Turbulence in the Environment

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Examples

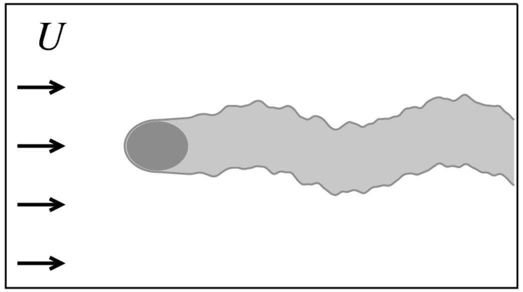
- Submersible wakes in a stratified environment
- Internal gravity waves and turbulent mixing near sloping topography in the ocean

Problem 1
Spatially evolving stratified wake

with Matt de Stadler

How are wakes simulated?

Stationary frame



Limited to small domain

Very expensive

No ad-hoc ICs

State of the art

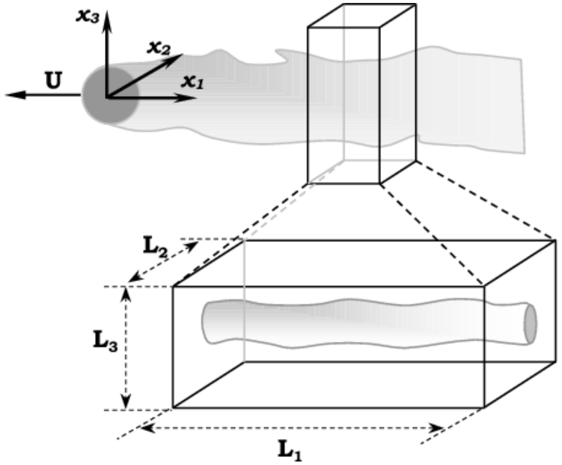
Re = 1,000 Fr = 0.6 (DNS)

Gushchin & Matyushin *ECCOMAS CFD* 2006

Re = 10,000 Fr = 25 (LES)

Pasquetti *CF* 2011

Temporally evolving frame



Can run to the far wake

Relatively cheap

High uncertainty in ICs

State of the art

Re = 50,000, Fr = 4 (DNS)

2 x10^9 pts Brucker & Sarkar, *JFM*, 2010

Re = 100,000 Fr = 32 (LES)

Diamessis et al, *JFM* 2011

Unstratified sphere: Re = 3,700 (DNS) Rodriguez et al. *JFM* 2010

Unstratified golf-ball: Re = 1.1*10^5 (DNS) Smith et. al. *IJHFF* 2010

Numerical method details

3D unsteady, incompressible Navier-Stokes equations with Boussinesq approximation

Immersed boundary method to represent sphere in domain

Collocated grid arrangement using pressure-correction algorithm

Semi-implicit mixed RK3-ADI method for time advancement

Low storage RK3 for nonlinear terms and Boussinesq term

ADI for viscous and pressure gradient terms

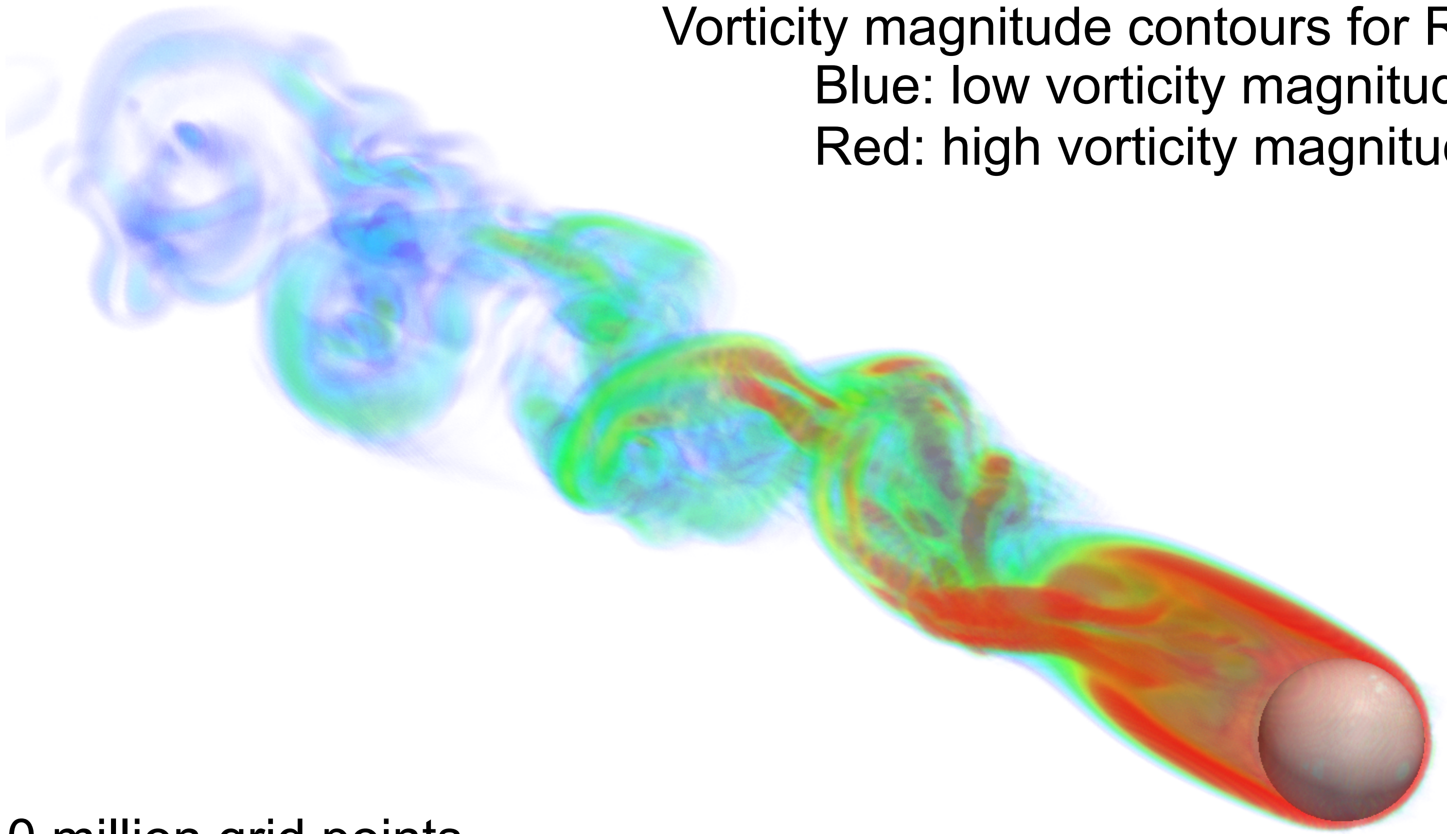
2nd order centered differences for spatial terms

Parallel semi-coarsening multigrid pressure solver

3-D domain decomposition using MPICH II

Sponge region at physical boundaries

What does an unstratified wake look like?



Vorticity magnitude contours for Re=1,000

Blue: low vorticity magnitude

Red: high vorticity magnitude

About 10 million grid points

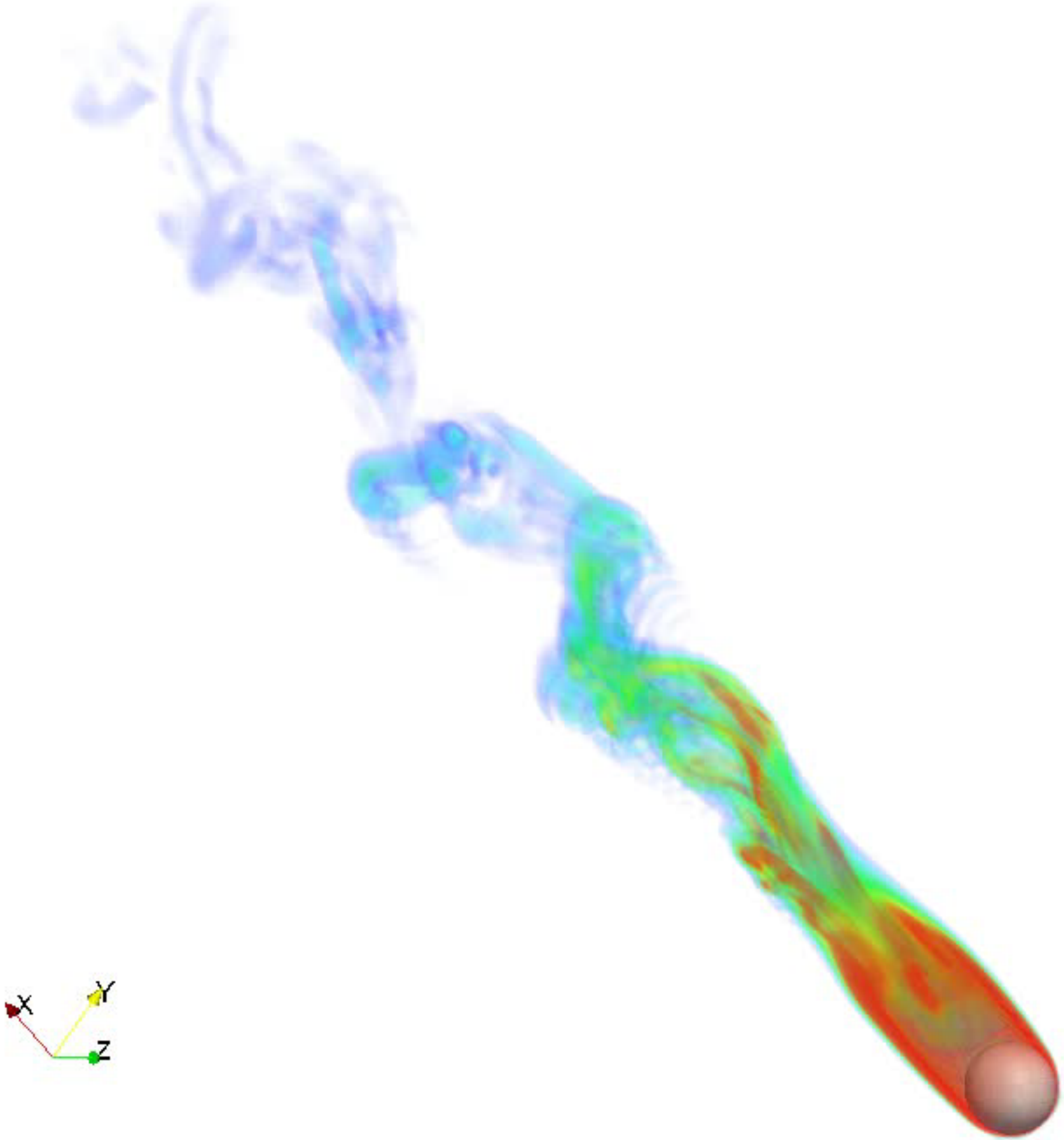
Thin laminar boundary layer forms on the body

Unsteady vortex shedding at low frequency leads to large scale spiral structure

BL separates and forms thin shear layer

Shear layer becomes unstable due to KH instability

Growth of instability leads to turbulence and breakdown of spiral structure

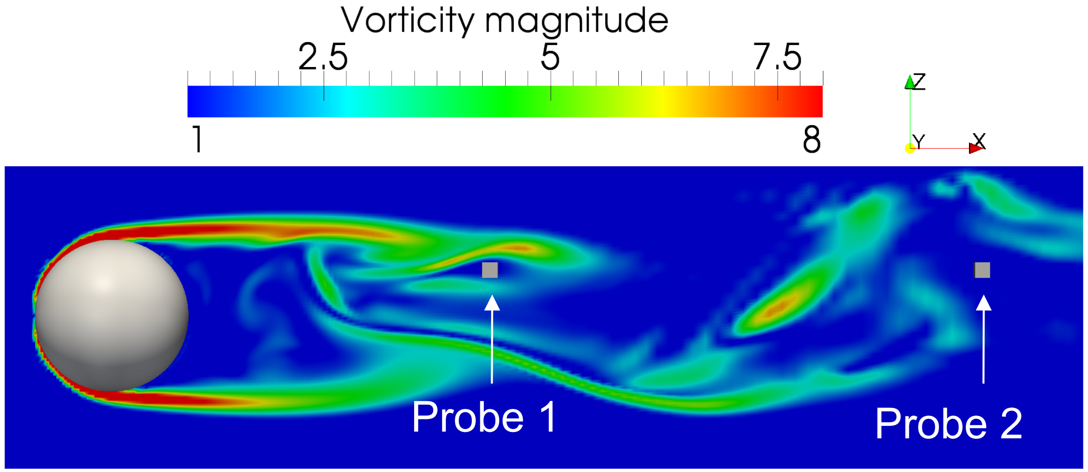

X
Y
Z

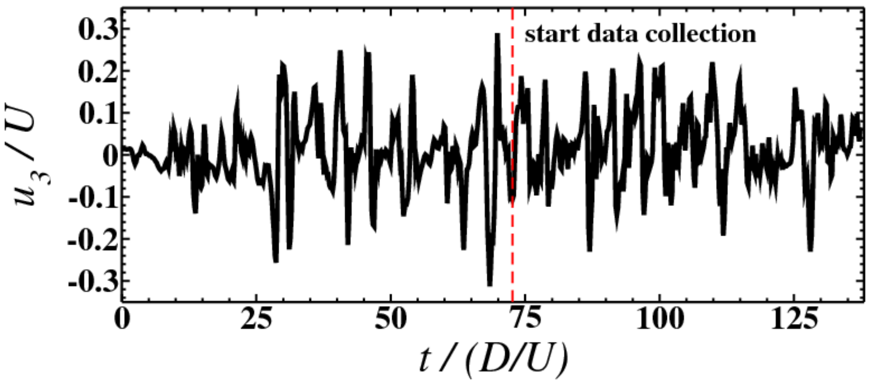
Wake instabilities and frequencies

Two dominant frequency emerge:

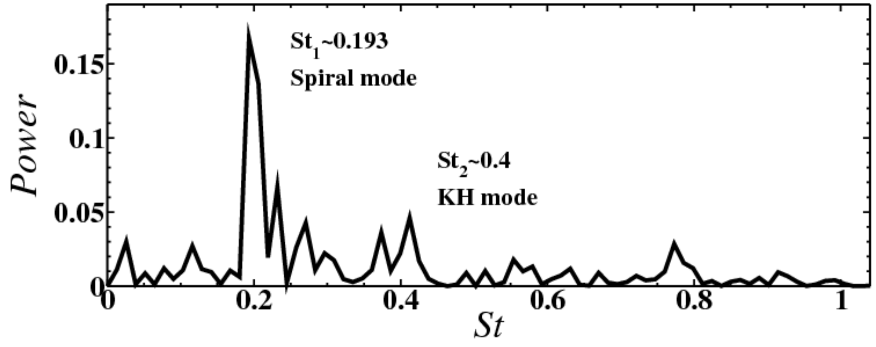
Spiral mode related to large scale 'flapping' of the wake

Kelvin-Helmholtz mode from the separated BL shear layer



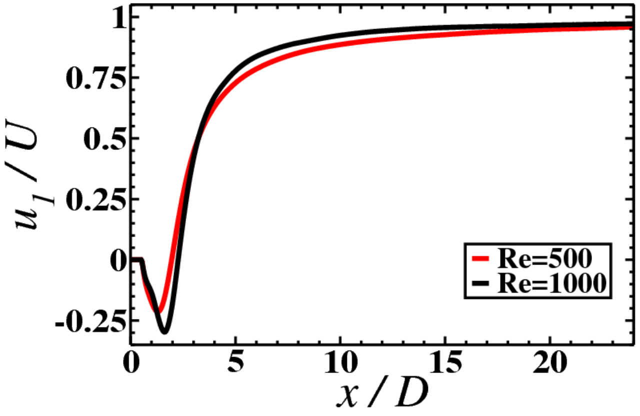


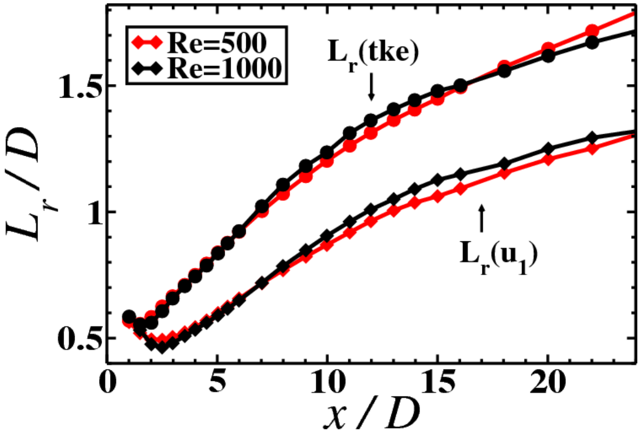
Vertical velocity trace at probe 2

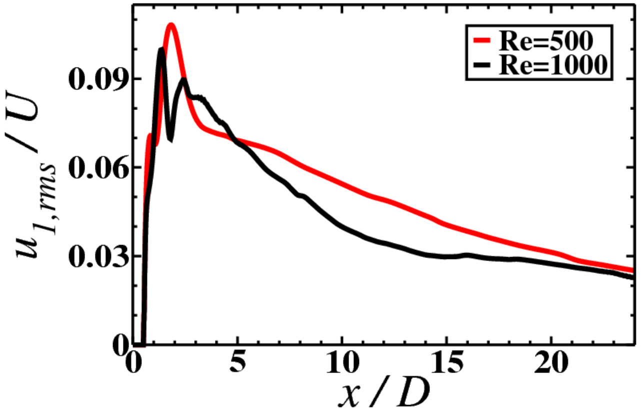


Vertical velocity trace at probe 2

Unstratified wake results at Re=500,1000


Mean streamwise velocity


Wake dimensions


RMS streamwise velocity

Our results are similar to those of Tomboulides & Orszag, JFM 2000 and Wu & Faeth, AIAA 1993

Rapid decay of defect velocity after the separation bubble

Fluctuating region broader than the mean region

Turbulence intensities peak in the near wake

Features of turbulent wakes in stratified fluids

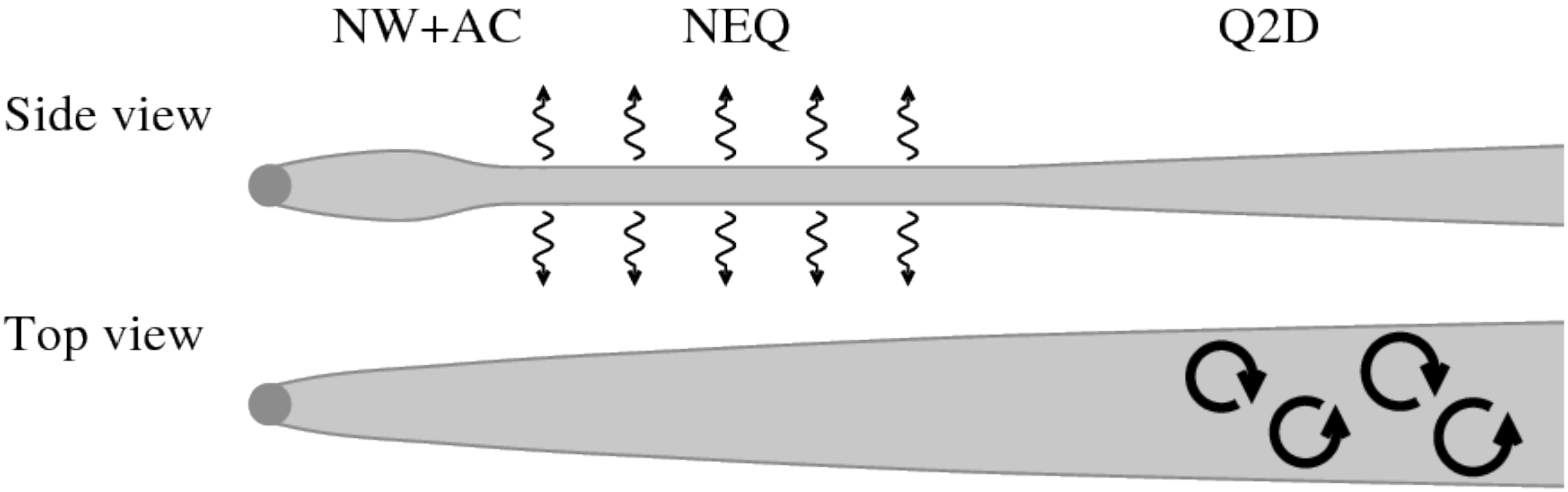
Stratification breaks radial symmetry: vertical motion inhibited

Transfer between kinetic and potential energy

Internal waves radiated

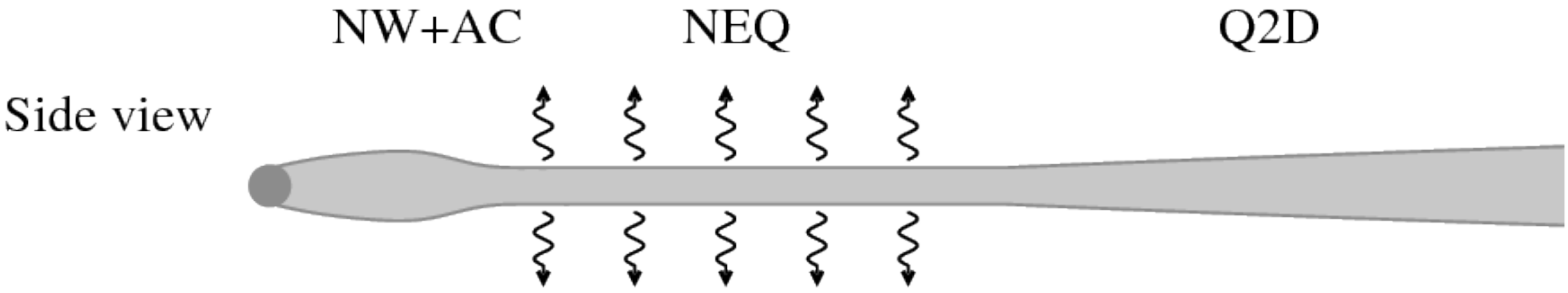
Late time quasi-2D flow

Very different than unstratified wake



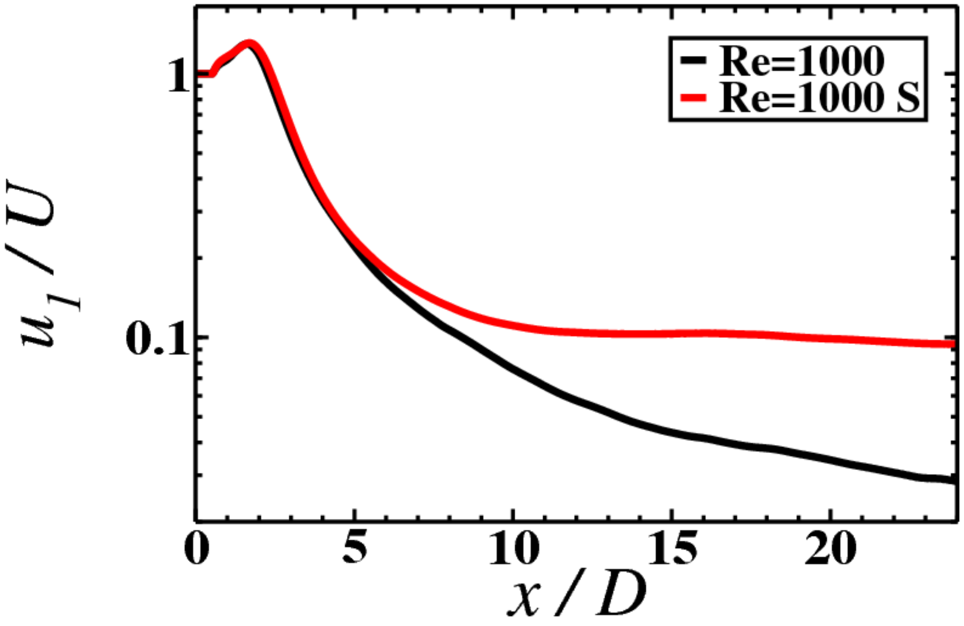
Motivating questions for spatially evolving flow past a sphere

1. How are the mean and fluctuating fields correlated in the near wake? Collapsed region?
2. How do internal waves alter the velocity, density and vorticity structure?
3. How is energy re-distributed during the collapse?
4. Is the near wake as insensitive to *Fr* as often assumed?
5. How is a temporally evolving wake simulation initialized with realistic initial conditions different from one based on idealized conditions?



Flow evolution: Defect velocity and wake dimensions

Defect velocity



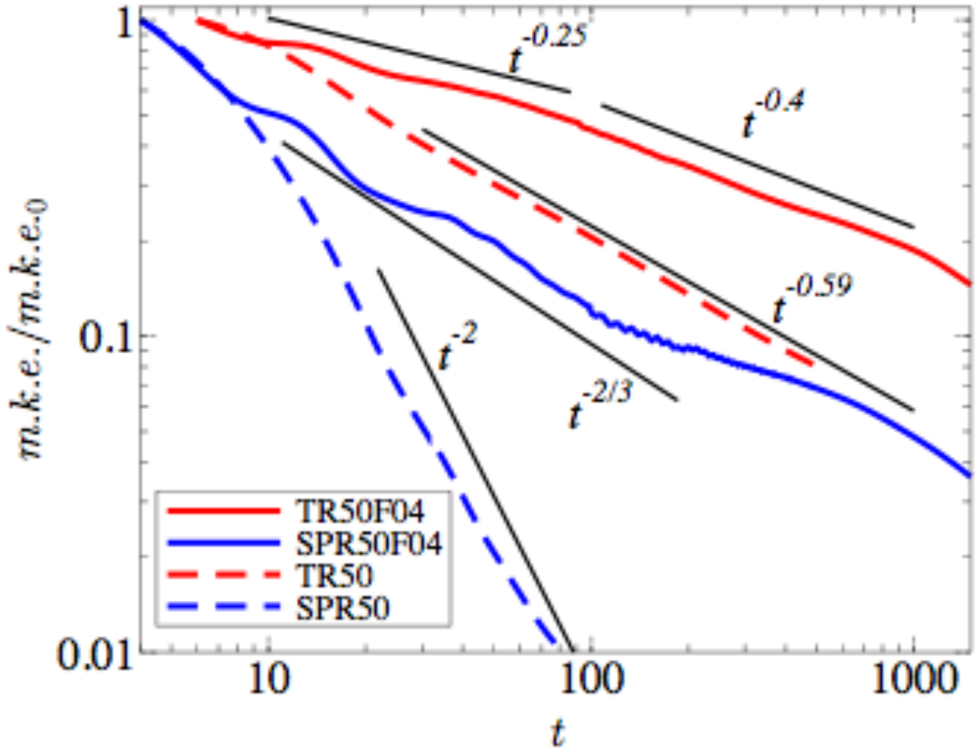
Stratification preserves the defect velocity

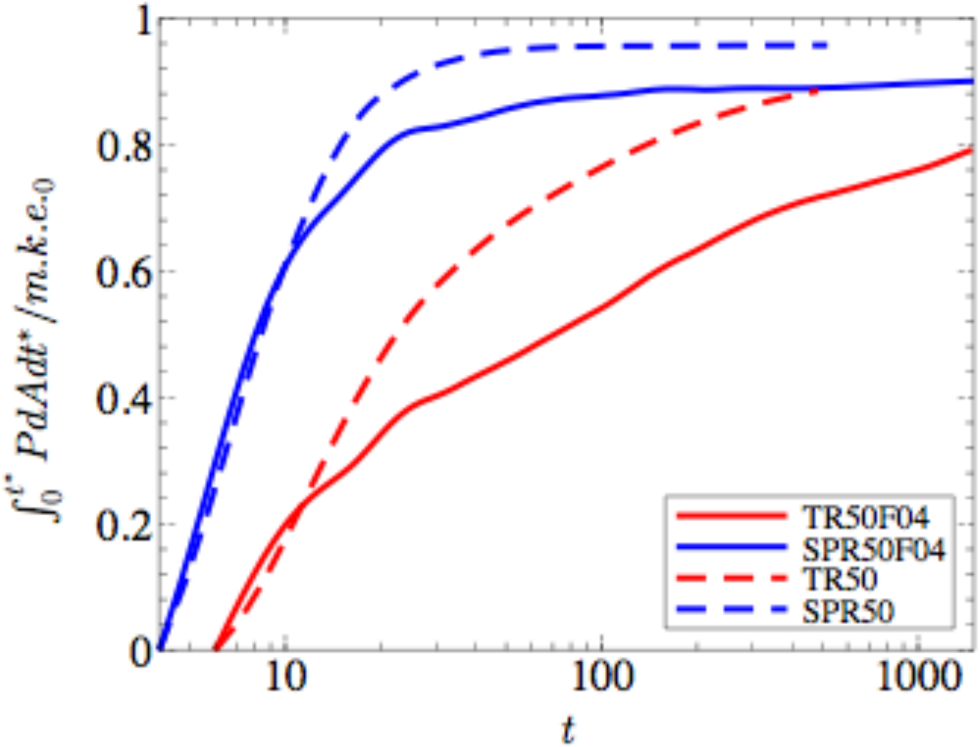
Stratification reduces vertical extent of the wake

The wake experiences a collapse around x/D = 12, Nt=3

Kinetic energy in the wake can no longer support the displaced potential energy (heavy fluid lifted up, light fluid pushed down)

Wake energetics (from temporal DNS)





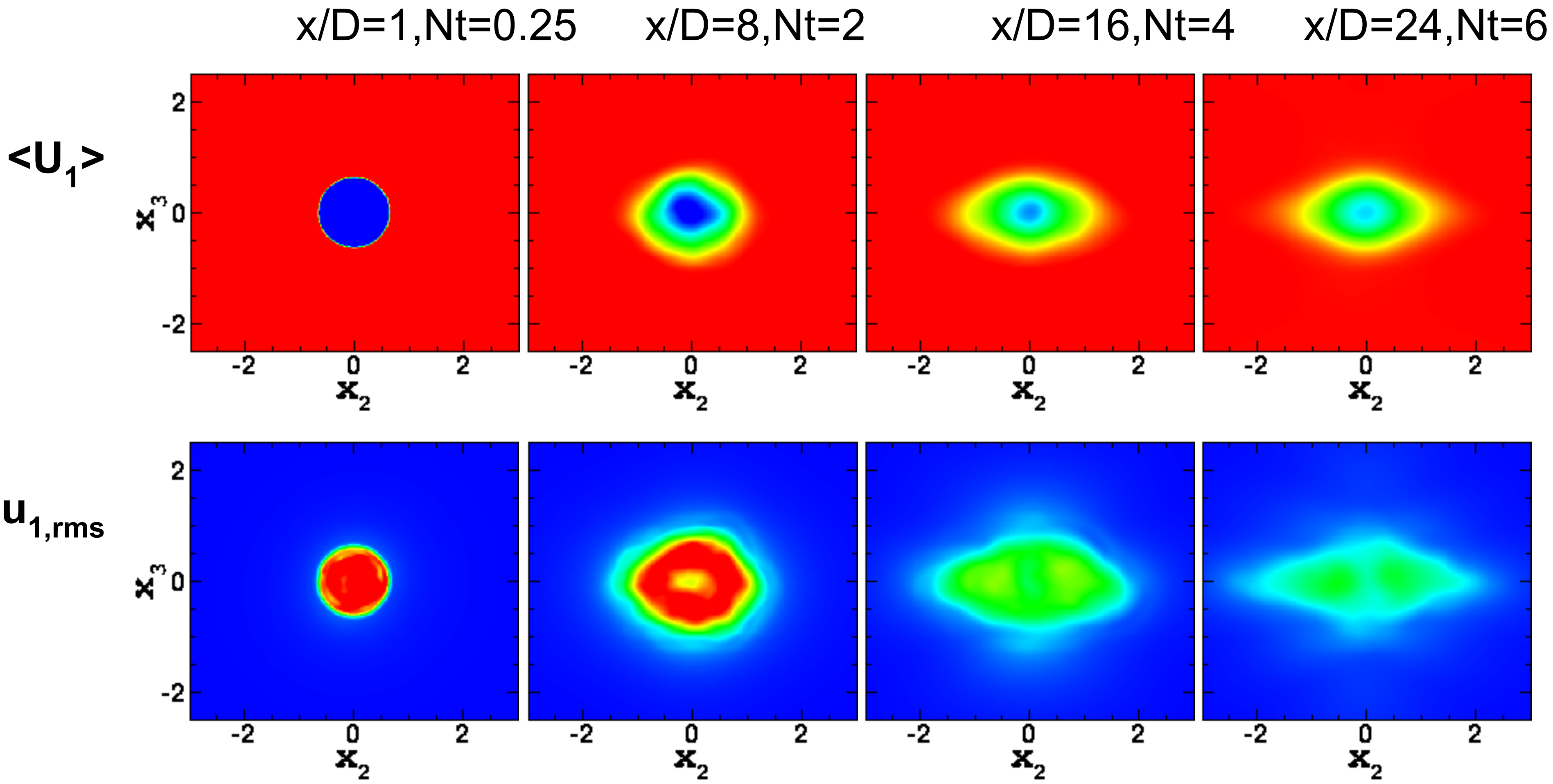
- The integrated m.k.e decreases primarily due to transfer to turbulence

$$\frac{D(m.k.e.)}{Dt} = -P - \bar{\epsilon} - \frac{\partial T_i}{\partial x_i} \simeq P \text{ for } t < 100$$

- Buoyancy effects reduces *P* and therefore the m.k.e. is long lived (compare solid to dashed lines).

- The shape of the SP mean profile increases the mean shear, increases *P*, and therefore the decay rate relative to T profile

Streamwise velocity (spatial evolution)

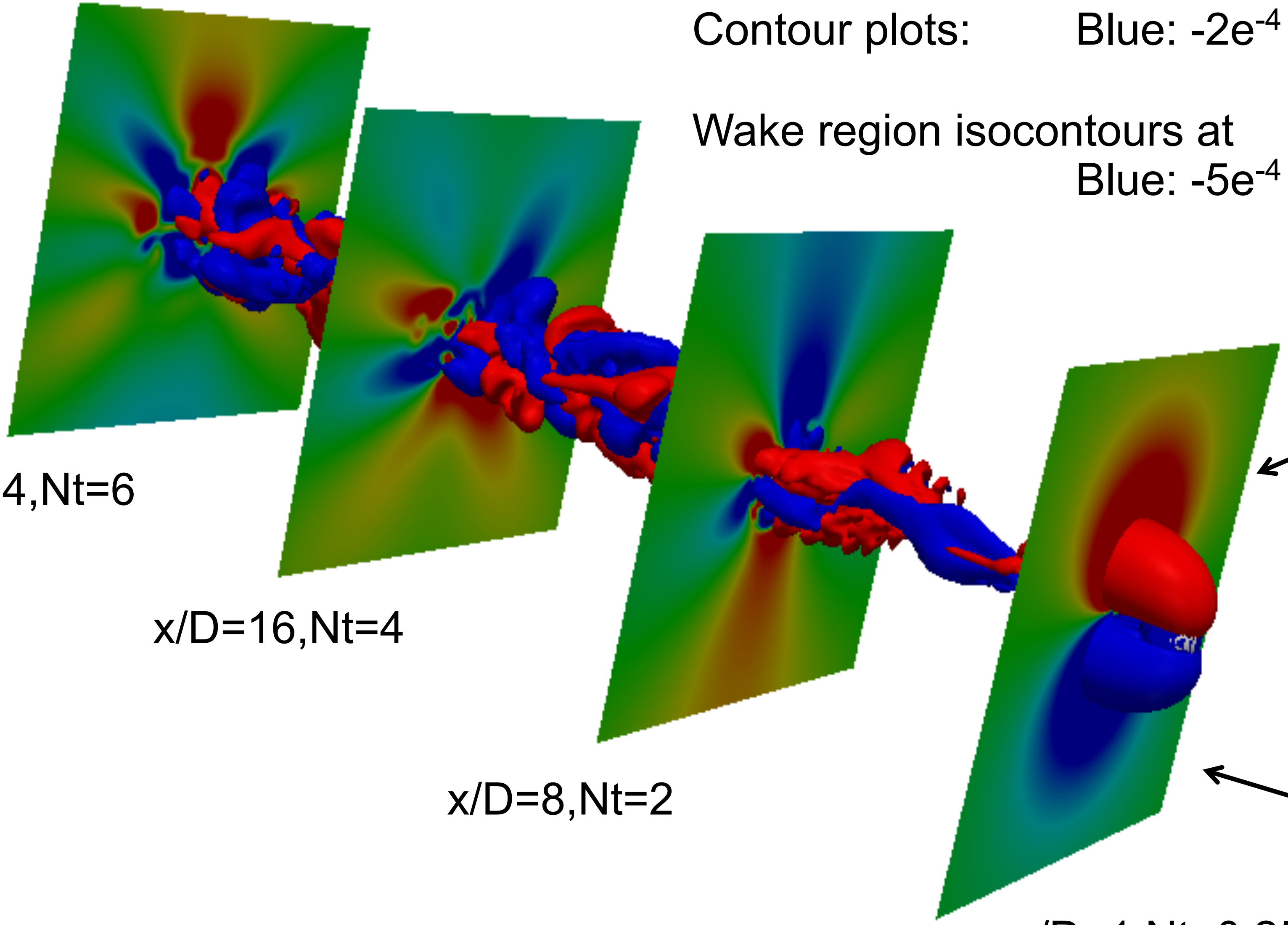


Initial symmetric profile is quickly lost

By x/D=16 the wake has spread more in the horizontal than vertical

Fluctuations extend further than the mean

Visualizing internal waves with density perturbation



Contour plots: Blue: $-2e^{-4}$ Red: $2e^{-4}$

Wake region isocontours at
Blue: $-5e^{-4}$ Red: $5e^{-4}$

x/D=24,Nt=6

x/D=16,Nt=4

x/D=8,Nt=2

x/D=1,Nt=0.25

Heavy fluid lifted up

Light fluid pushed down

Internal waves are radiated by the wake to the background

Carry energy and momentum to surroundings

Problem 2
Internal waves and boundary turbulence

with Bishakh Gayen

Ocean mixing

- About 2 TW of energy required to maintain the overturning circulation that prevents a stagnant and uniformly cold, salty ocean.
- Internal waves forced by surface tides and wind in equal parts supply this energy, Munk and Wunsch (1998).
- Mixing and transport of mixed fluid into the interior occurs at localized and intermittent spots.
- Where and how do internal waves break down to turbulence and what are the energetic balances?

Internal tides and dissipation hotpots

Rudnick et al, Science (2003)

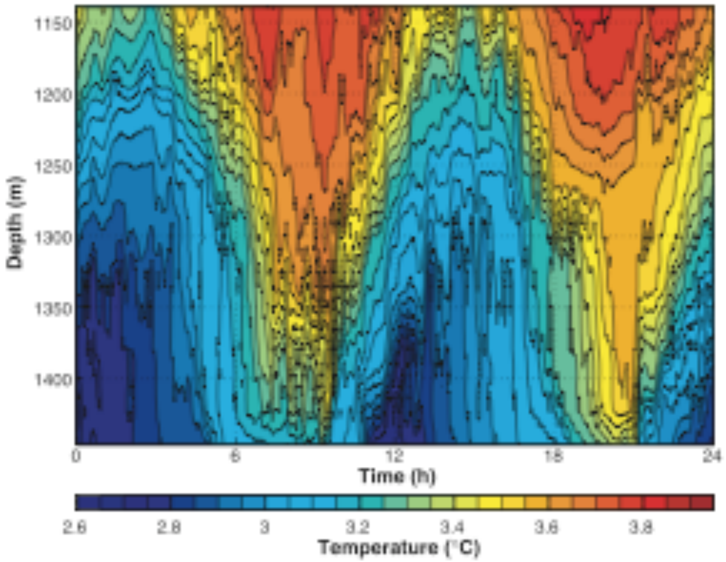
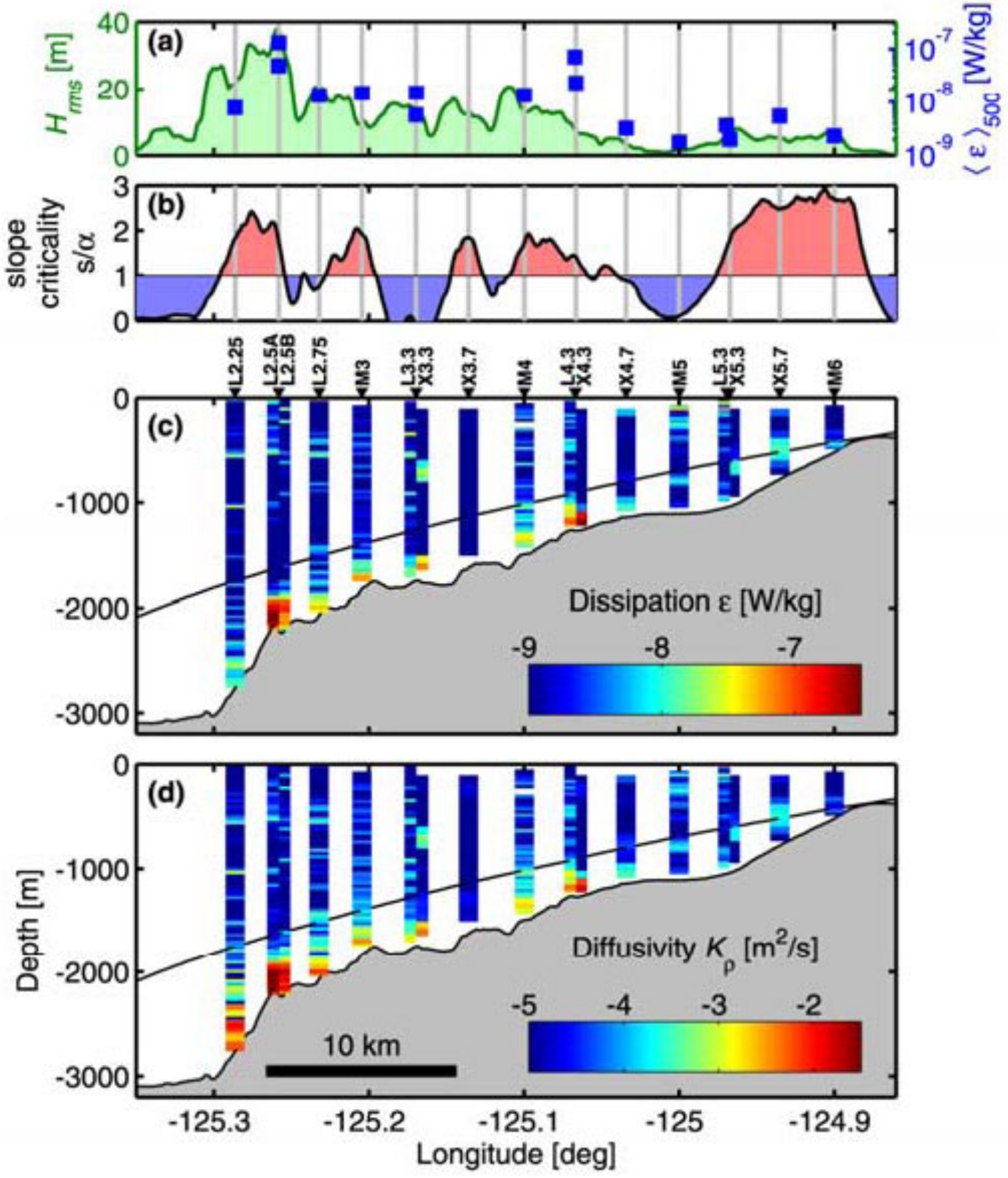


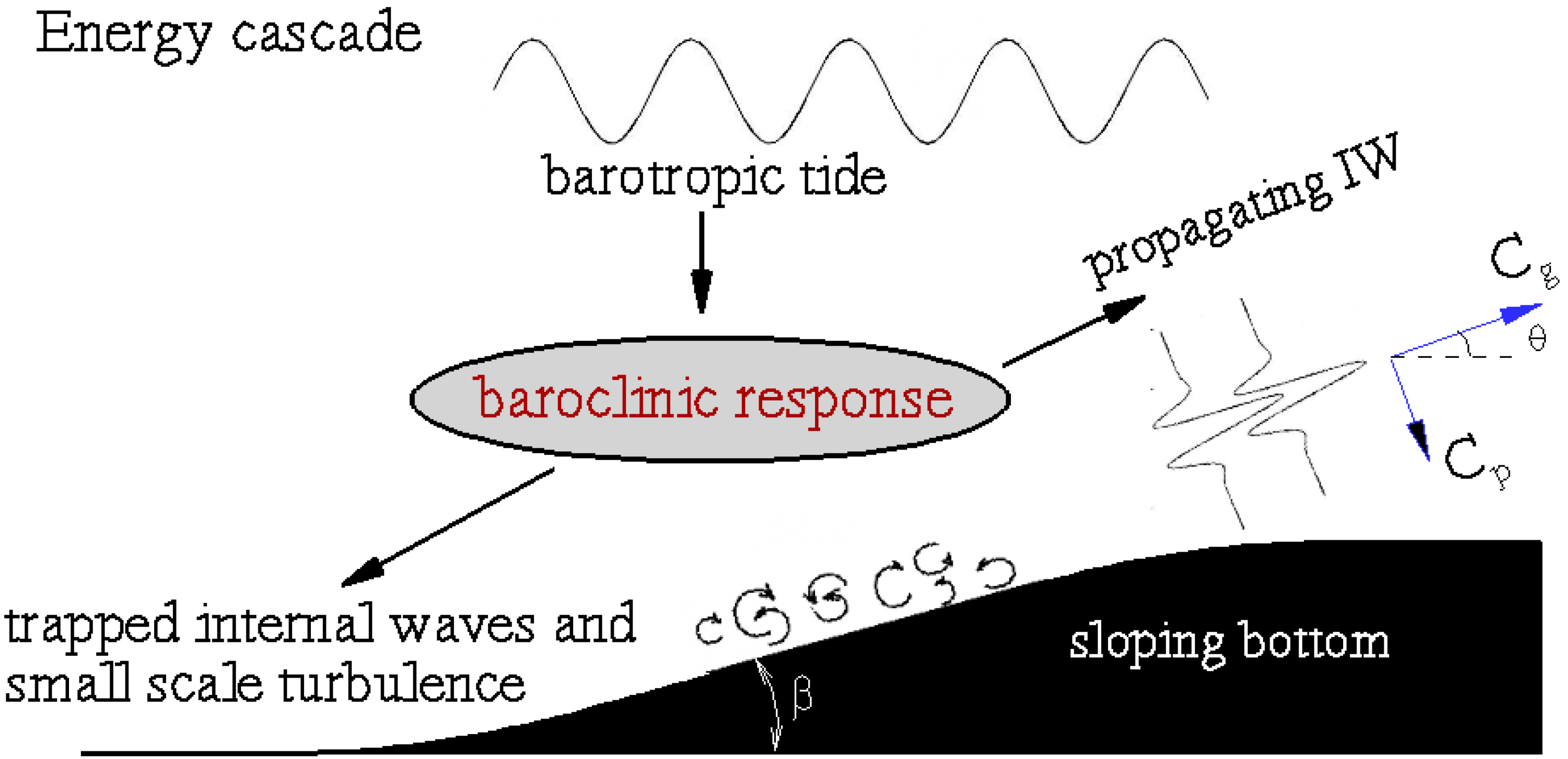
Fig. 2. Temperature as a function of depth and time, measured on a mooring on the flank of the ridge in water with a depth of 1453 m during spring tide. The position of the mooring is shown by the yellow cross in Fig. 1. At the semidiurnal period, the peak-to-peak displacements are 300 m.

300 m vertical displacement of fluid in a M2 tidal cycle

Nash et al, GRL (2007)

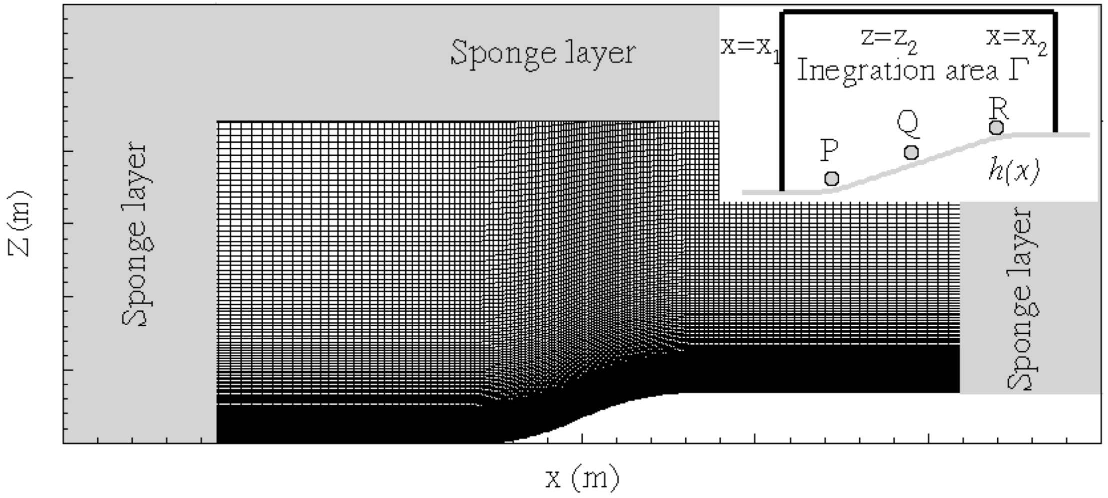


Turbulence during wave generation



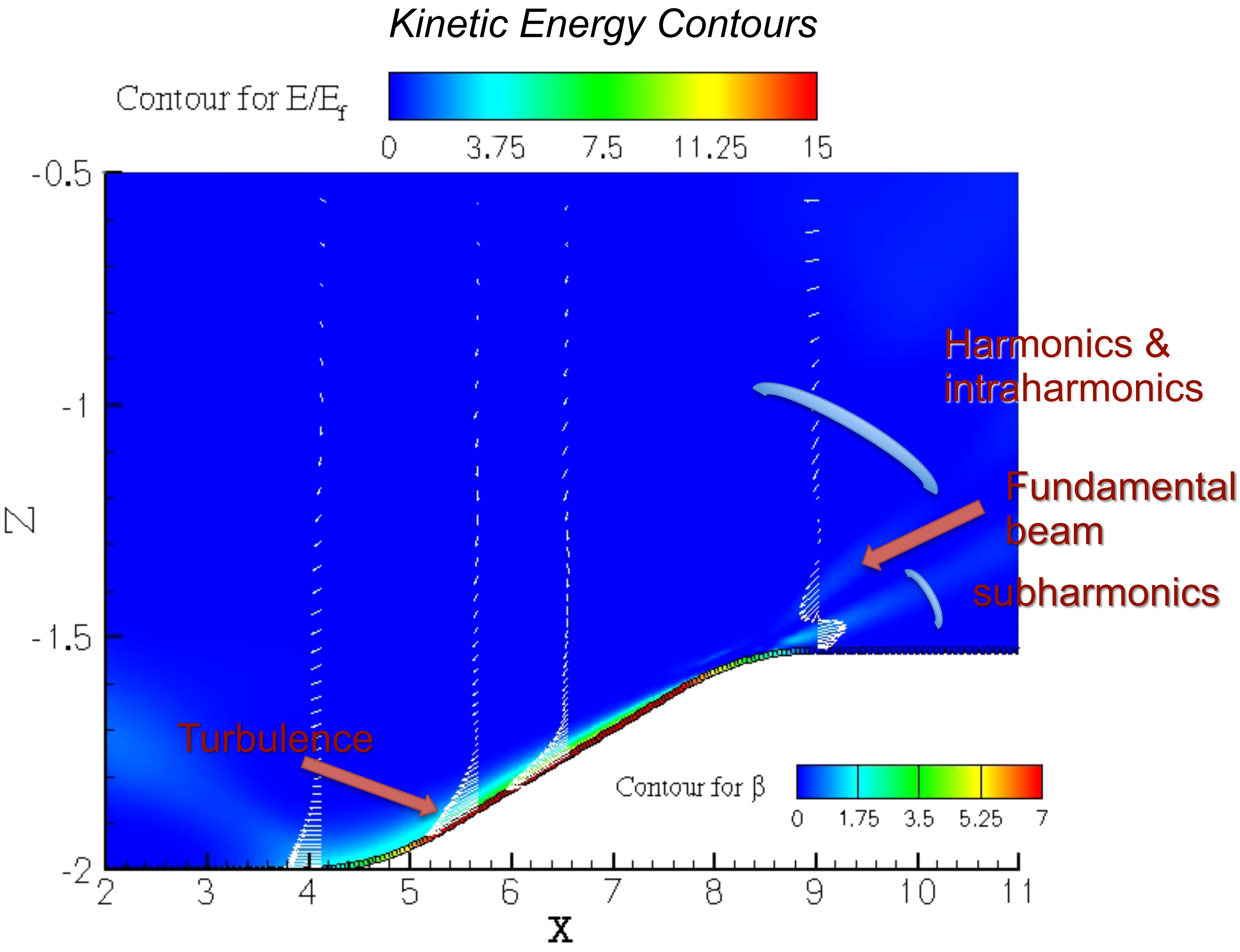
- The oscillatory tide over topographic roughness leads to the formation of internal gravity waves i.e. internal tides.
- The internal tides can have significantly higher velocities and amplitudes than the surface tide.
- Critical case, slope angle = angle of wave propagation, is resonant.

Numerical Method



- Three-dimensional, unsteady NS equations are solved in generalized coordinates on a *boundary-conforming* grid.
- Third-order Runge-Kutta method for time stepping
- ADI for viscous terms
- Spanwise derivatives: pseudo-spectral. Others 2nd order finite differences.
- A multigrid algorithm for pressure solver.
- DNS & LES modes
- Spanwise periodic BC. Bottom boundary: no slip, adiabatic. Top and lateral boundaries: sponge region

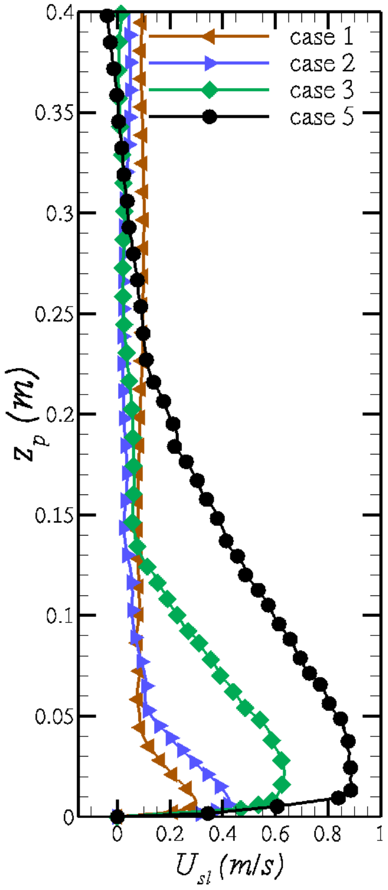
Near-critical slope: Evolution of Kinetic energy



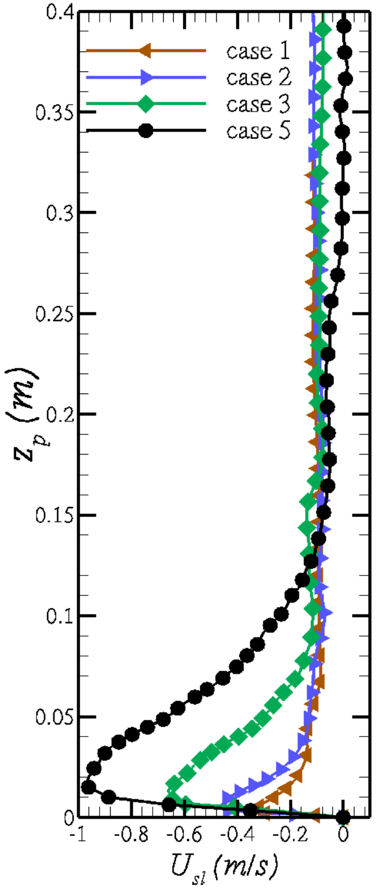
DNS at slope length of 1.7 m, Re_S = 177. Details in Gayen & Sarkar, Phys. Rev. Letters (2010).

Baroclinic boundary flow strength and width (LES)

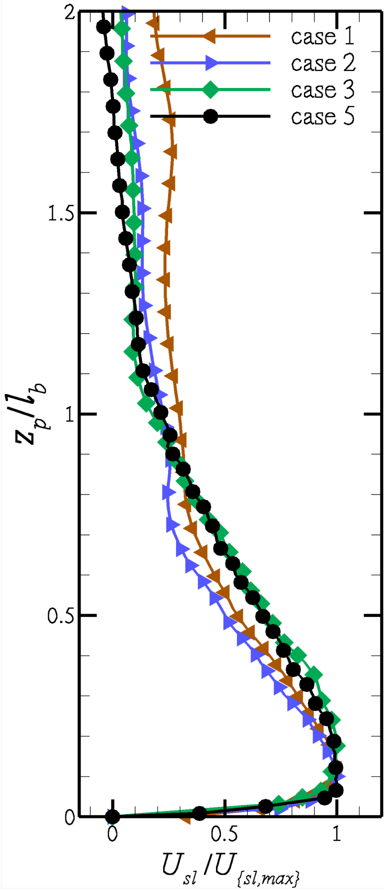
Maximum upslope flow
phase=0



Maximum downslope flow
phase=180



Maximum upslope flow
(Selfsimilar structure)



•Beam peak velocity and width increase with increasing slope length, 1 m to 25 m.

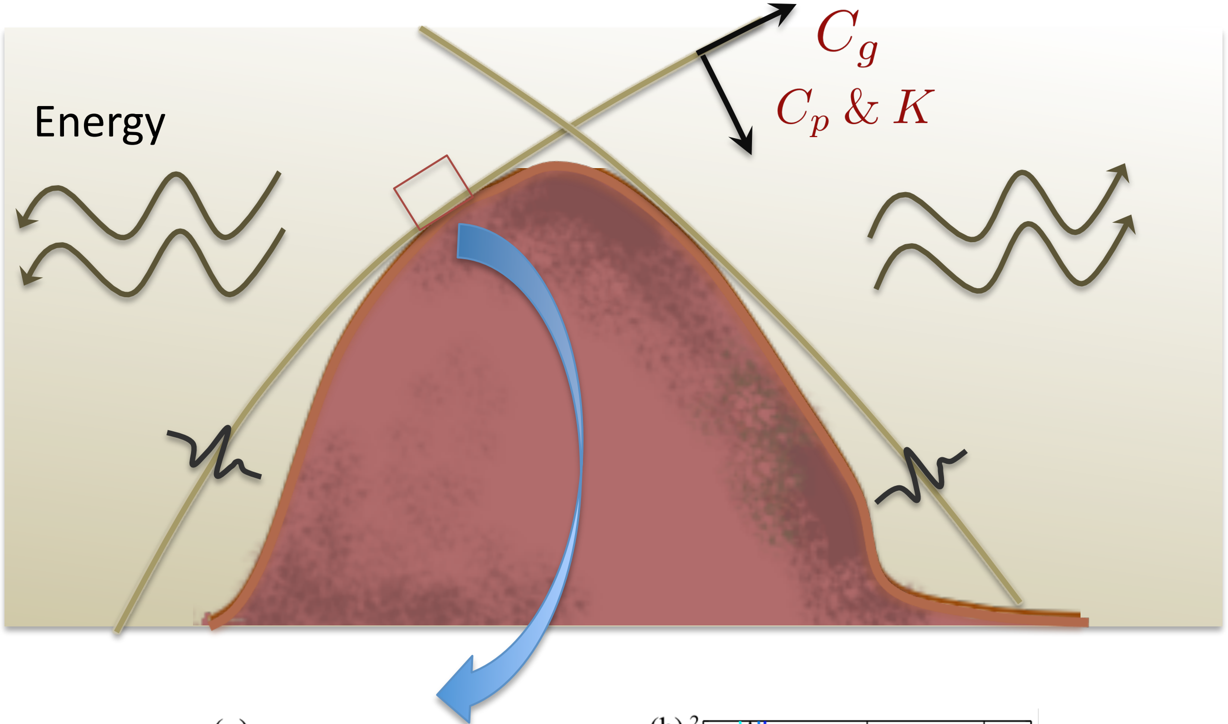
• Asymmetry. Beam width decreases during down slope flow for same slope length.

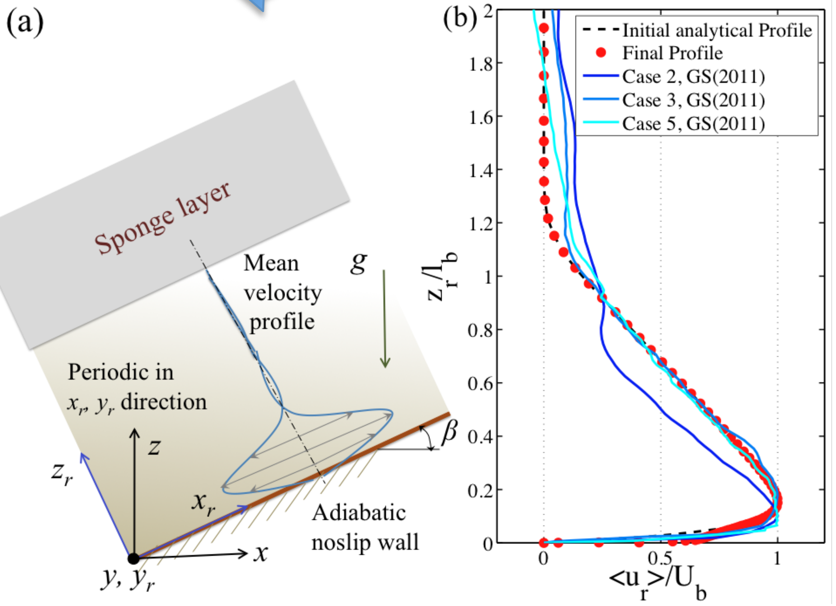
•Selfsimilar structure when scaled with peak velocity and beam width.

•Model give the beam width and beam velocity approximately proportional to $l^{0.5}$.

Gayen and Sarkar, JFM (2011)

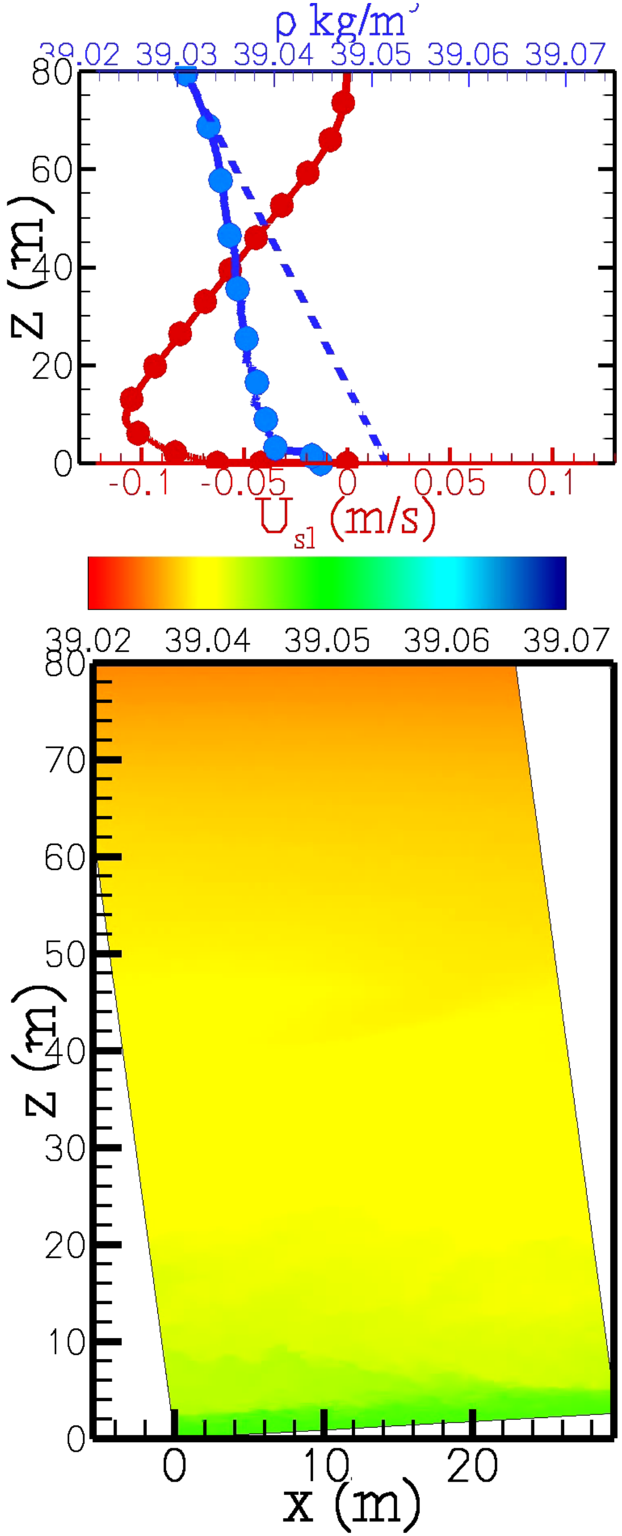
LES of a patch of an oceanic IW beam



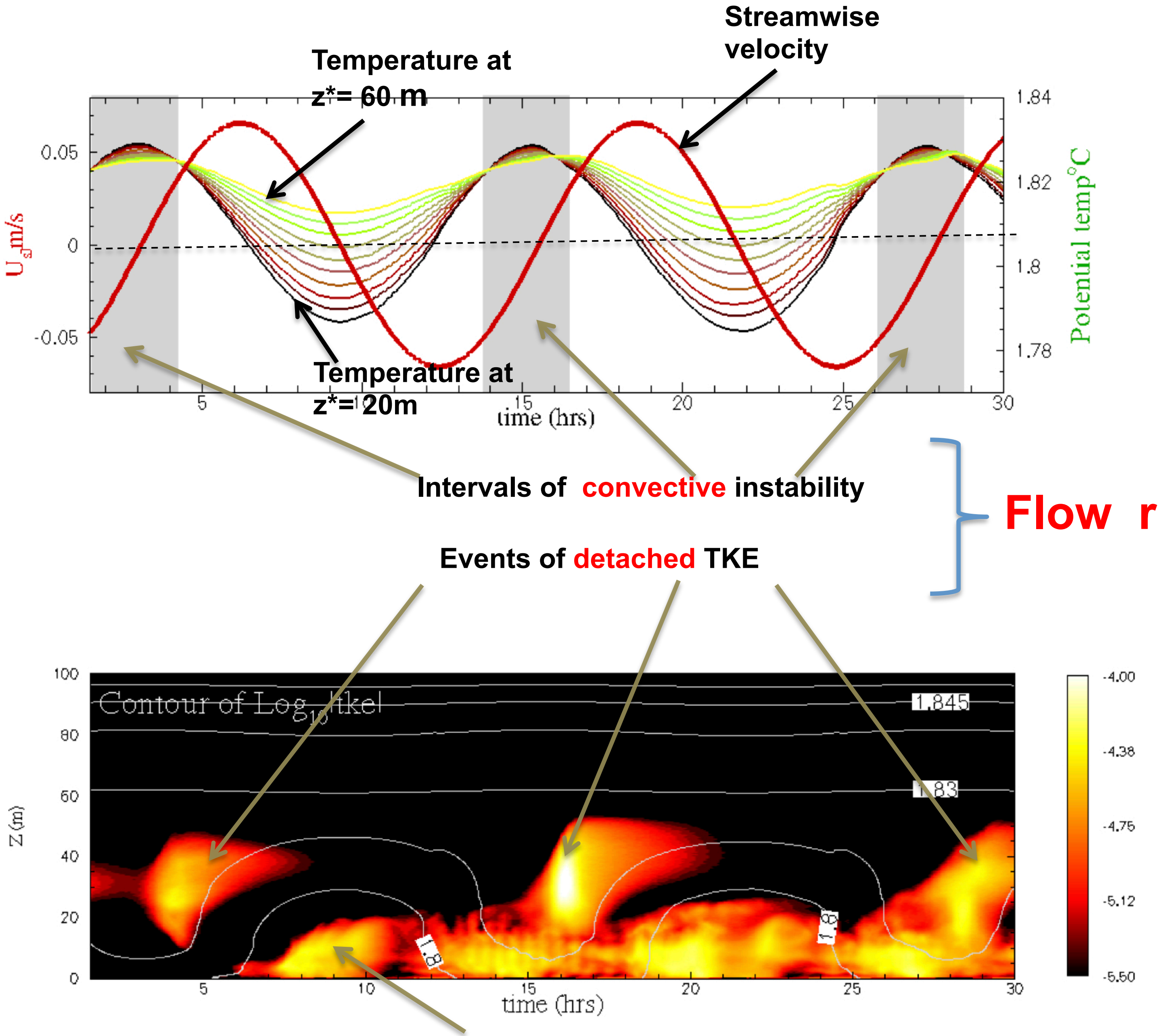


NS equations in rotated coordinates
Streamwise periodic
60 m beam width
Initialized with self-similar velocity found in previous LES

Gayen & Sarkar, GRL (2011)


ρ kg/m³
39.02 39.03 39.04 39.05 39.06 39.07
80
60
40
20
0
z (m)
-0.1 -0.05 0 0.05 0.1
U_s1 (m/s)
39.02 39.04 39.05 39.06 39.07
80
70
60
50
40
30
20
10
0
z (m)
0 10 20
x (m)

Phase dependent TKE in beam



Streamwise velocity

Temperature at z*= 60 m

Temperature at z*= 20m

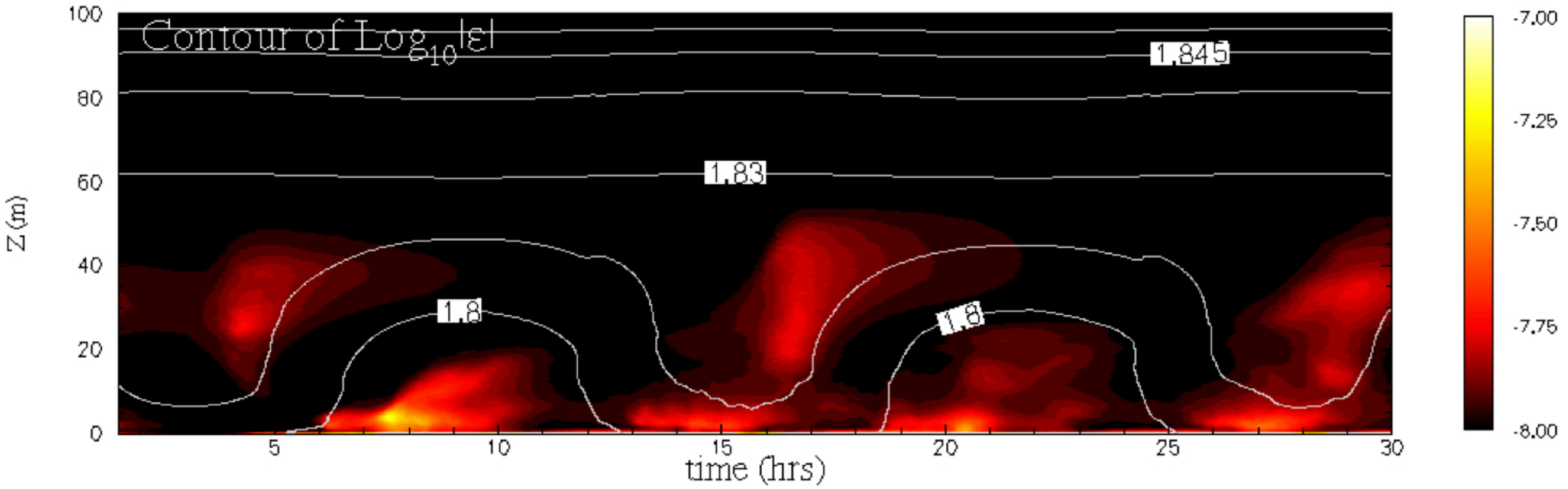
Intervals of convective instability

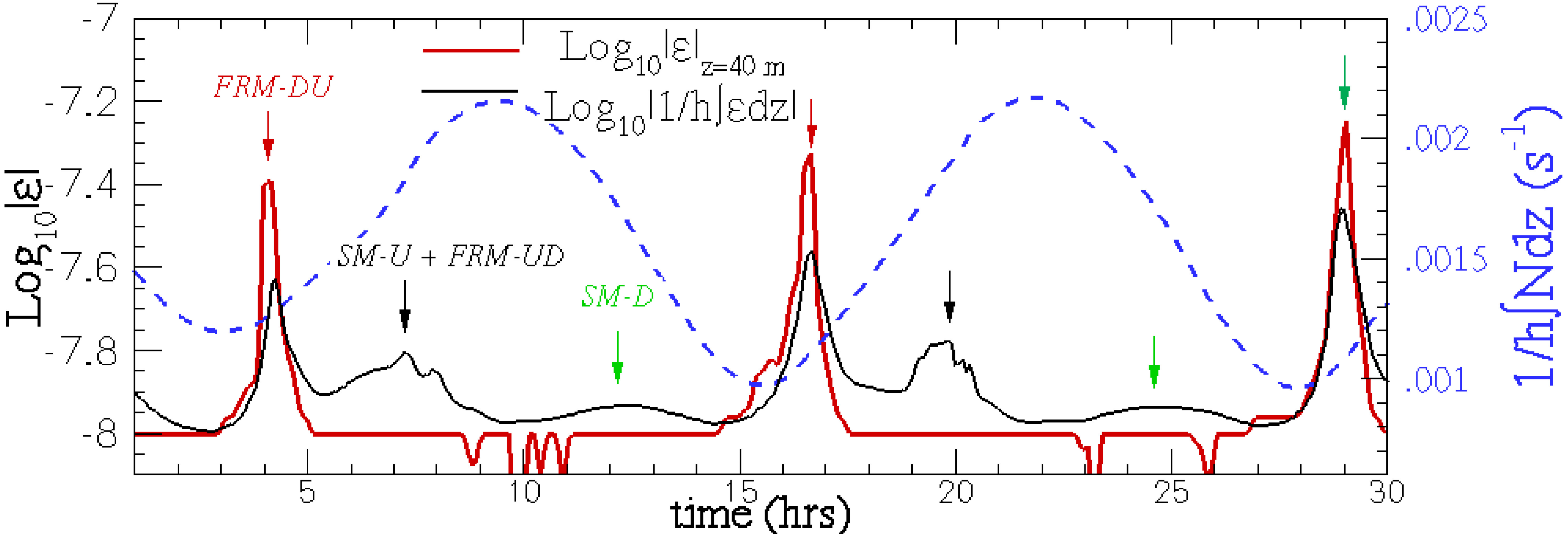
Events of detached TKE

Flow reversal mixing

Attached boundary layer TKE, shear instabilty

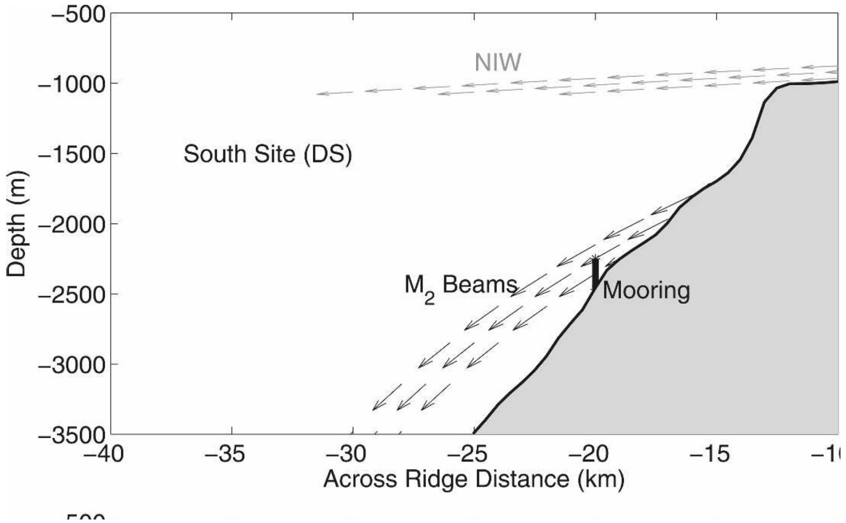
Near-bottom dissipation rate in beam

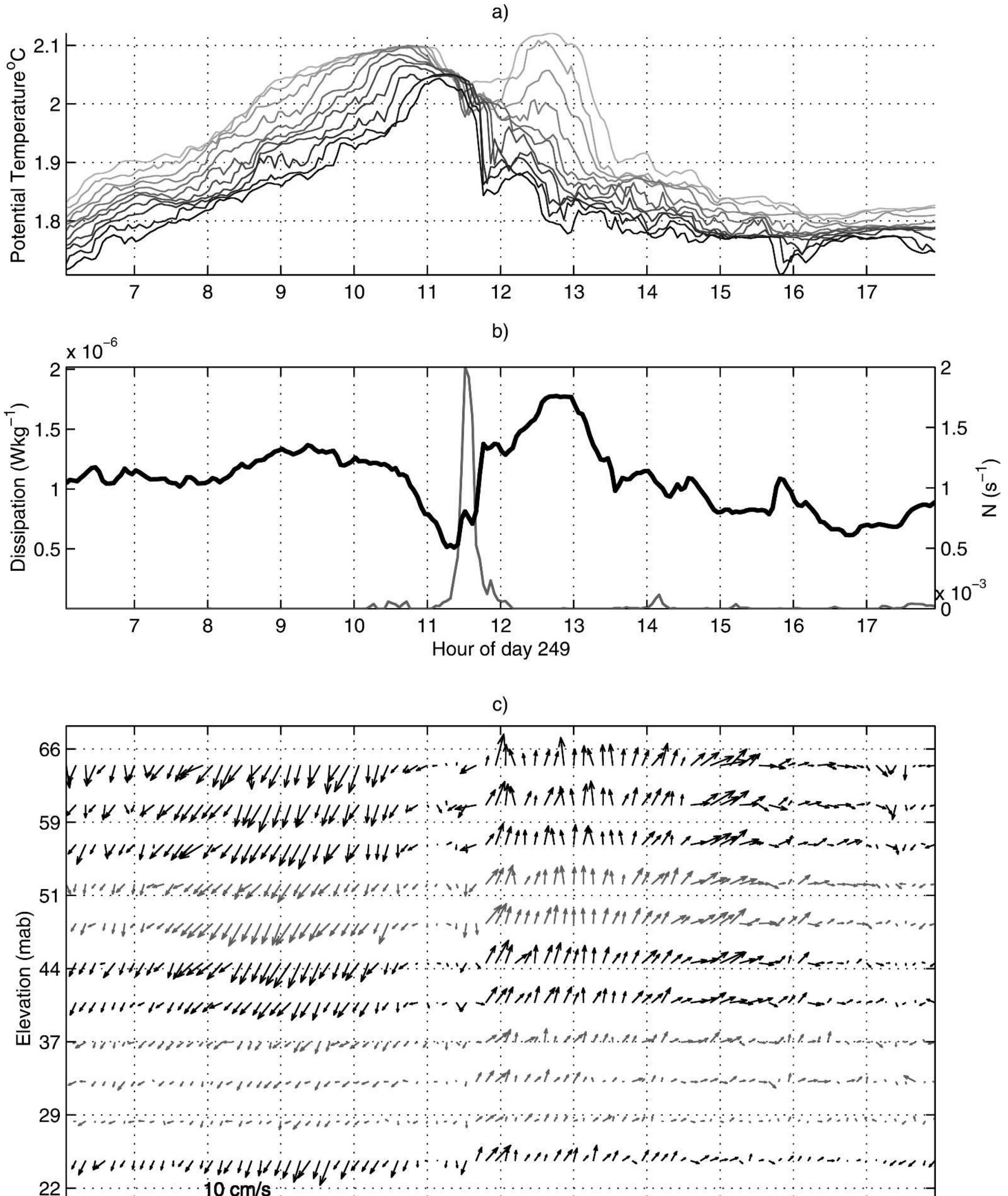




Observations of bottom mixing at Kaena Ridge

Aucan et al, JPO (2006) reported observations from a mooring (DS) on south flank of Kaena Ridge. 200m bottom layer of turbulence is observed with strong overturns during *flow reversal* from down to up flow. A M2 beam is locally generated in the vicinity.





Conclusions

- Turbulence resolving simulations along with theory can be used to understand & model (parameterize) complex, unsteady flows in the natural environment.
- In the ICASE spirit!