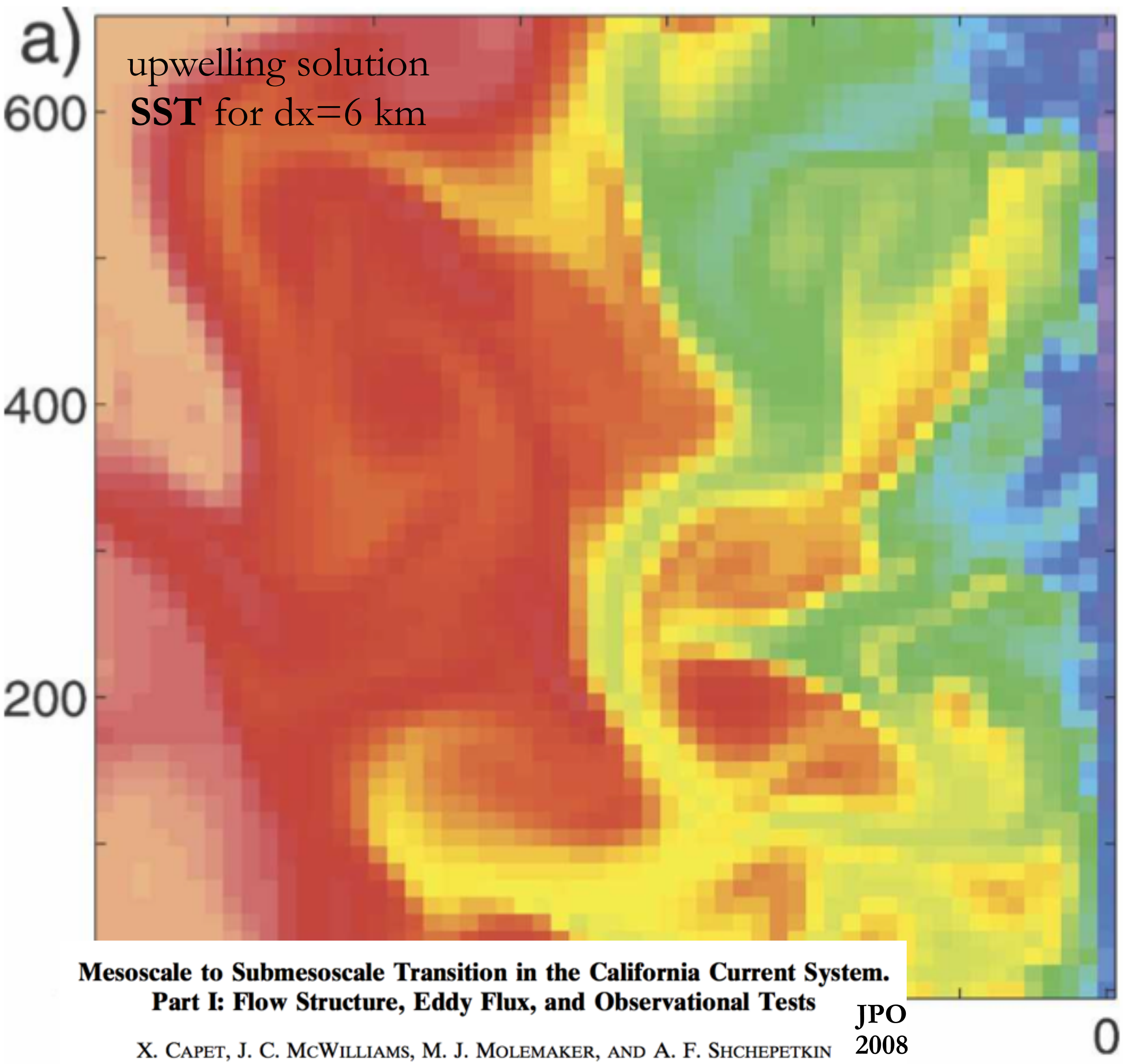
Ocean Scale Interactions - Brest, June 2014

SUBMESOSCALE FRONTAL TURBULENCE: RECENT PROGRESS AND SOME PERSPECTIVES

X. Capet (LOCEAN)

Acknowledgements: P. Klein, G. Roullet, J. McWilliams, P. Marchesiello, J. Jouanno, J. Molemaker, F. Colas, M. Lévy, G. Madec, G. Maze, L. Hua, A. Ponte, S. Smith, T. Penduff

What happens when resolution is enhanced in ocean models ?

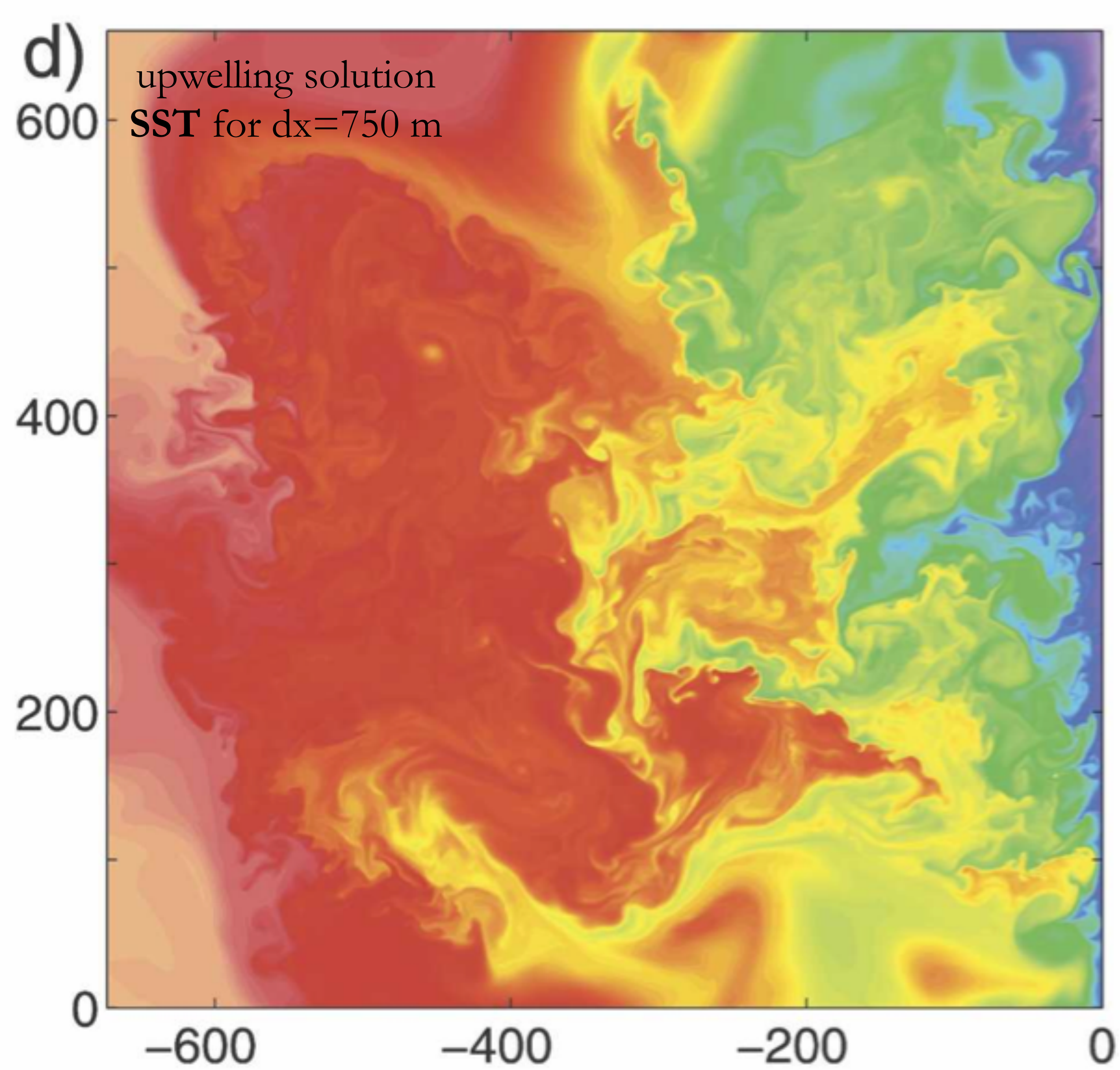


Mesoscale to Submesoscale Transition in the California Current System. Part I: Flow Structure, Eddy Flux, and Observational Tests

X. Capet, J. C. McWilliams, M. J. Molemaker, and A. F. Shchepetkin

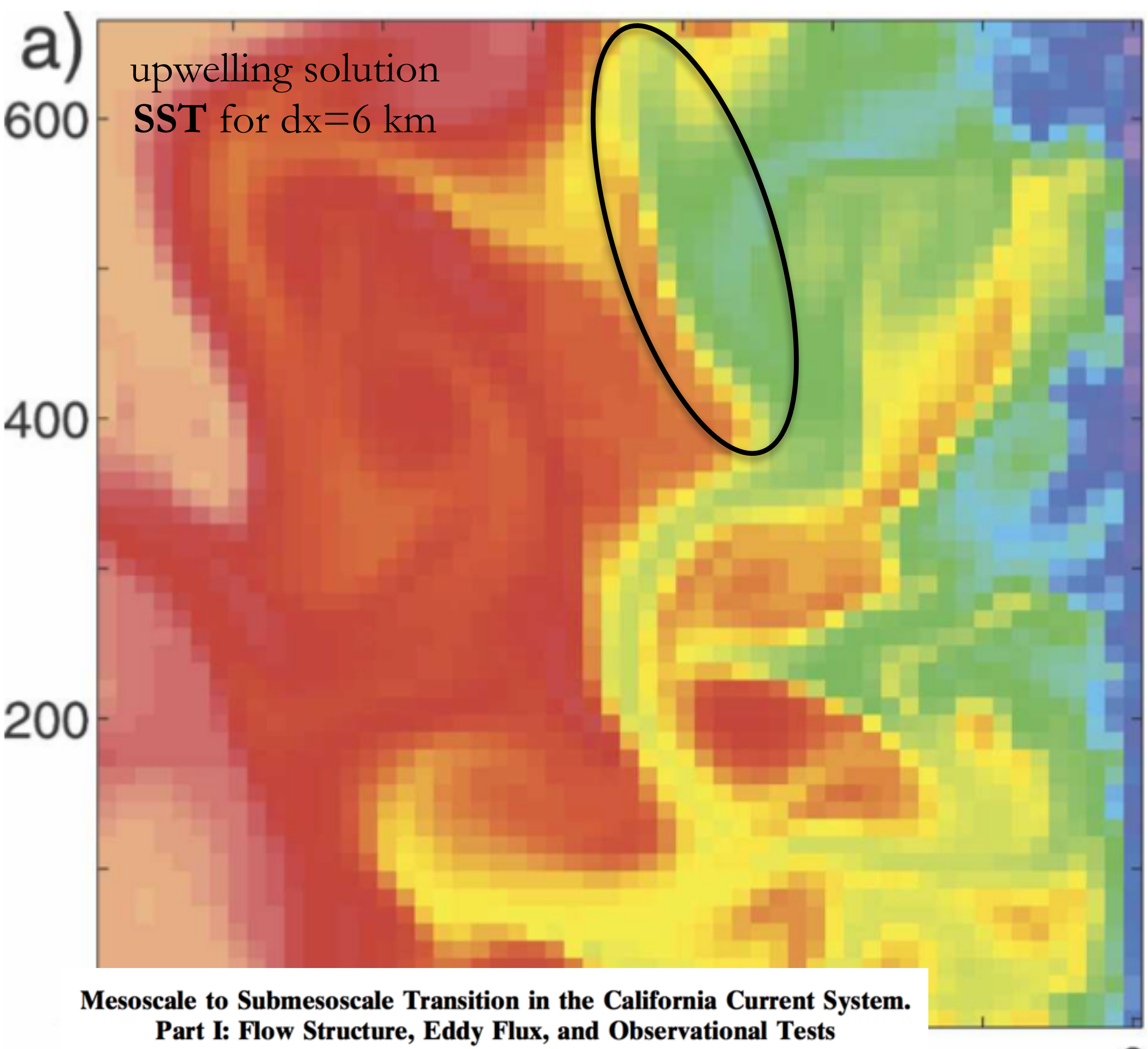
JPO 2008

not a refinement of the existing turbulent structures



new structures:
multiplication / complexification
of fronts

What happens when resolution is enhanced in ocean models ?



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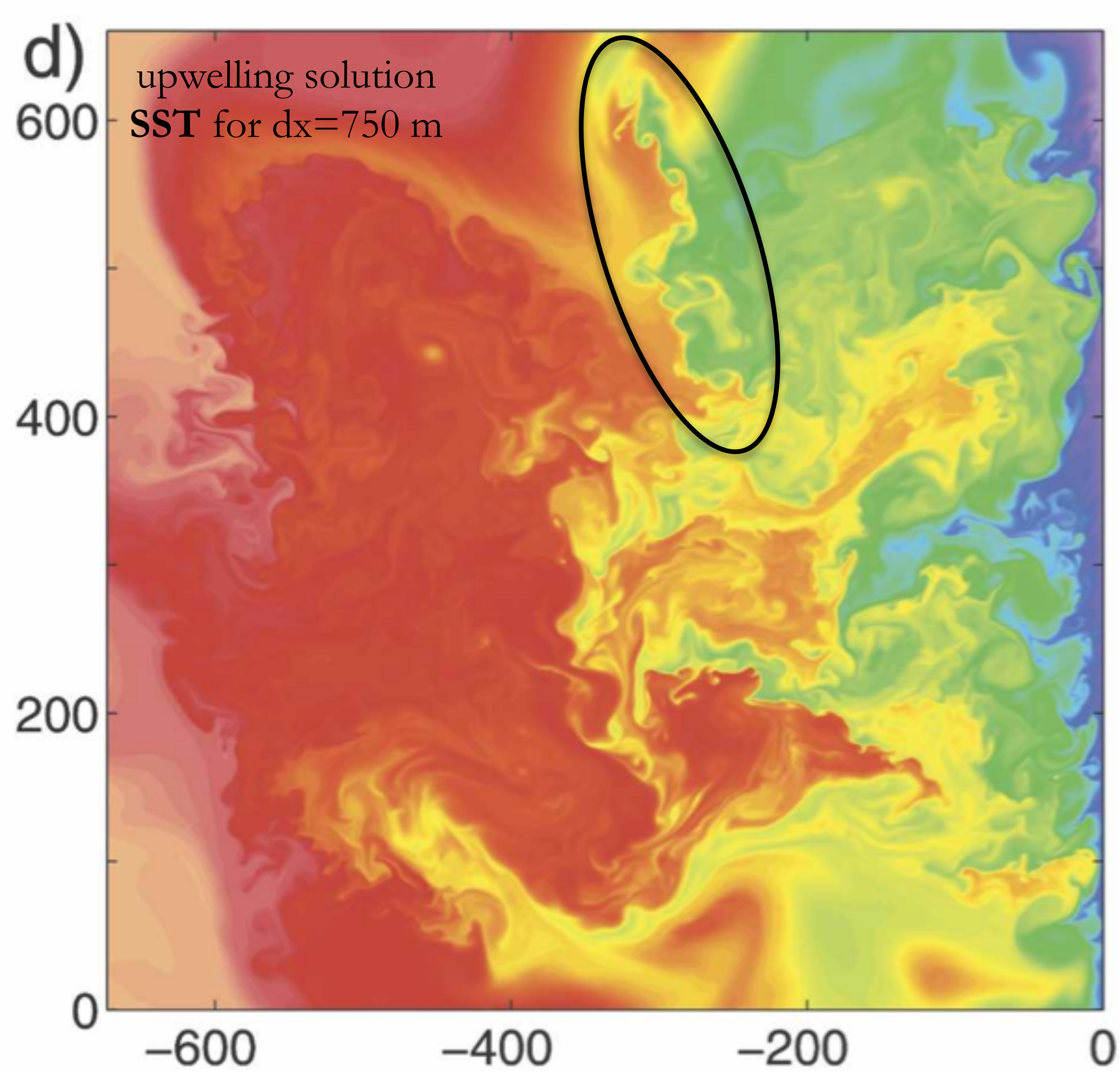


new structures:
fronts influenced by **rotation** but **large deviations from QG** (local Ro,Ri ~ 1, large w)

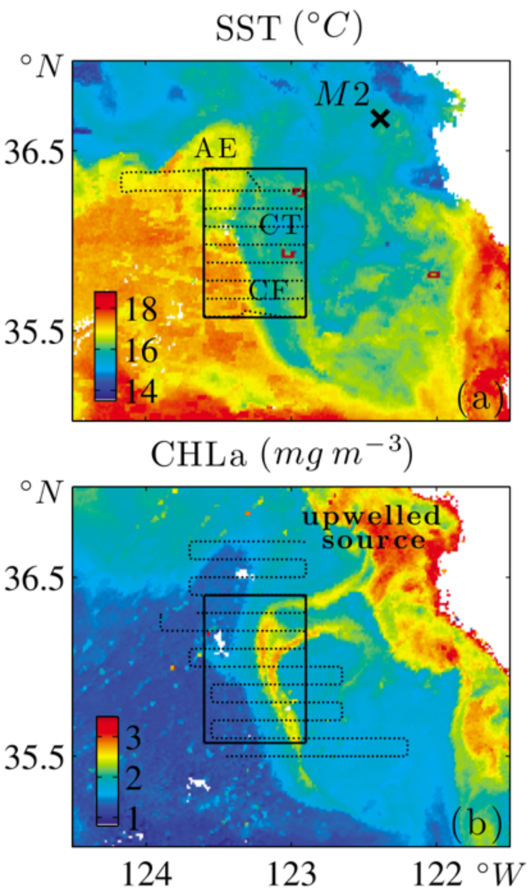
more energy at SMS than predicted by QG
(ample evidence from KE spectra)

accurate representation of ocean turbulence

Frontal dynamics in a California Current System shallow front: 1. Frontal processes and tracer structure

JGR 2010

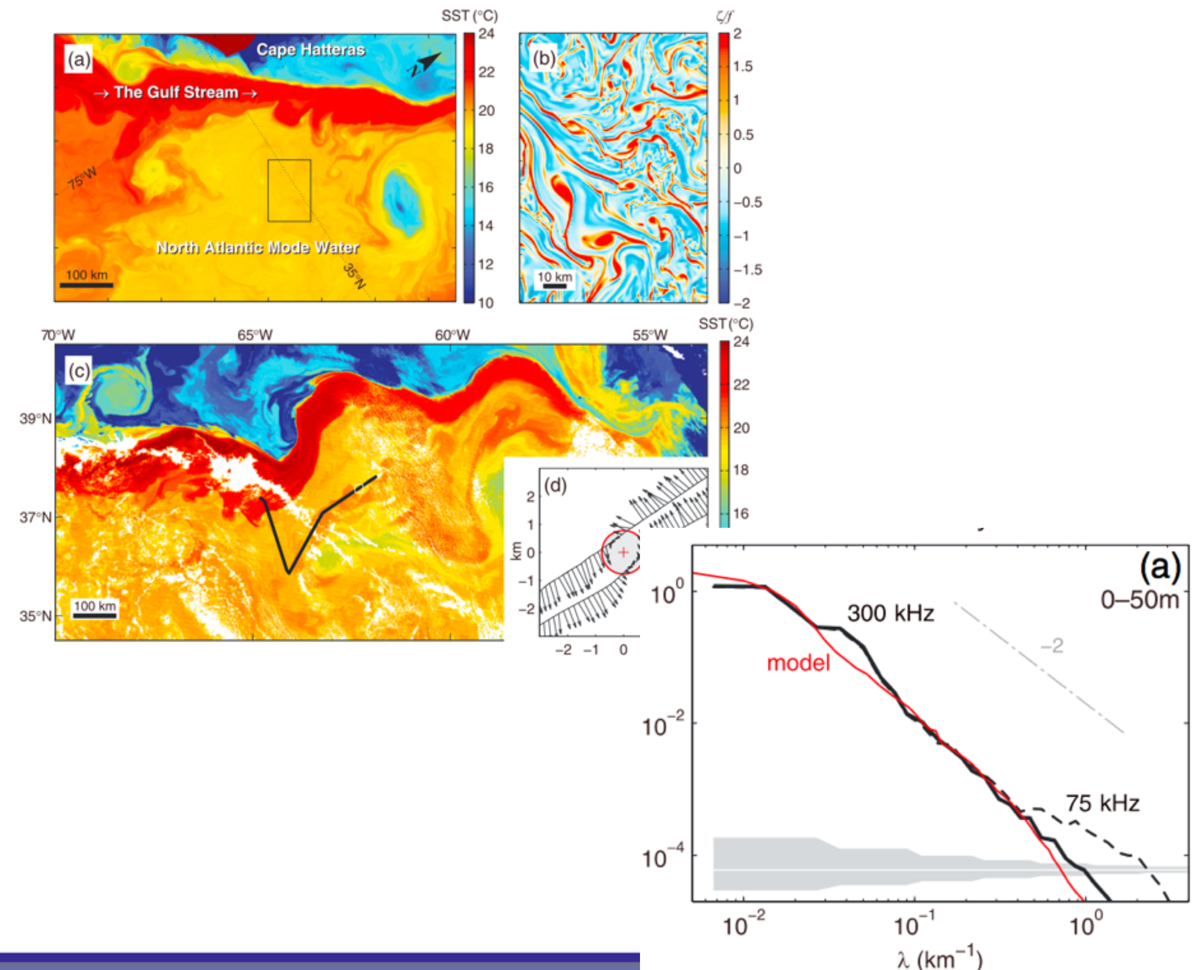
E. Pallàs-Sanz,[1,2] T. M. S. Johnston,[1] and D. L. Rudnick[1]



Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field

GRL 2013

Andrey Y. Shcherbina,[1] Eric A. D'Asaro,[1] Craig M. Lee,[1] Jody M. Klymak,[2] M. Jeroen Molemaker,[3] and James C. McWilliams[3]



SMS FRONTS & MIXED LAYER DYNAMICS

restratification

SMS FRONTS & SURFACE-SUBSURFACE EXCHANGES

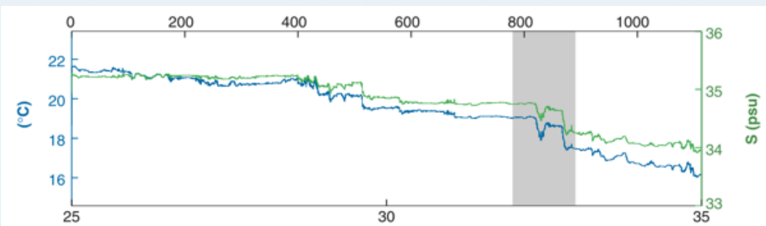
subduction, upwelling

ENERGY DISSIPATION OF THE BALANCED CIRCULATION

forward cascade

Compensation of Horizontal Temperature and Salinity Gradients in the Ocean Mixed Layer Science, 1999

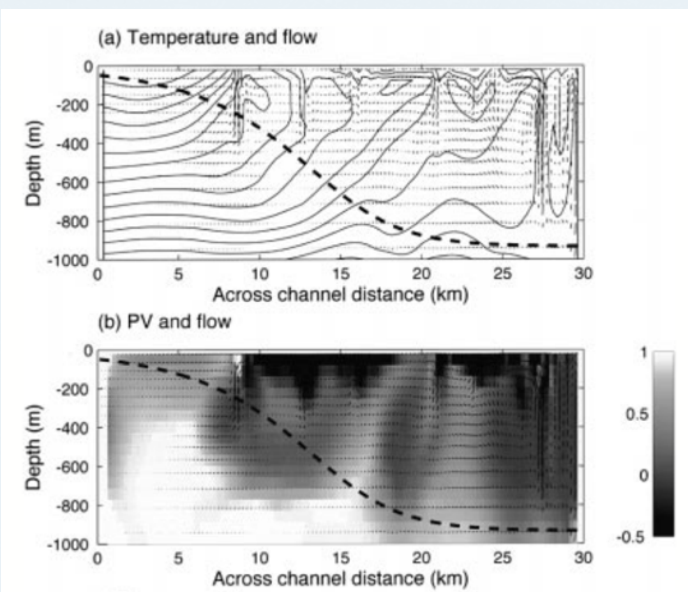
Daniel L. Rudnick* and Raffaele Ferrari



mixed layer T,S observations reveal major density-compensations between the two tracers spatial fluctuations over a wide range of scales
⇒ there must be very effective processes at work against density fronts in the ML

Gravitational, Symmetric, and Baroclinic Instability of the Ocean Mixed Layer

Thomas W. N. Haine* and John Marshall JPO, 1998

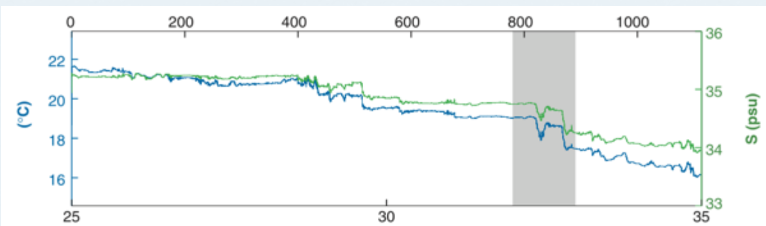


Small-scale baroclinic instability affects the evolution and dynamics of the mixed layer in frontal regions
HM consider a forced case and pose the problem in terms of lateral flux v'b' in a baroclinic zone with heterogeneous buoyancy loss.

Compensation of Horizontal Temperature and Salinity Gradients in the Ocean Mixed Layer

Daniel L. Rudnick* and Raffaele Ferrari

Science, 1999



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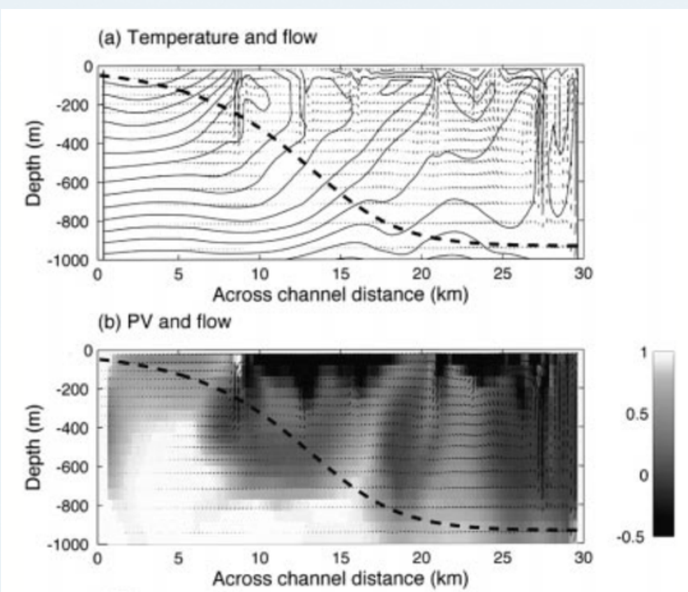


Mixed Layer Instabilities and Restratification

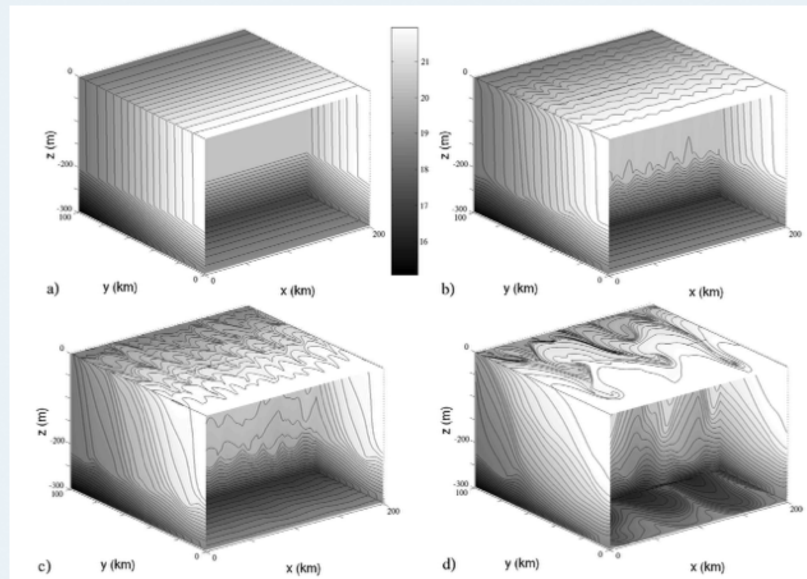
Giulio Boccaletti, Raffaele Ferrari, and Baylor Fox-Kemper

JPO 2007

Parameterization of Mixed Layer Eddies. Part II: Prognosis and Impact

Baylor Fox-Kemper* and Raffaele Ferrari

JPO 2008

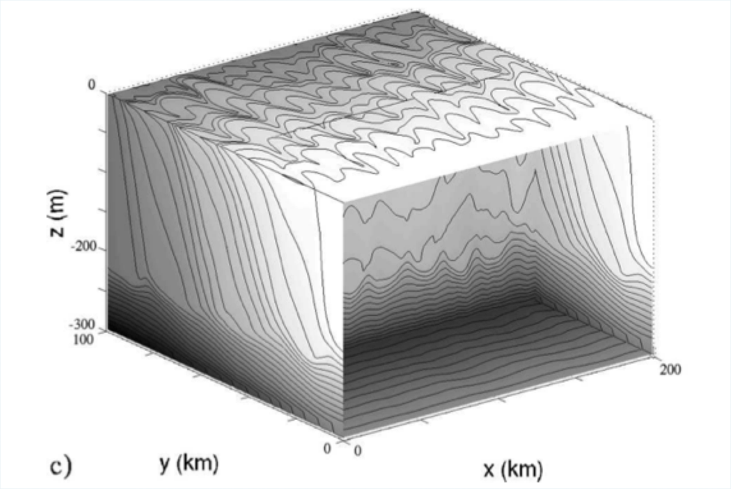


FK08 parameterization:

- mimics adiabatic slumping of ML fronts due to mixed layer baroclinic instability with advection by an eddy-induced streamfunction (restratification)
- Ri and Ro are the key parameters

Simplifications and limitations to FK08:

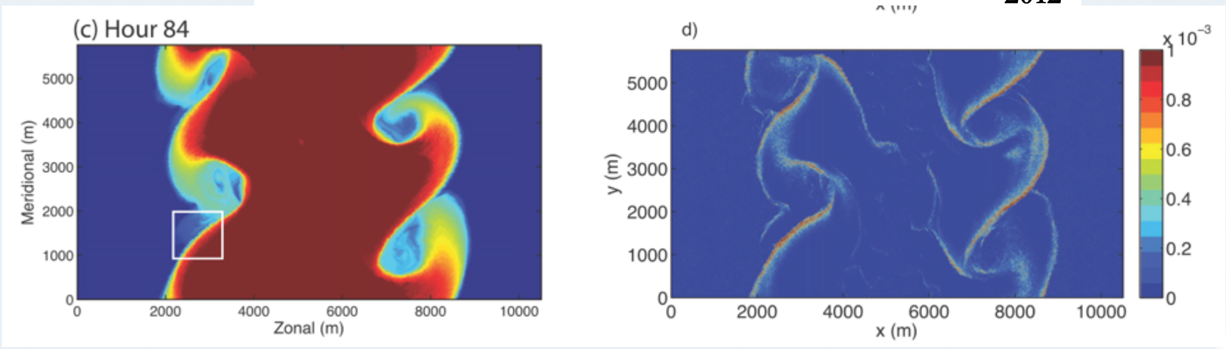
- Exchanges with the ocean interior are ignored (the setup has a a sharp transition between a mixed layer and a strongly stratified interior)
- Diapycnal mixing is not accounted for
- It does not include forcing or dissipation ? In some conditions where atmospheric forcings are present exchanges with the ocean interior is an intrinsic part of the solution



Baroclinic Frontal Instabilities and Turbulent Mixing in the Surface Boundary Layer. Part I: Unforced Simulations

ERIC D. SKYLLINGSTAD AND R. M. SAMELSON

JPO 2012



Frontogenesis, subduction/upwelling

Pollard & Regier, JPO 1992 …

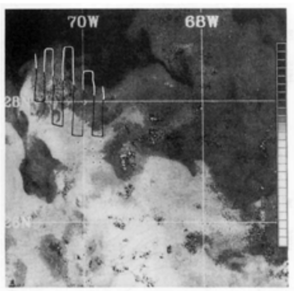
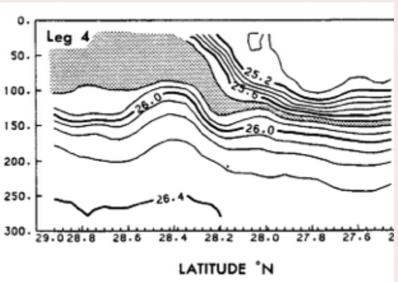


FIG. 2. A satellite image on 22 February (two days after the end of the survey shown in Fig. 1) shows a mesoscale tongue of warm water pushing northward on the western side of the survey track.



observational evidence that straining by the mesoscale eddy field is an important agent for vertical movements (also Rudnick et al, 1996; Naveira-Garabato et al, 2001 …)

Model of frontogenesis: Subduction and upwelling

by Dong-Ping Wang[1] JMR, 1993

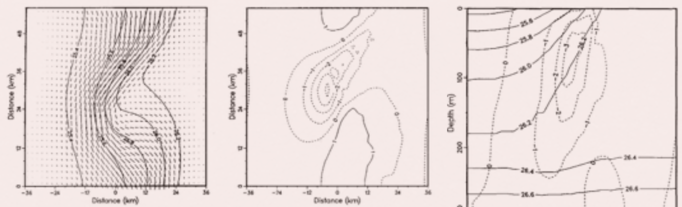
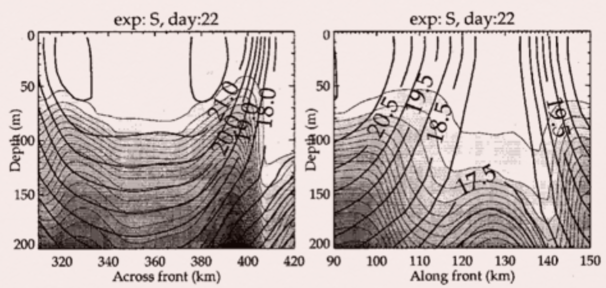


Figure 8. (a) Surface velocity and density distribution and (b) vertical velocity at 100 m (10^{-2} cm/s), for narrow jet with a high eddy viscosity at day 5.

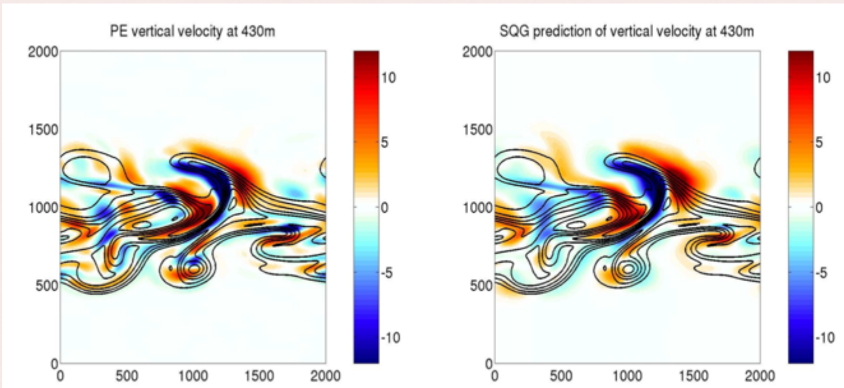
Impact of sub-mesoscale physics on production and subduction of phytoplankton in an oligotrophic regime

by Marina Lévy[1], Patrice Klein[2] and Anne-Marie Treguier[2] JMR, 2001



numerical demonstrations that the straining field associated with a baroclinically unstable flow can lead to substantial frontal subduction and upwelling with important implications for BGC tracers

density ≠ C^{te} is equivalent to adding a thin PV sheet at the boundary (Bretherton, 1966).



Dynamics of the upper oceanic layers in terms of surface quasigeostrophy theory

G. Lapeyre

P. Klein JPO 2006

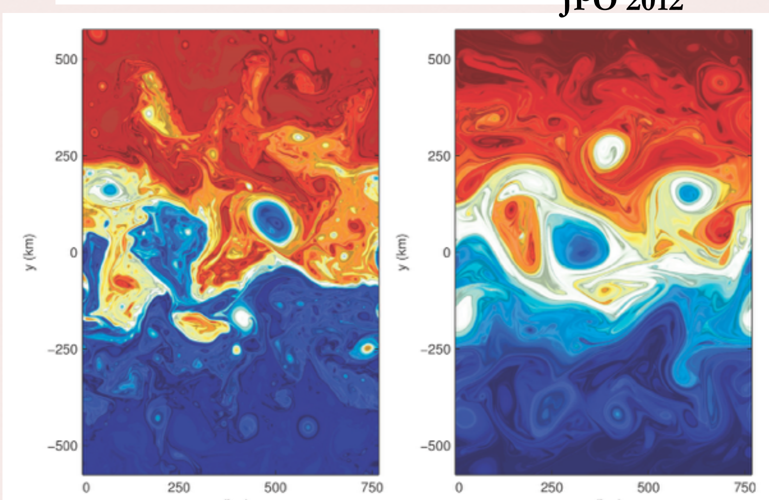
surface PV can be the main driver of ocean circulation at submesoscale

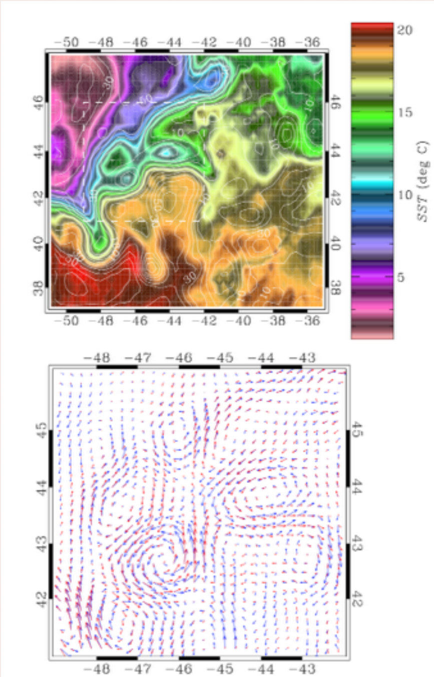
SQG leads to surface intensification (KE spectra) and energy fluxes ~ compatible with what we know of the submesoscale turbulence regime. Particularly true when it is coupled to an interior QG (also true in the atmosphere - Tulloch and Smith, 2008).

Properties of Steady Geostrophic Turbulence with Isopycnal Outcropping

G. Roullet et al

JPO 2012



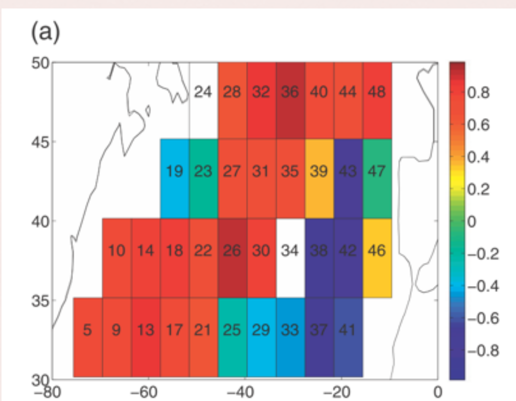


Potential use of microwave Sea Surface Temperatures for the estimation of ocean currents

J. Isern-Fontanet,[1,2] B. Chapron,[2] G. Lapeyre,[3] and P. Klein[1]

GRL 2006

good agreement between QG velocities derived from SLA and SQG velocities derived from SST in the north Atlantic



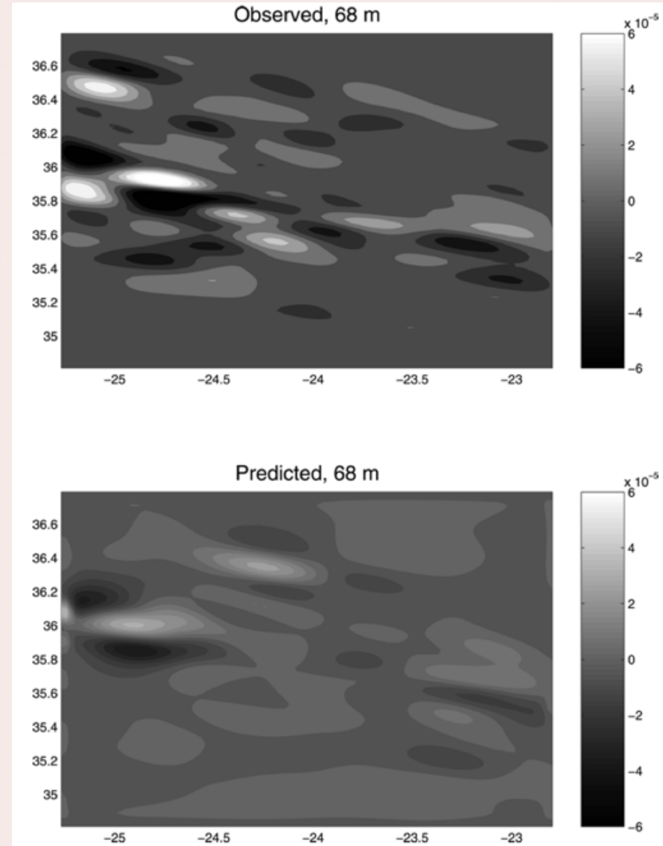
What Vertical Mode Does the Altimeter Reflect? On the Decomposition in Baroclinic Modes and on a Surface-Trapped Mode

GUILLAUME LAPEYRE JPO 2009

surface velocities in many ocean sectors in the north atlantic "project" mainly on the SQG mode (as opposed to the first baroclinic mode)

Estimating subsurface horizontal and vertical velocities from sea-surface temperature

by J. H. LaCasce[1] and A. Mahadevan[2] JMR 2006

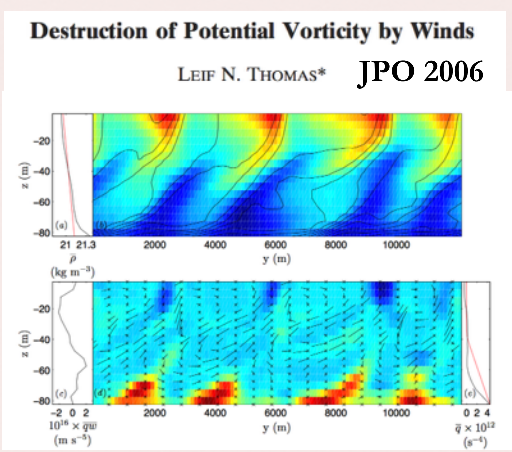


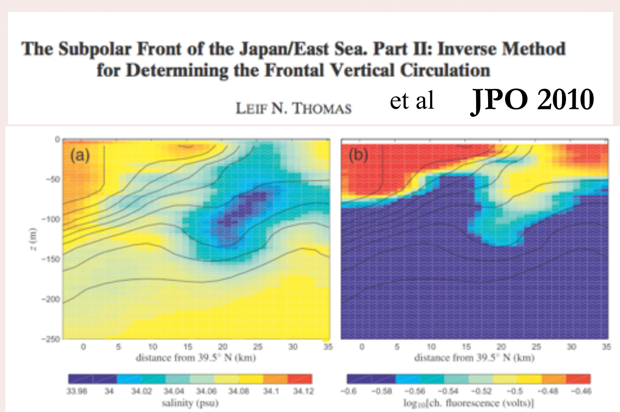
qualitative agreement for horizontal velocities using 2 data sets. Less clear for vertical velocities derived from the omega-equation (for only one data set).

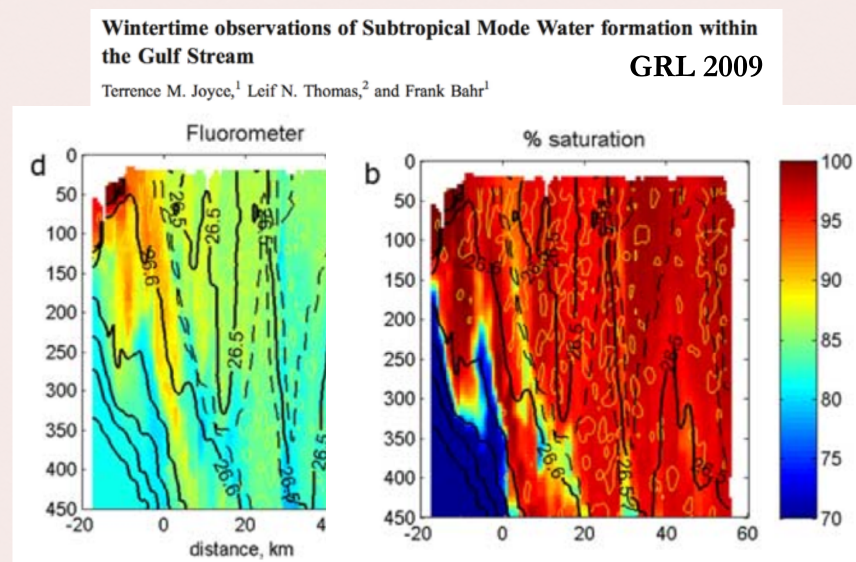
Quantitative skills require that:

- **interior PV has no important structure at fine scale (or that these structures are entirely correlated to the surface field)**
- **stratification is not too complex (but ML impact can be partly included, Ponte et al, 2013)**
- **ageostrophic processes are unimportant (although some may be included, Badin et al 2012 - semi-geostrophy).**

Frontogenetic conditions can be strongly affected by frictional and diabatic forcings. Intense subduction events take place in frontal conditions where mesoscale strain AND PV destruction actively contribute.







SMS impact on N-limitation → SMS impact on light-limitation

Model of frontogenesis: Subduction and upwelling

by Dong-Ping Wang[1] JMR, 1993

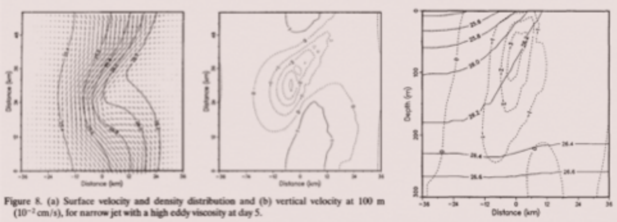


Figure 8. (a) Surface velocity and density distribution and (b) vertical velocity at 100 m (10^{-2} cm/s), for narrow jet with a high eddy viscosity at day 5.

A numerical model of mesoscale frontal instabilities and plankton dynamics — I. Model formulation and initial experiments

S.A. Spall, K.J. Richards

Impact of sub-mesoscale physics on production and subduction of phytoplankton in an oligotrophic regime

by Marina Lévy[1], Patrice Klein[2] and Anne-Marie Treguier[2] JMR, 2001

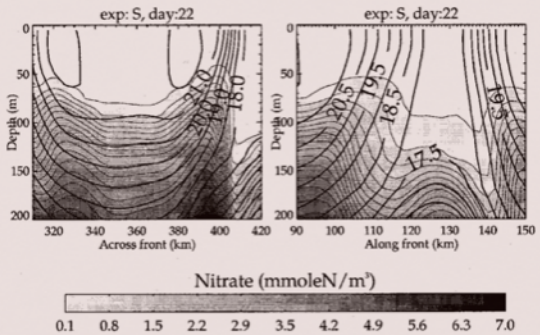
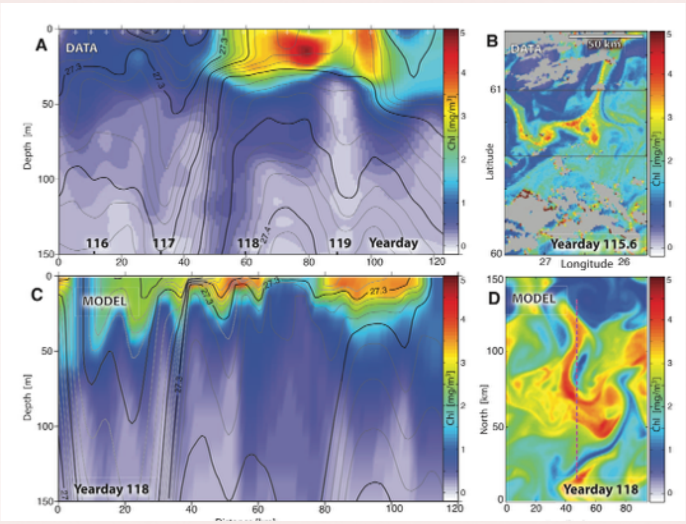


Figure 14. Vertical sections of temperature and nitrate at day 22, across an anticyclone (left figures) and a cyclone (right figures) in the mesoscale M and the sub-mesoscale S experiments.

Eddy-Driven Stratification Initiates North Atlantic Spring Phytoplankton Blooms

Amala Mahadevan,[1] Eric D'Asaro,[2*] Craig Lee,[2] Mary Jane Perry[3]

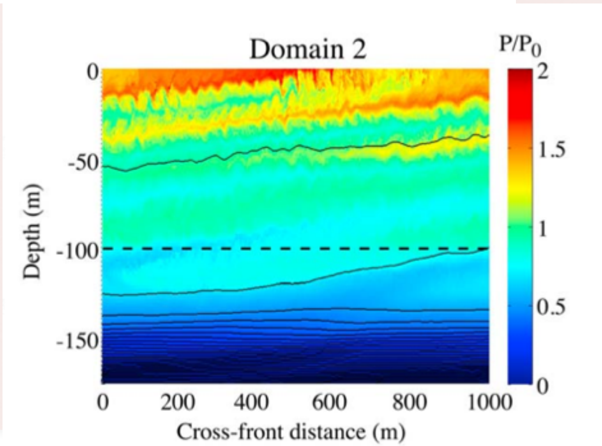
Science 2012



Ocean fronts trigger high latitude phytoplankton blooms

J. R. Taylor[1] and R. Ferrari[2]

GRL 2011

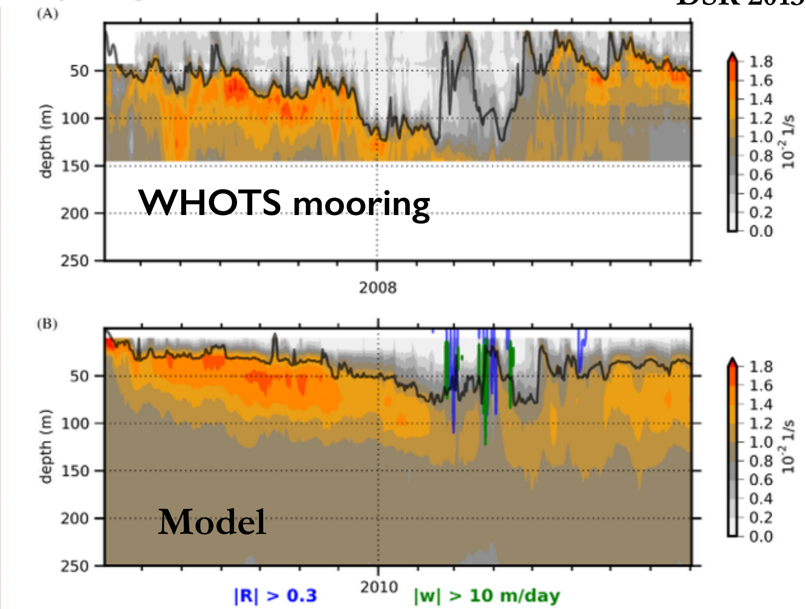


Mooring and long-term profiler observations in the subtropical Pacific + model
Limited indications of nitrate upwelling related to submesoscale frontal events

Physical and biological controls of nitrate concentrations in the upper subtropical North Pacific Ocean

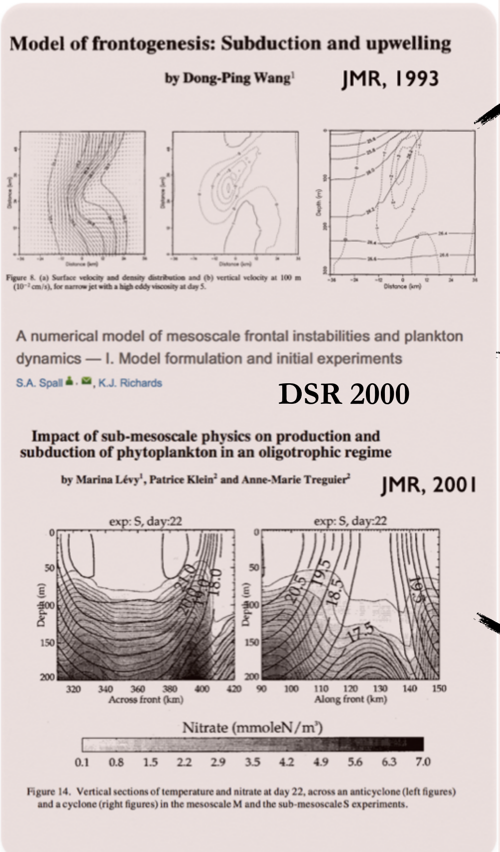
François Ascani [a,b,*], Kelvin J. Richards [a,b], Eric Firing [a], Scott Grant [a], Kenneth S. Johnson [c], Yanli Jia [b], Roger Lukas [a], David M. Karl [a,d]

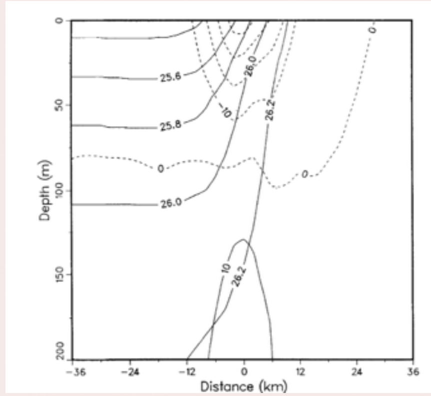
DSR 2013



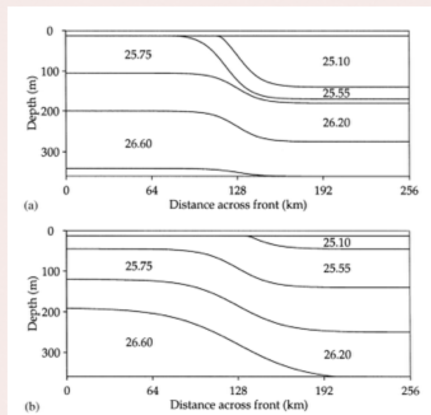
This work calls for caution in applying to the North Pacific subtropical ocean the results of idealized numerical studies concerning the effect of frontal submesoscale processes on the depth of the nutricline. The key factor is the position of the nutricline with respect to density fronts. To our knowledge, in all numerical studies that show the importance of submesoscale processes, the nutricline initially *crosses* the density front (Lévy, 2008; Lapeyre and Klein, 2006; Lévy et al., 2001; Nurser and Zhang, 2000; Spall and Richards, 2000; Thomas et al., 2008). This is a valid configuration for the strong and deep density fronts observed along the Kuroshio Extension and the Gulf Stream, but it is not applicable to the fronts near Station ALOHA. There, the

Frontogenesis, subduction/upwelling



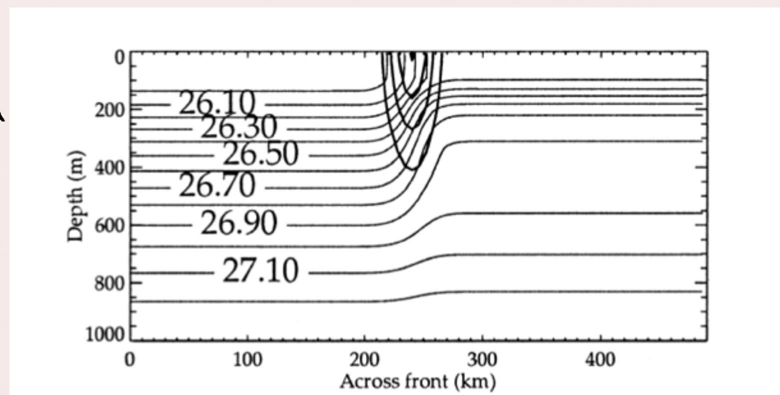


> 200m mixed layer on the cold side.
< 0.6kg/m3 in 200 m on the warm side



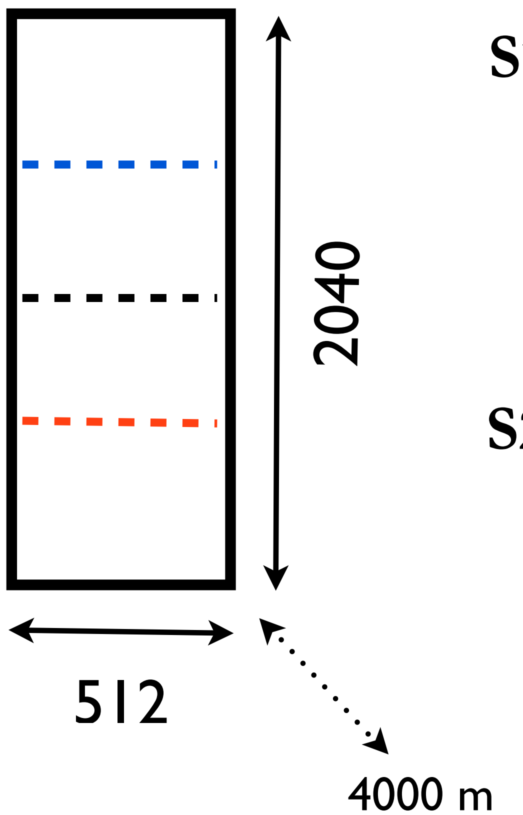
> 100m destratifed layer. < 1kg/m3 in 350m.

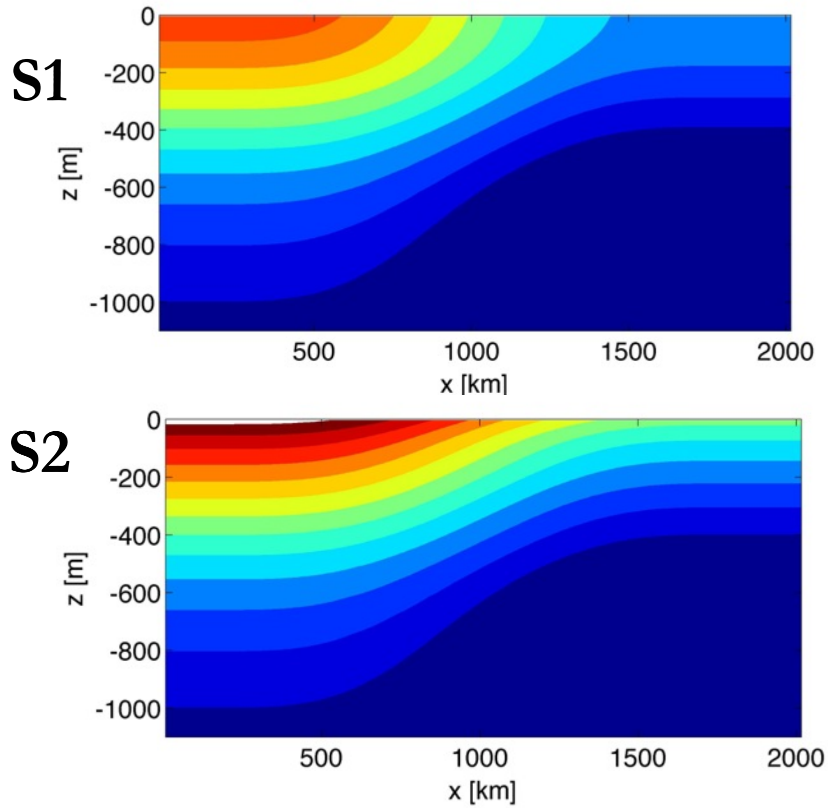
< 1kg/m3 in 350m.

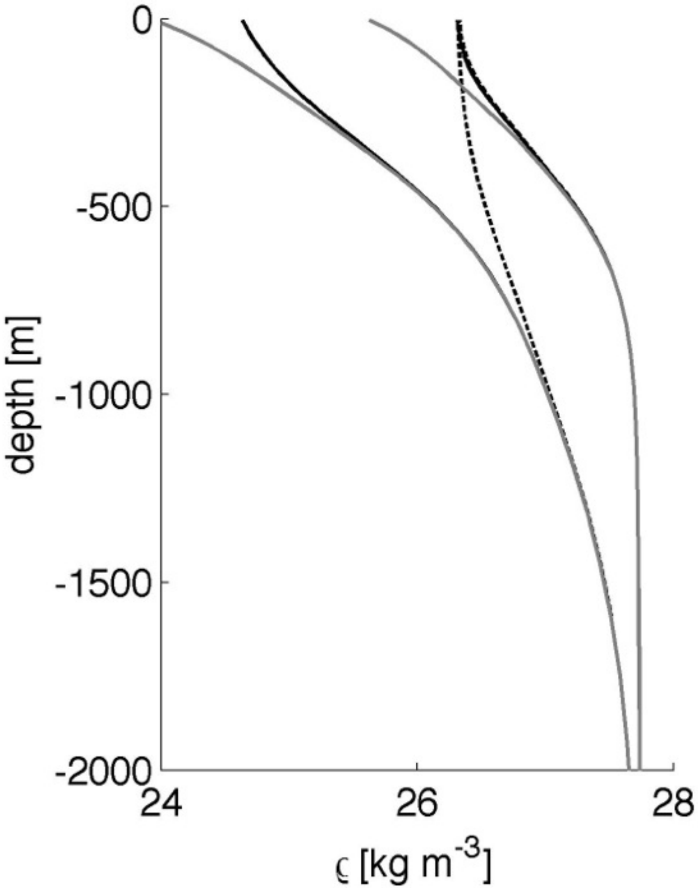


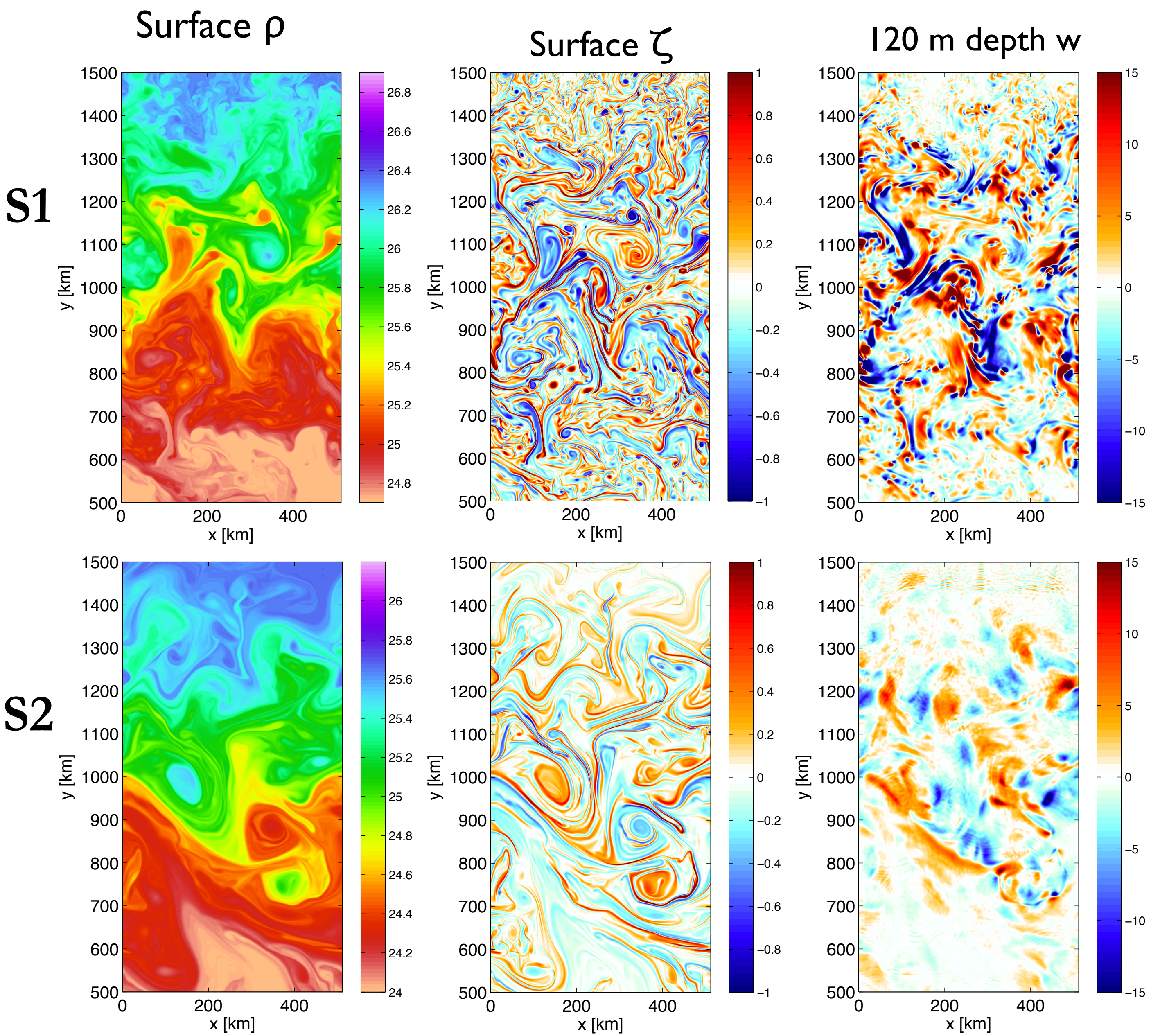
~ 100m mixed layer.
< 0.5 kg/m3 in 250 m
< 1kg/m3 in 900 m

- Reentrant zonal channel with a baroclinically unstable flows (maintained through restoring of zonally averaged u and ρ)
- Identical lateral buoyancy gradients









Submesoscale activity much more energetic in S1 (difference in APE distribution and release)

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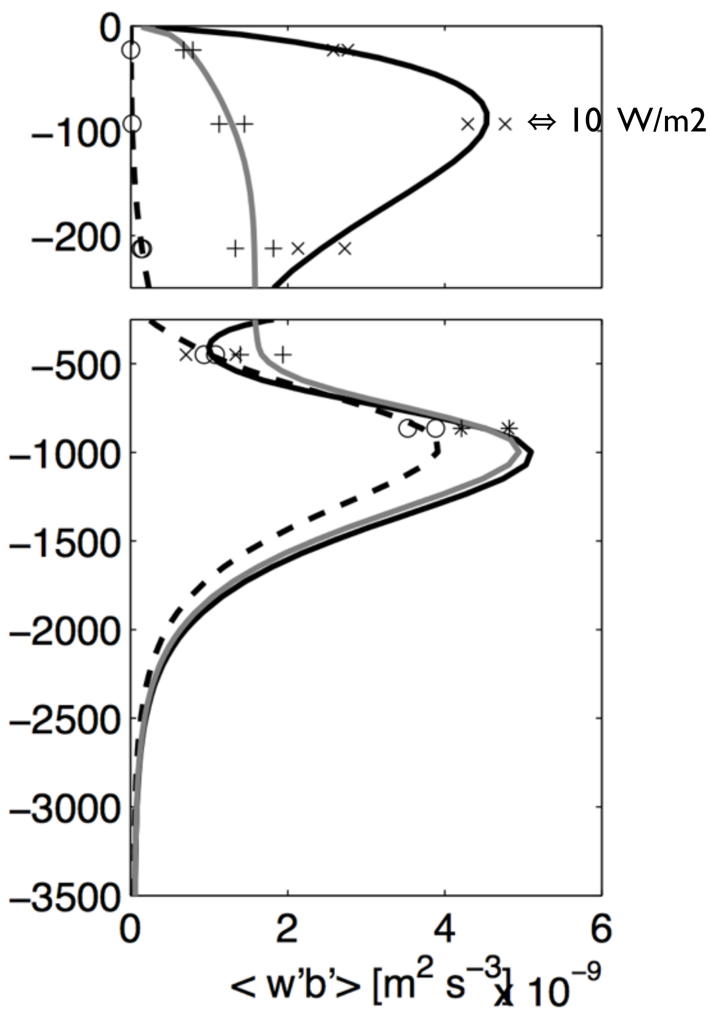
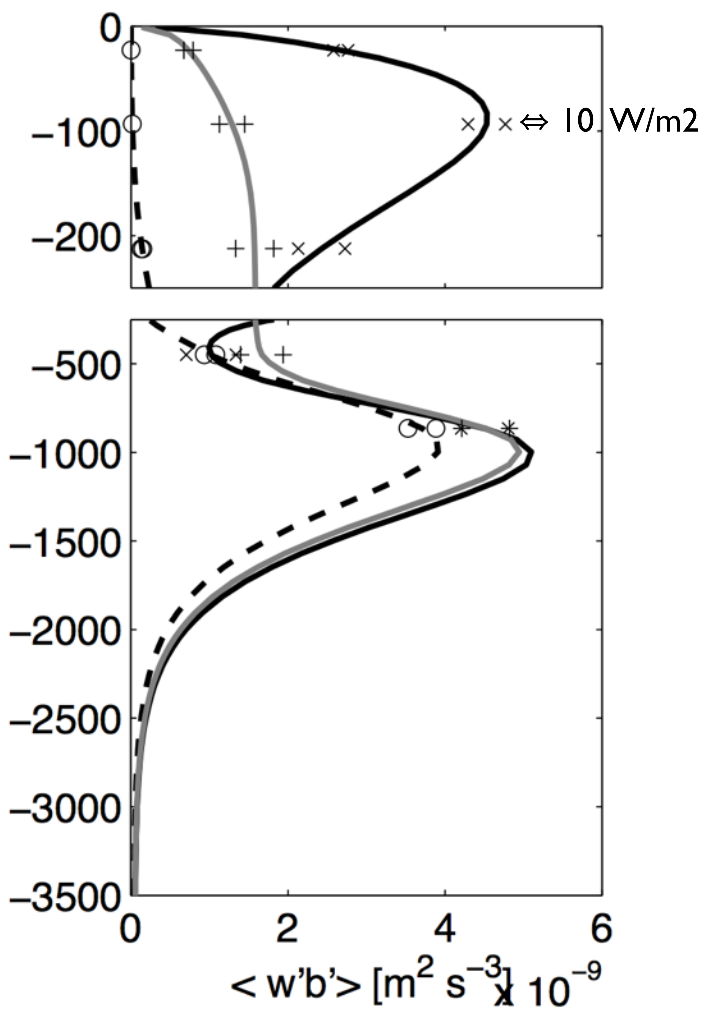
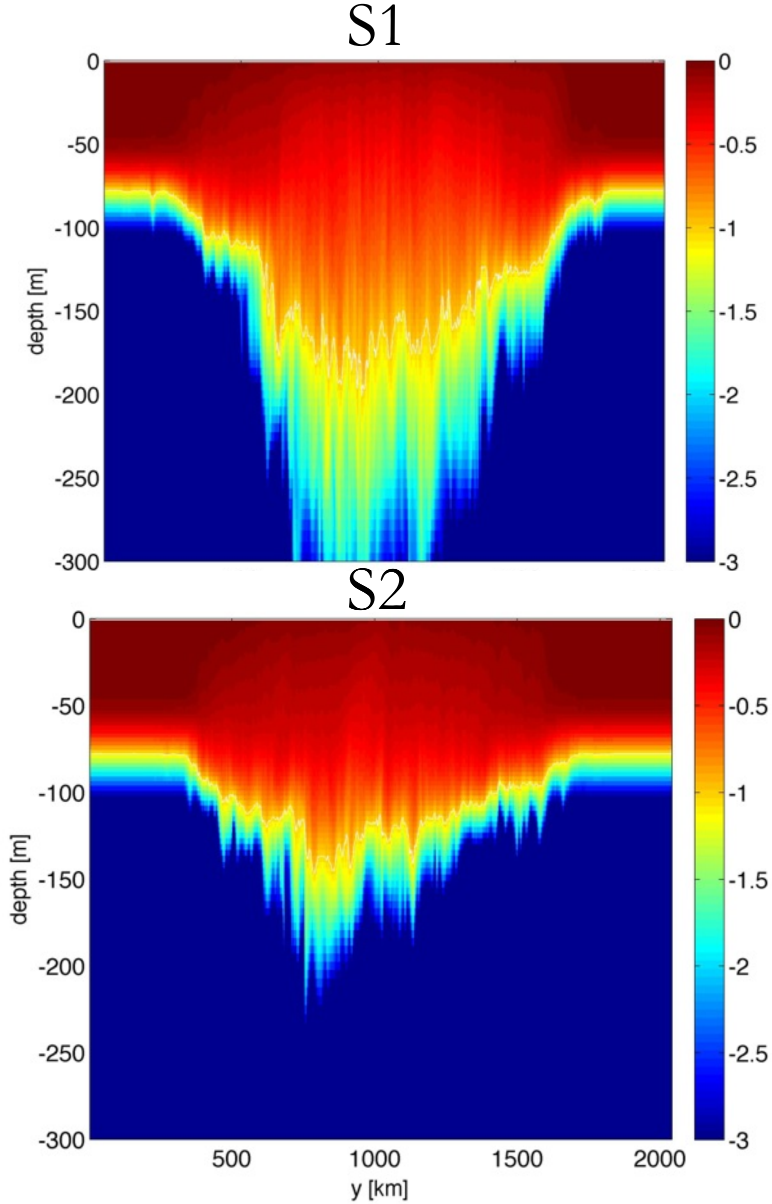


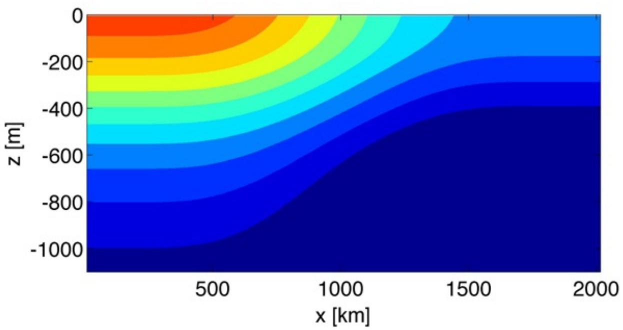
Submesoscale activity much more energetic in S1 (difference in APE distribution and release)

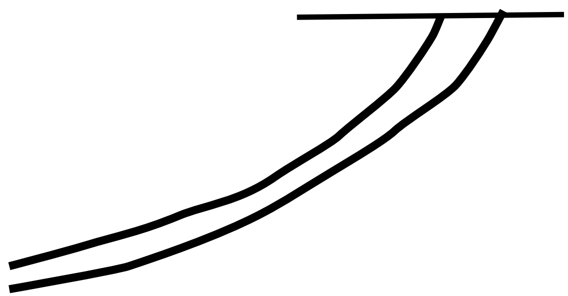


ML tracer distribution after 30 days of spin down (zonal average, log scale)

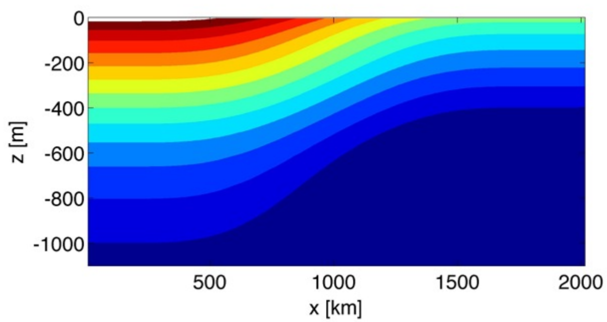


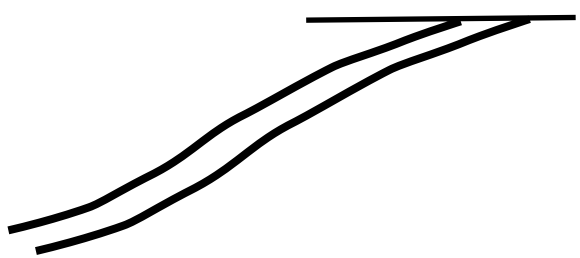
S1 has not just more APE than S2. Their density distribution is such that the change of isopycnal slope with depth are of opposite signs in the two simulations, near the surface.





$$\partial_z s_b > 0$$



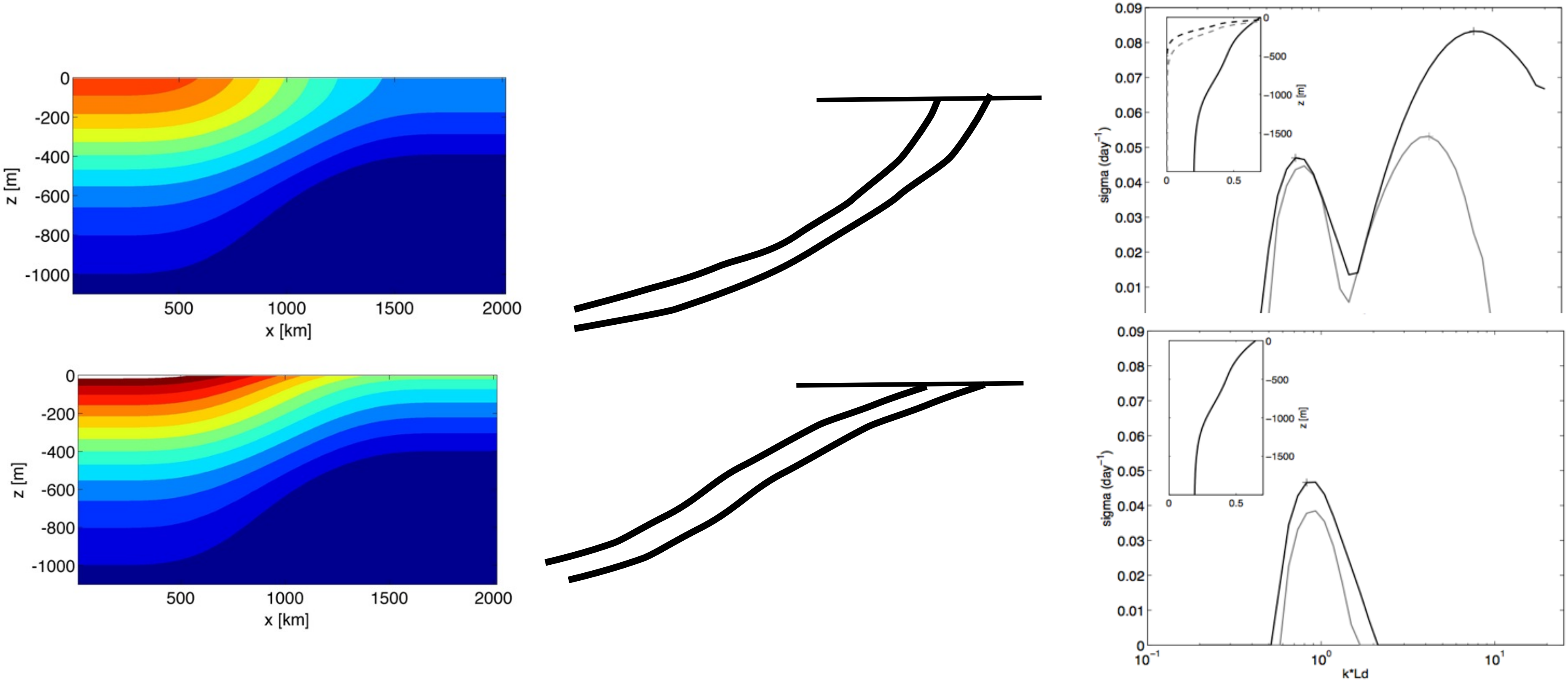


$$\partial_z s_b < 0$$

Coupling with equivalent PV associated with the surface density gradient in S1 leads to another instability mode (Charney).

$$\partial_y Q = \beta - f\partial_z s_b + \frac{f^2}{N^2}\partial_z U\,\delta_0$$

S1 has not just more APE than S2. Their density distribution is also such that the change of isopycnal slope with depth are of opposite signs in the two simulations.



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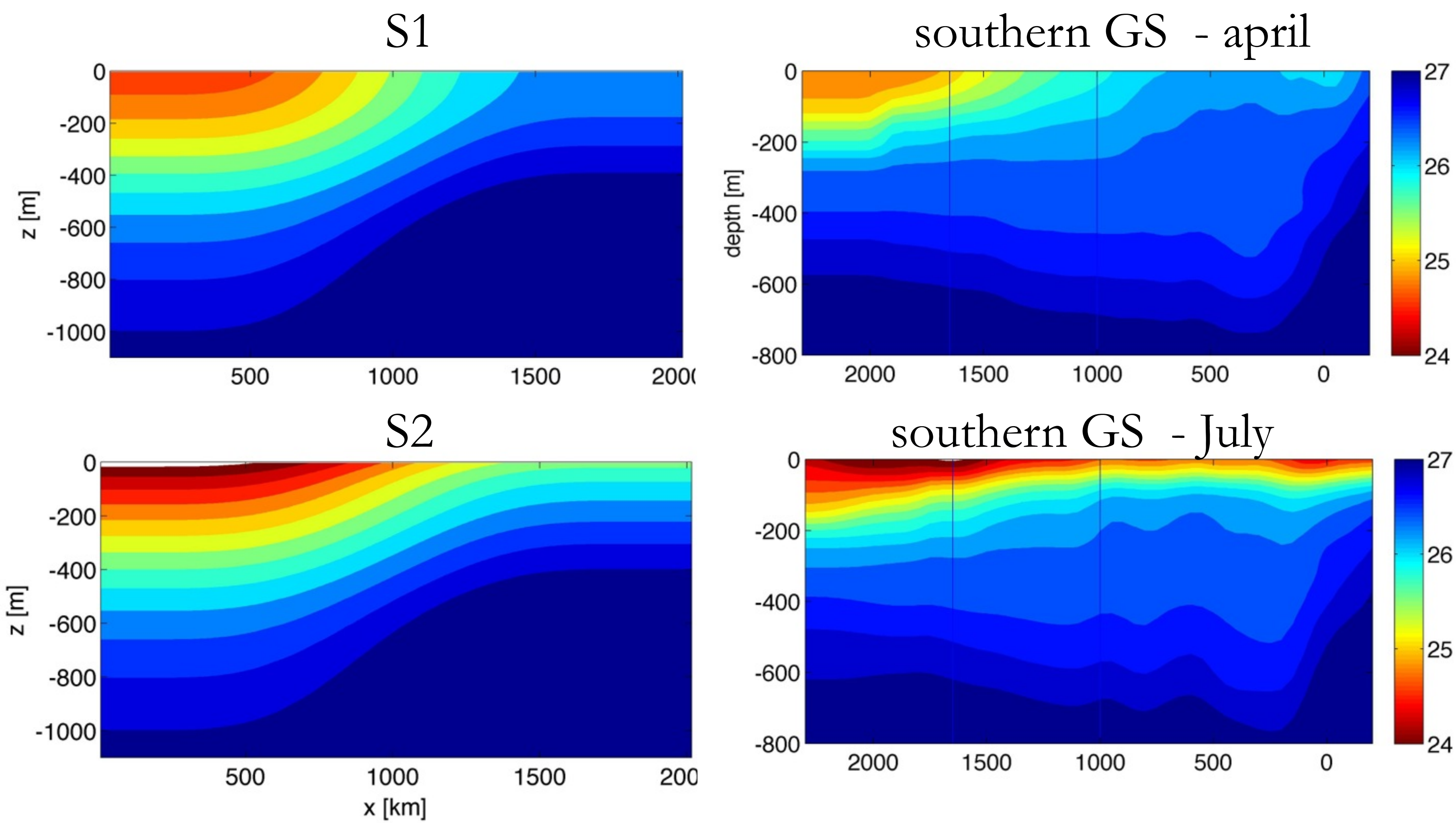
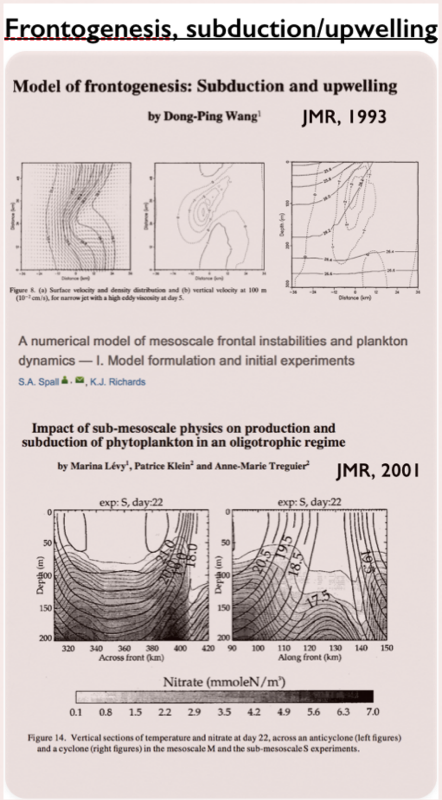
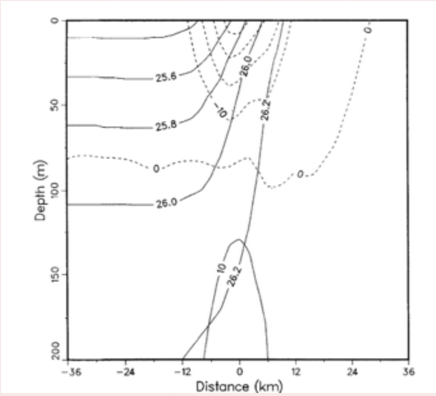
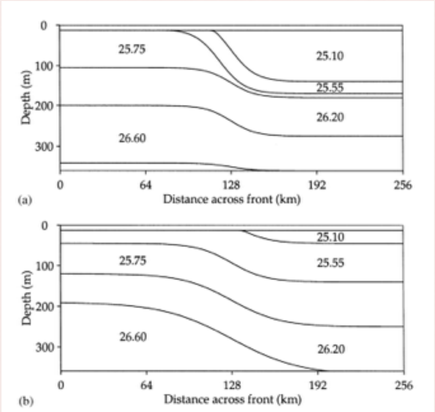
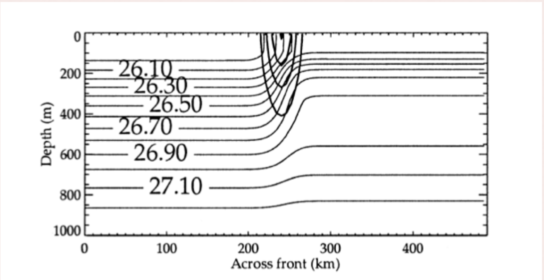


S1-like configuration can be found in the ocean but very rare









Many BCI modes are possible. What situations are we in ?

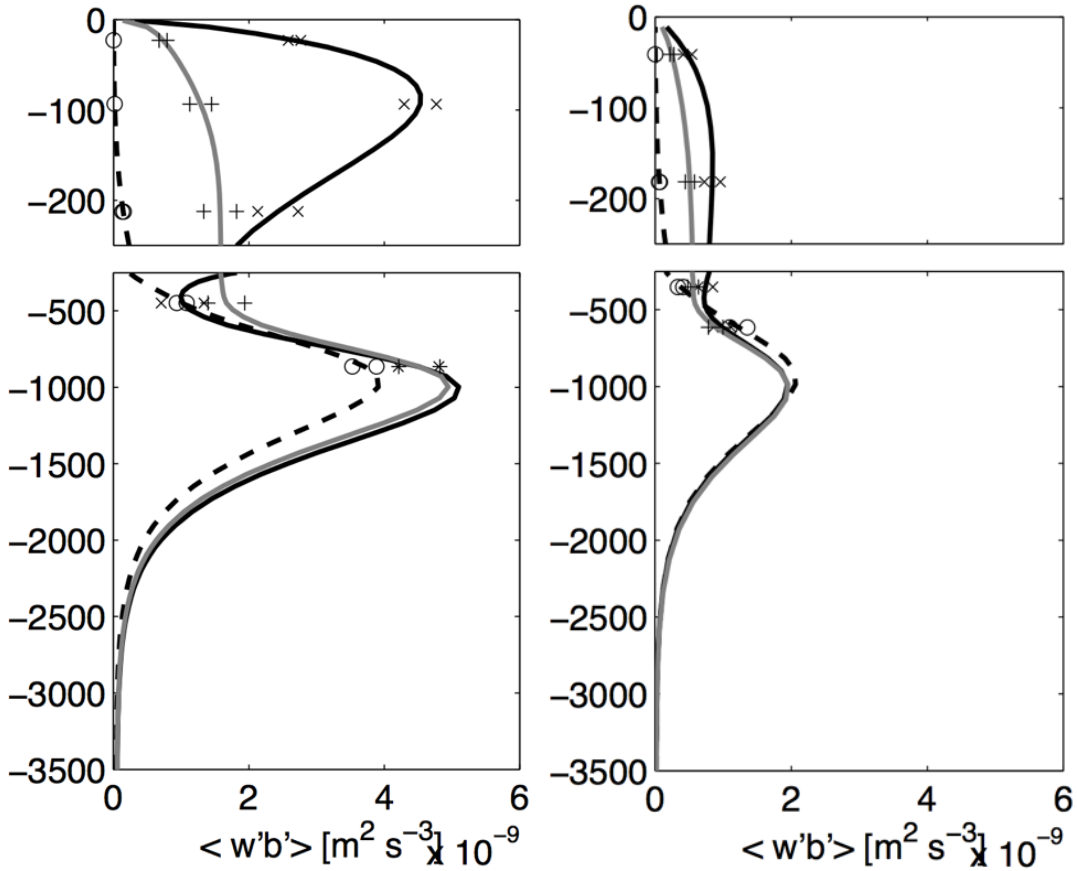
Vertical exchanges at fronts need to be reconsidered with closer attention to realism and parameter sweep: the details of the subsurface thermohaline structure are critical for exchanges.

Atmospheric forcings are also critical

NB1: numerical convergence (COMODO) — Vertical exchanges

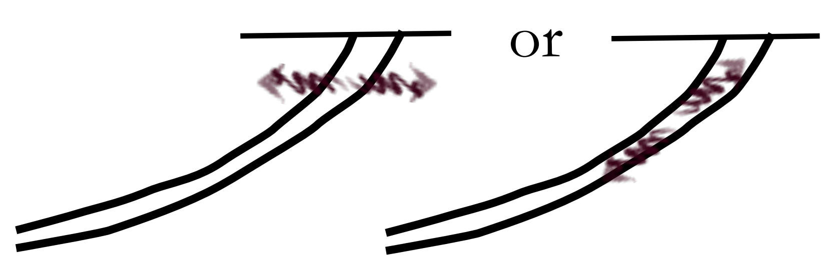
complex situation where numerical convergence is achieved for some quantities (eke) but not other (w, w'b')

Changes in <w'b'> between 8km and 1km are very large in S1, not so in S2
Major differences in <w'b'> related to how tracer mixing is being done (isopotential versus isopycnal).



F. Lemarié [a] L. Debreu [b] A.F. Shchepetkin [a] J.C. McWilliams [a]

On the Stability and Accuracy of the Harmonic and Biharmonic Adiabatic Mixing Operators in Ocean Models

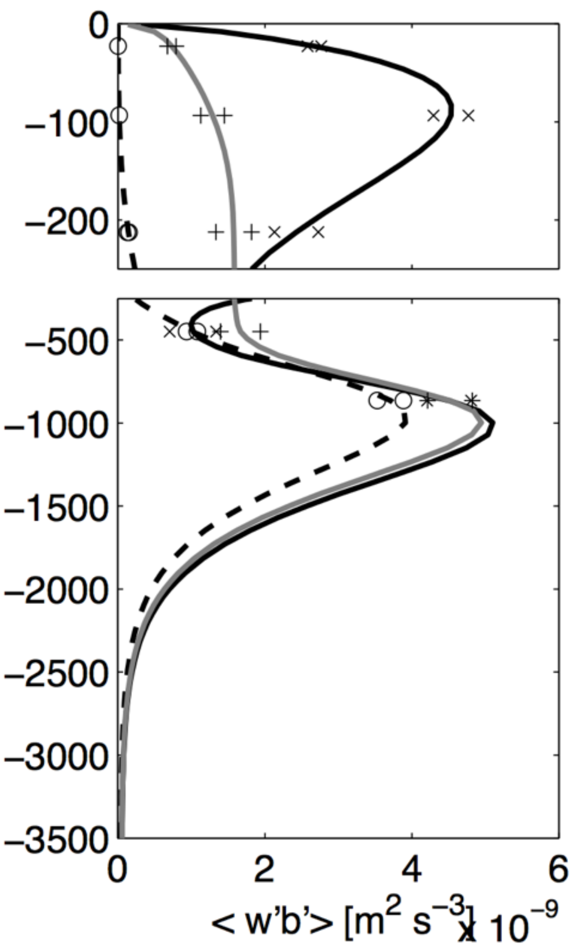


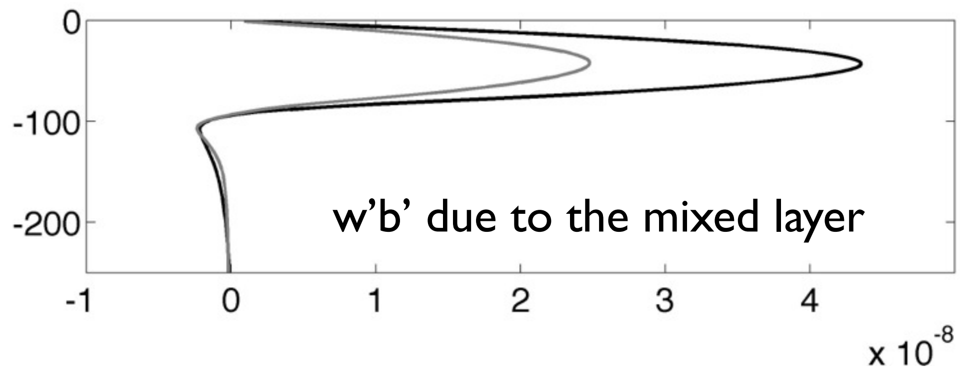
Need for more studies resolving frontal arrest

FK: lid below the ML which can be considered in isolation

$$\langle w'b' \rangle \propto h_{bl} \times |\nabla b|^2$$

A 70 m mixed layer in S1 and S4 leads to buoyancy flux increase but x 2 stronger in S1

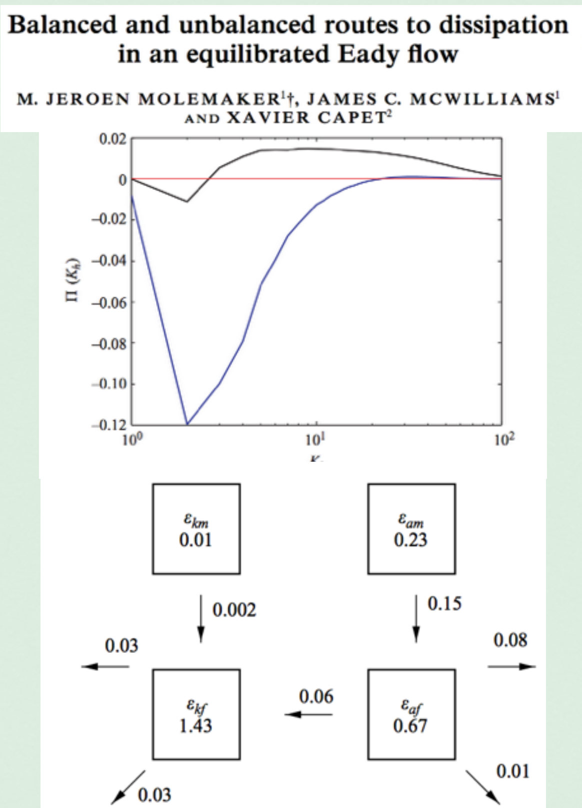


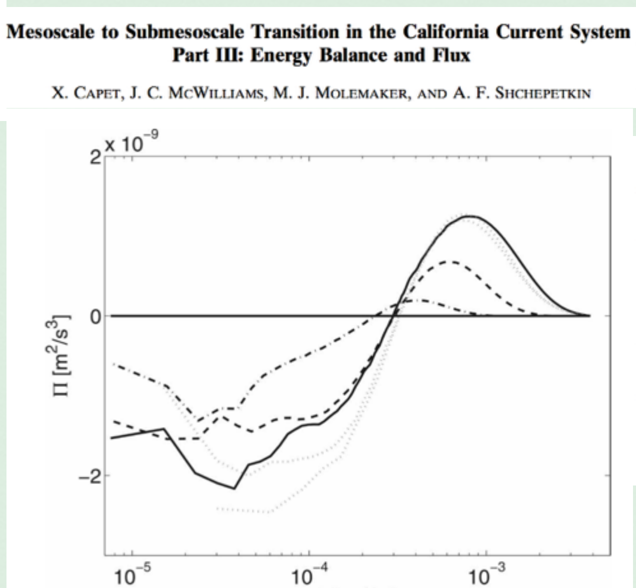


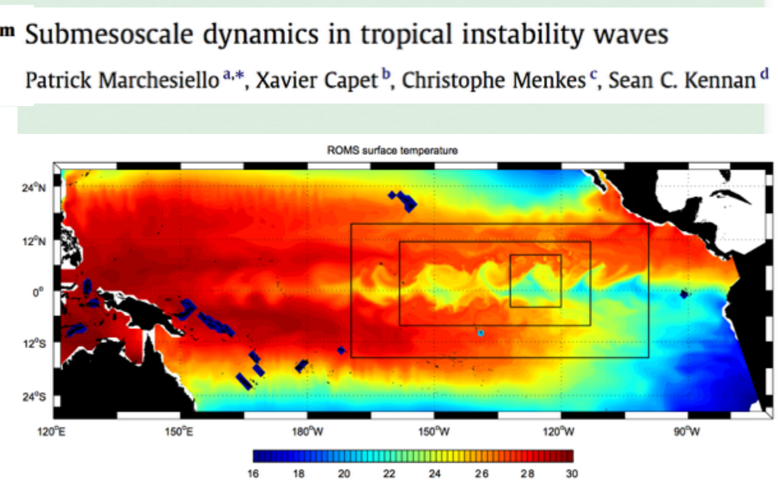
with low stratification values at/below the mixed layer base (here N ~ 3-5 10^{-3} s^{-1}) both the interior and the mixed layer seem to combine their efforts to restratify the mixed layer

In the vicinity of fronts, Ri and Ro ~ 1 suggest that loss of balance will occur. Some of the energy in the submesoscale range may thus escape the classical inverse cascade (leakage toward dissipation) through nonlinear transfers

Surface intensified flows tend to show a genuine forward energy cascade **but**
~ 30% of the dissipated energy in an Eady flow
< 10% of the wind input to the geostrophic circulation in an upwelling region
~ 5% of the energy input into S1







we are collectively much better equipped for SMS ventures with new theoretical developments and a rich toolbox of routine diagnostics (spectral energy budgets, scale decompositions, diagnostics of frontogenetic tendencies, ftle, fsle …)

The question of surface-surface exchanges remains delicate. SMS frontal processes contribute but primarily in conditions where

- the mixed layer/ocean interior transition is least clear
- classical "frontogenesis" is not appropriate
- assumptions underlying SQG are badly violated
- a new range of instability processes need to be included (SI, GI).

→ We need controlled parameter sweeps for the weakly stratified frontal regime typical of high latitudes

Downscale energy transfers associated with SMS frontal dynamics are very likely not substantial even in very energetic conditions.