Linking 2D+1 and 3D+1 Transport in the Ocean

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In collaboration with:

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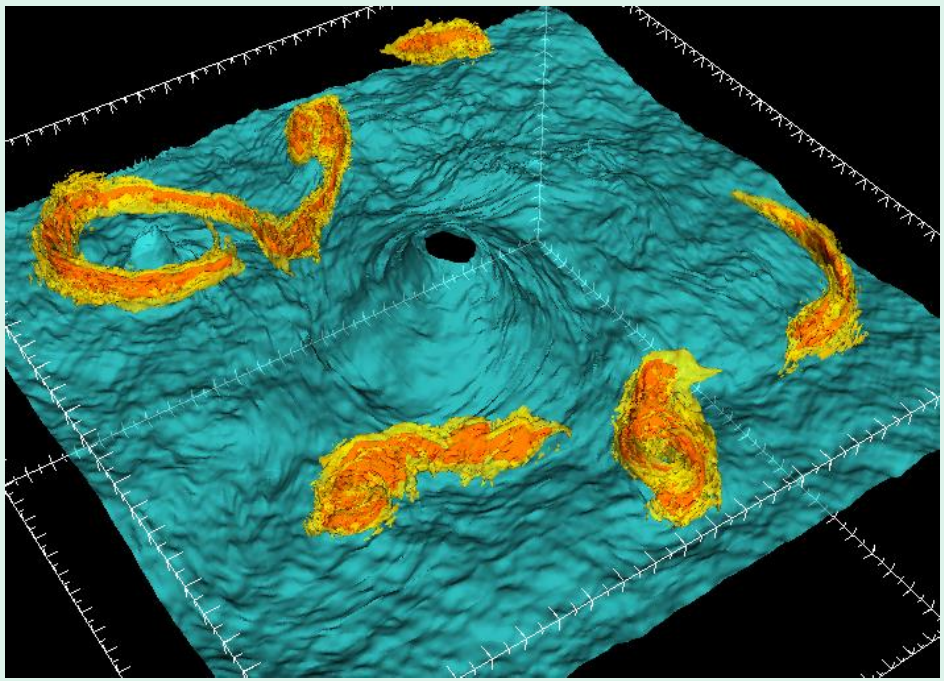


MURI Review Meeting, DC, May 2013

OUTLINE:
applications of 3D+1 tools to observed oceanic flows

a) 3D+1 dynamics in the deep ocean (industrial application):

- Mixing in single-phase buoyant plumes (LES)
- Mixing in two-phase buoyant plumes (LES)

b) Multi-scale 3D+1 dynamics in the upper ocean:

- How do mixed layers and mesoscale eddies interact (LES)?
- Formation of “star eddies” by 3D processes (LES)
- Is there a connection to the canonical rotating can problem (LES)?
- Can 3D+1 methods help with a definition of the mixed layer depth (LES)?
- Mixed layer and eddy interactions in the North Atlantic (HYCOM)

c) Ocean experiments on transport processes:

What did we learn on 3D+1 transport from LIDEX (Ligurian Sea) and
Grand Lagrangian Deployment (GLAD, GoM) experiments?

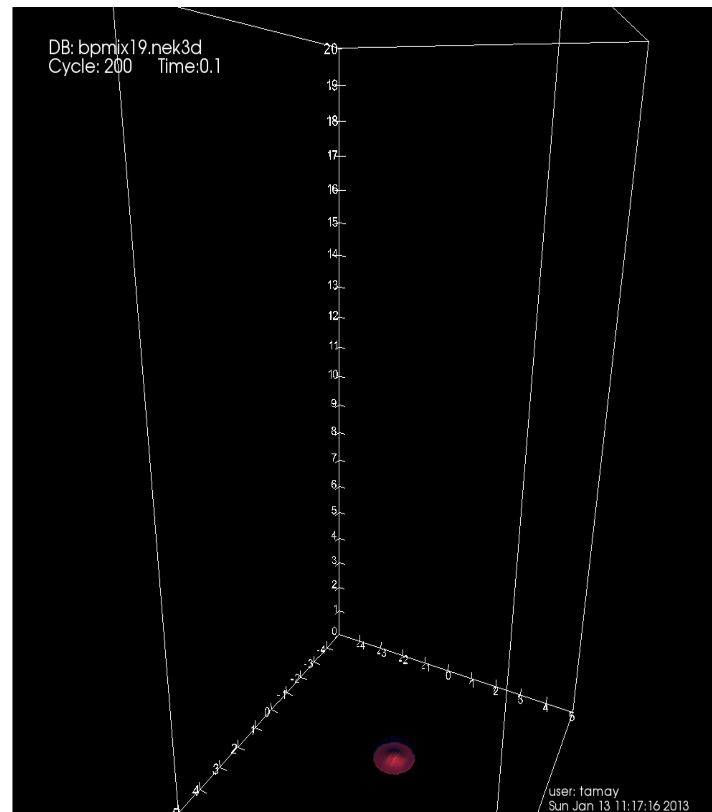
Are 3D+1 Methods Useful in 3D Turbulent Flows or or Limited to 2D (backward cascade -> long lasting features) ?

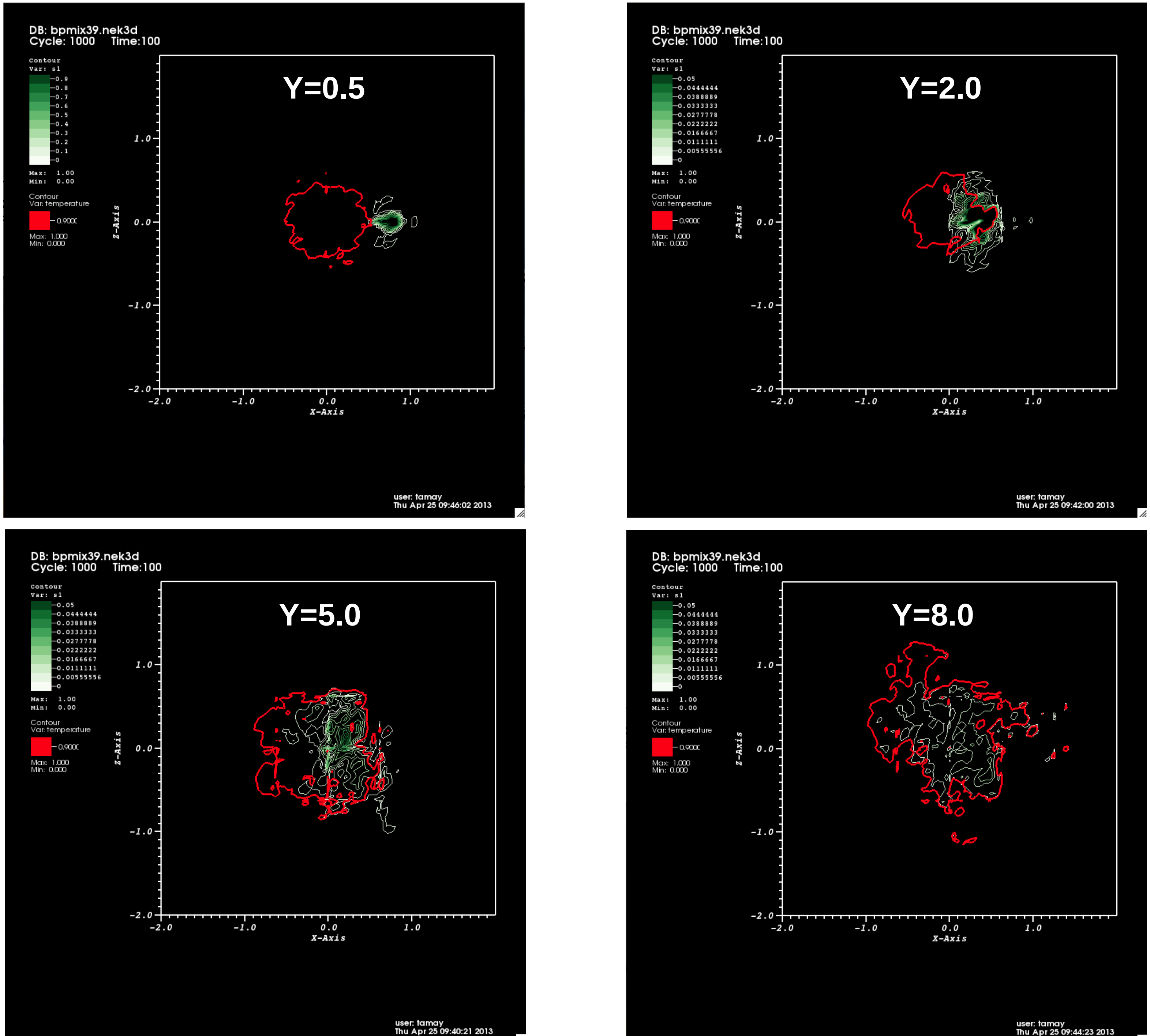
Application of dispersants during the BP oil spill: Important industrial problem used as a test case…

Practical Objective:

Minimize amount of toxic dispersant injected:

- How effective is the mixing?
- How far from the source for complete mixing?





DB: bpmix39.nek3d
Cycle: 1000 Time:100
Contour
Var: s1
Max: 1.00
Min: 0.00
Contour
Var: temperature
0.9000
Max: 1.000
Min: 0.000
Y=0.5
Y=2.0
Y=5.0
Y=8.0
Z-Axis
X-Axis
-2.0
-1.0
0.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.05
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0.0111111
0.00555556
user: tamay
Thu Apr 25 09:46:02 2013
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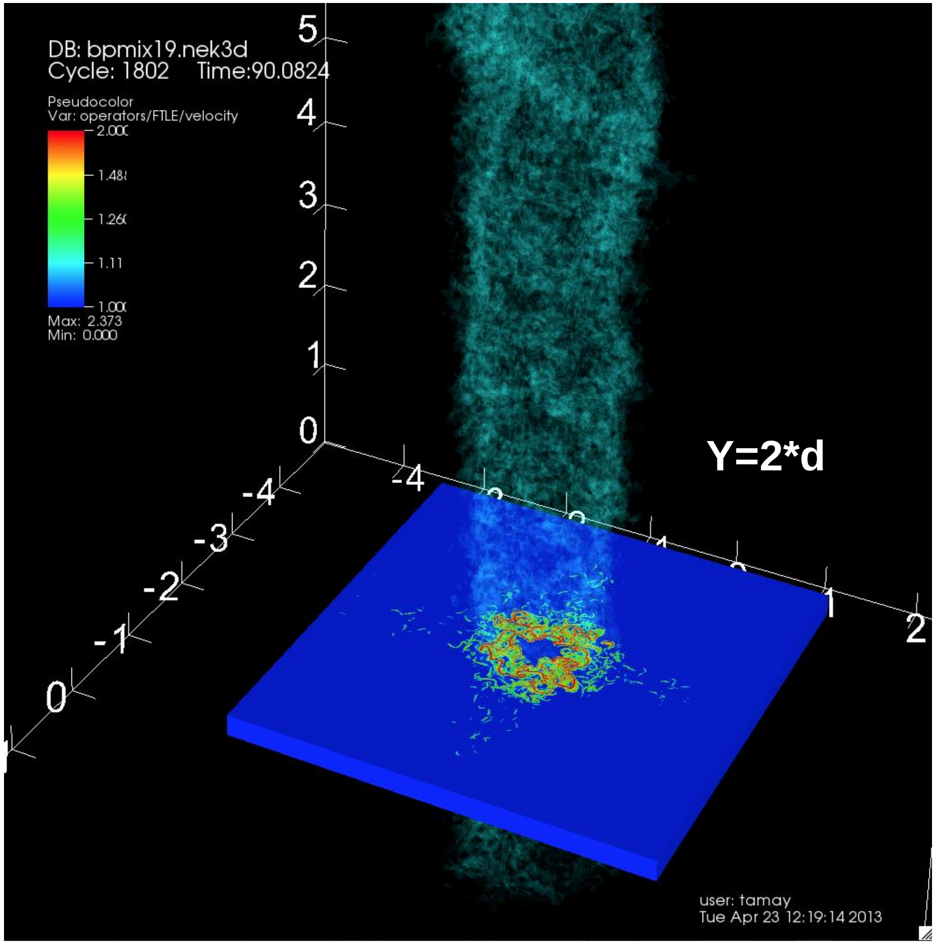
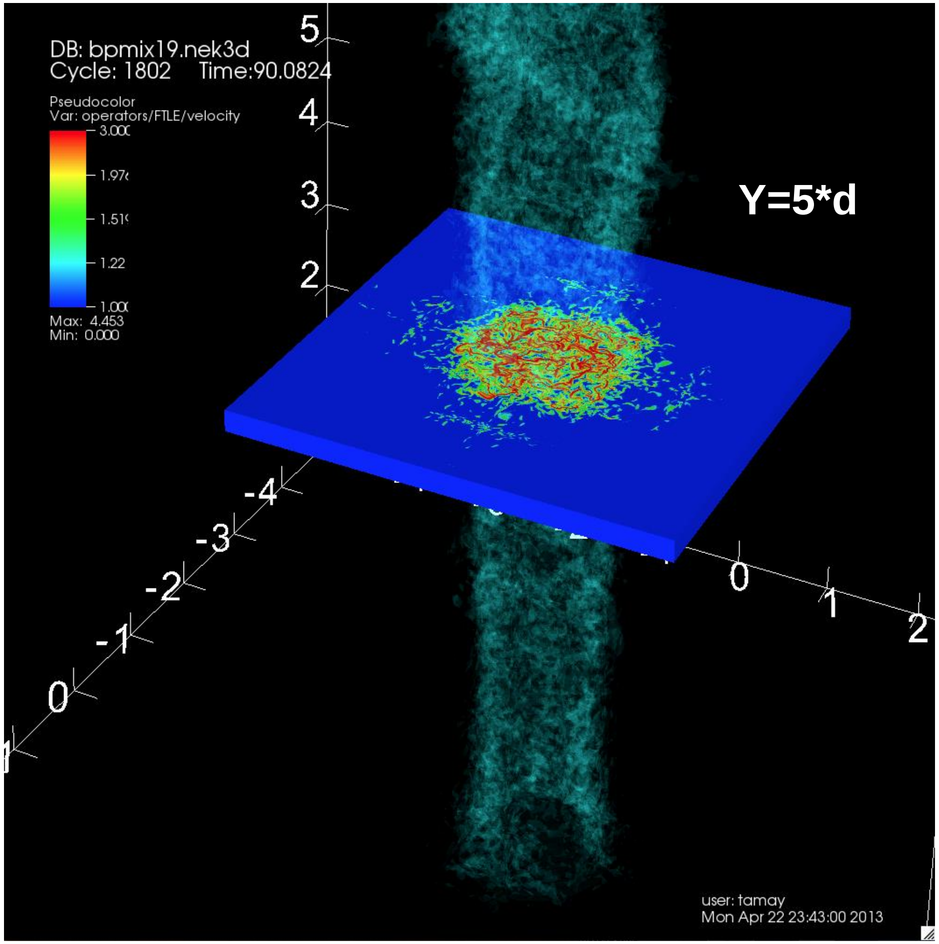
Thu Apr 25 09:44:23 2013

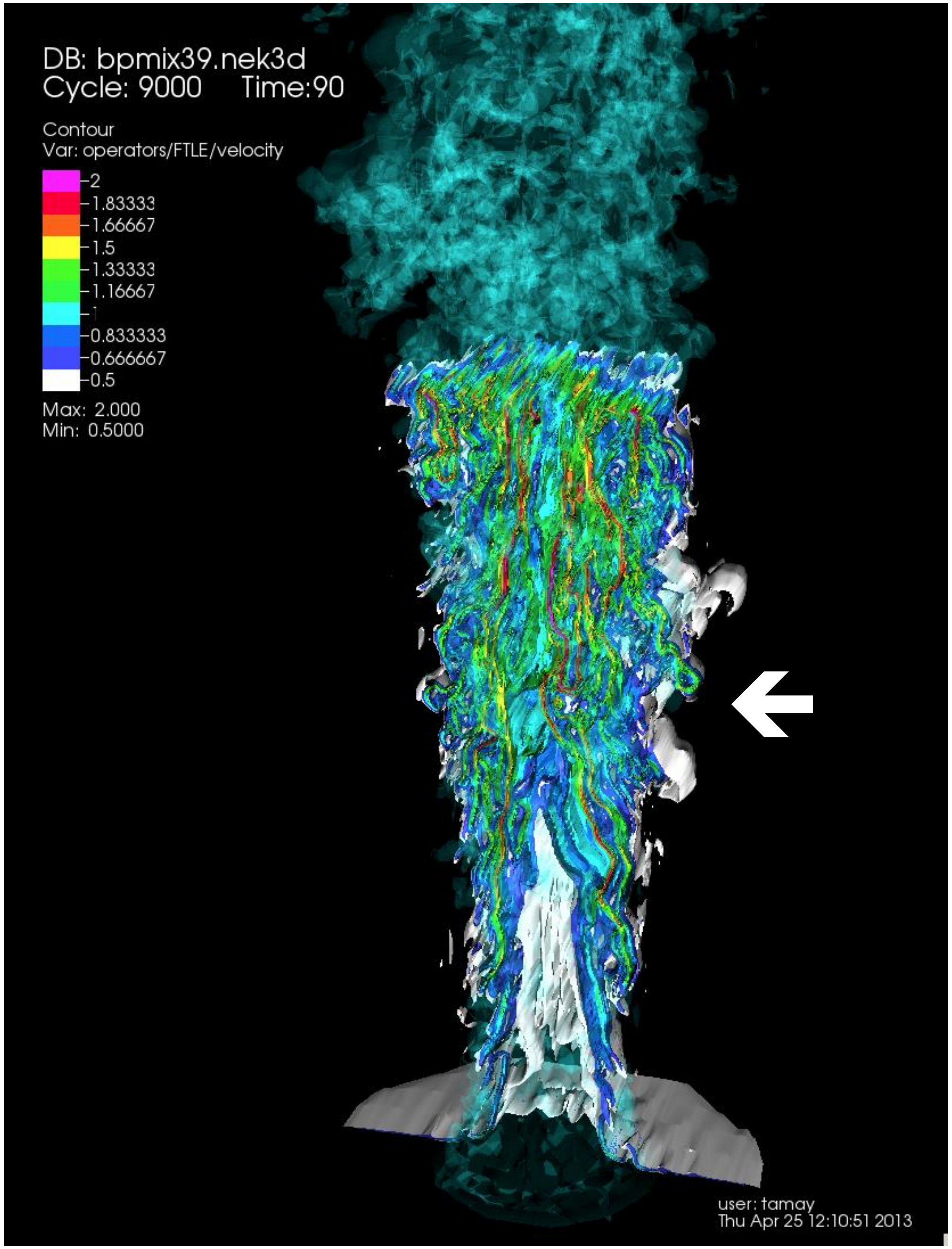
Do the 3D FTLEs detect any coherent features in a highly turbulent situation?





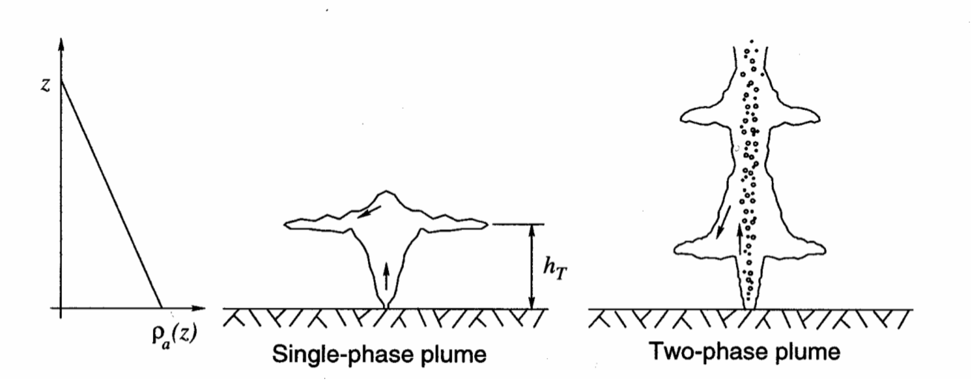
Jet core has a transport barrier near the inflow, which breaks down at 3 to 5 d facilitating full mixing across the jet of ambient tracers.

3D FTLE View of the Collapse of Jet Core:

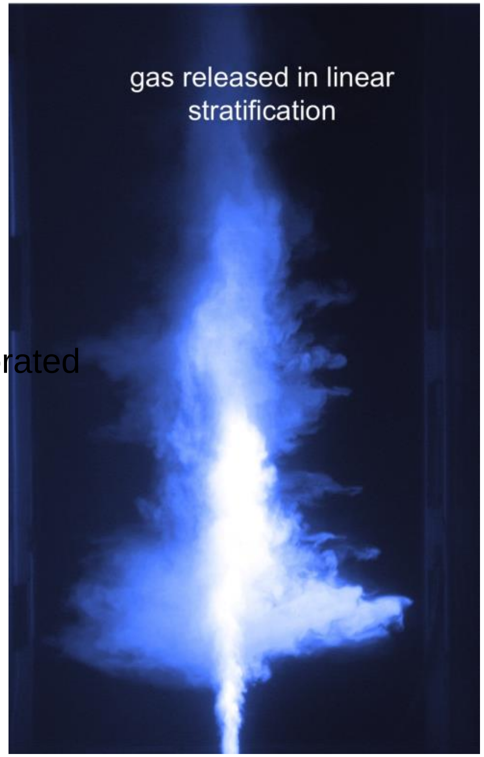


Spray dispersant here from at least two sides for best mixing

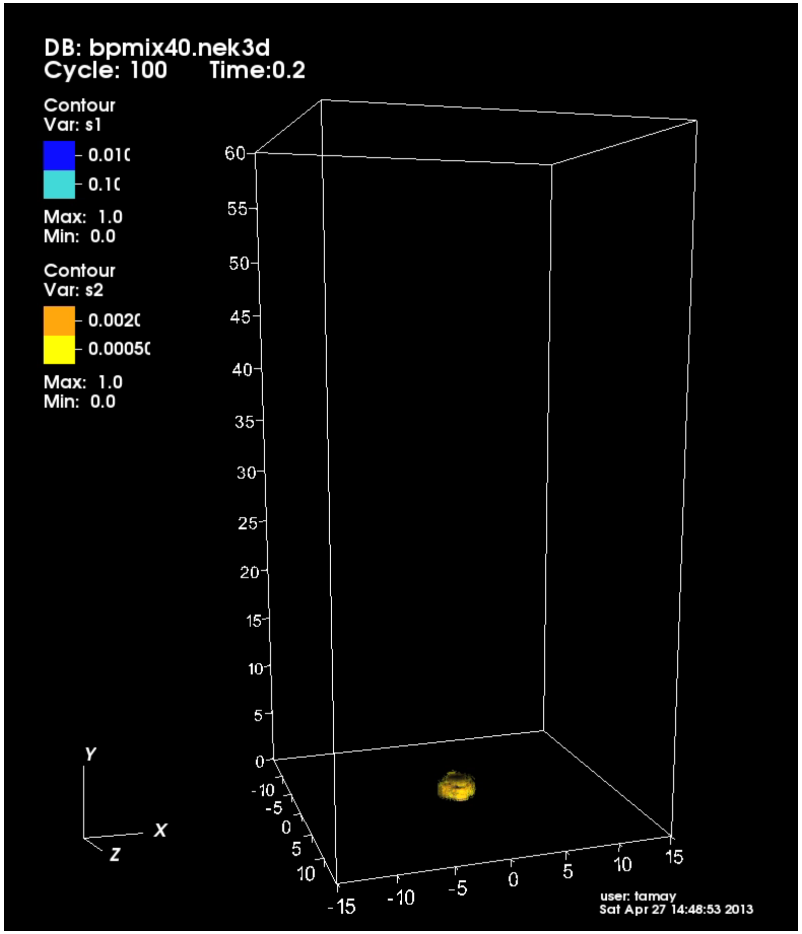
Two-Phase (Bubble) Plumes – Potential of Additional Coherent Structures:



Adams and Socolofsky (2004)



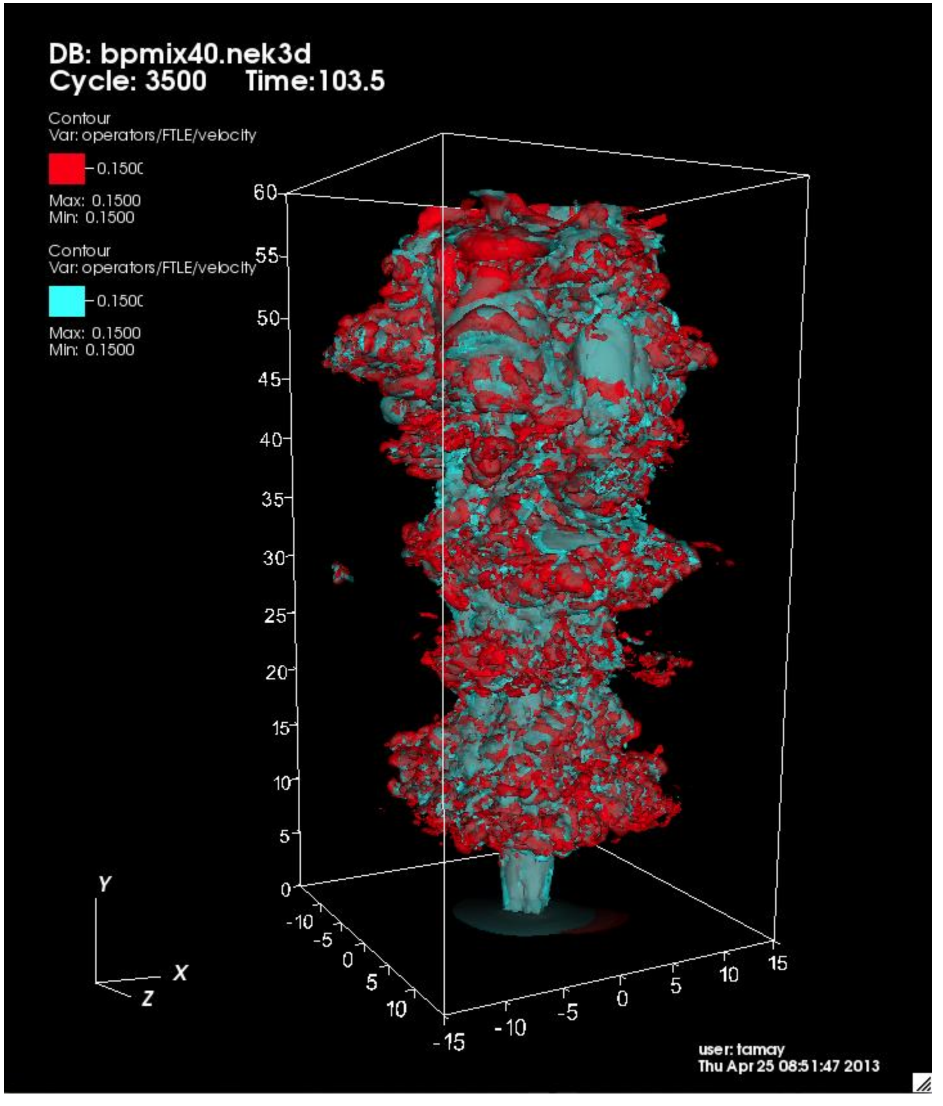
Multi-scale problem with
fast turbulent motions
carrying out the mixing and
slowly-evolving (coherent) equilibrated
intrusions



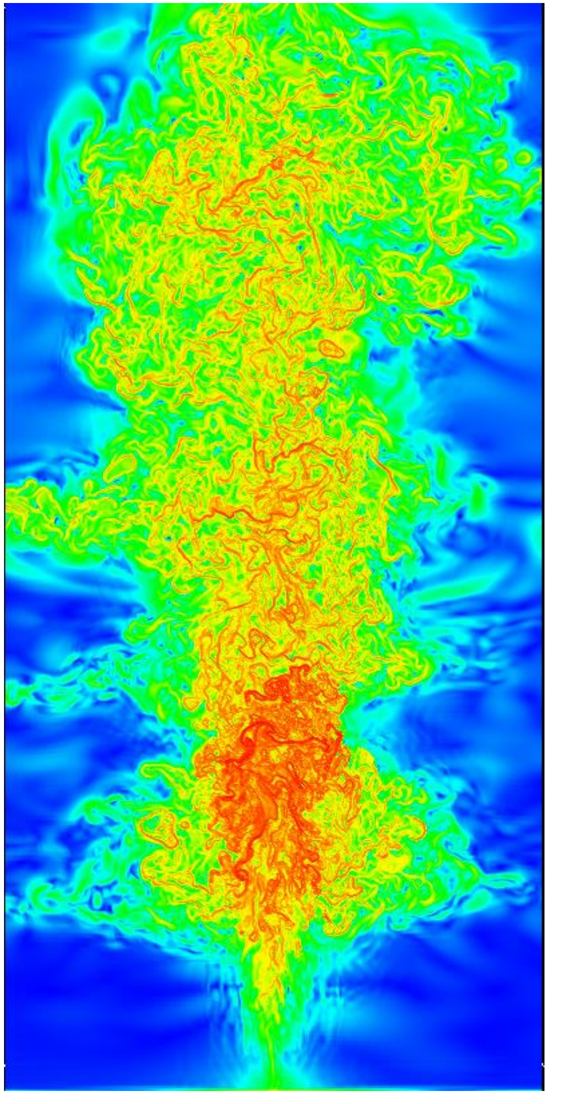
Socolofsky and Adams (2003)

3D FTLE Structure in Two-Phase Plumes

Backward (red) & Forward (blue) FTLE



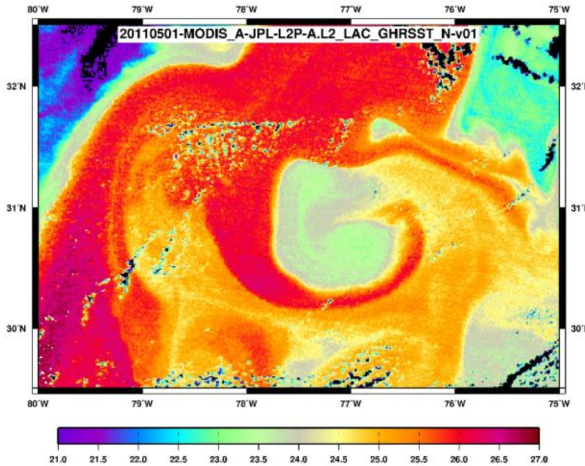
Backward FTLE section



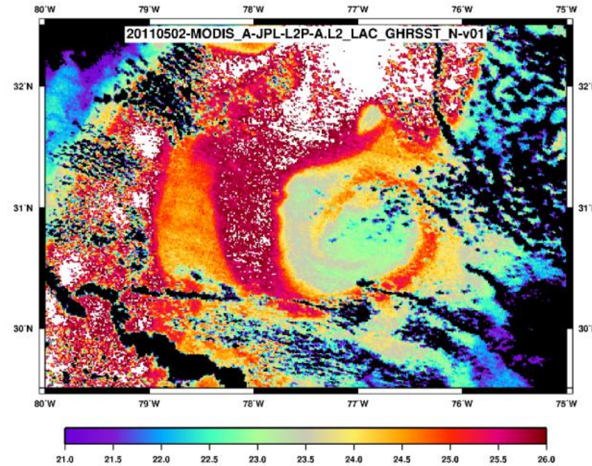
A combination of turbulent (fast) and coherent (slowly evolving) regions visualized efficiently

Upper Ocean SST Images Reveal Multi-Scale Transport Phenomena:

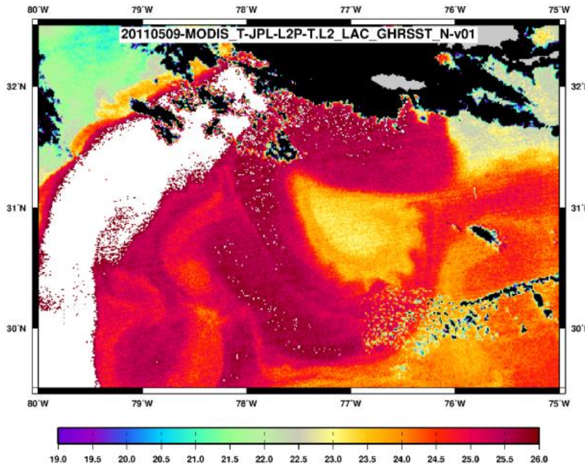
t0: May 1, 2011



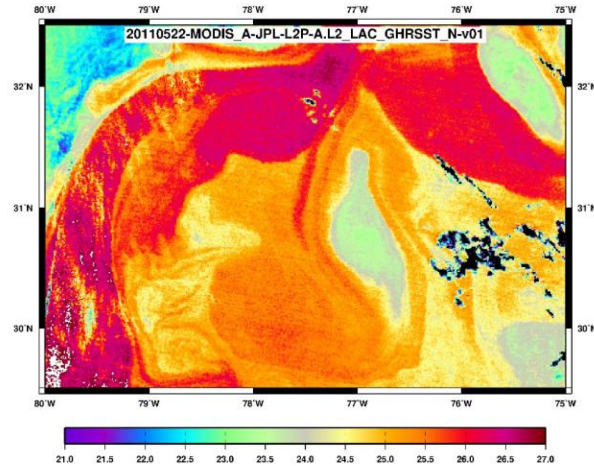
t0 + 1 day



t0 + 2 days

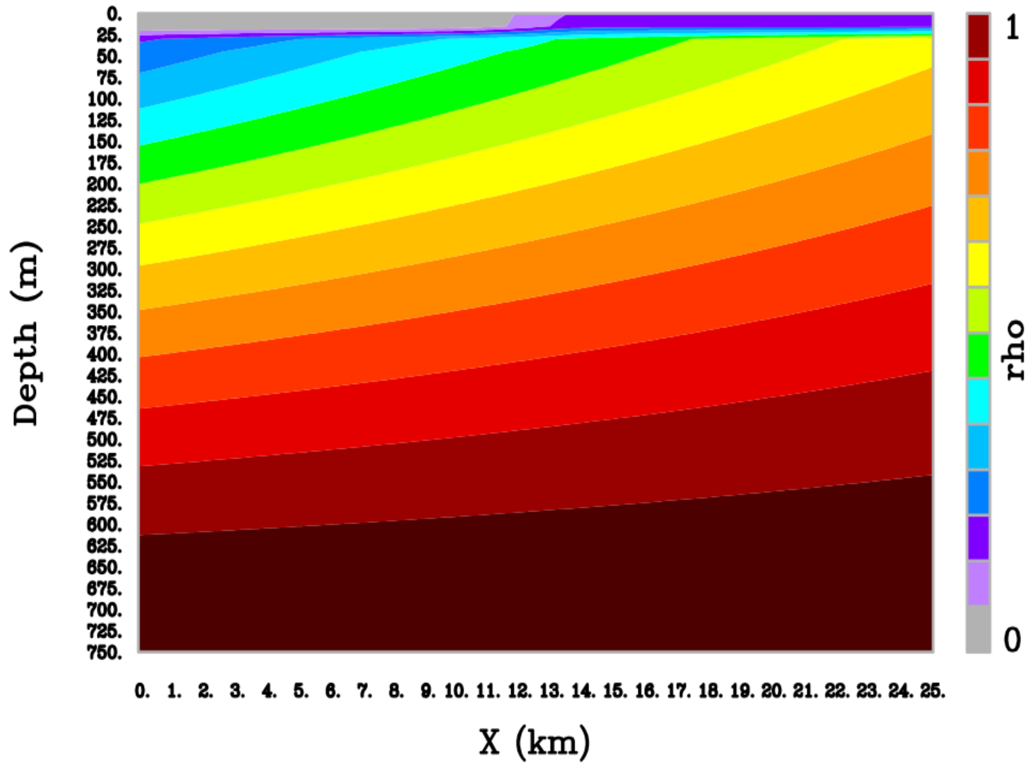


t0 + 21 days



Can Submescales Survive the Encounter With Mesoscale Eddies?

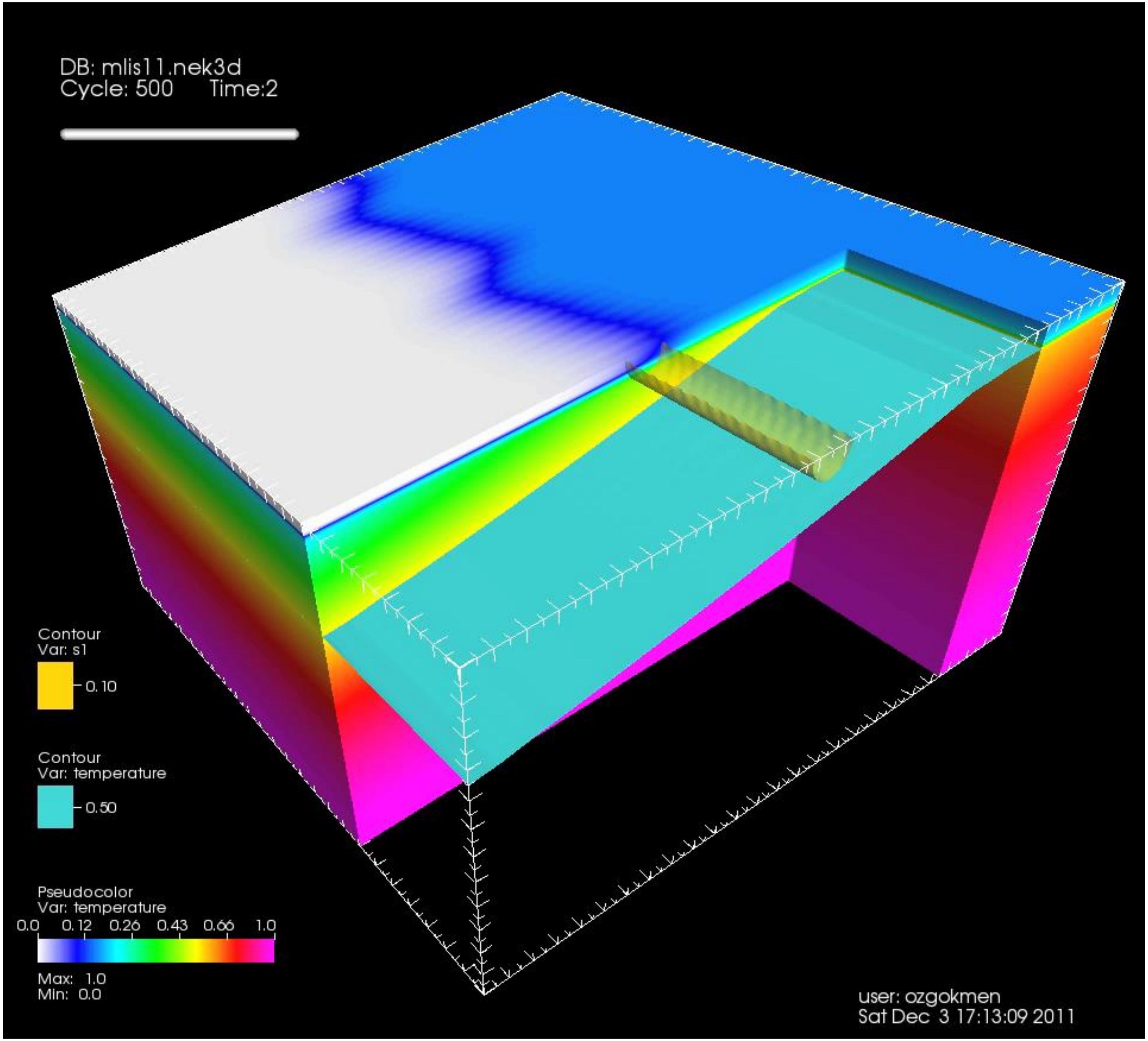
Multi-Scale (Submesoscale/Mesoscale) Baroclinic Instability Problem*:*



* Domain: 25 km x 25 km x 0.75 km

* Shallow (25 m) weak ML front to get 10x scale separation between MLI and deep eddies; no winds or other forcing

* 22×10^6 mesh points (dx=17 m, dz=0.75 m near surface), 2×10^5 time steps
  Compute time: 3 days on 256 CPUs (18k CPU hours) of Cray XE6m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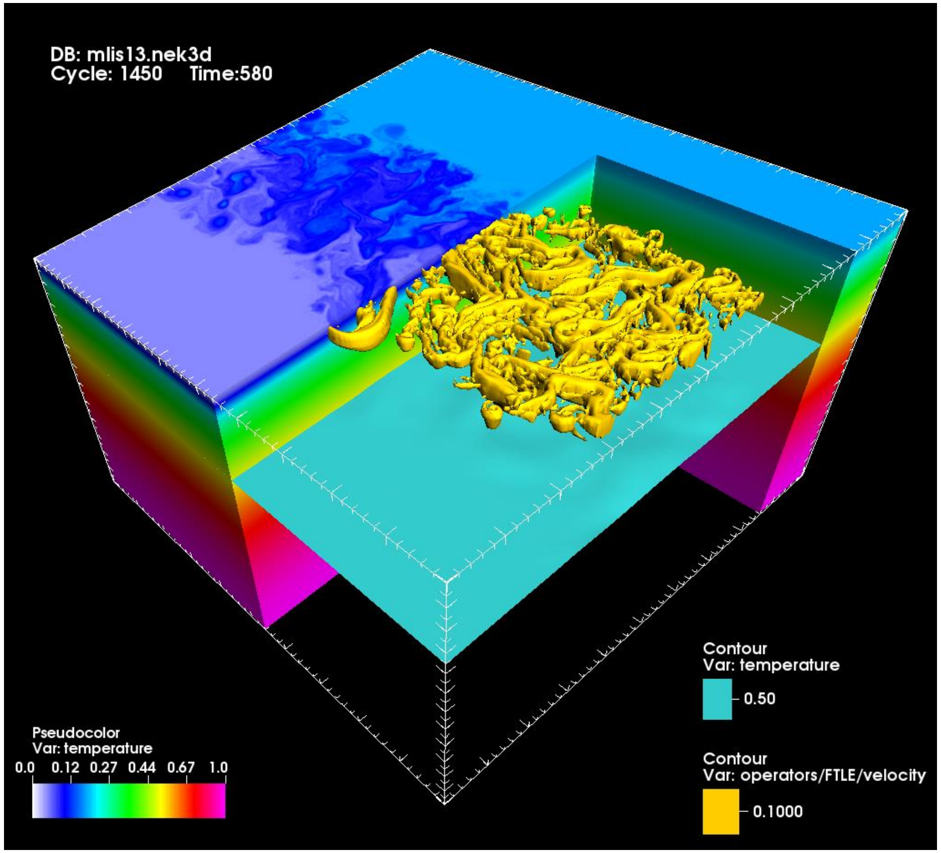
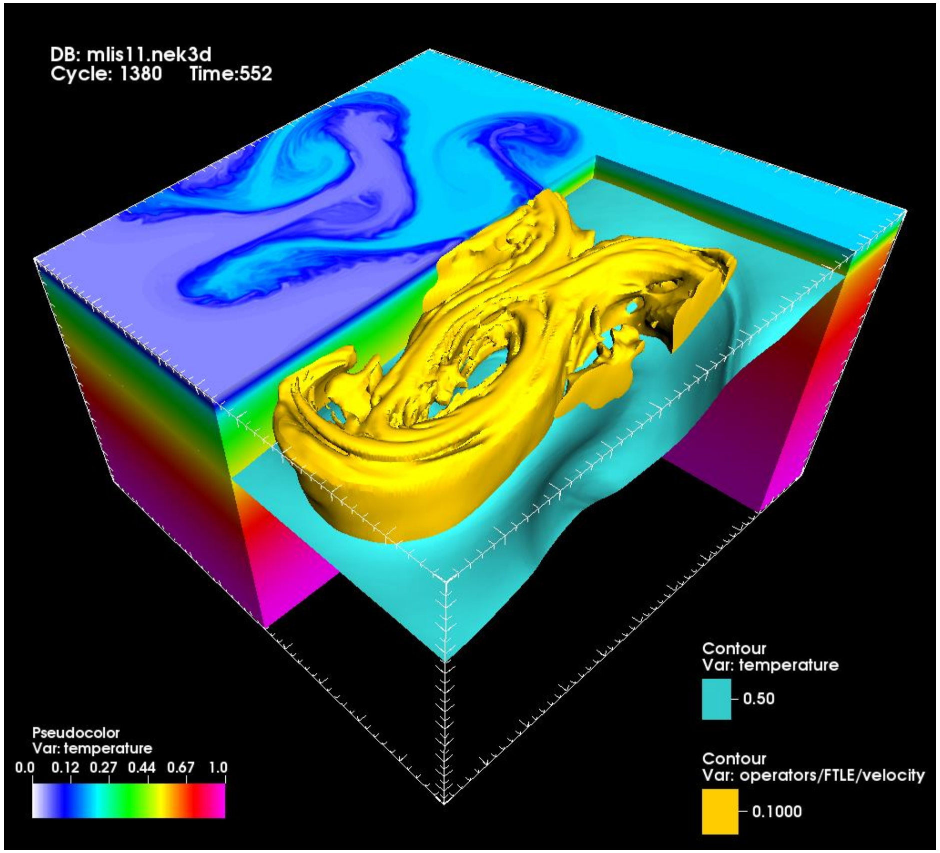
Contour
Var: s1
0.10
Contour
Var: temperature
0.50
Pseudocolor
Var: temperature
0.0 0.12 0.26 0.43 0.66 1.0
Max: 1.0
Min: 0.0
user: ozgokmen
Sat Dec 3 17:13:09 2011

3D FTLE:

Submesoscale phase:

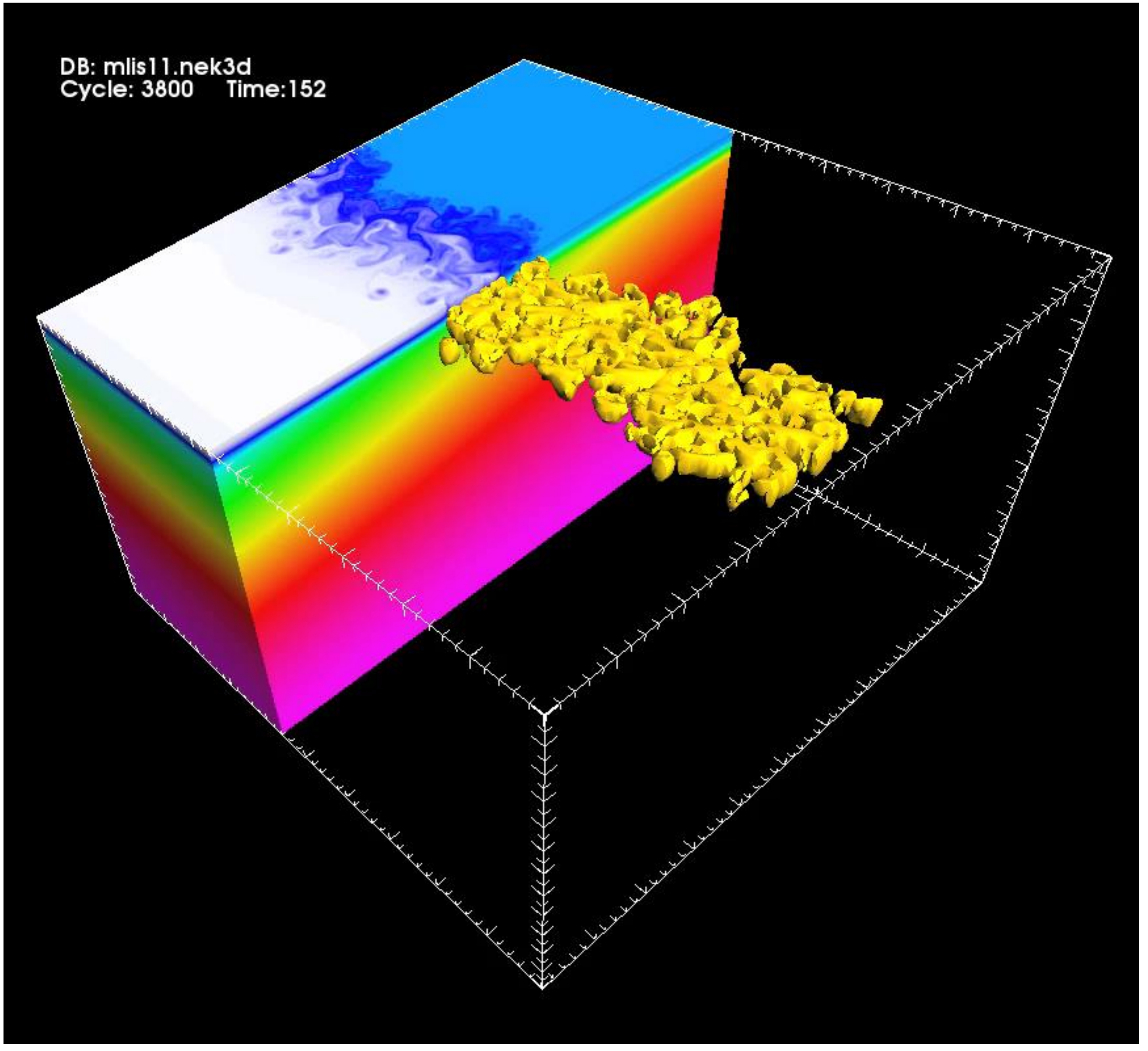


Mesoscale phase:

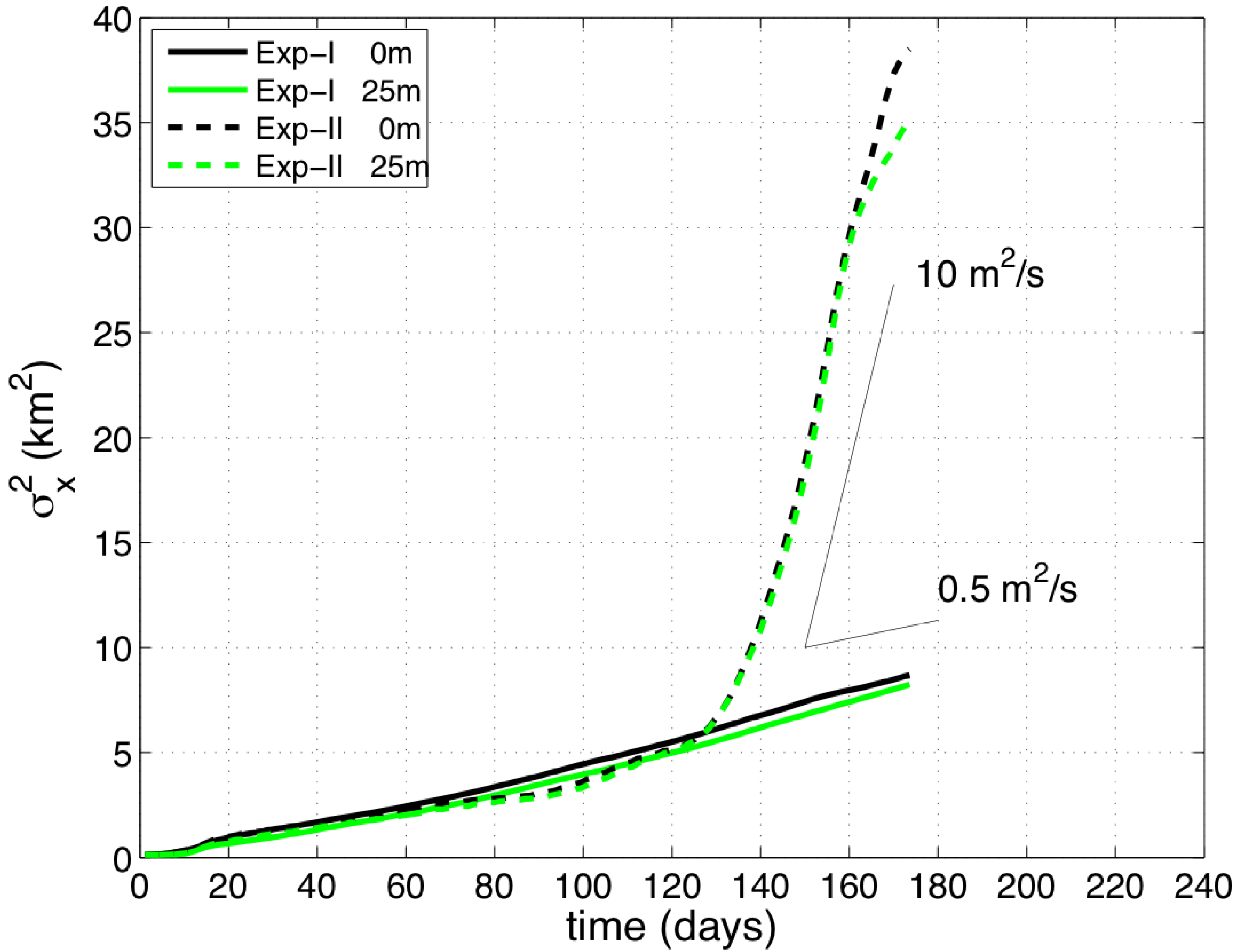


Clearly different turbulent coherent structures:
shallow submesoscale eddies vs deep mesoscale features…

Transformation of Coherent Structures:

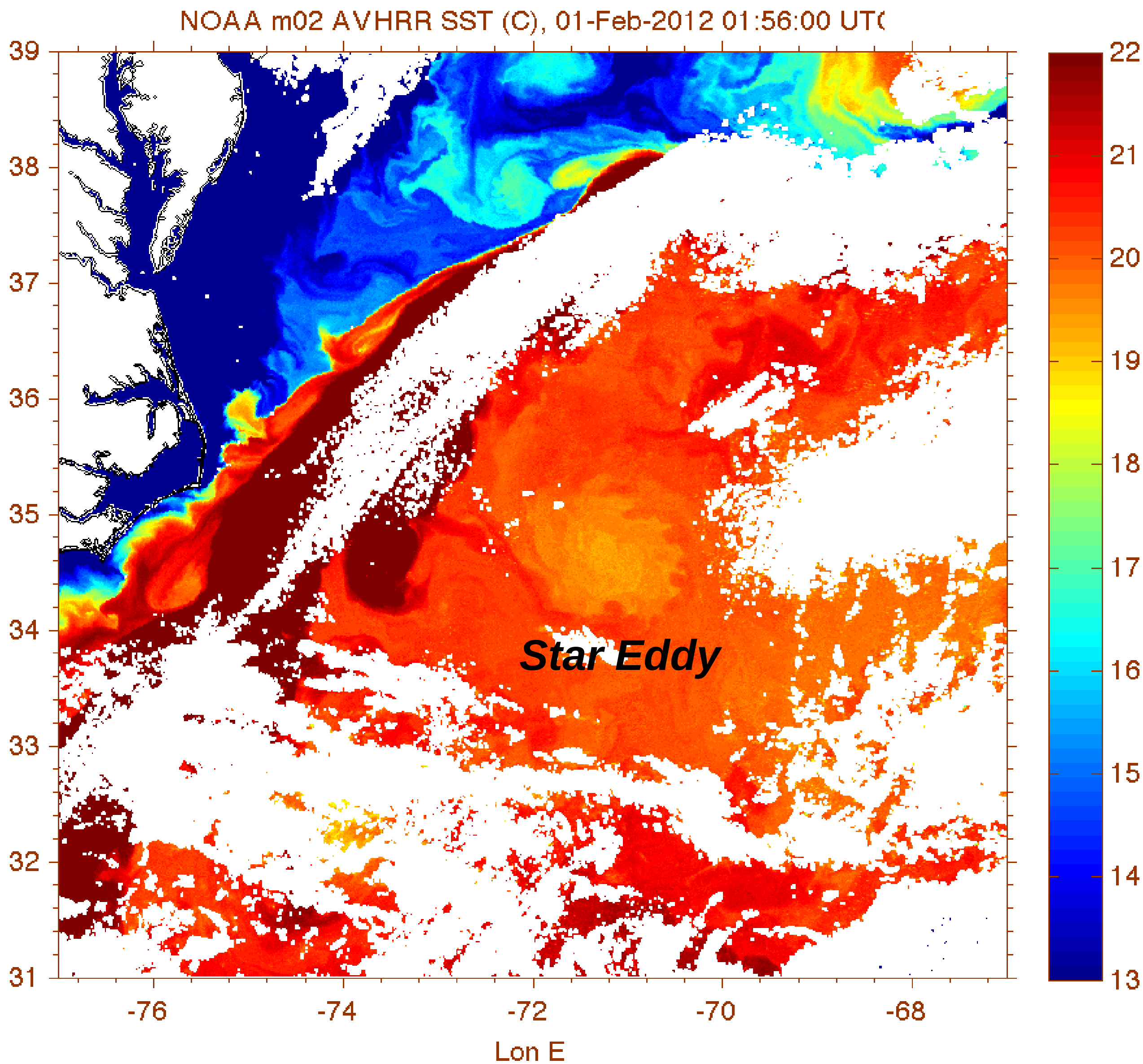


Turbulent exchange quantified from tracer release:



An order of magnitude increase in frontal turbulent diffusivity after the deep instability kicks in; submesoscale overcome by mesoscale in this case

Cohabitation of Mesoscale and Submesoscale:

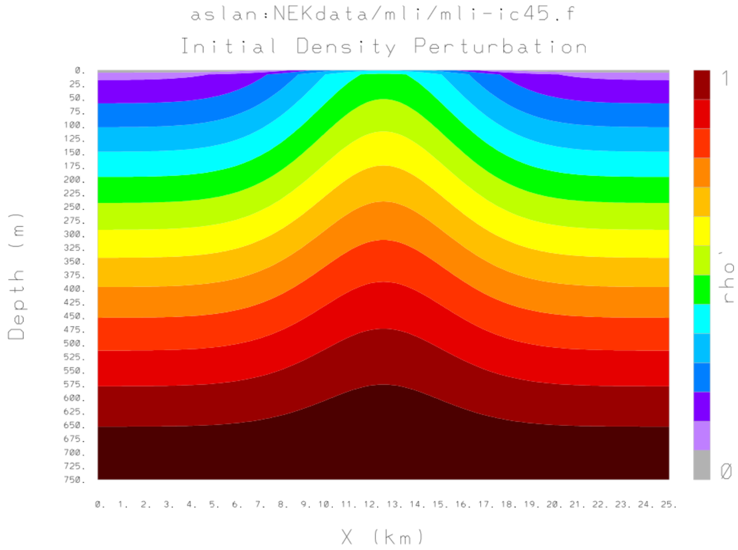


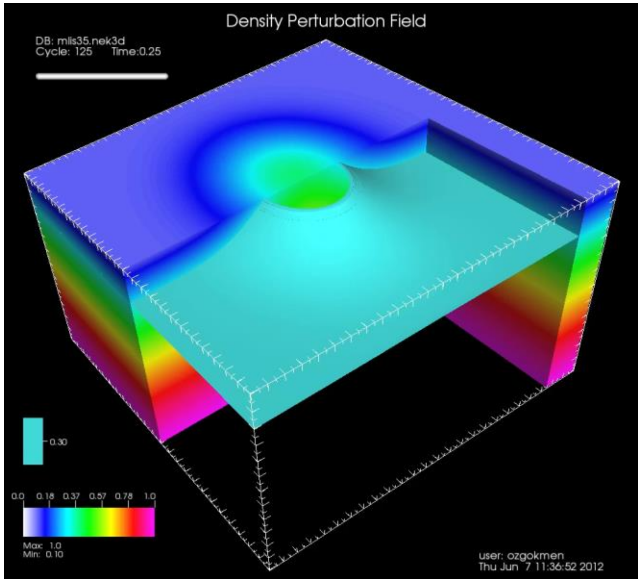
Do MLI play a role in the formation of star eddies?

A Cyclone Protruding into the Mixed Layer:

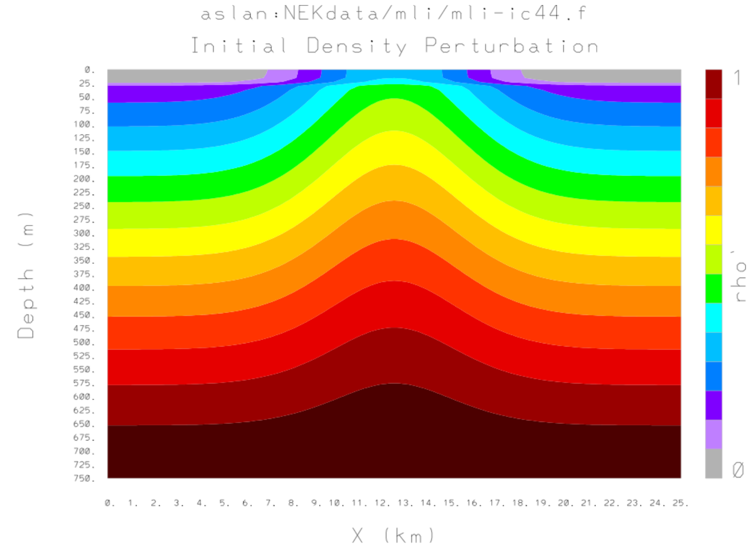
Domain: 25 km x 25 km x 750 m

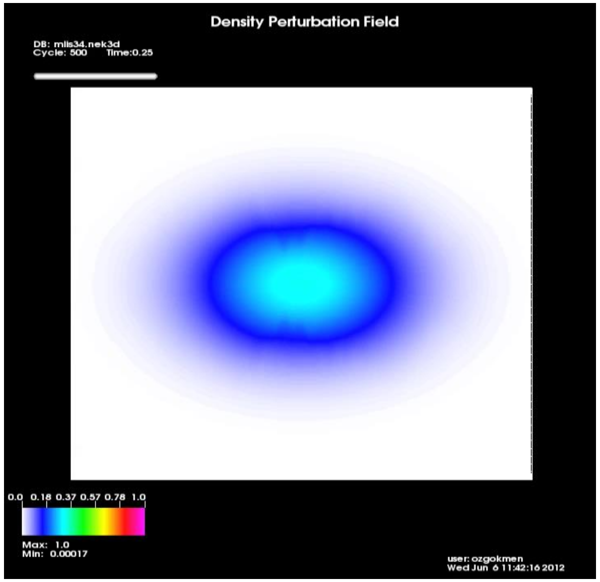
MLD=0 m



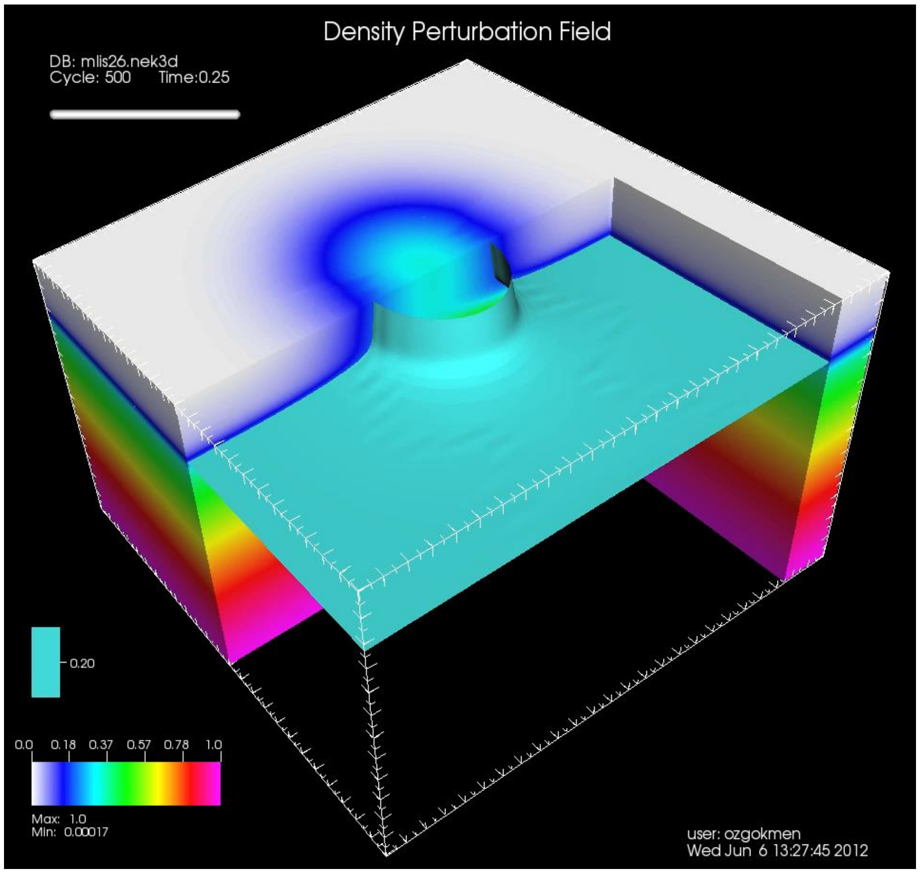


MLD=25 m

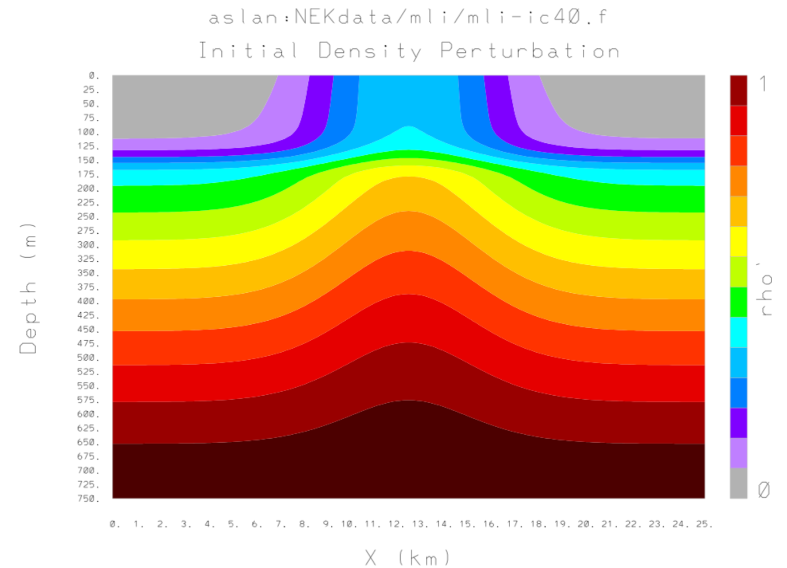




Deeper Mixed Layer for Stronger Submesocales:

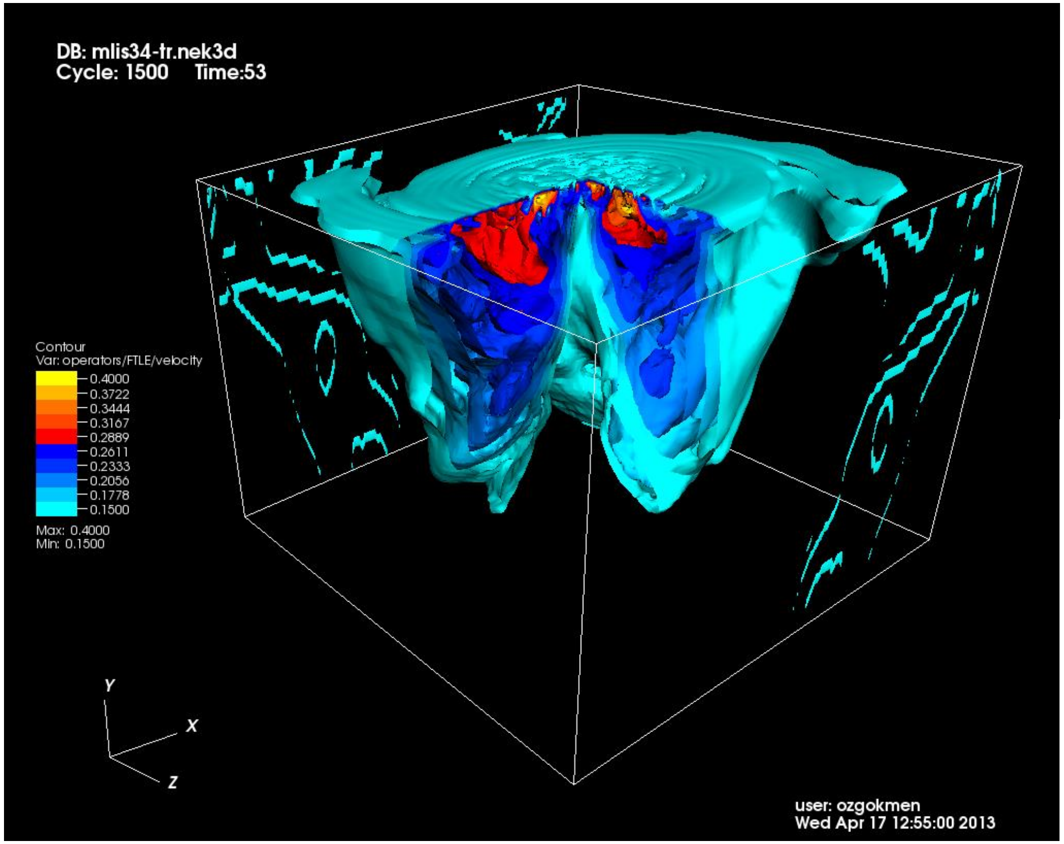


MLD=150 m

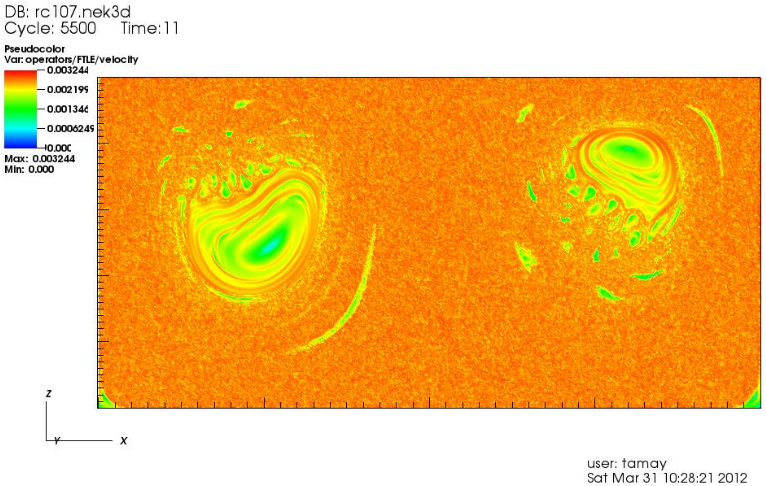


The net dispersive effect of inertia-gravity waves (3D+1 phenomenon missing in OGCMs) emitted fro the ageostrophic breakdown
is under investigation

3D FTLEs From LES of Oceanic Eddies:



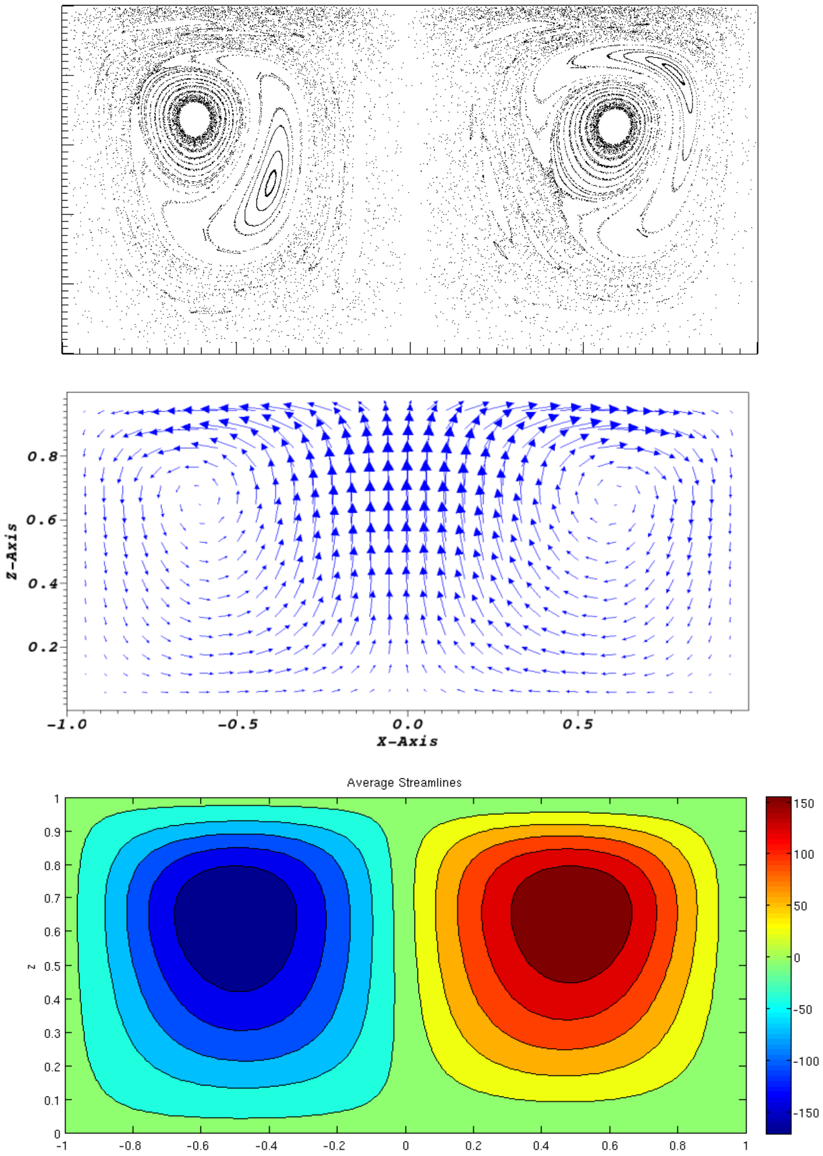
Rotating can example:



Do tori exist in more realistic eddies? Look into the influences of
(a) high Re, and (b) high aspect ratio, [(c) stratification, (d) time dependence]

Transport Behavior as a Function of Reynolds Number

Re=32



Re=512:

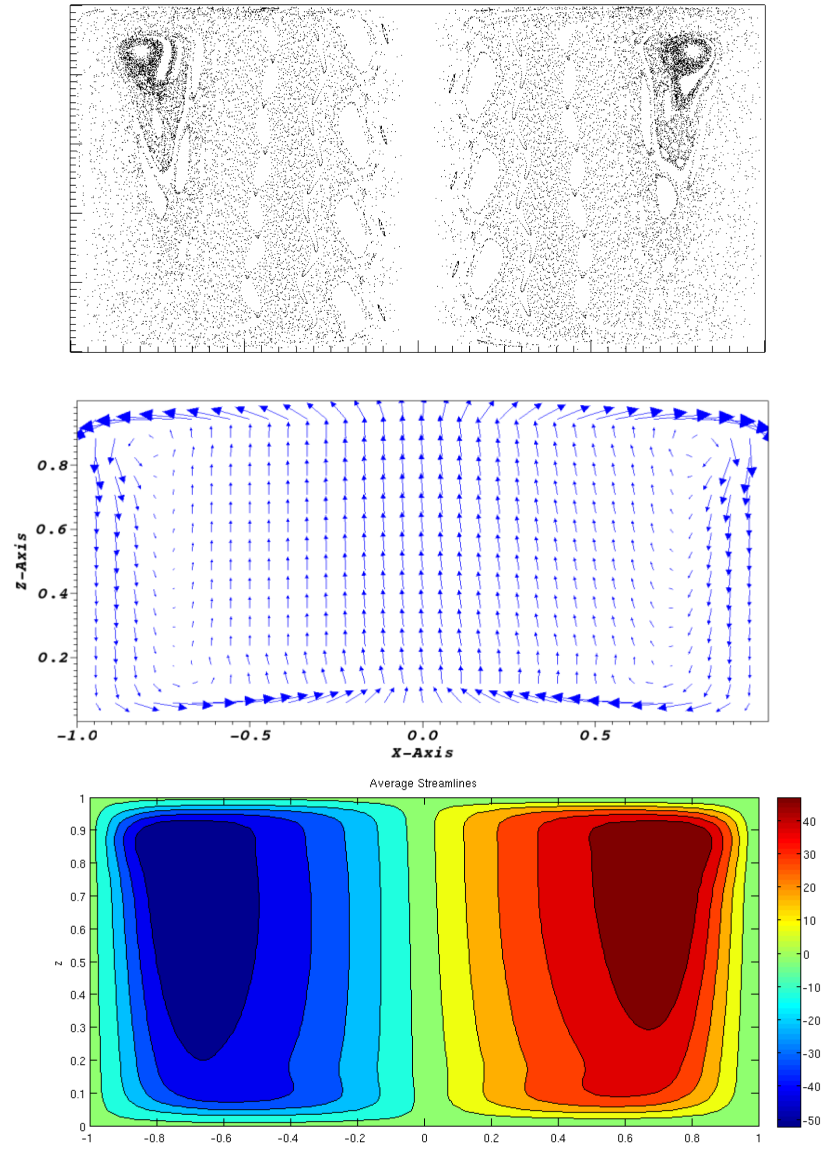
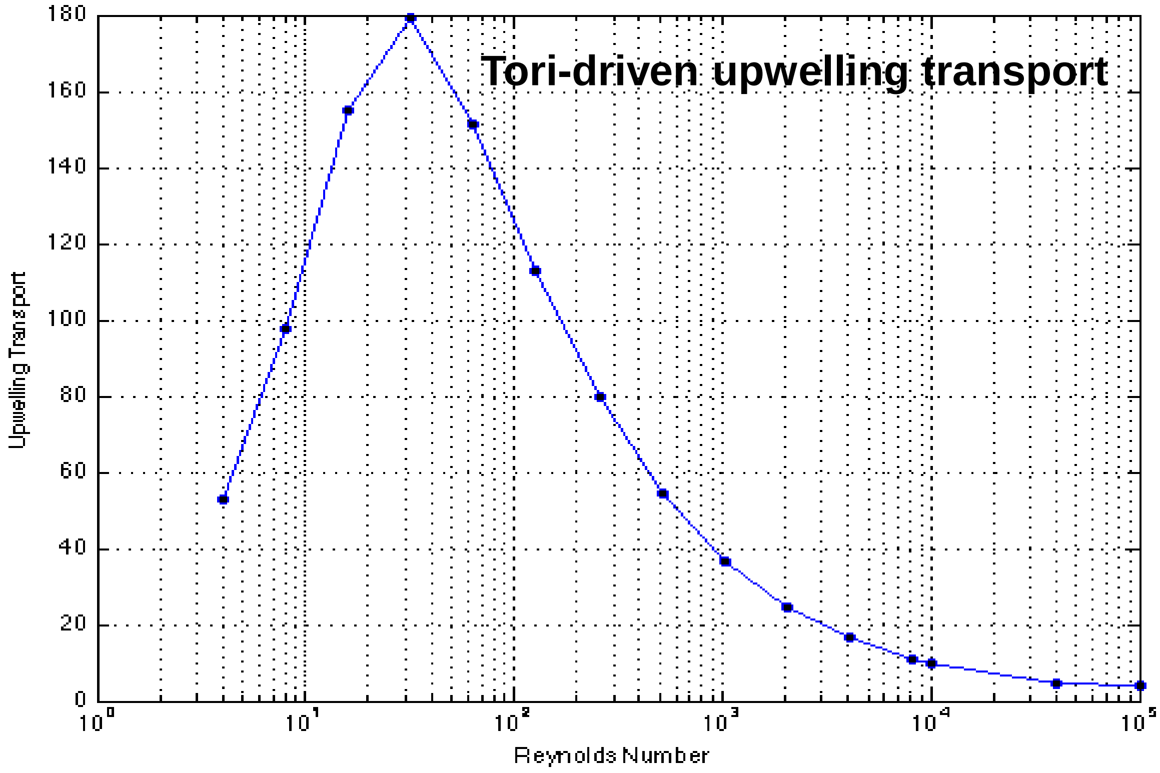


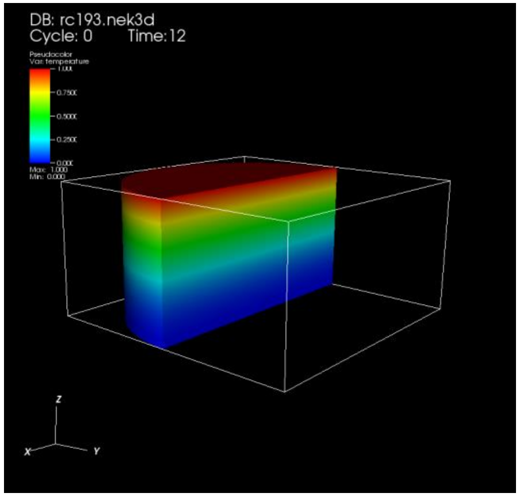
Image credit: Wang

Overturning Streamfunction vs Reynolds Number

Max. overturning streamfunction is important for biogeophysical transport within eddies…



Re=32



Re=512

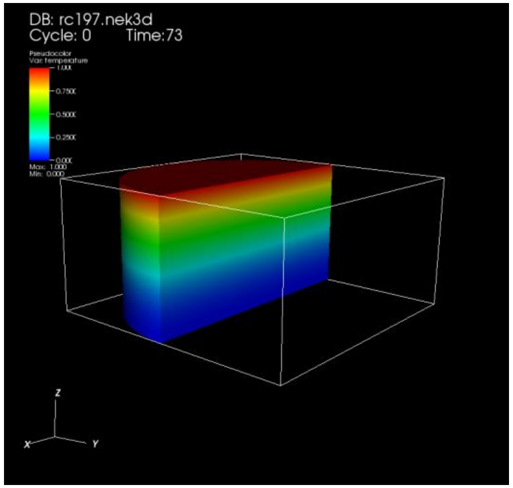
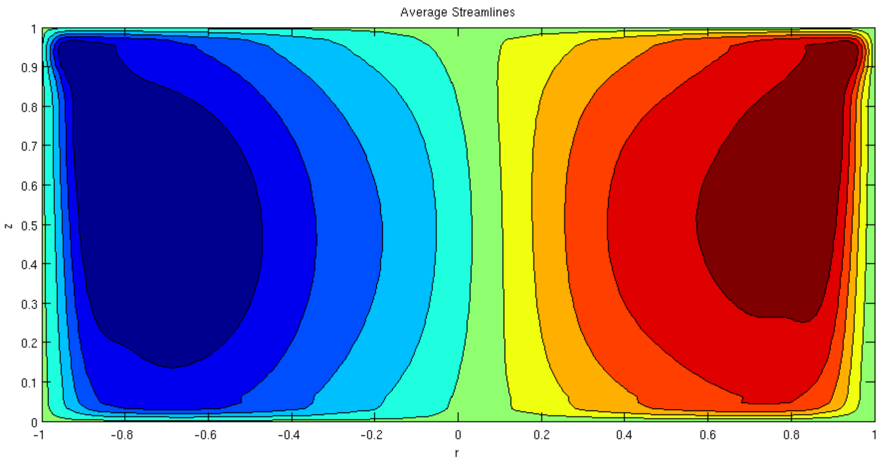
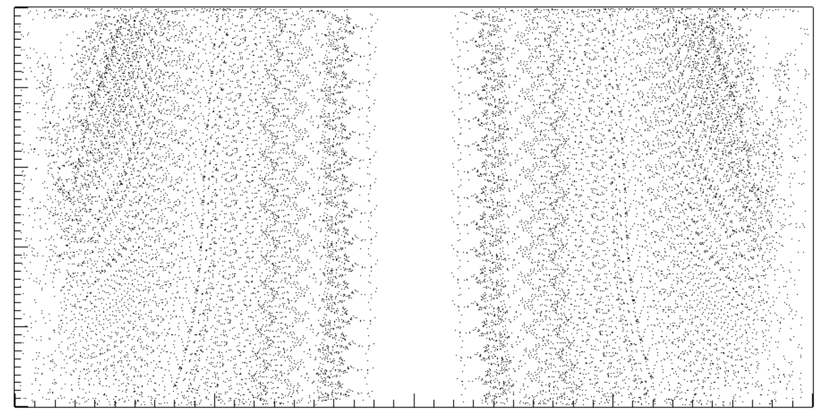


Image credit: Wang

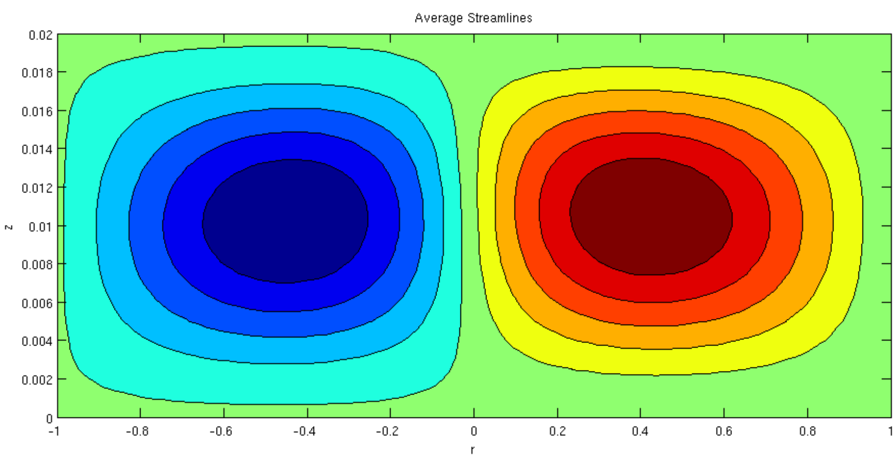
Transport Behavior as a Function of Aspect Ratio

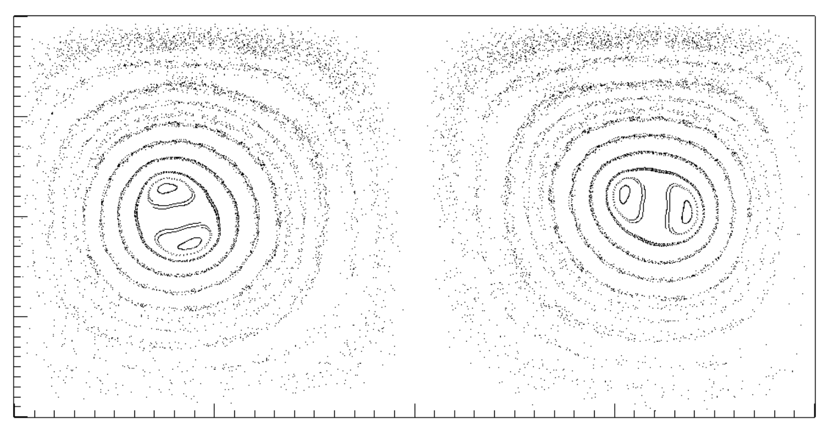
Re=8192, Aspect=1





Re=8192, Aspect=1/50 (stretched)





Return of the tori

Image credit: Wang

Can 3D+1 Methods Help Define Mixed Layer Depth?

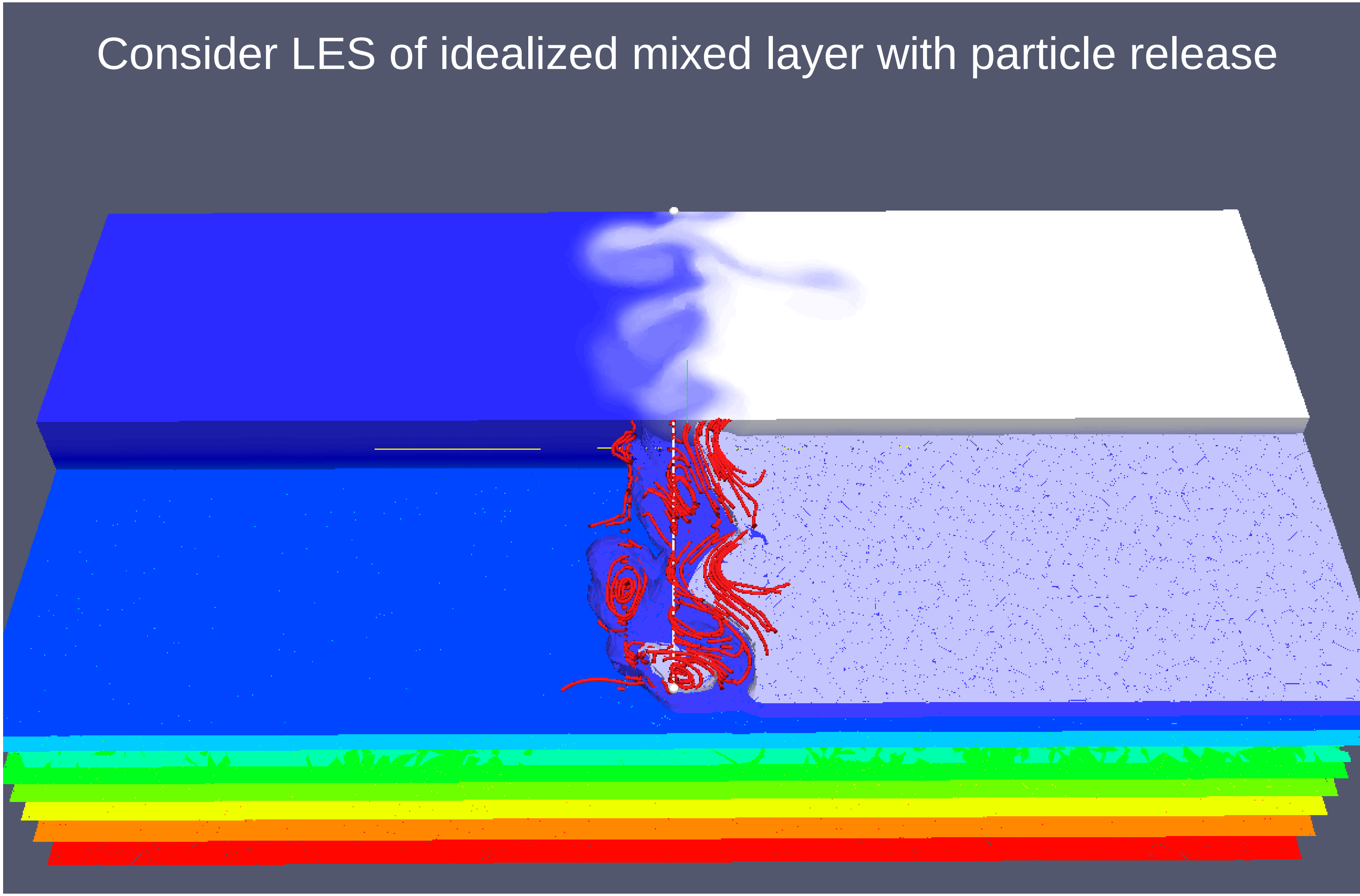


Image credit: Mensa

Mixed Layer Depth = Vertical FSLE Ridge (possibly leaky transport barrier)?

HYCOM definition
of 0.3 C difference
leads to spurious MLD

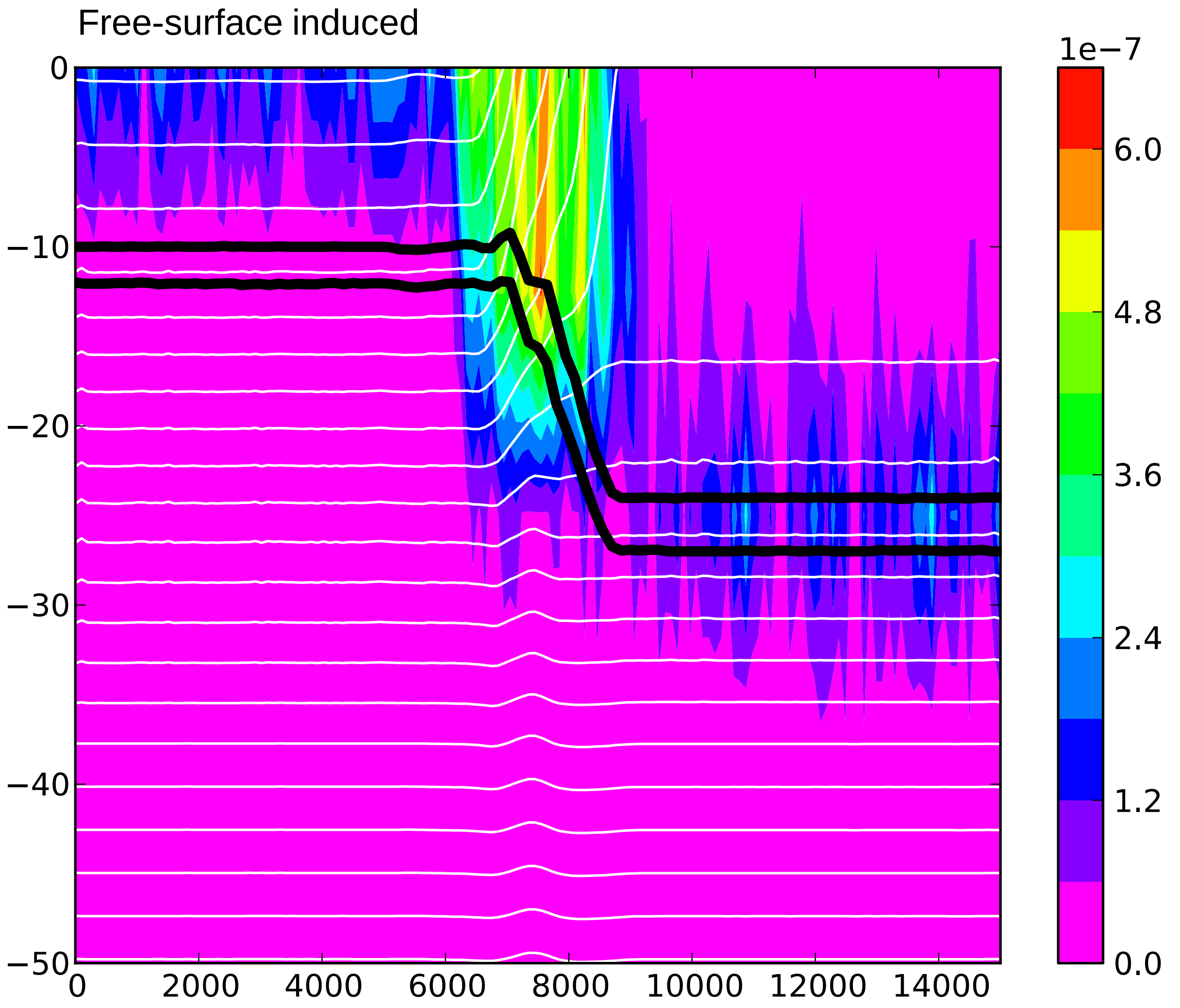


Image credit: Mensa

Going fully realistic: HYCOM simulation of the Gulf Stream region

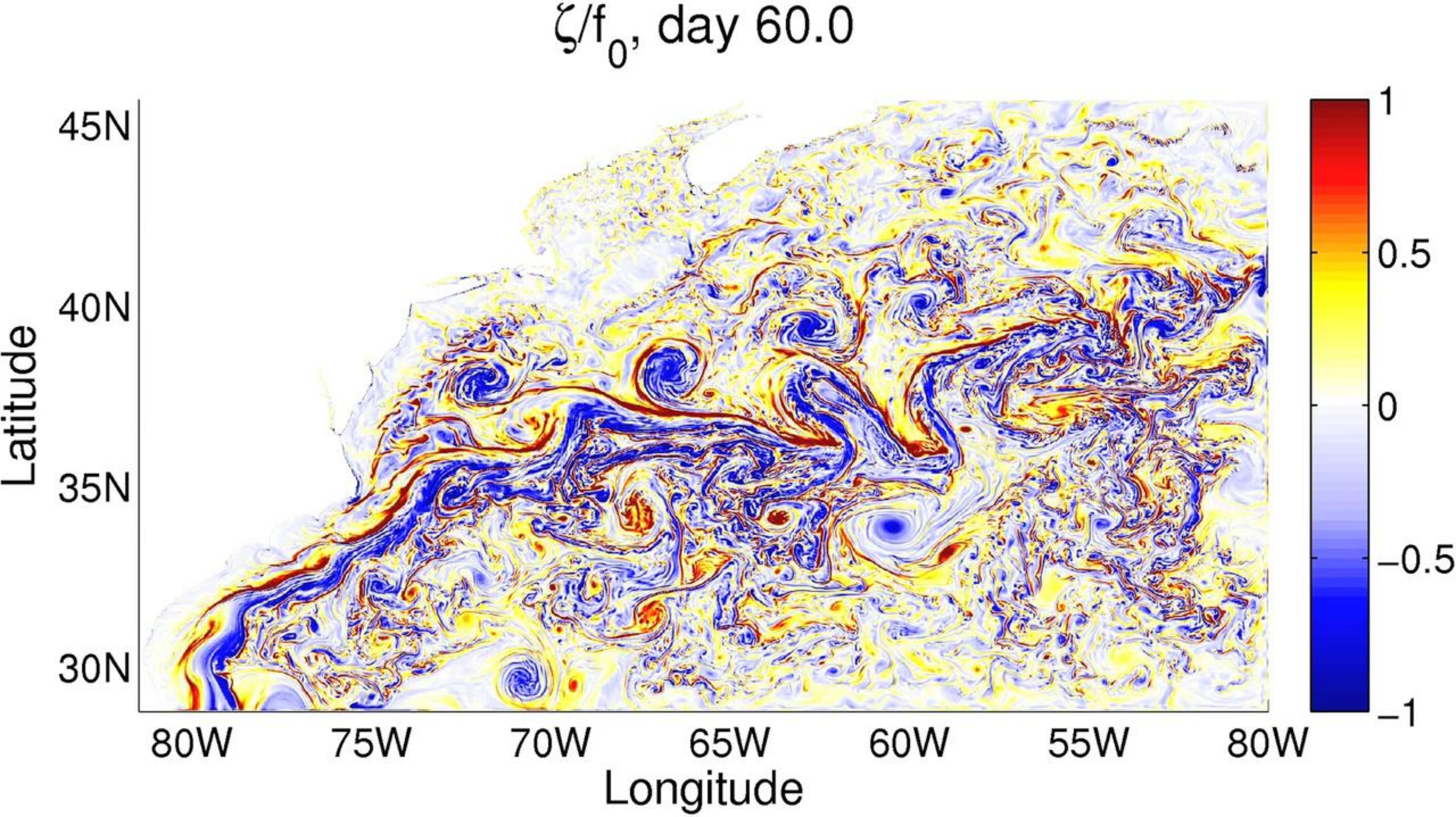
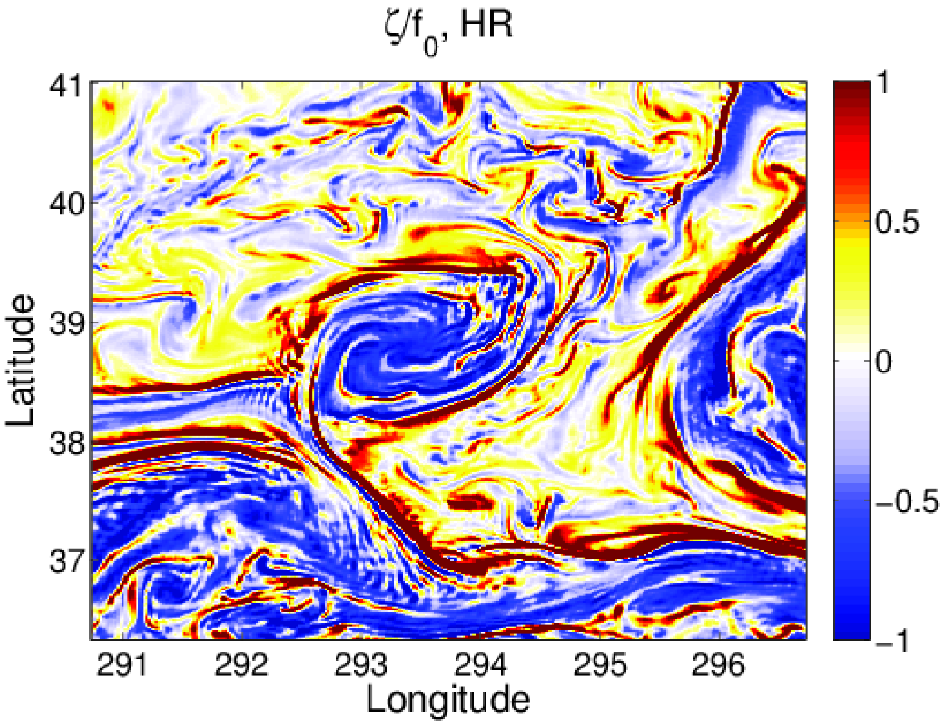


Image credit: Mensa

Focus Near the Surface Instead of Deep Ocean:

Explore Mixed Layer & Eddy Interactions

- Two seasons: summer and winter
- Two rings: cyclonic and anticyclonic
- Two resolutions: 1/48 (submesoscale permitting) and 1/12



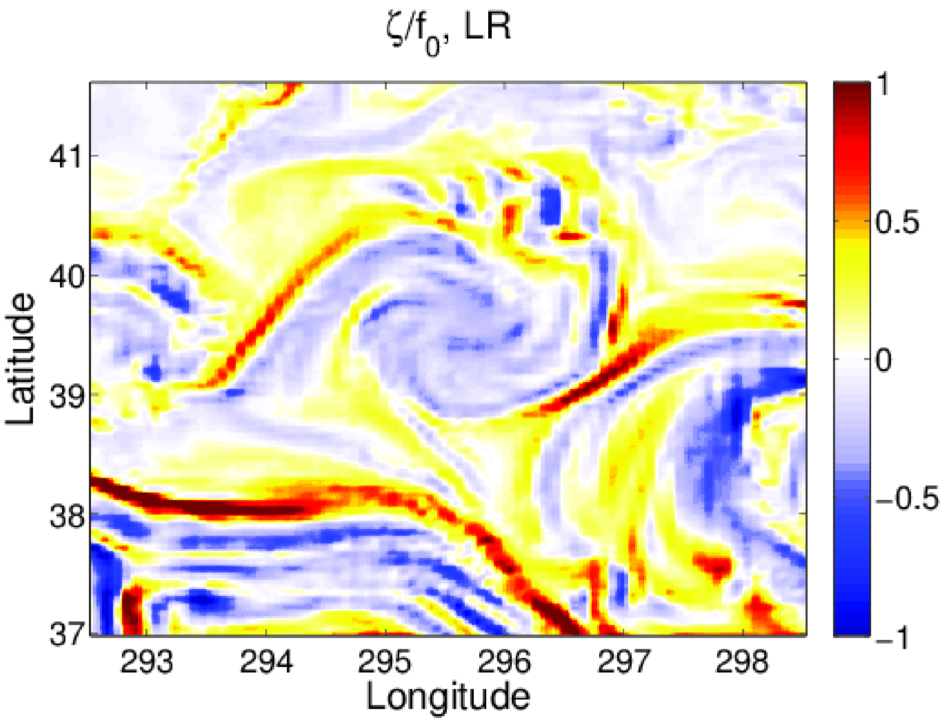


Image credit: Mensa

Modified vertical exchange due to the active mixed layer processes:

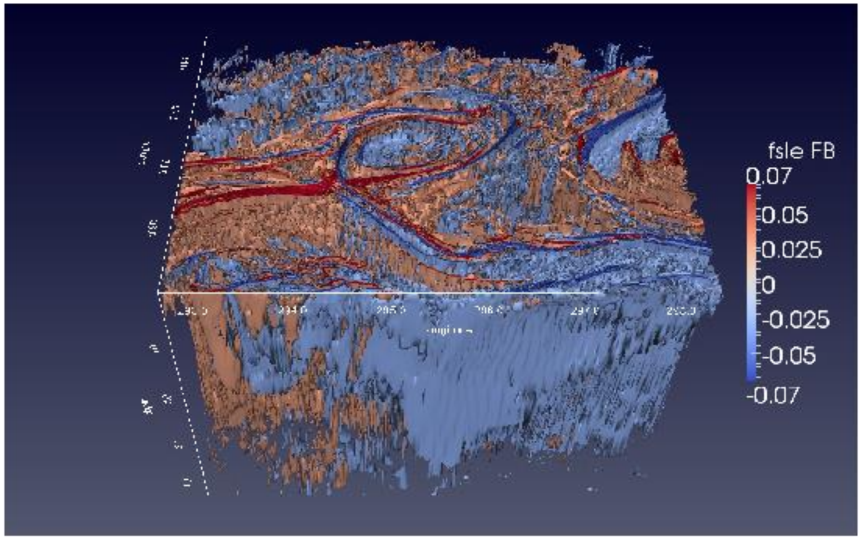
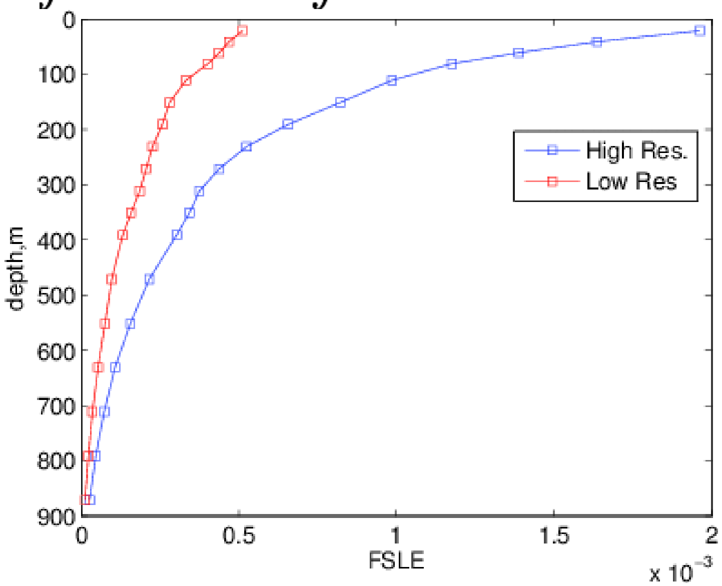
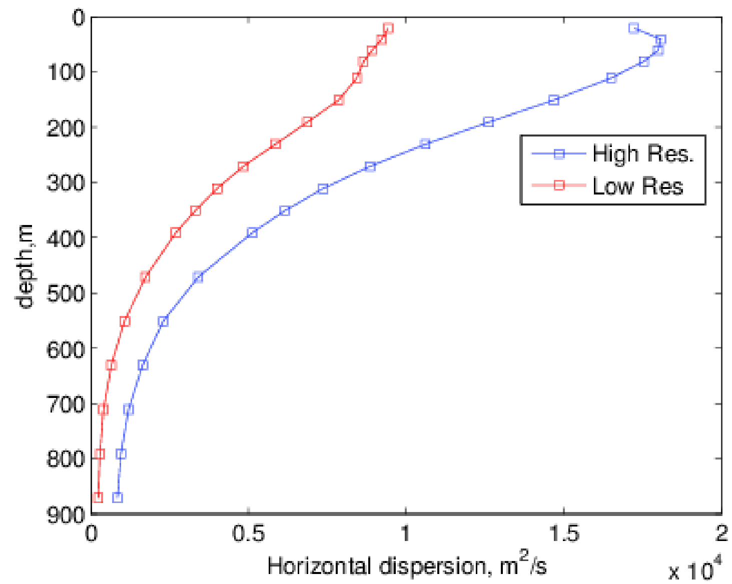


Image credit: Chang & Mensa

$$\int \lambda(\delta) d\,A = \int log(\alpha)/\langle\tau(\delta)\rangle\, d\,A$$



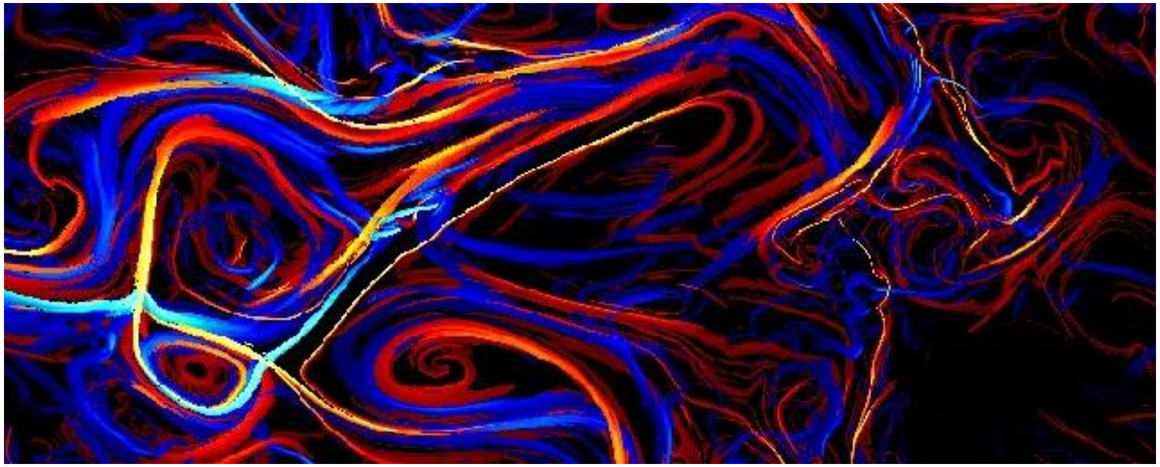
$$\int K_h(t)\, dA = \int \frac{1}{2}\frac{d}{dt}\langle|x_i(t) - \langle x_i(t)\rangle|^2\rangle\, dA$$



Which Scales Control Transport in the Ocean?

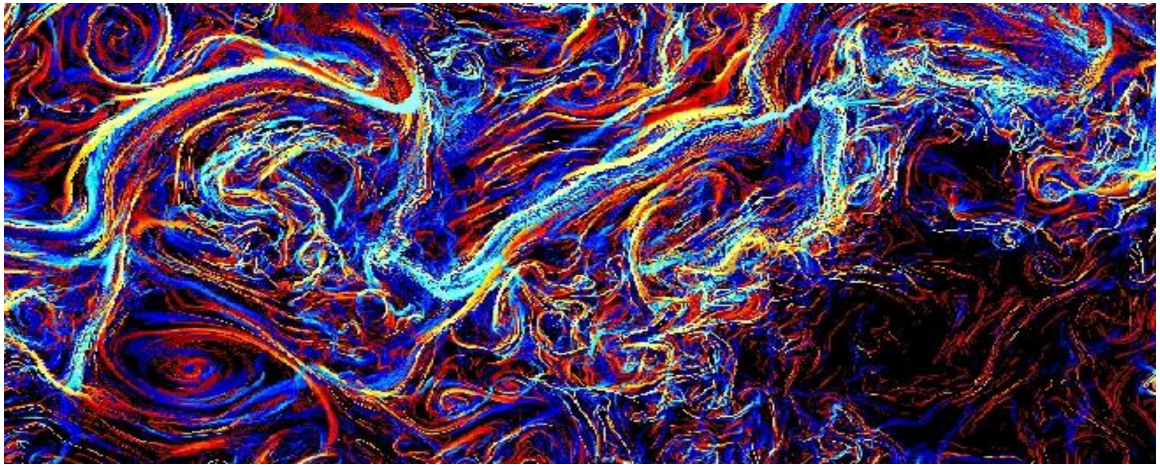
Poje et al. (2010)

Haza et al. (2012)



1/12 degree HYCOM

Image credit: Haza



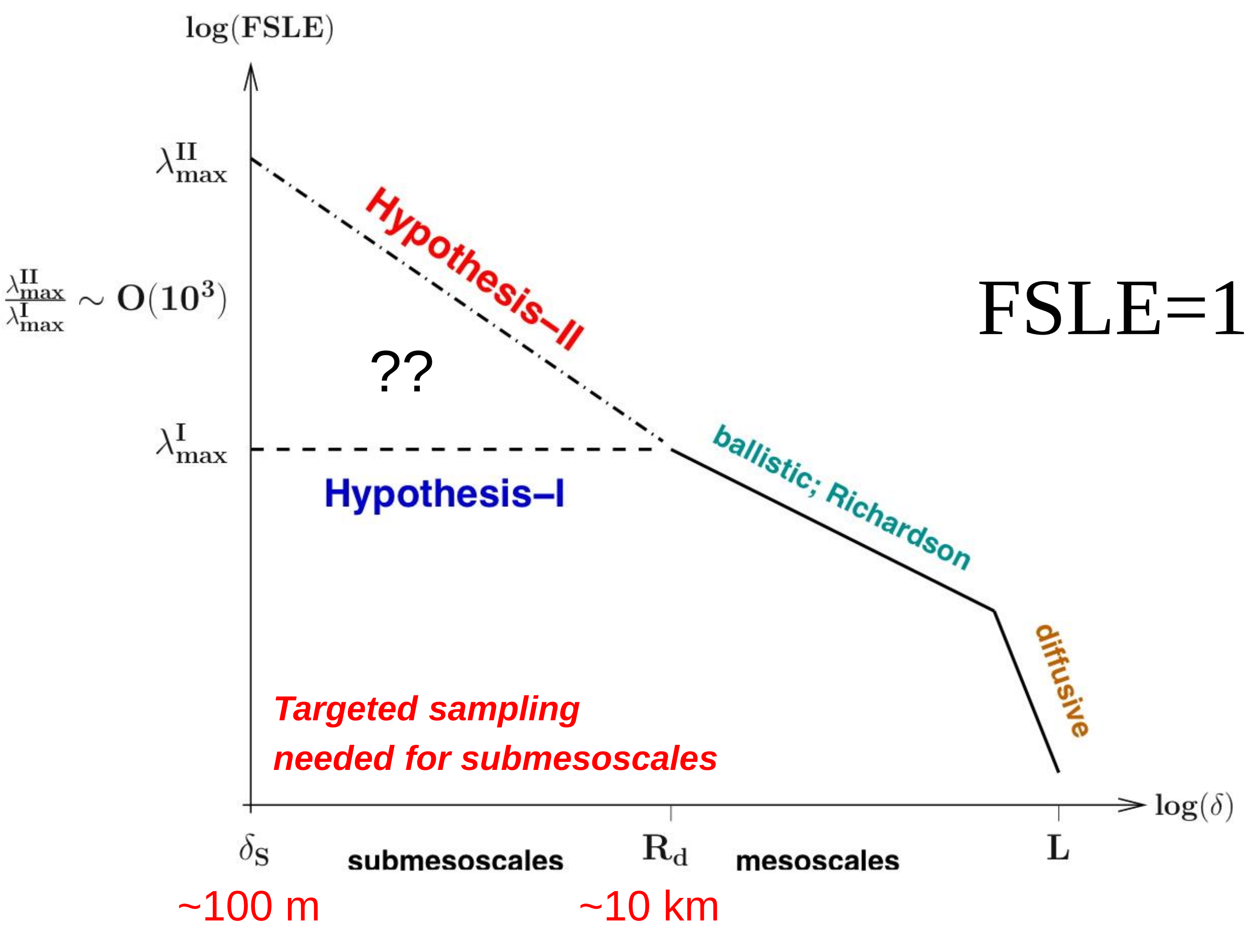
1/48 degree HYCOM

• Which turbulent features control the transport?

(I) Are the long-living, slow mesoscale features enough to compute transport?

(II) Or, rapidly-evolving, smaller submesoscale transport barriers are needed?

A Scale-Dependent Lagrangian Measure of Ocean Transport



$$\text{FSLE} = 1/\tau$$

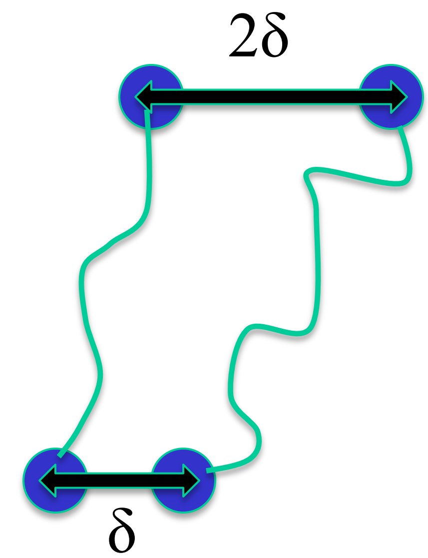


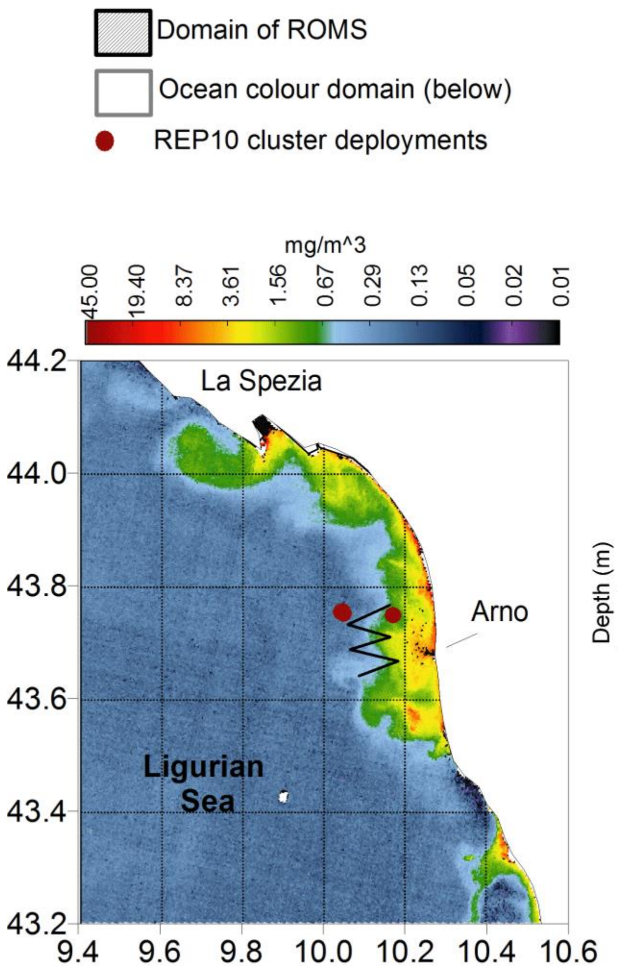
Image credit:
Özgökmen & Poje

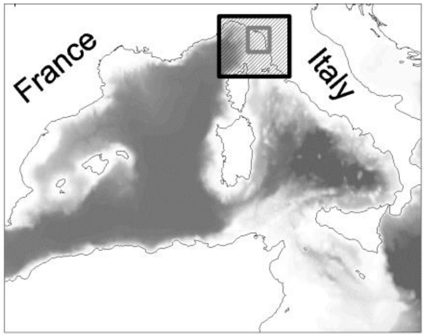
Hypothesis-I : energetic and slowly-evolving turbulent features in control,
data-assimilating OGCMs would be adequate to give good predictions

Hypothesis-II : rapidly-evolving small scales dictate relative dispersion at submesoscales,
parameterizations for submesoscale processes would be needed in OGCMs

Experiment Targeting a Coastal Buoyant Discharge (with NURC, CNR)

- Two experiments (LIDEX), one month apart were conducted at same place in 2010; experimental deployment templates were tested with two dozen drifters; has set the stage for GLAD (Grand Lagrangian Deployment)





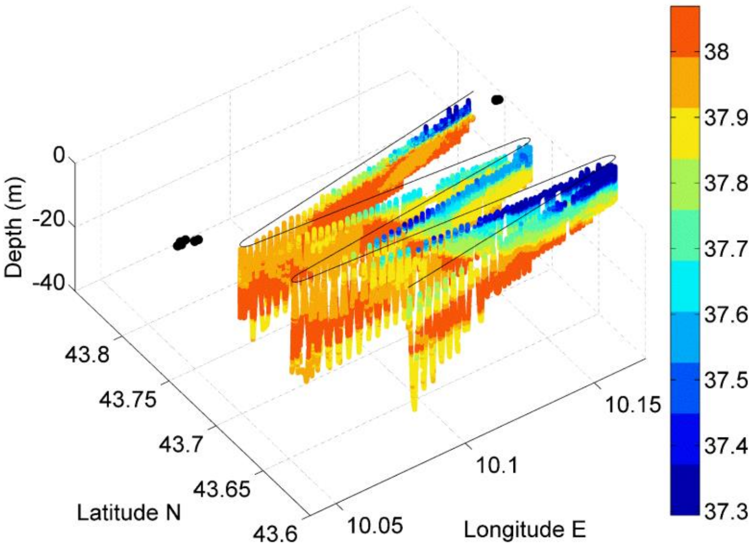
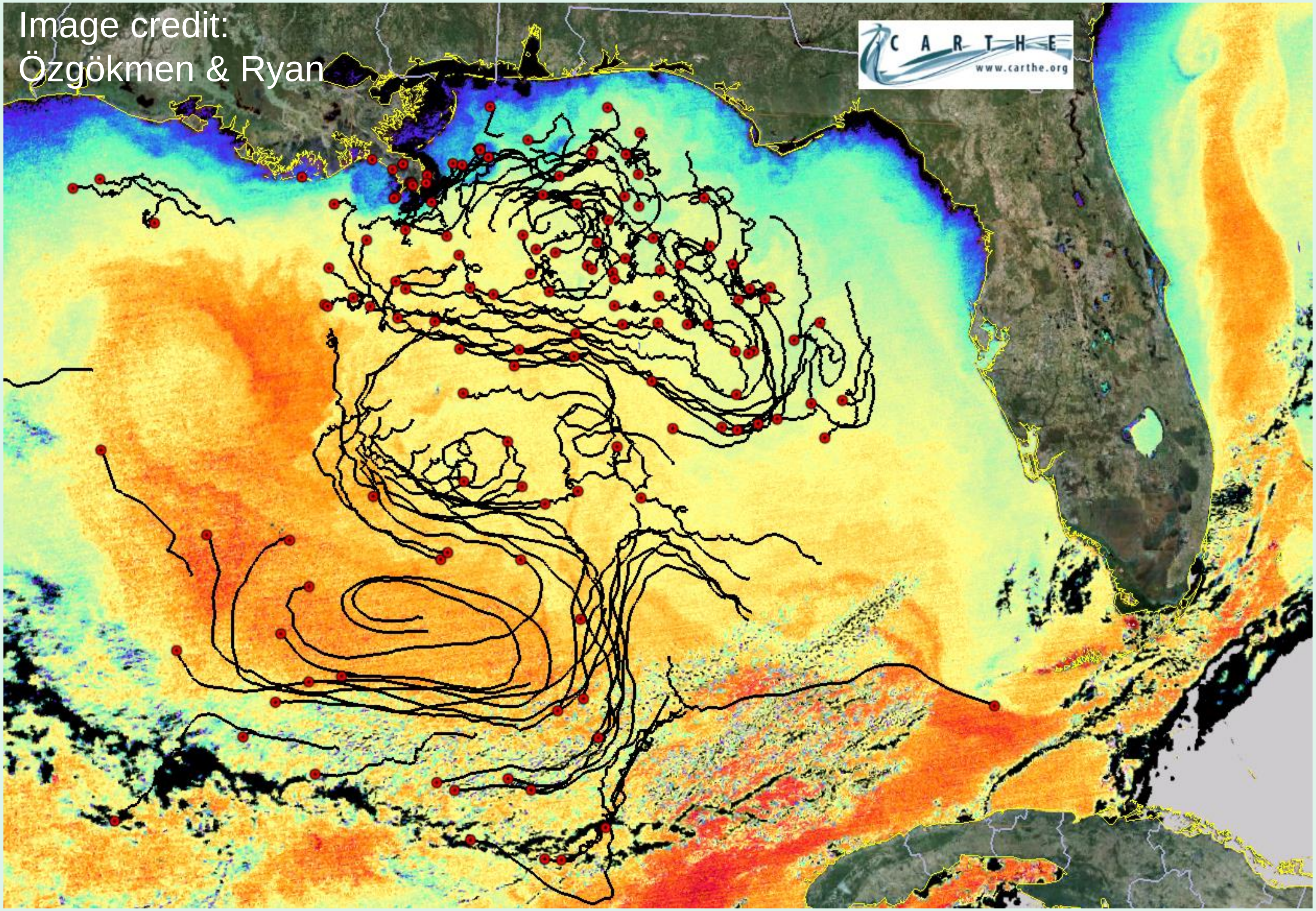


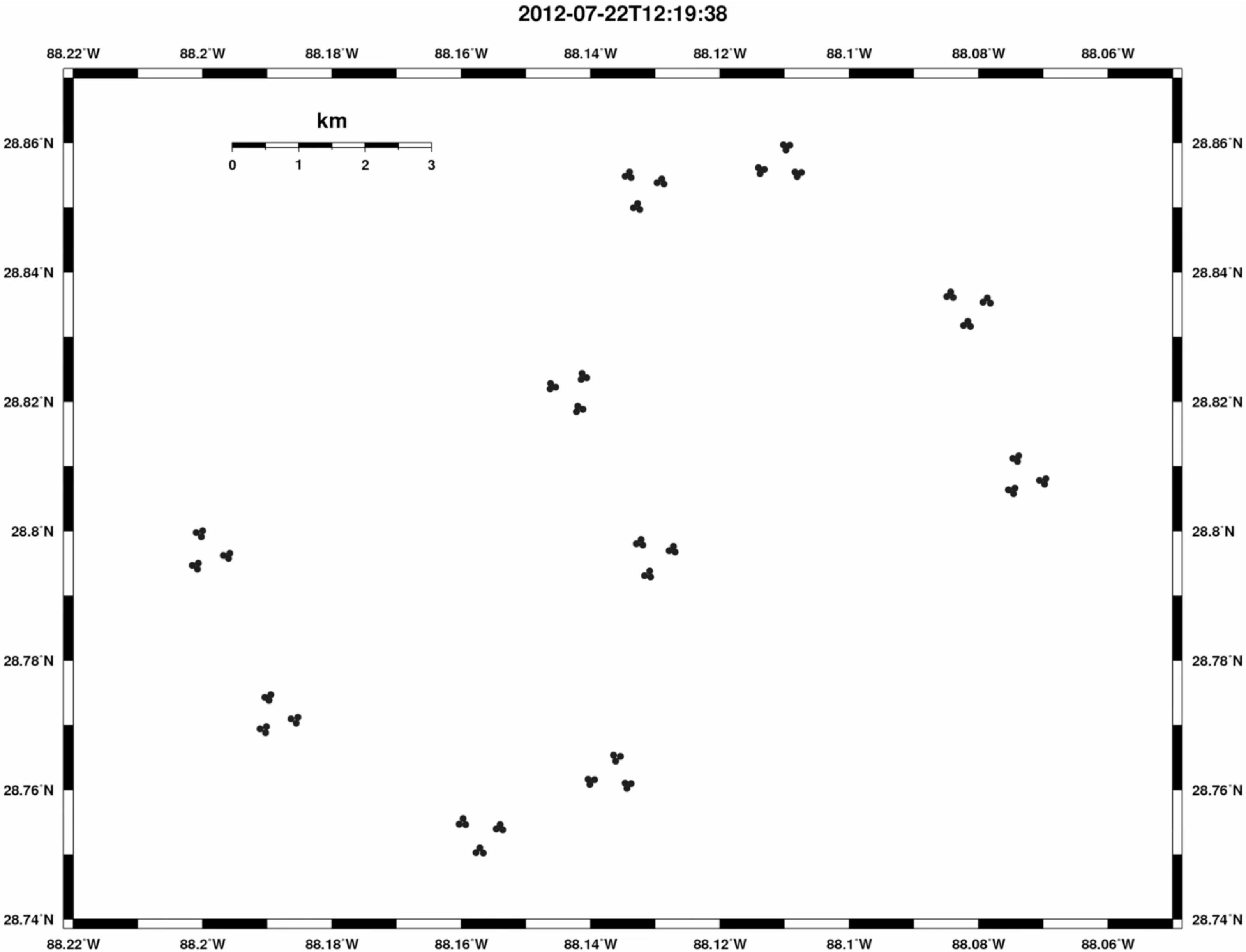
Image credit: Griffa

Grand Lagrangian Deployment (GLAD) in the GoM



Designed based on LES and NRL/OGCM studies: 317 drifters with 100 m to 10 km spacings, 5-15 mins position transmission, 5 m position accuracy, > 2 months tracking, largest ever synoptic drifter deployment *(GoMRI supported)*

Multi-Scale Deployment Template:



What Does GLAD Show: Hypothesis-I or Hypothesis-II?

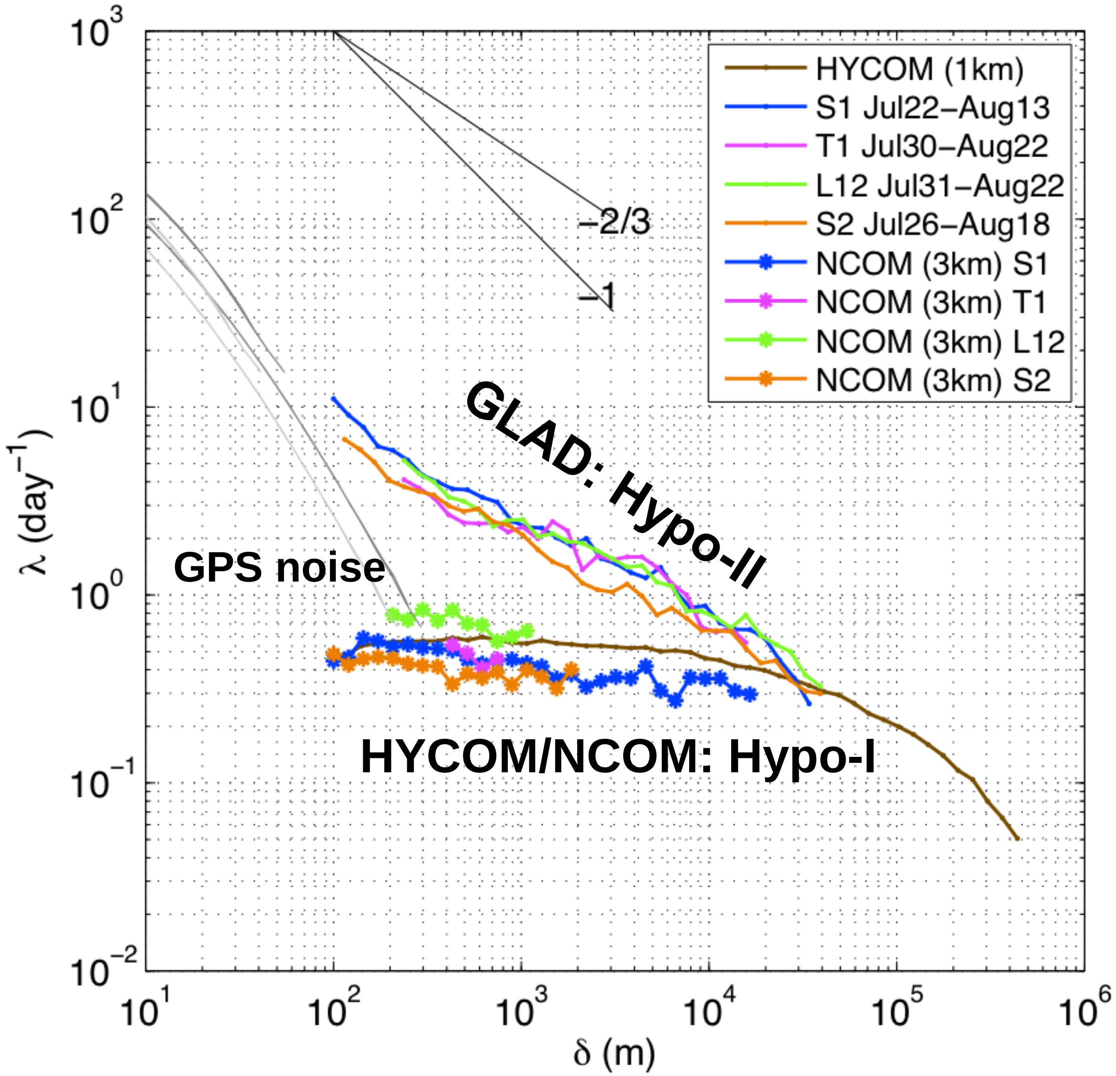


Image credit: Haza

Richardson scaling from 100 m to 20 km; ***submesoscales affect transport!***
(similar to results from Ligurian Sea experiments)

Parameterizations by Haza et al. (2012) can be applied to fix the dispersion deficit in OGCMs now that the truth is known.

Publications Fully or Partially Supported by 3D+1 MURI:
(5 published, 1 in revision, 2 submitted, 1 almost ready, much of the work in flux)

1) Özgökmen, T.M., A.C. Poje, P.F. Fischer, and A.C. Haza, 2011: Large eddy simulations of mixed layer instabilities and sampling strategies. Ocean Modelling, 39, 311-331.

2) Haza, A.C., Özgökmen, T.M., A. Griffa, Z. D. Garraffo and L. Piterbarg, 2012: Parameterization of particle transport at submesoscales in the Gulf Stream region using Lagrangian subgridscale models. Ocean Modelling, 42, 31-49.

3) Schroeder, K., Chiggiato, J., Haza, A.C., A. Griffa, Özgökmen, T.M., P. Zanasca, A. Molcard, M. Borghini, P.M. Poulain, R. Gerin, Z. Zambianchi, P. Falco and C. Trees, 2012: Targeted Lagrangian sampling of submesoscale dispersion at a coastal frontal zone. Geophys. Res. Lett., 39, L11608, doi:10.1029/2012GL051879.

4) Özgökmen, T.M., A.C. Poje, P.F. Fischer, H. Childs, H. Krishnan, C. Garth, A. Haza and E. Ryan, 2012: On multi-scale dispersion under the influence of surface mixed layer instabilities and deep flows. Ocean Modelling, 56, 16-30.

5) Griffa, A., Haza A.C., Özgökmen, T.M., A. Molcard, V. Taillandier, K. Schroeder, Y. Chang and P.M. Poulain, 2013: Investigating transport pathways in the ocean. Deep Sea Research II, 85, 81-95.

6) Pratt, L., I. Rypina, T.M. Özgökmen, H. Childs and Y. Bebieva: Chaotic advection in a sready, three-dimensional, Ekman-driven eddy. Journal of Fluid Mechanics, submitted: 17 September 2012, in revision: March 2013.

7) Mensa, J., A. Griffa, Z. Garraffo, T.M. Özgökmen and M. Veneziani: Seasonality of the submesoscale dynamics in the Gulf Stream region. Ocean Dynamics, submitted: March 2013.

8) Piterbarg, L.I., V. Taillandier, and A. Griffa: Investigating frontal variability from repeated glider transects in the Ligurian Current (North West Mediterranean Sea). J. Mar. Sys., submitted (April 2, 2013).

9) Haza, A.C., Özgökmen, T.M. and A. Griffa: Impact of noise and sampling on relative dispersion estimates at oceanic submesoscales. Near completion.

Summary:

1) A 3D FTLE (backward and forward, steady state) software was developed within a 3D parallel visualization package in collaboration with their developers at LBNL.

2) We find that 3D+1 methods are insightful even in highly turbulent problems involving coherent structures generated by (i) rotational control, (ii) stratification, and (iii) boundary layer stabilization.

3) Near-surface flows are not only of interest for the navy & general public but also where some of the highest vertical transport in the ocean takes place. As such, we have focused much of our attention on the exchange between mixed layer and deeper ocean using mostly nonhydrostatic (prognostic W) modeling.

4) Some industrial and pollution problems also involve high vertical velocities and can readily benefit from methodologies and insight being developed with the support of this MURI.

5) Tracer methods are complementary to particle methods:
   - *Tracer* : easy to visualize, reflects cumulative effect of motions but metrics of quantification underdeveloped

   - *Particles* : backward advection is useful and numerically trivial, many measures of mixing, but conservative nature may create detail that may not survive diffusivity.

Summary:

6) Questions about the multi-scale nature of transport in the ocean implied by 2D+1 LCS analysis have fueled oceanic experiments that have pushed forward the envelope of our understanding of the ocean:

   We now know that ageostrophic 3D+1 processes control transport at the oceanic submesoscales (100 m to 10 km);

   3D+1 analysis tools are critical for gaining insight into transport processes at the ocean's surface,
   and
   possibly any flow encountering complex geometry as well.

7) Any insights gained within the 3D+1 MURI were instantly transferred to problems tackled by Lateral Mixing DRI and GoM projects, and vice versa; efficient broader impacts.

8) Very strong ties with NRL prediction group (Jacobs) due to GoM project as well as Bruce's efforts (first talk after lunch…).