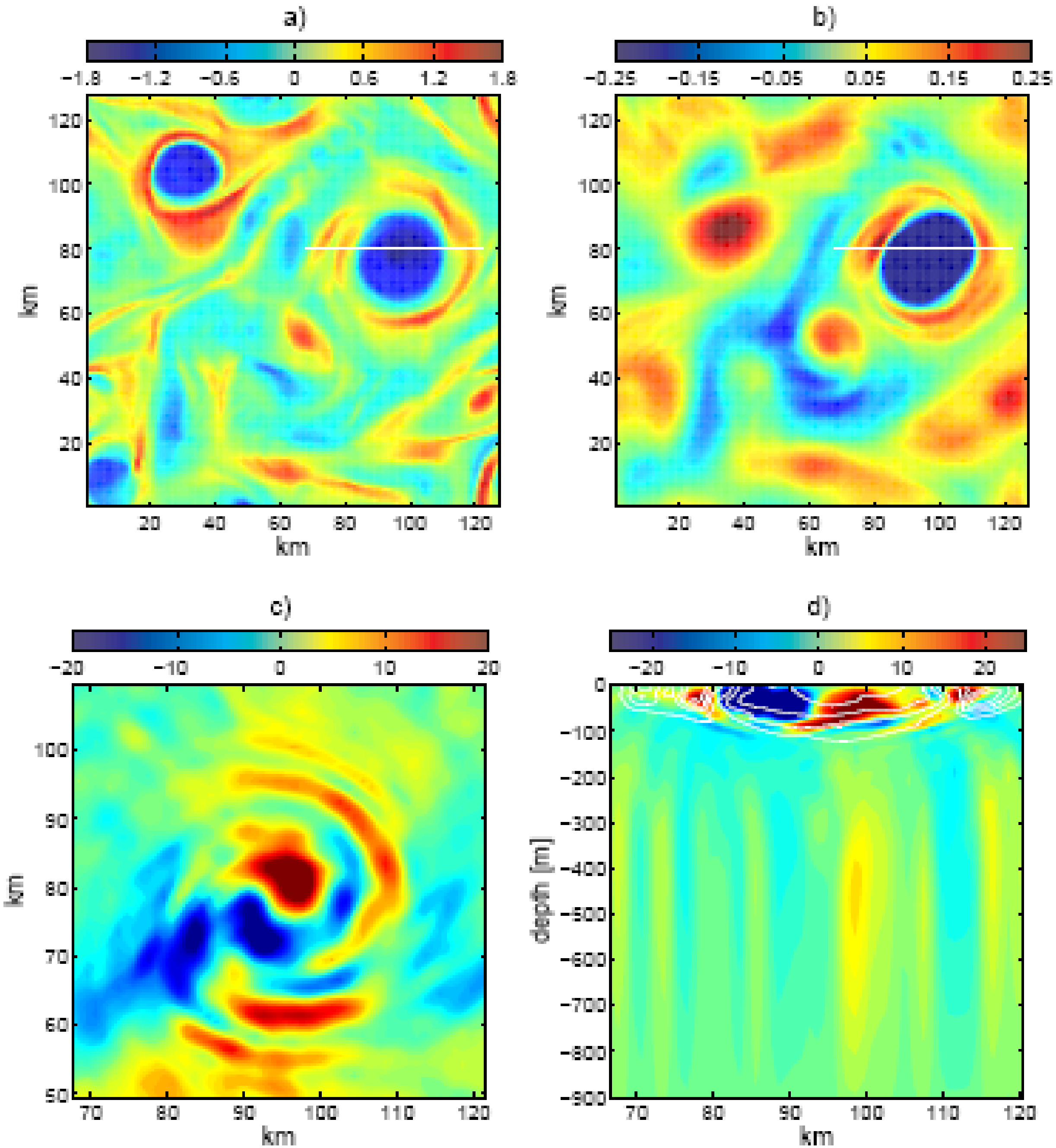
Polvani et al., 1994: phenomenological observations: asymmetry increases with Fr and cyclones correspond to contractions of the fluid layer (negative free surface, $\eta < 0$). Anticyclones are internally more coherent and grow more easily

Thomas and Rhines, 2002: positive feedbacks between Ekman transport and negative vorticity in presence of rotational surface

Graves et al., 2006: Explanation of physical mechanism: in SW strained induced on the periphery of the vortices by Vortex Rossby Waves contributes to weaken cyclones and strengthen anticyclones, particularly if Rossby deformation radius ~ size of vortices.

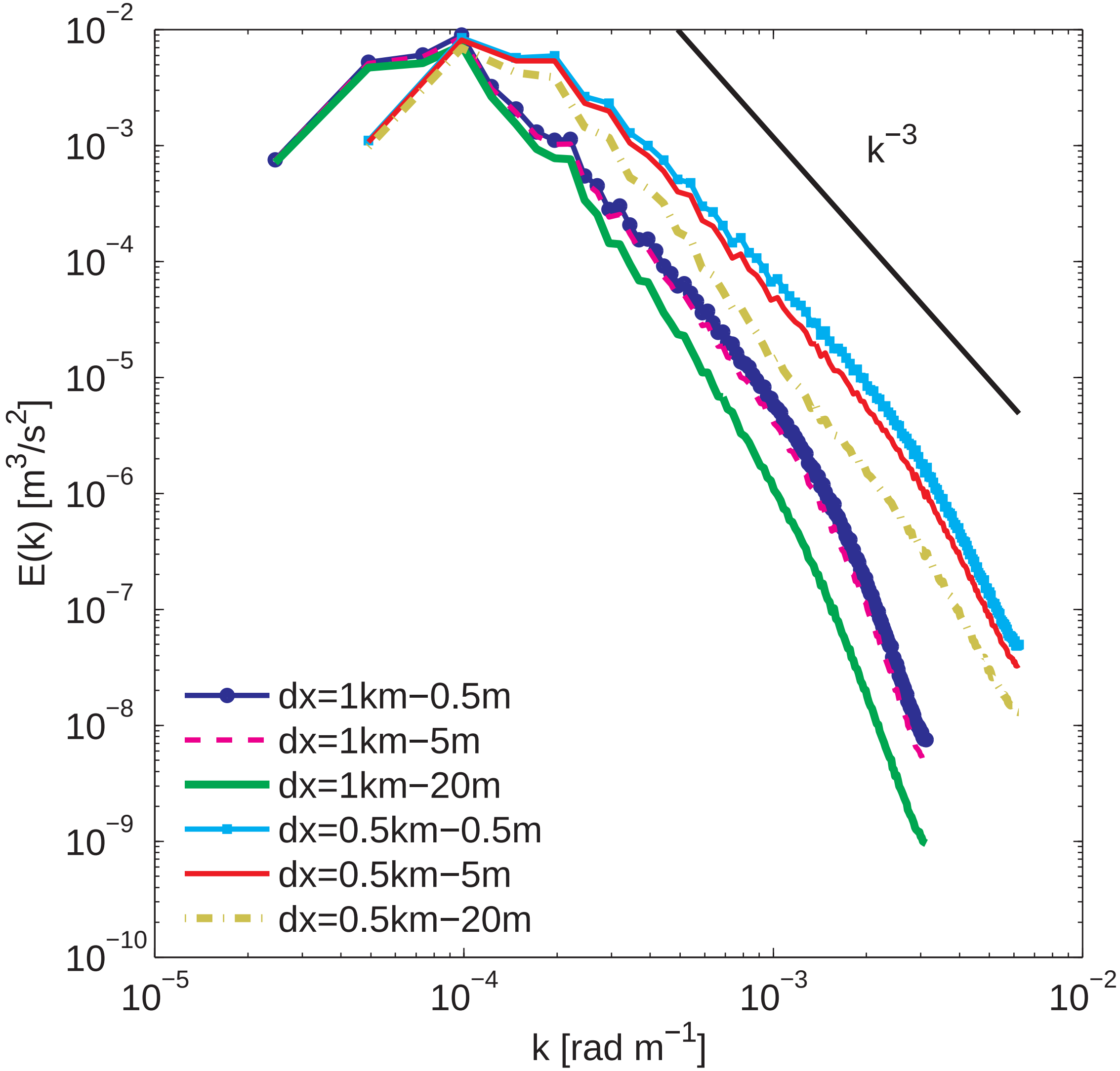
Top: Vertical component of normalized relative vorticity ζ/f at the surface (left) and at 78m depth (right). It provides an estimate of the local value of the Rossby number.

Bottom: Vertical velocity in m/day at 78m depth (left); vertical section of vertical velocity (in m/day) across the line indicate above

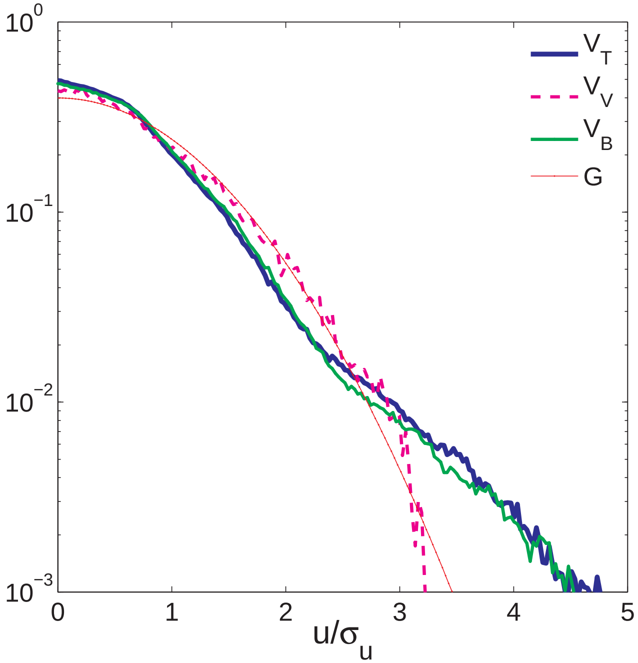


Horizontal motion

2D power spectra of kinetic energy as function of depth

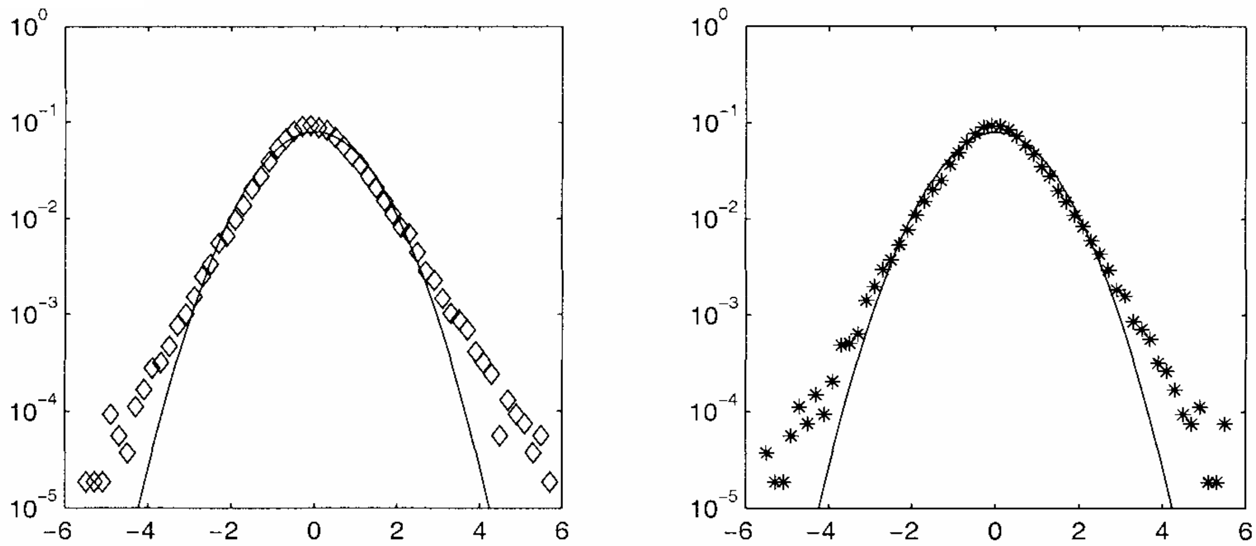


in the model



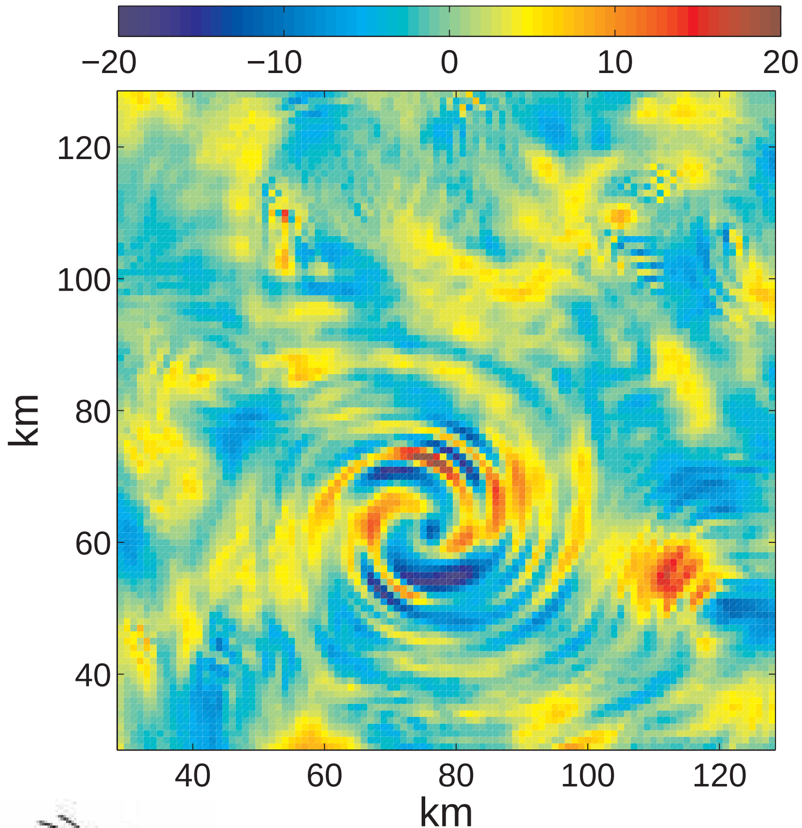
Horizontal velocity distributions

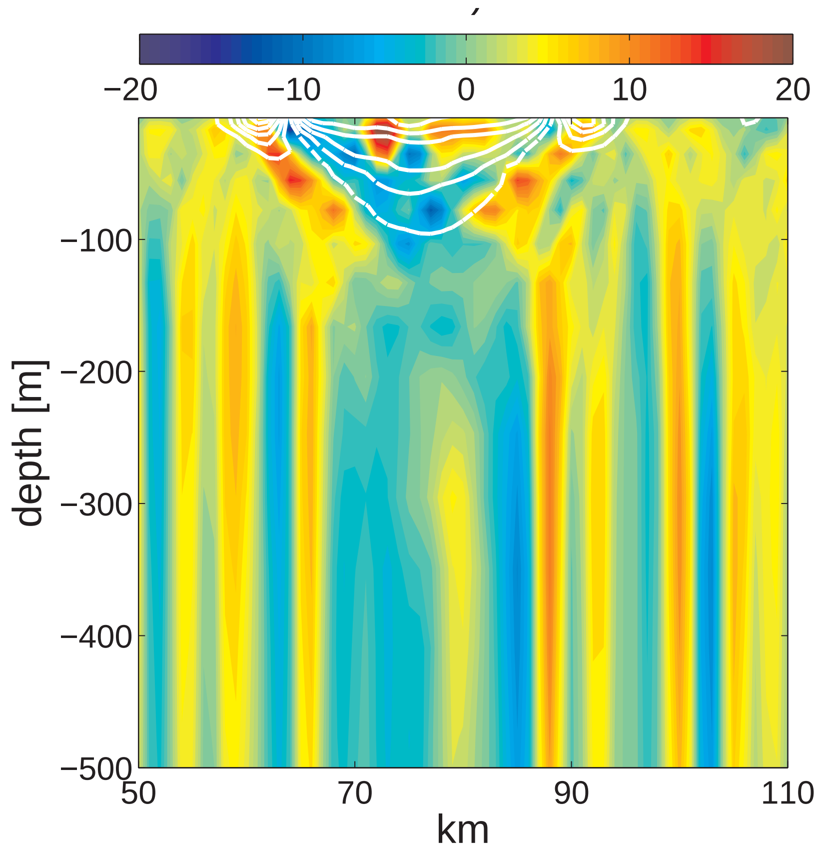
Western North Atlantic z < 1000m



from Bracco et al., JPO, 2000

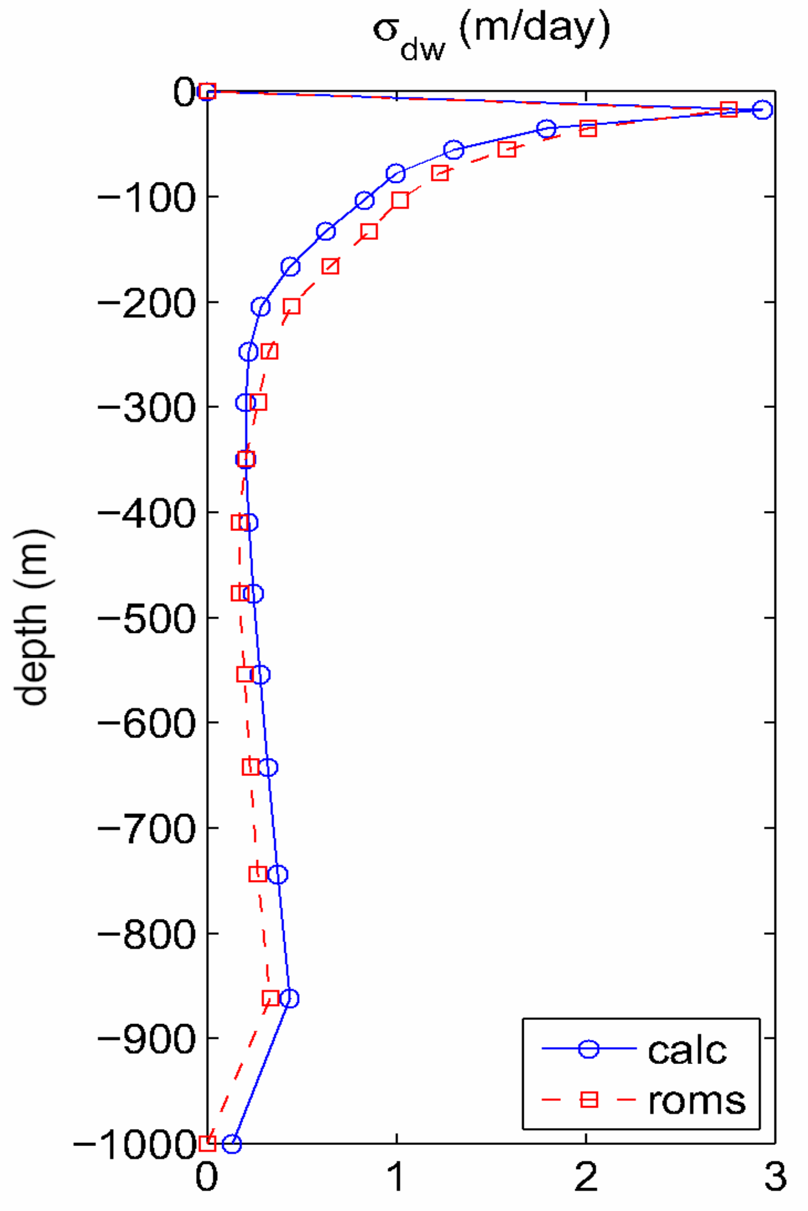
what are the components contributing to the vertical velocities?

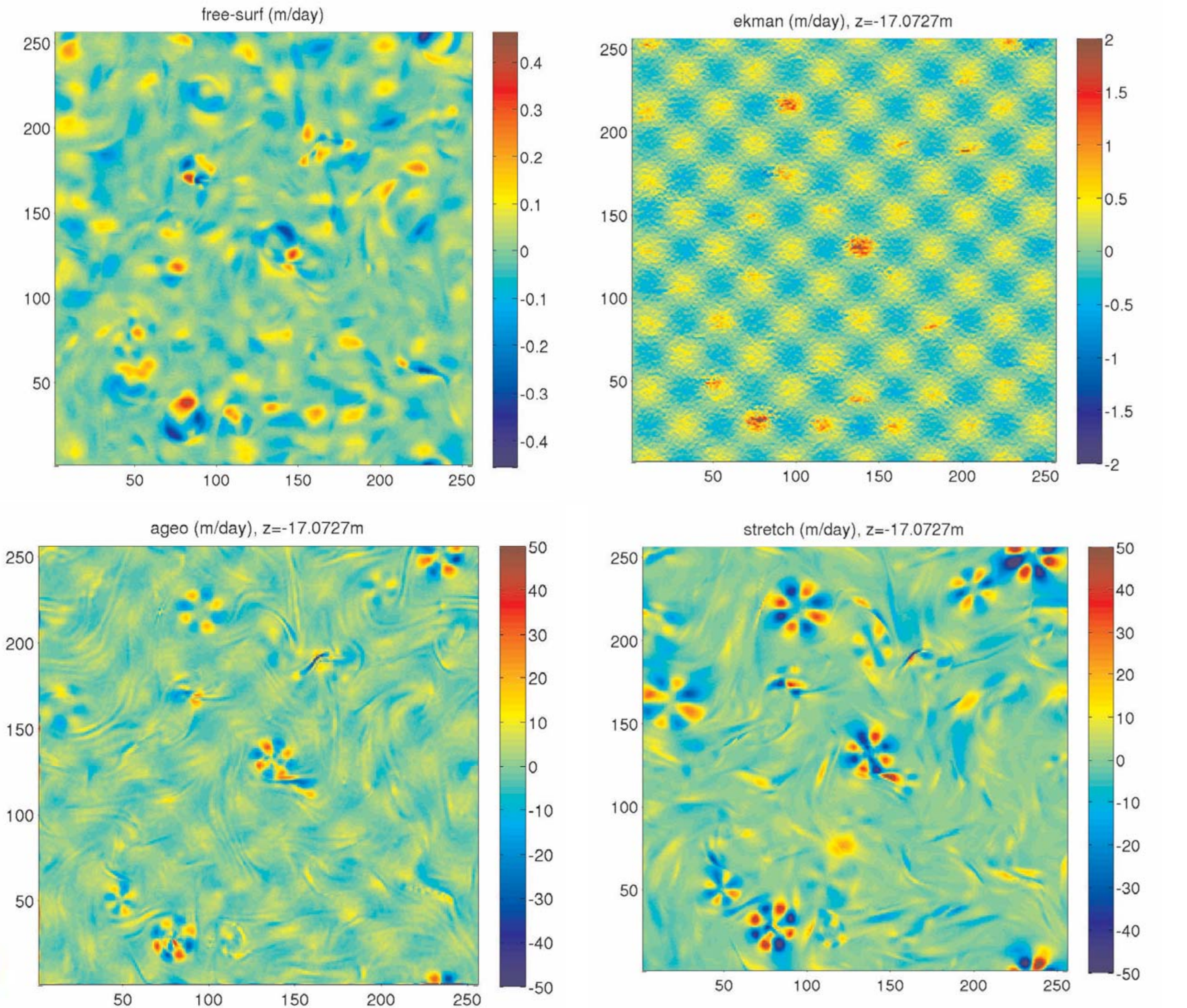




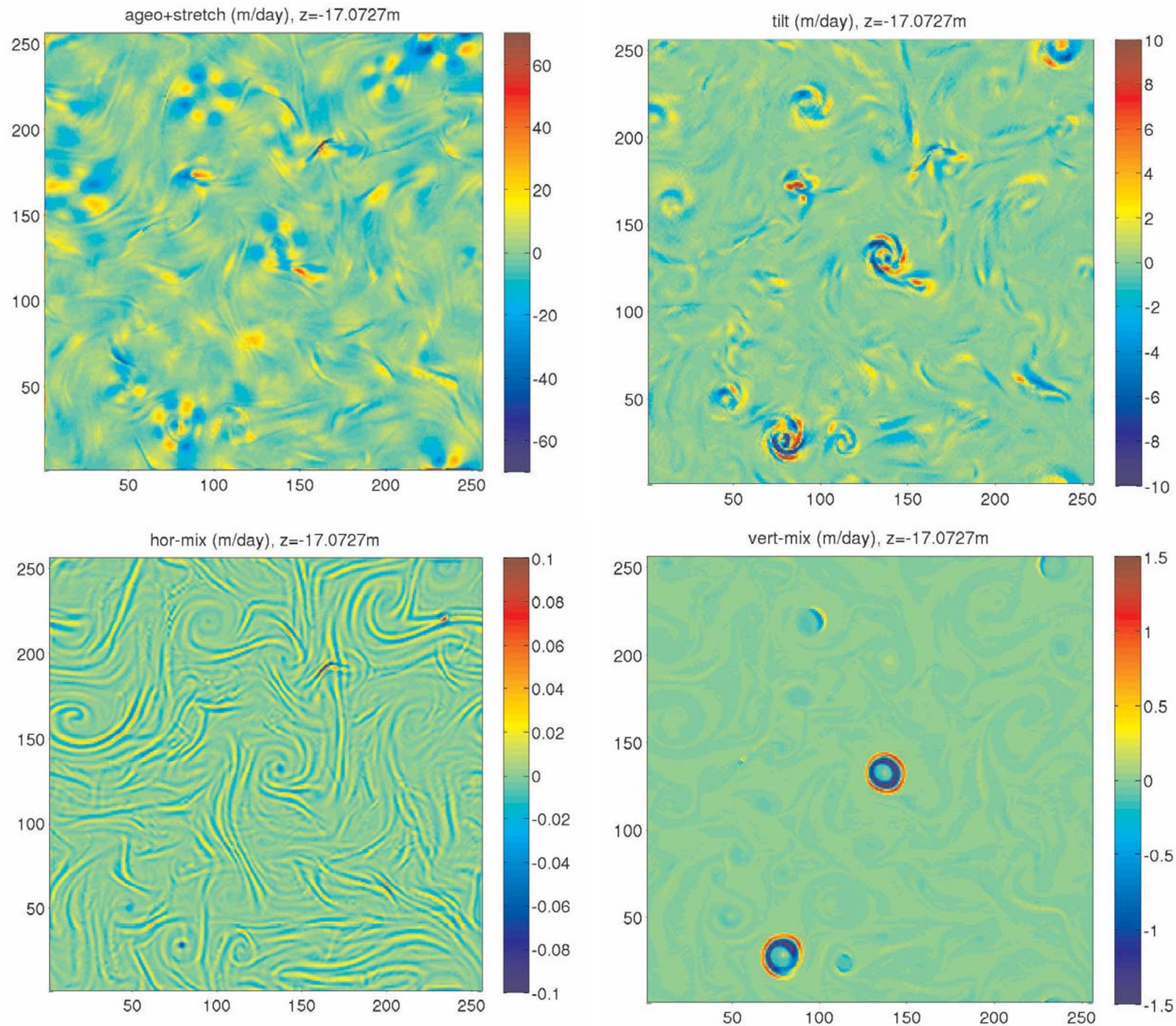
$$
\begin{aligned}
w(x,y,z) = {} & \overset{\text{FREE SURFACE}}{\frac{D\eta}{Dt}} - \\
& \overset{\text{AGEOSTROPHIC}}{-\int_z^\eta \frac{1}{f+\zeta_1}\left[\frac{\partial\zeta_1}{\partial t} + u\frac{\partial\zeta_1}{\partial x} + v\frac{\partial\zeta_1}{\partial y} + w\frac{\partial\zeta_1}{\partial z}\right] dz} - \\
& \overset{\text{AGEOSTROPHIC}}{-\int_z^\eta \frac{1}{f+\zeta_2}\left[\frac{\partial\zeta_2}{\partial t} + u\frac{\partial\zeta_2}{\partial x} + v\frac{\partial\zeta_2}{\partial y} + w\frac{\partial\zeta_2}{\partial z}\right] dz} - \\
& \overset{\text{STRETCHING}}{-\int_z^\eta \frac{1}{f+\zeta_1}\left[\chi_2\zeta_1\right] dz - \int_z^\eta \frac{1}{f+\zeta_2}\left[\chi_1\zeta_2\right] dz} - \\
& \overset{\text{TILTING}}{-\int_z^\eta \frac{1}{f+\zeta_1}\left[\frac{\partial w}{\partial x}\frac{\partial v}{\partial z}\right] dz + \int_z^\eta \frac{1}{f+\zeta_2}\left[\frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right] dz} + \\
& \overset{\text{WIND STRESS}}{+\int_z^\eta \frac{1}{\rho_o(f+\zeta_2)}\left[-\frac{\partial}{\partial y}\frac{\partial \tau_x}{\partial z}\right] dz} + \\
& \overset{\text{HORIZ MIXING}}{+\int_z^\eta \frac{A_H}{f+\zeta_1}\left(\frac{\partial^4\zeta_1}{\partial x^4} + \frac{\partial^4\zeta_1}{\partial y^4}\right) dz + \int_z^\eta \frac{A_H}{f+\zeta_2}\left(\frac{\partial^4\zeta_2}{\partial x^4} + \frac{\partial^4\zeta_2}{\partial y^4}\right) dz} + \\
& \overset{\text{VERT MIXING}}{+\int_z^\eta \frac{1}{f+\zeta_1}\frac{\partial}{\partial x}\frac{\partial}{\partial z}\left(K_v\frac{\partial v}{\partial z}\right) dz - \int_z^\eta \frac{1}{f+\zeta_2}\frac{\partial}{\partial y}\frac{\partial}{\partial z}\left(K_v\frac{\partial u}{\partial z}\right) dz},
\end{aligned}
$$

profile of standard deviation of the vertical velocity from ROMS and calculated from formula



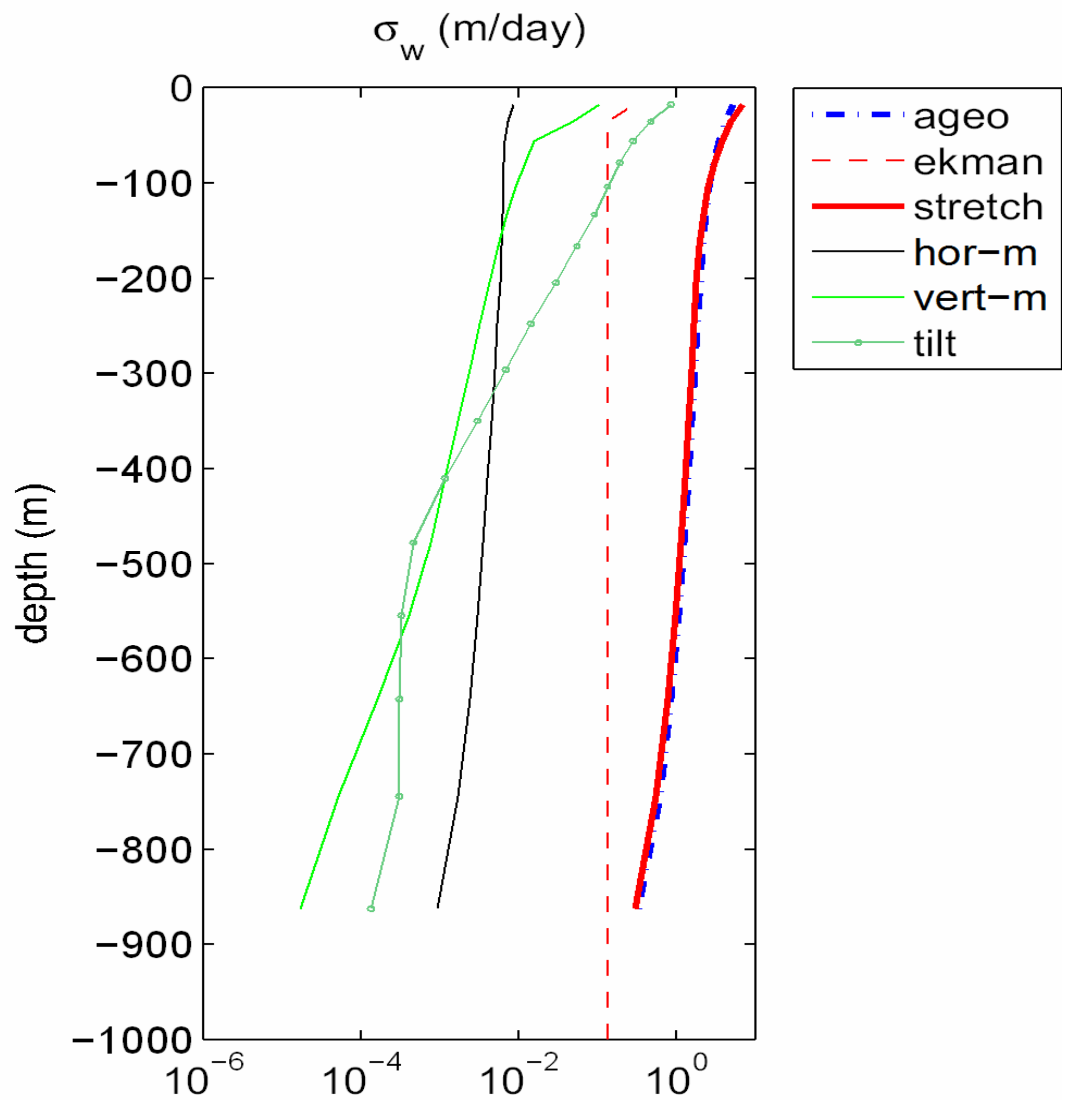


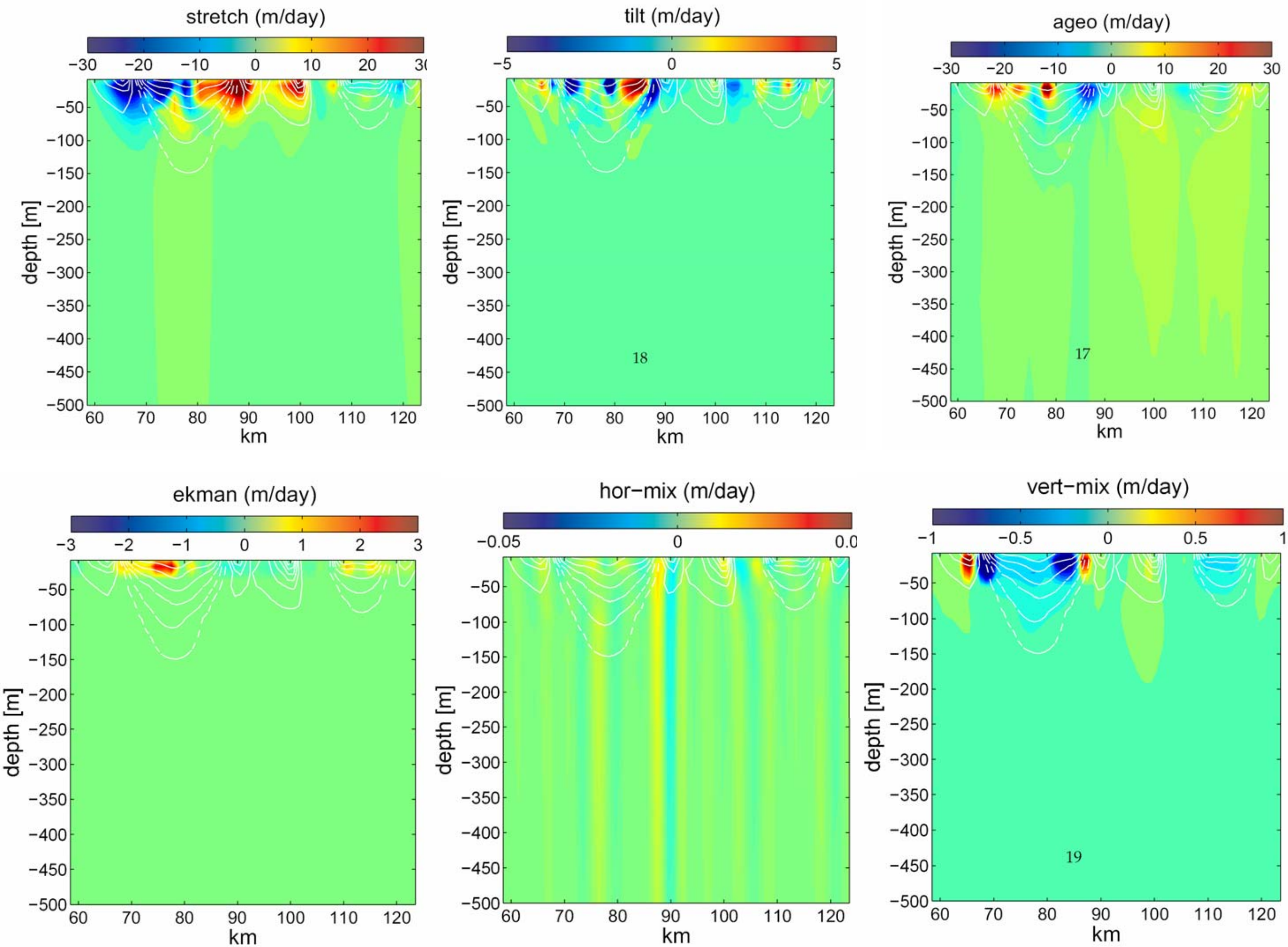
GEORGIA TECH



ageo+stretch (m/day), z=-17.0727m
250
200
150
100
50
50
100
150
200
250
60
40
20
0
-20
-40
-60
tilt (m/day), z=-17.0727m
250
200
150
100
50
50
100
150
200
250
10
8
6
4
2
0
-2
-4
-6
-8
-10
hor-mix (m/day), z=-17.0727m
250
200
150
100
50
50
100
150
200
250
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
vert-mix (m/day), z=-17.0727m
250
200
150
100
50
50
100
150
200
250
1.5
1
0.5
0
-0.5
-1
-1.5

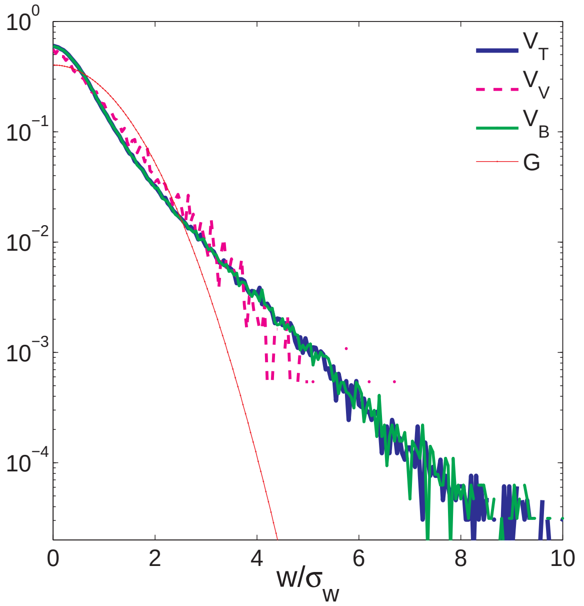
Profile of the std of the contribution of different terms to the vertical velocity (integrated in the vertical). Note the logarithmic scale.



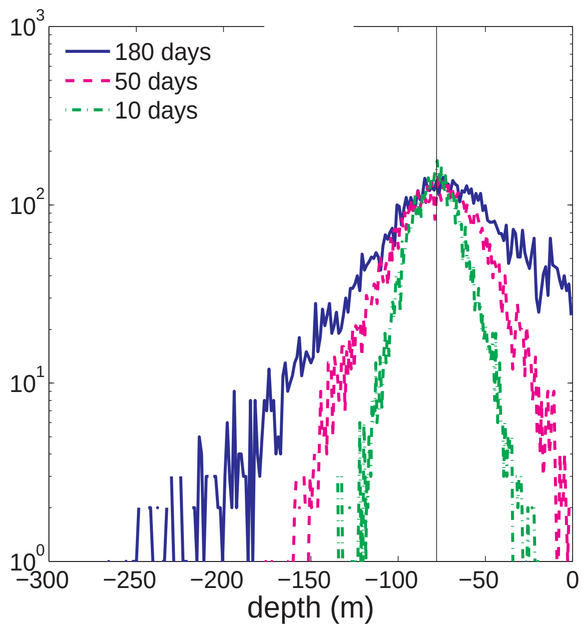


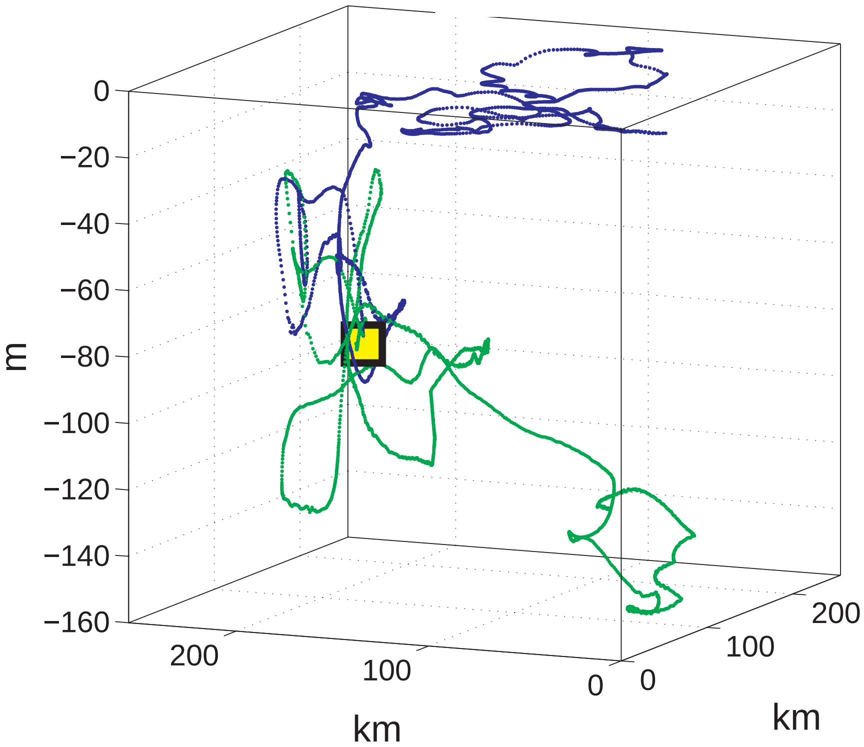
stretch (m/day)
tilt (m/day)
ageo (m/day)
ekman (m/day)
hor−mix (m/day)
vert−mix (m/day)
depth [m]
km
18
17
19

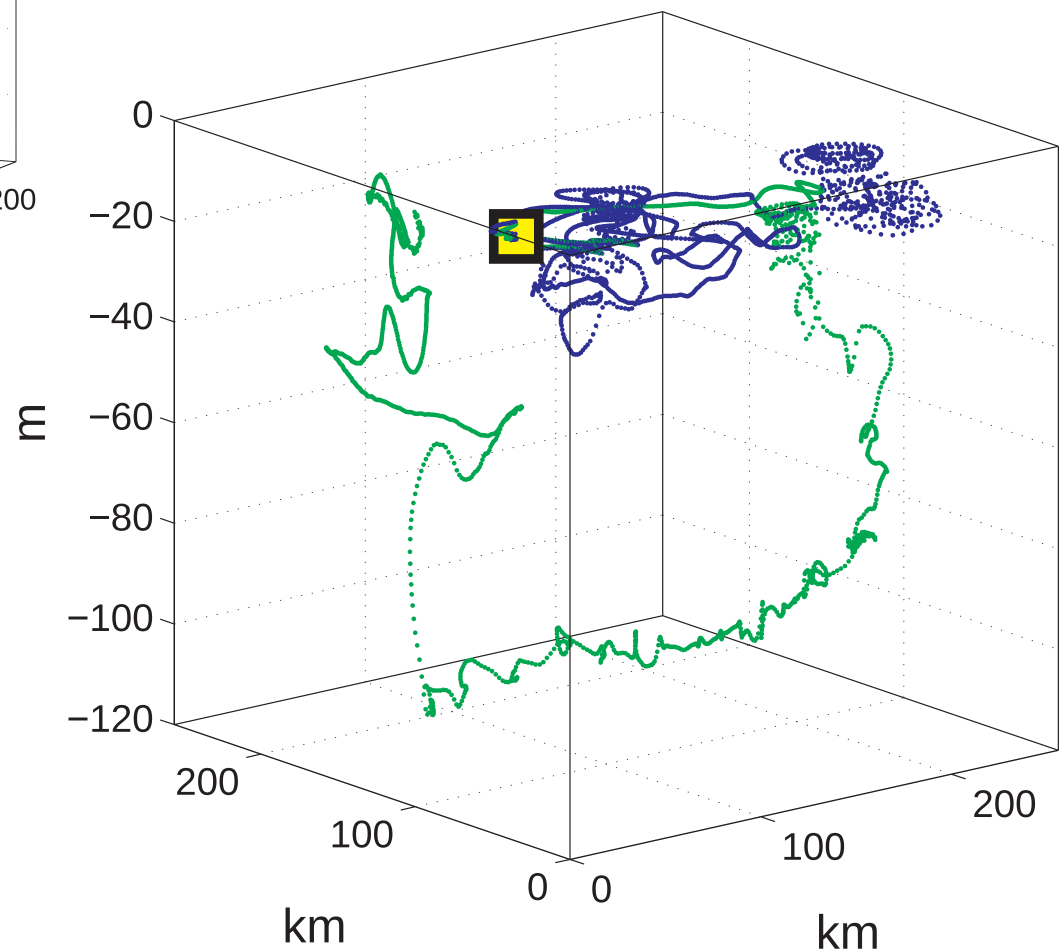
The distributions of vertical velocities are non-Gaussian at all depths



and vertical velocities strongly impact the vertical displacement of Lagrangian tracers







Example trajectories of initially close-by particle pairs released at 78m (top) and at the surface (right)

conclusions

- wind-forced periodic “ocean” with small internal Rossby deformation radius with respect to the domain size ⟶ surface intensified coherent anticyclones.

- In the upper 150 meters of the water column
  a) the vortical motion dominates over the divergent component
  b) near-inertial waves are negligible
  c) most statistical properties of horizontal flows (apart from the cyclone-anticyclone asymmetry) are similar to those of 2D / QG turbulence, including horizontal velocity distributions and absolute and relative dispersion

- Vertical velocity are complex and cannot be described by simpler models → fine spatial structure

- Upwelling and downwelling regions alternate and do not correlate with vorticity or its gradient

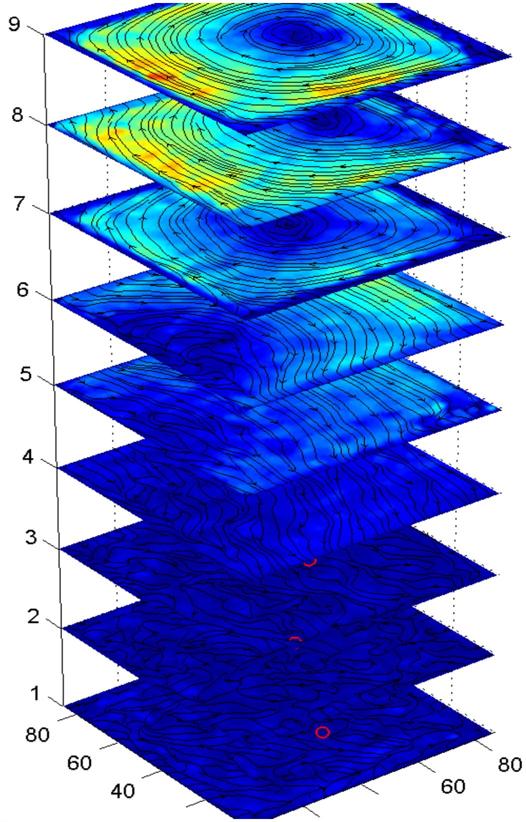
- The primary balance for w is by ageostrophic and stretching terms (O(100m/day));The tilting term contribution is of O(10m/day) at the surface and declines with depth. Free-surface, rotation of the wind stress and mixing terms are smaller by three to four orders of magnitude

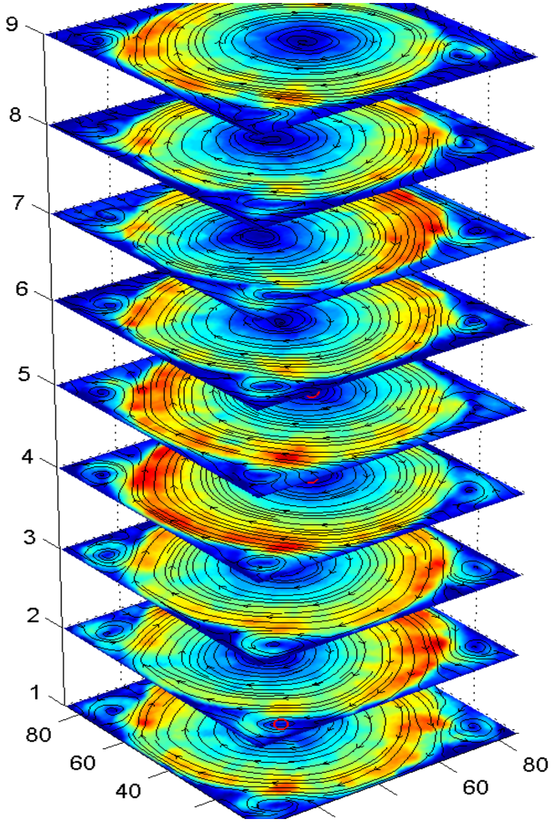
- All terms in w are modulated by $(f+\zeta)^{-1}$ → large inside anticyclones where $|\zeta| \sim f$ → ageostrophic effects. This explains the absence of simple correlation between vertical velocities and the vorticity field or its gradients

finally…

is this of any relevance for the real world?

At least from lab experiments seems to be the case





courtesy of John Wettlaufer and Michael Patterson