Numerical Simulations of a Stratified Oceanic Bottom Boundary Layer

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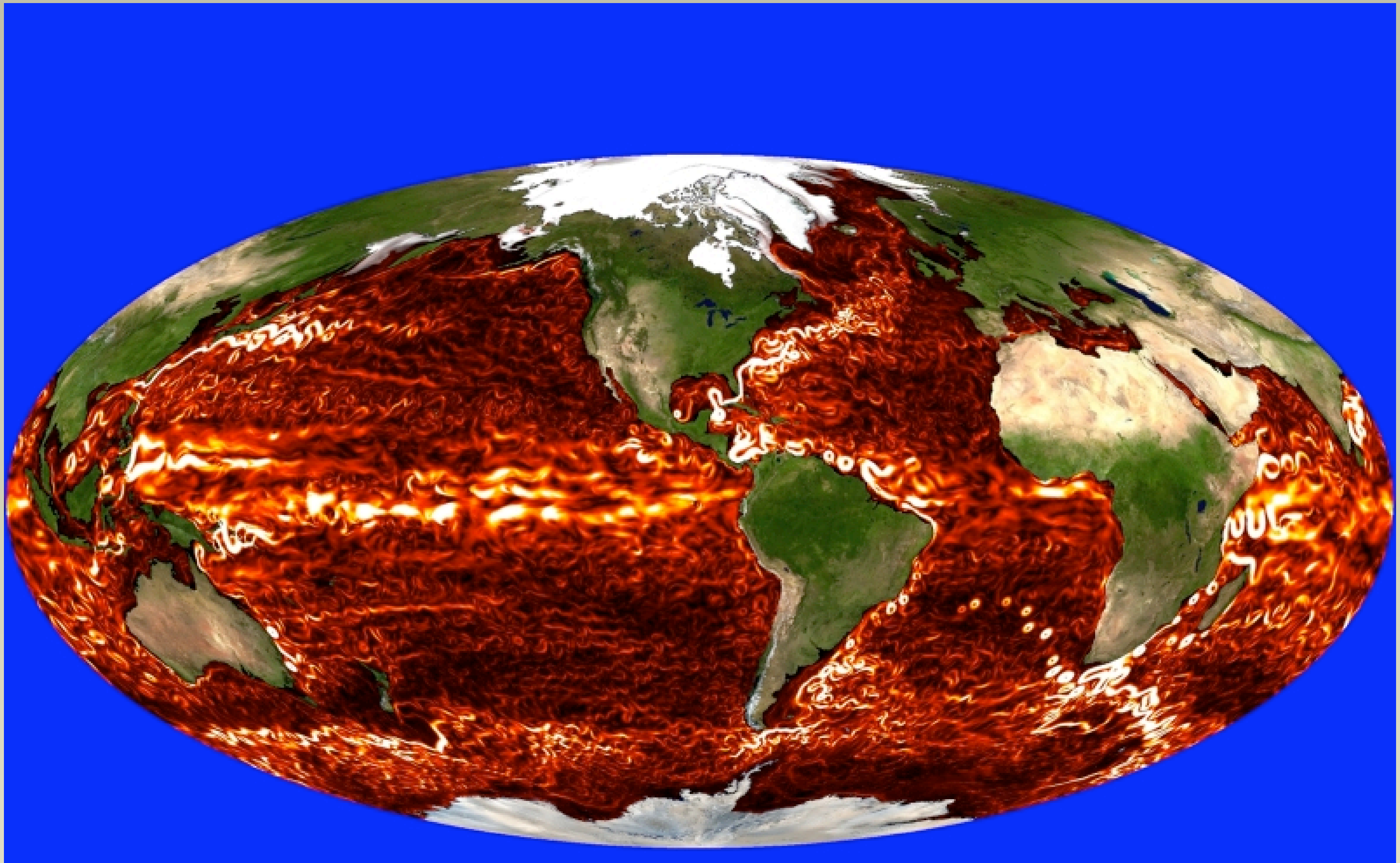
Image NASA

Motivation

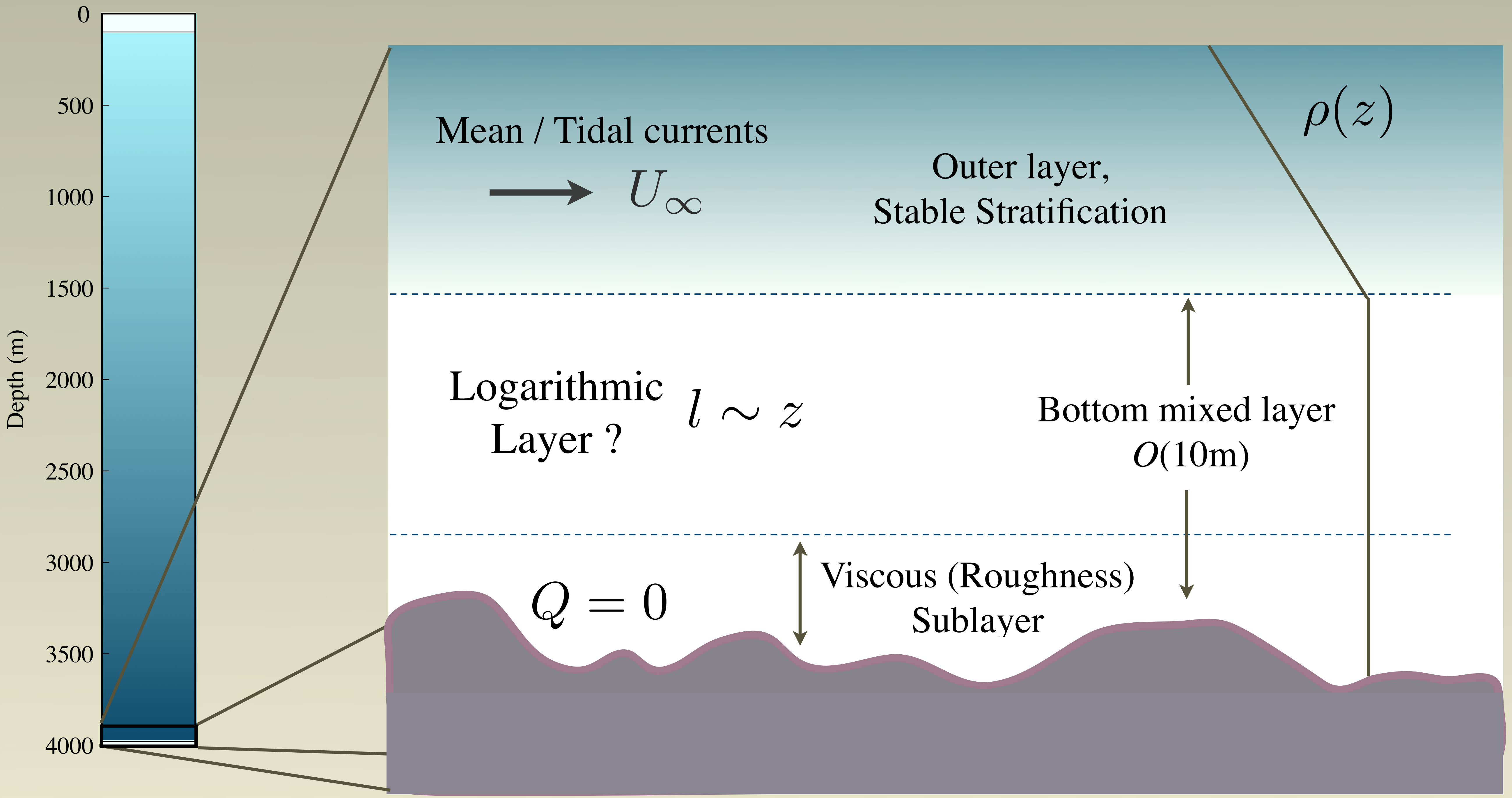
Objective I: Assess and improve parameterizations of the bottom boundary layer in ocean models.



Velocity magnitude, MITgcm
(Chris Hill personal communication)

- Numerical ocean models are very important to accurate weather and climate prediction.
- Ocean models cannot resolve three-dimensional turbulence in the bottom boundary layer.

Oceanic Bottom Boundary Layer



Mean / Tidal currents

U_∞

Outer layer,
Stable Stratification

$\rho(z)$

Logarithmic
Layer ?

$l \sim z$

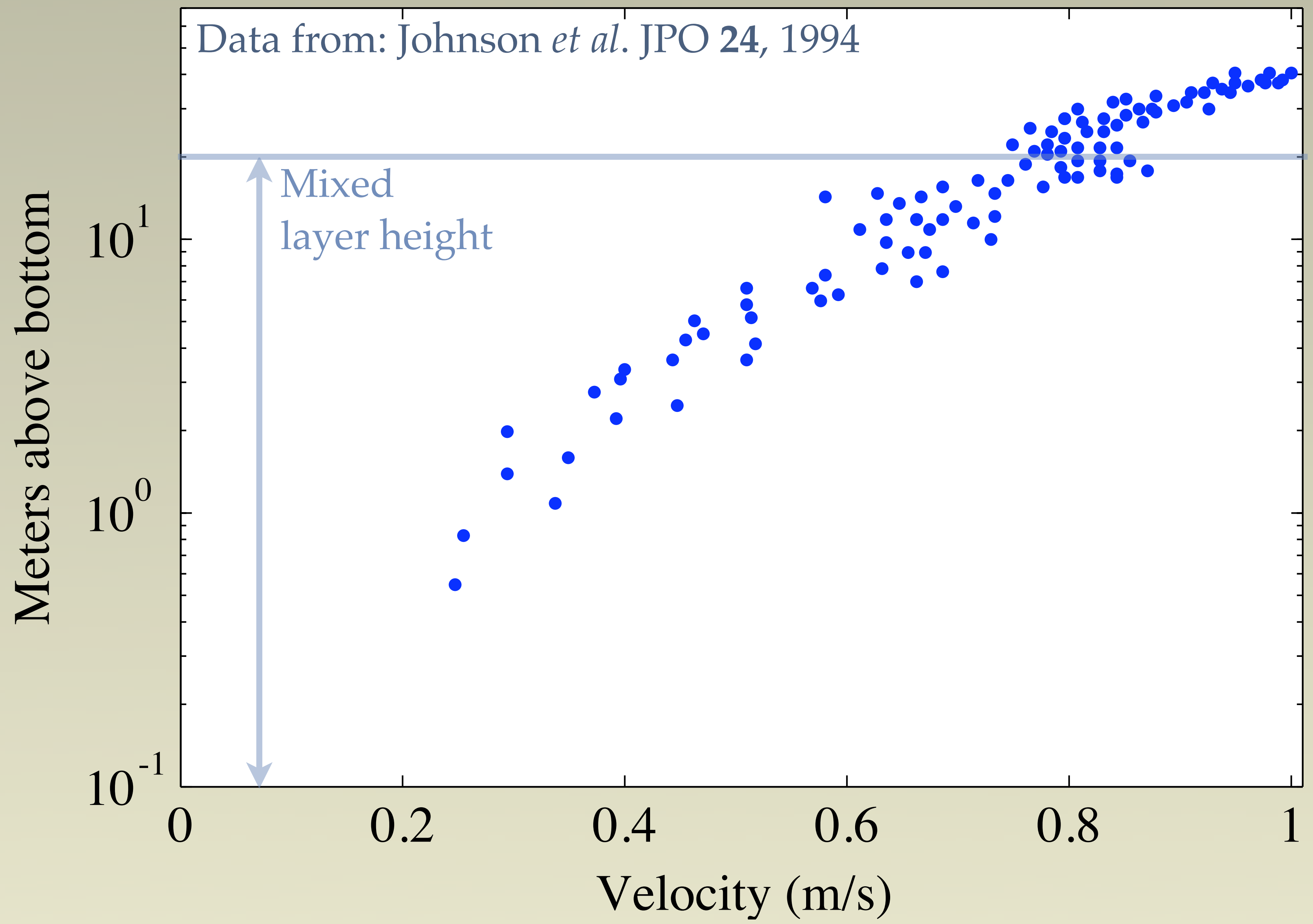
Bottom mixed layer
O(10m)

$Q = 0$

Viscous (Roughness)
Sublayer

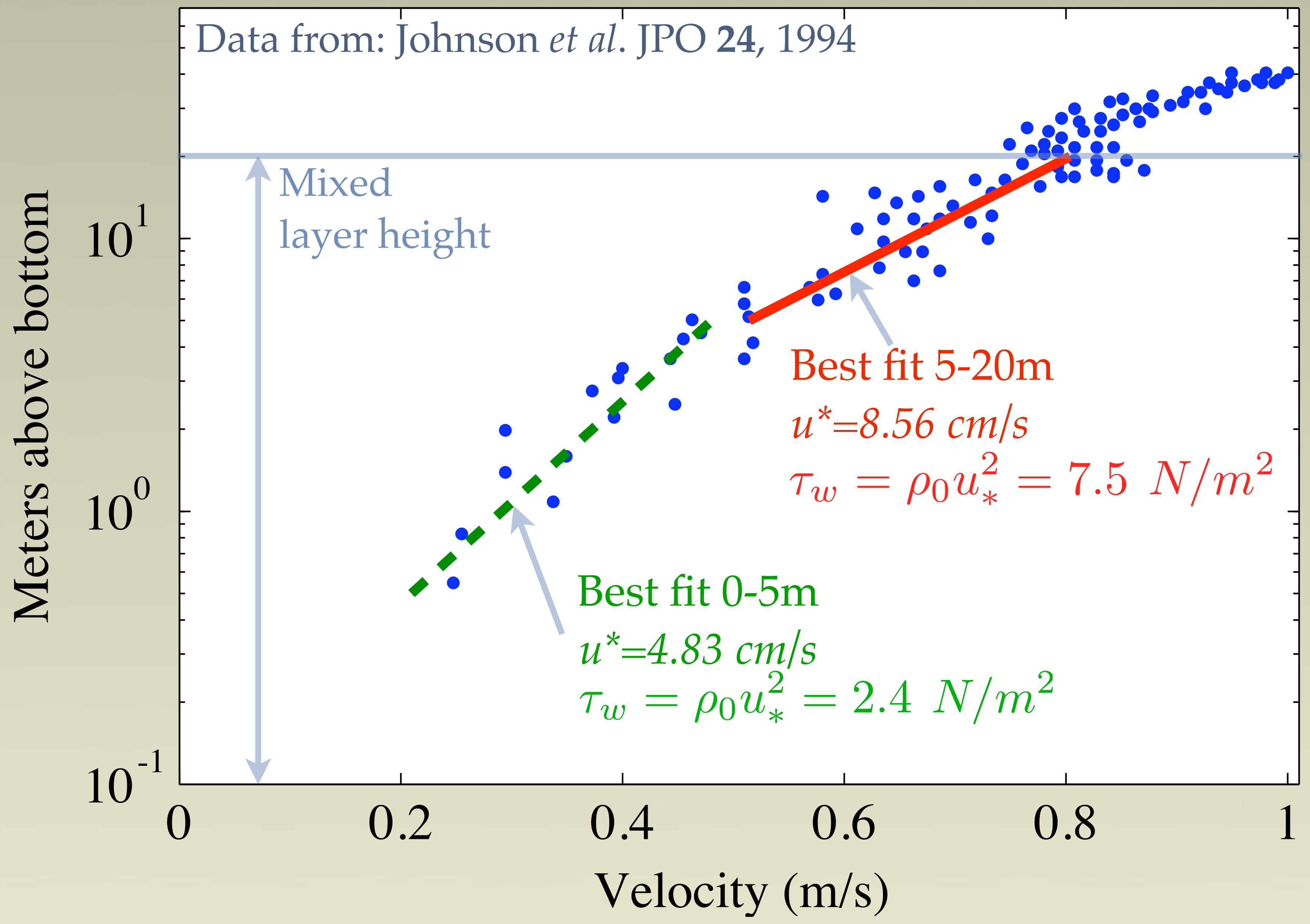
Field Observations

Objective II: Provide a database to help interpret field data



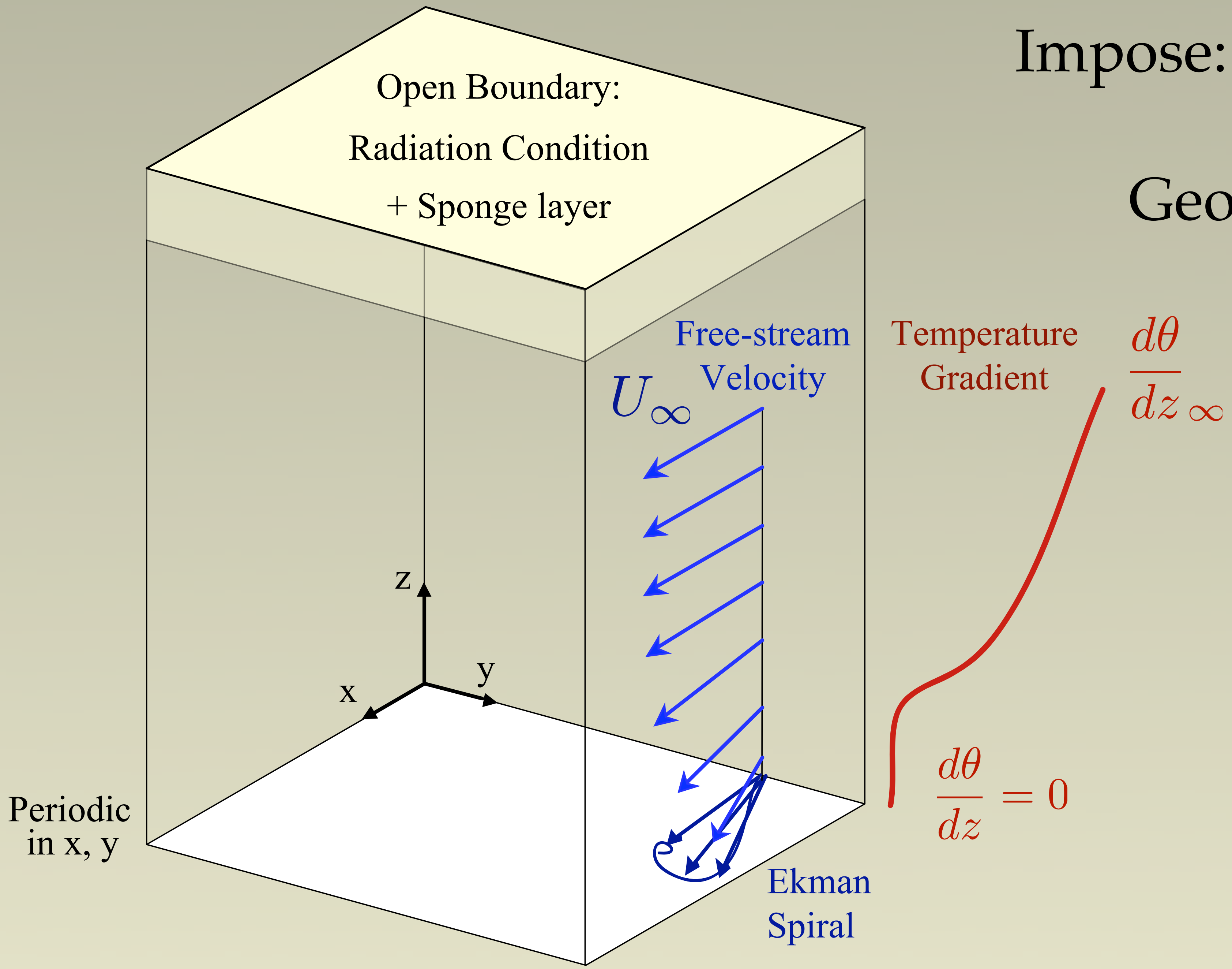
- The seafloor stress is often estimated by fitting a logarithmic profile to the observed velocity profile.

Field Observations



- Shear is larger at the top of the mixed layer.
- Can lead to a dramatic overestimate in the wall stress.

Computational Domain



Open Boundary:
Radiation Condition
+ Sponge layer

Free-stream Velocity U_∞

Temperature Gradient $\frac{d\theta}{dz}_\infty$

$\frac{d\theta}{dz} = 0$

Periodic in x, y

Ekman Spiral

Seafloor: Non-sloping, hydrodynamically rough wall

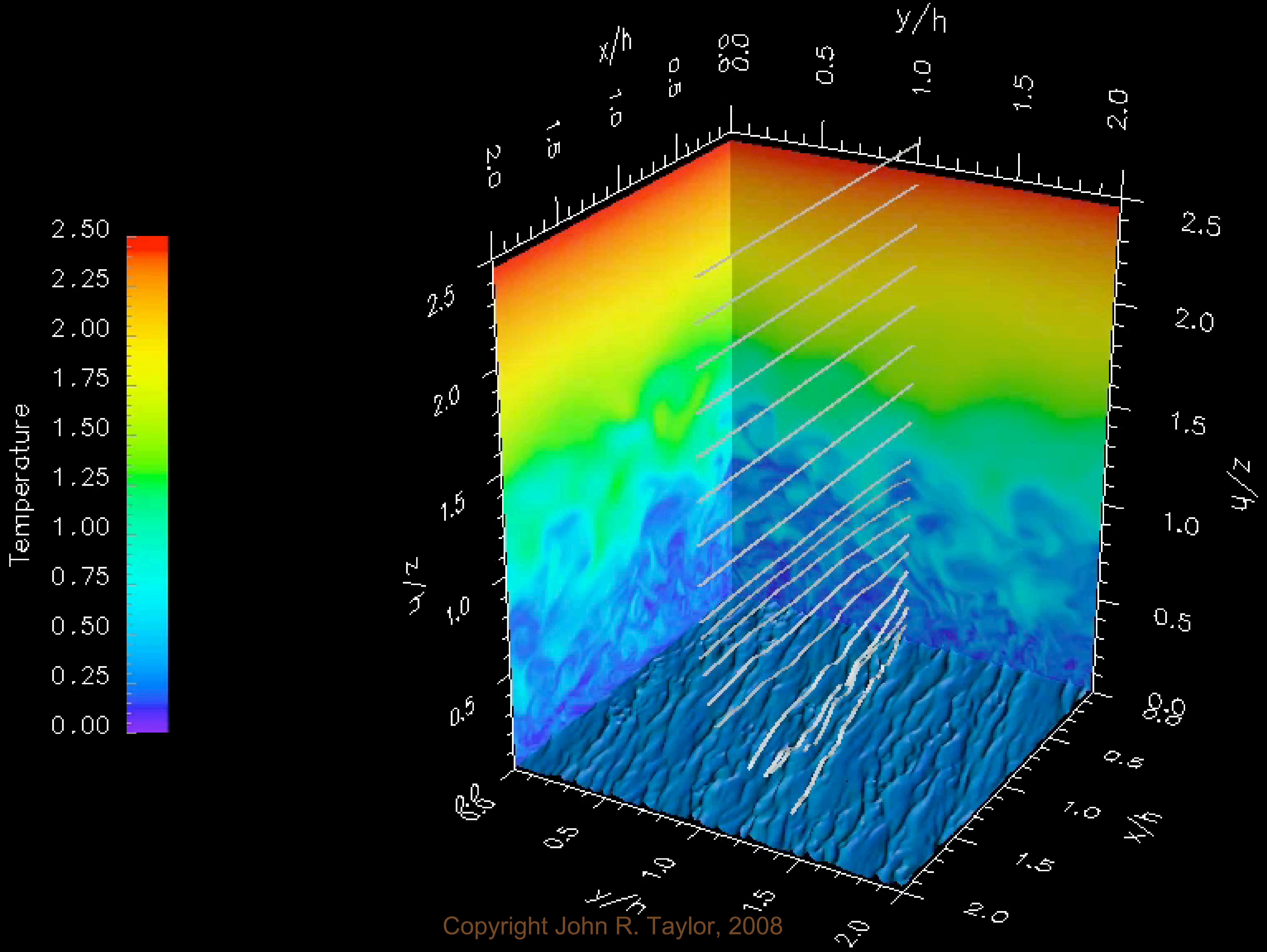
Impose: $U_\infty, \quad \frac{d\theta}{dz}_\infty, \quad f$

Geostrophy: $fU_\infty = \frac{dP}{dy}$

$Ri_* = N_\infty^2/f^2$
0
100
1000
5625

$$\left(N_\infty^2 = \alpha g \frac{d\theta}{dz}_\infty \right)$$

Turbulent Ekman Layer



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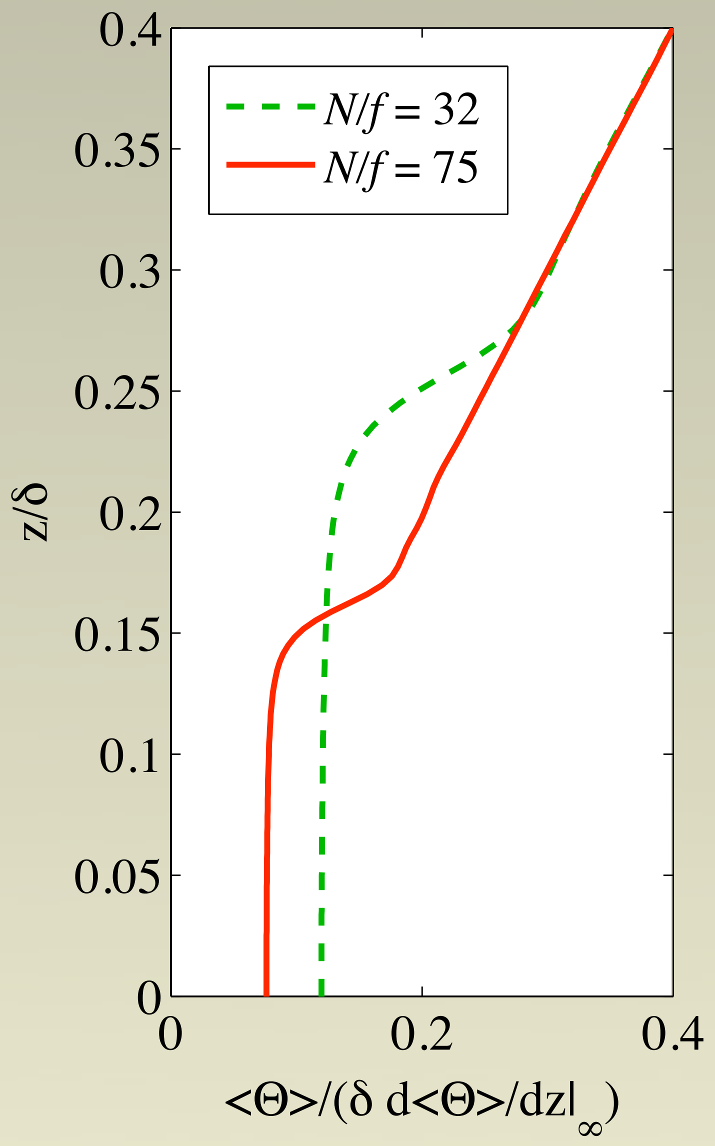
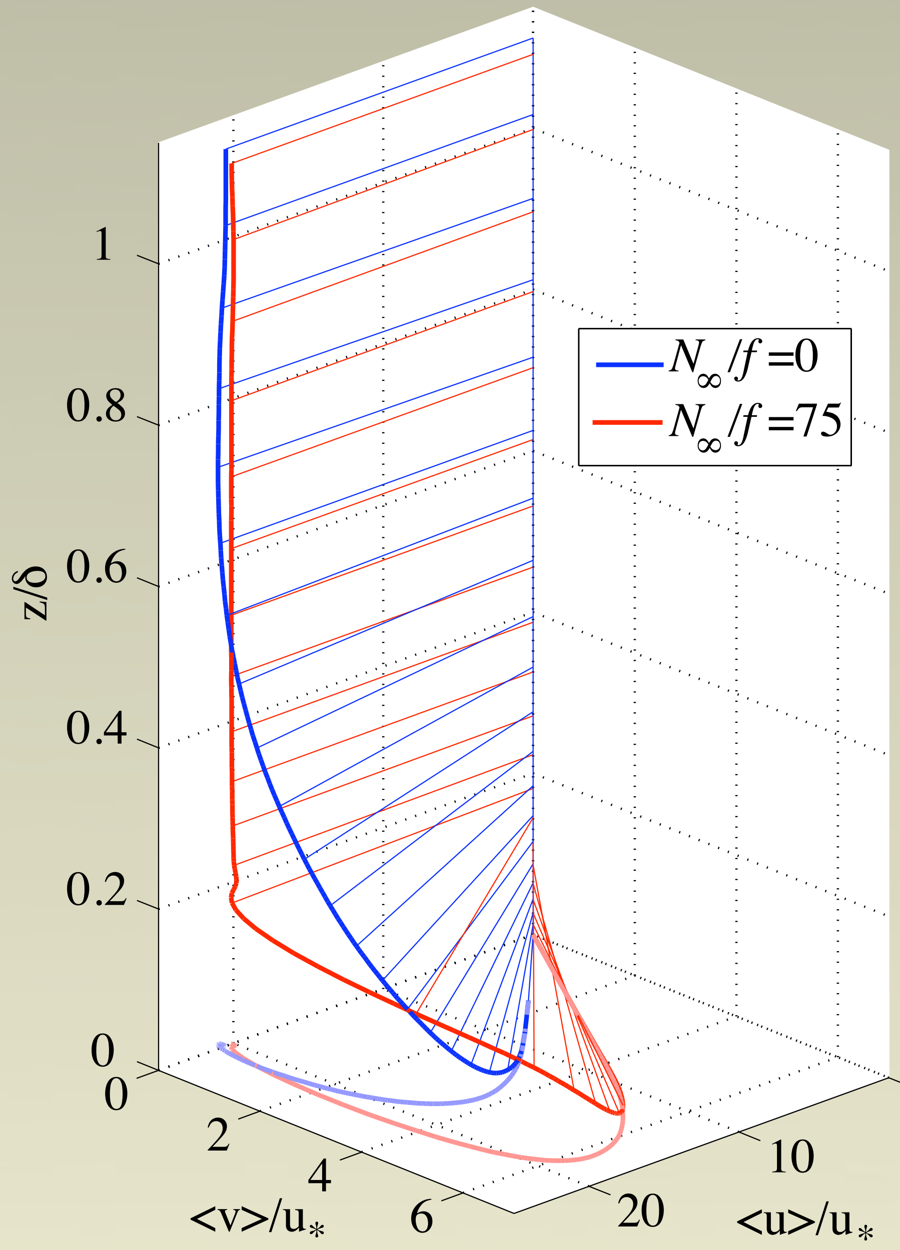
Density, Velocity

- Mixed layer, Ekman height are limited by stratification.
  - Associated with a small increase in the drag coefficient





Steady state balance:

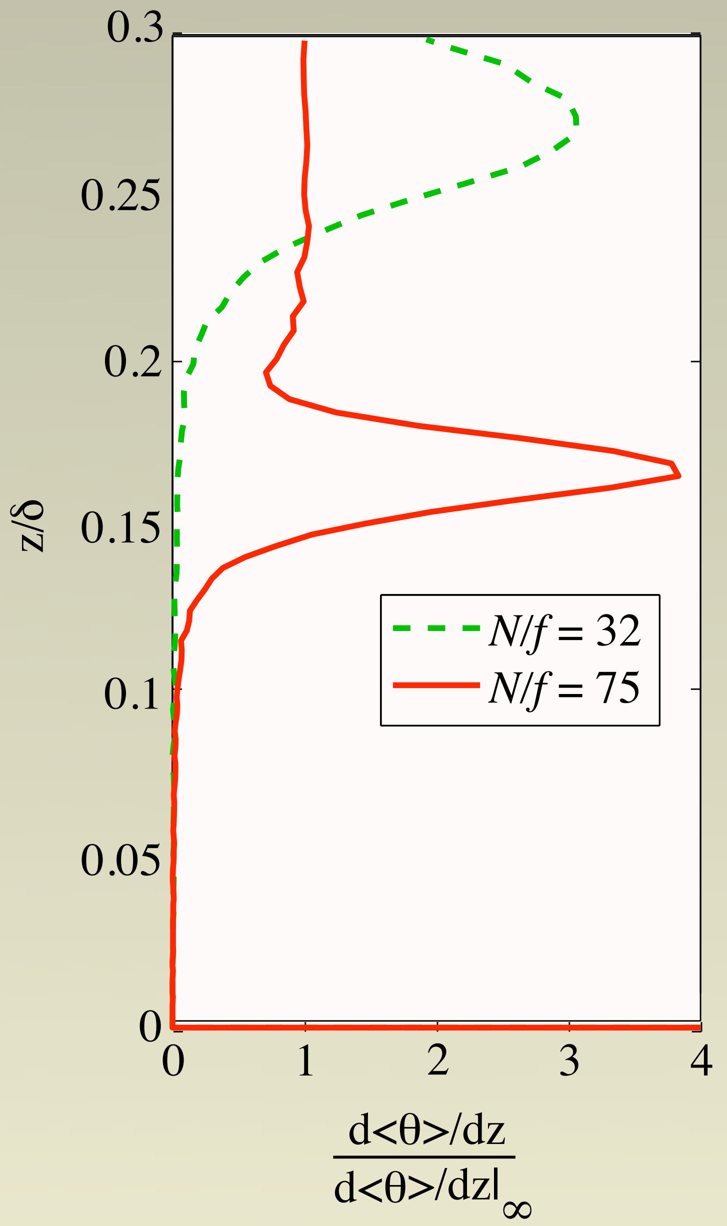
$$f\int_0^\infty < v > dz = \tau_w$$

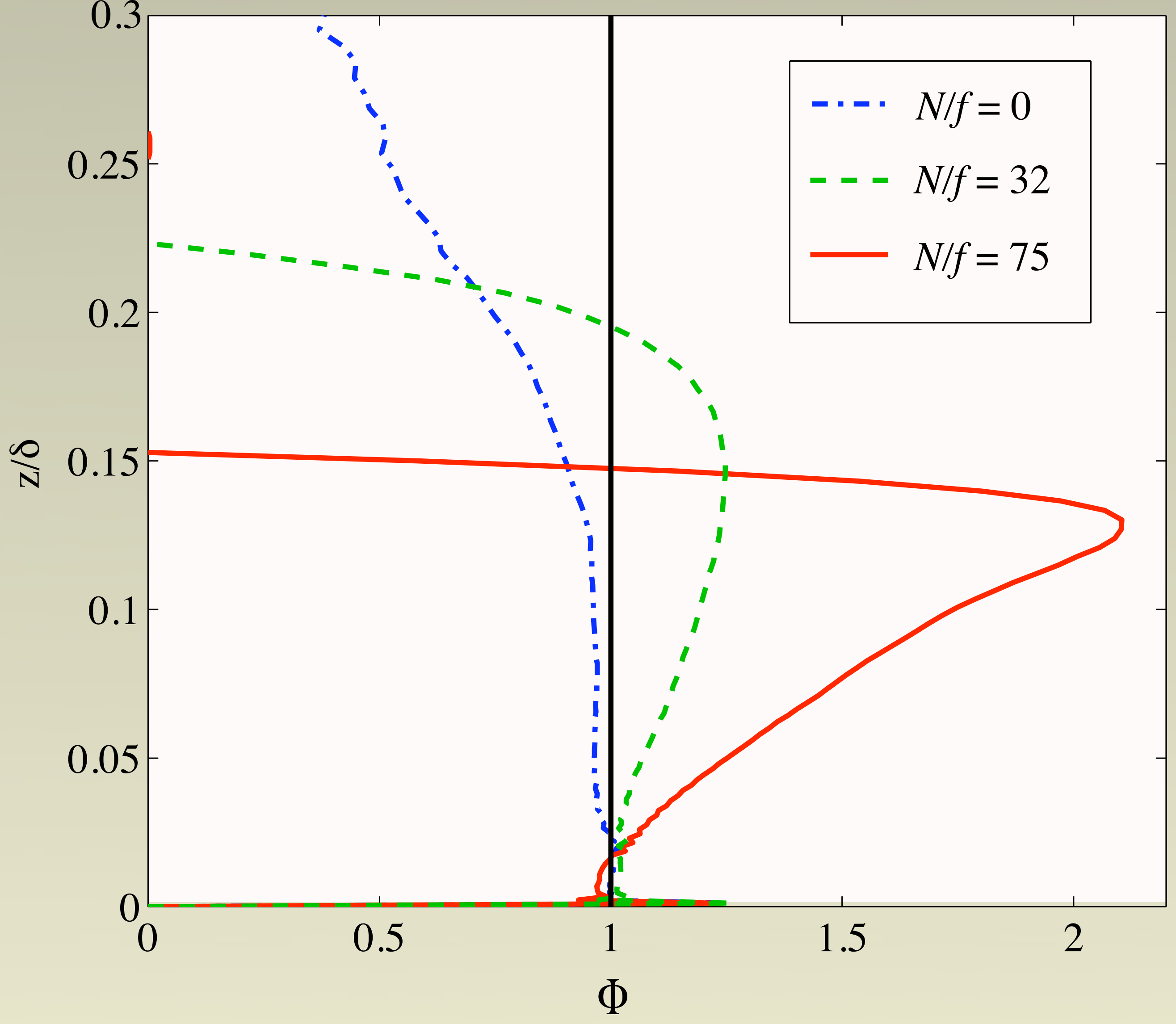
Drag Coefficient

N_∞/f	0	32	75
u_*/U_∞	0.0488	0.0490	0.0497

Density, Velocity Gradients

- Stratification causes an increase in the mean shear.


Density gradient



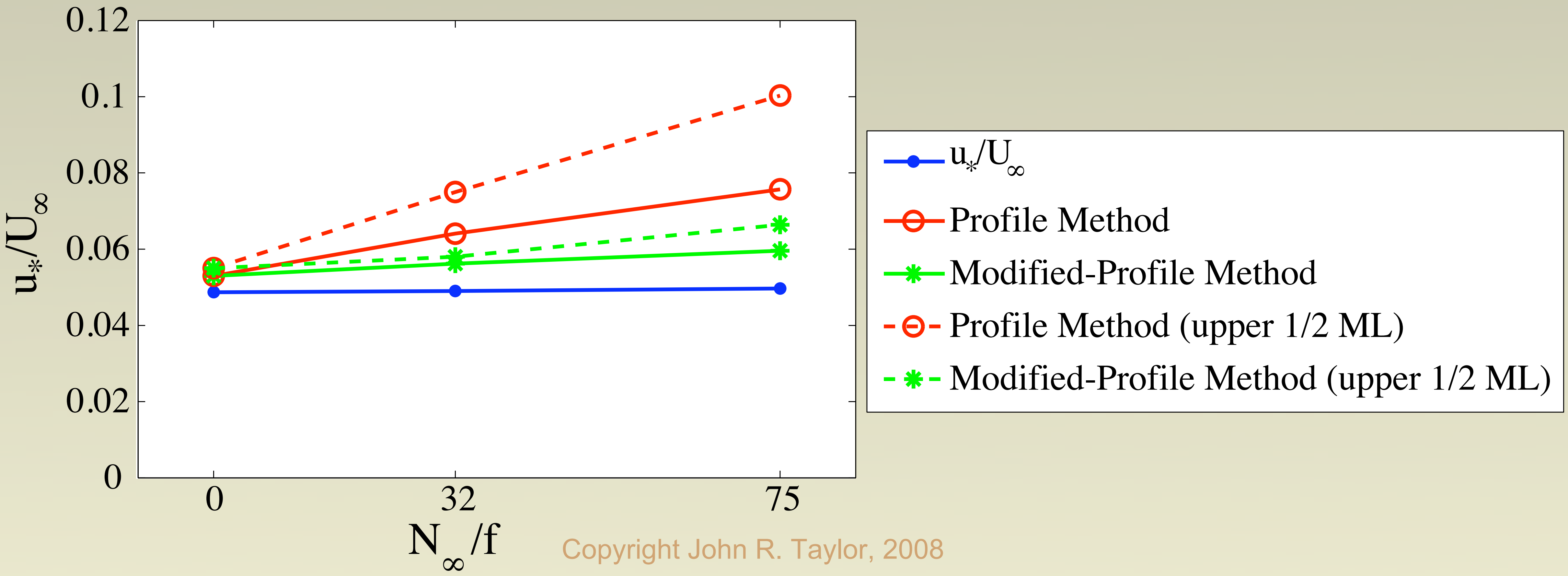
$$\Phi = \left(\frac{\kappa z}{u_*}\right) \frac{d\,\langle|\mathbf{u}|\rangle}{dz}$$

Friction Velocity Estimates

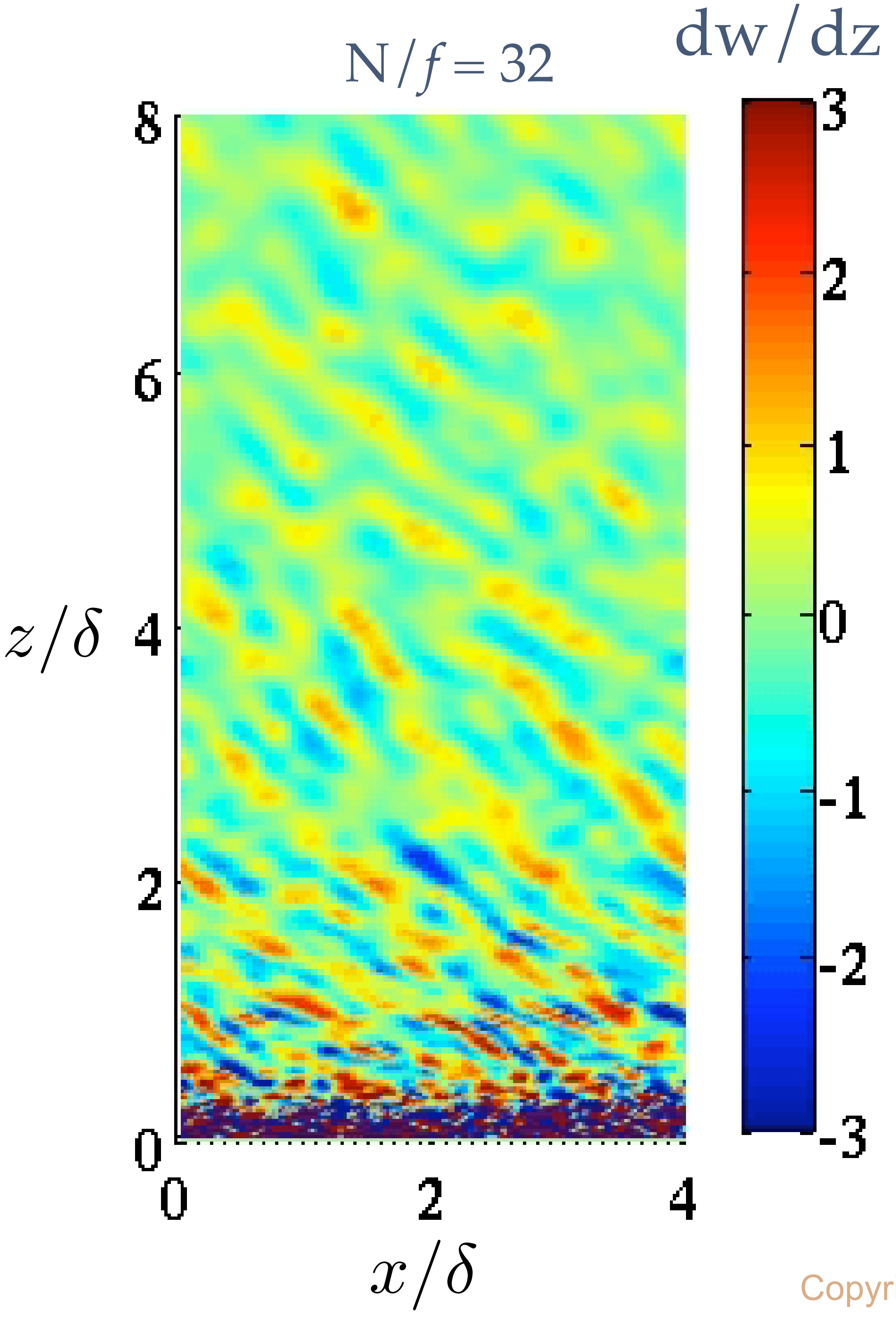
Profile Method, fit to: $\langle|\mathbf{u}|\rangle = \frac{u_*}{\kappa} log\left(\frac{z}{z_0}\right)$

Modified-Profile Method

$$\frac{1}{l} = \frac{1}{\kappa z} + \frac{N}{u_*} \quad , \quad \frac{d\langle|\mathbf{u}|\rangle}{dz} = \frac{u_*}{l} \quad \longrightarrow \quad \langle|\mathbf{u}|\rangle = \frac{u_*}{\kappa} log\left(\frac{z}{z_0}\right) + \int_0^z N(z')dz'$$



Outer-layer Internal Waves



$$\omega^2 = N^2 cos^2(\Theta) + f^2 sin^2(\Theta)$$

Studies of turbulence-generated IWs	Θ
Grid-generated Turbulence (Linden 1975, E&Hopfinger 1986, Dohan+Sutherland 2003,2005, etc.)	42-55°
Shear Layers (Sutherland & Linden 1988, Sutherland et al. 1994, Basak & Sarkar 2006, etc.)	45-60°
Gravity Currents (Flynn & Sutherland 2004, etc.)	41-64°
Rough Topography BL (Aguilar & Sutherland 2006, etc.)	40-46°
Wakes (Bonneton et al. 1993, Gourlay et al. 2001, Spedding 2002, Diamessis et al. 2005, etc.)	

Viscous Decay Model

1. Start with the equations for the turbulent kinetic energy and the perturbation potential energy.
2. Obtain an expression for the rate of change in wave energy owing to viscous dissipation (neglecting wave-wave interactions)
3. Given an initial wave amplitude and propagation speed, what is the expected amplitude at a height z following viscous dissipation.

Viscous Decay Model

Define wave energy, *W=KE+PE*

$$\frac{\partial W}{\partial t} + \nabla \cdot (W\mathbf{c}_g) = \nu \frac{d^2 W}{dz^2} - 2\nu|\mathbf{k}|^2 W \qquad \text{(linearized)}$$

Neglect viscous diffusion, assume $\nabla \cdot \mathbf{c}_g \approx 0$

$$\frac{DW}{Dt} = -2\nu|\mathbf{k}|^2 W$$

D/Dt is time derivative following c_g

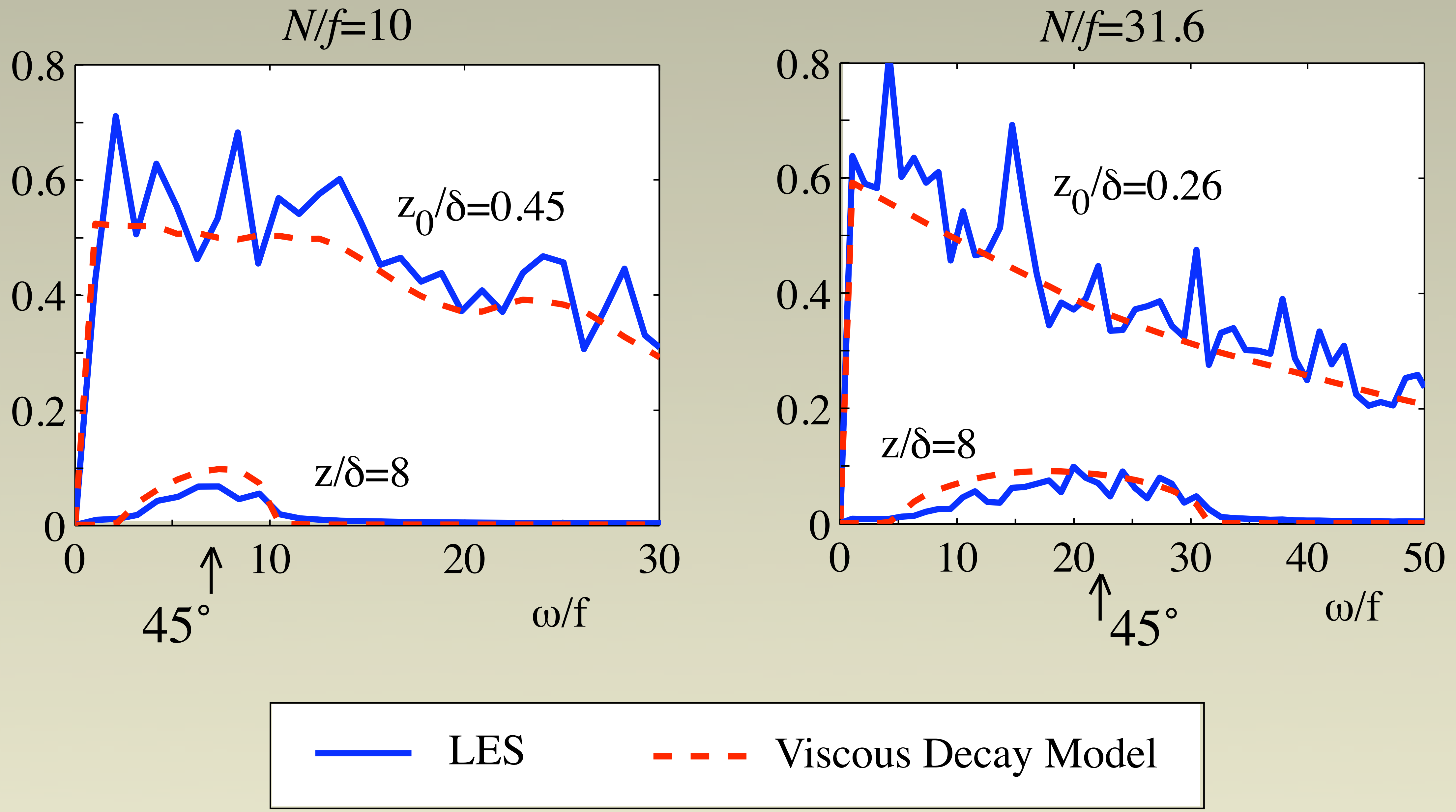
In a stationary frame in terms of vertical velocity amplitude:

$$A(z) = A_0 \frac{|\mathbf{k}_0|}{|\mathbf{k}|} exp[\frac{-\nu\omega}{k_h}(\omega^2 - f^2)^{-1/2} \int_0^z |\mathbf{k}|^4 (N^2 - \omega^2)^{-1/2} dz']$$

Given the initial amplitude, $A_0(k_h, \omega)$, we can predict $A(k_h, \omega, z)$

Viscous Decay Model

$$\left(\sum_k \left(\frac{\partial w}{\partial z}\right)^2\right)^{1/2}$$



Looking Ahead...

- Consider a time-dependent outer layer flow (tides or waves).
- How is the bottom boundary layer affected by lateral density gradients?
- Study the stability of a directional shear in a stratified fluid.
- Apply the internal wave model to other flows, e.g. stratified wakes, topographic generation.

Development of a CFD Code

- Developed in collaboration with Prof. Tom Bewley
- User selected combination of pseudo-spectral, finite differences.
- Large Eddy Simulation model (LES) using dynamic eddy-viscosity and/or scale-similar terms.
- Capable of considering an arbitrary number of passive and/or active scalars
- Parallelized using MPI
- Source code available from:

  numerical-renaissance.com/Diablo.html

Acknowledgments

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- Thesis committee: Tom Bewley, Paul Linden, Rob Pinkel, Bill Young
- Collaborator: Vincenzo Armenio
- Family: Erin, George + Cindy, Annie + Tim

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References

- Taylor J.R., S. Sarkar, and V. Armenio (2005). *Large eddy simulation of stably stratified open channel flow*. Phys. Fluids **17**, 116602.
- Taylor J.R., and S. Sarkar (2007). *Internal gravity waves generated by a turbulent bottom Ekman layer.* Journal of Fluid Mechanics **590**, 1, 331-354.
- Taylor J.R., and S. Sarkar (2007). *Direct and large eddy simulations of a bottom Ekman layer under an external stratification*. Int. J. Heat and Fluid Flow, **29**, 3, 721-732.
- Taylor J.R., and S. Sarkar (2007). *Stratification effects in a bottom Ekman layer.* Journal of Physical Oceanography, *in press*.

- Taylor J.R., and S. Sarkar (2007). *Internal wave generation by a turbulent bottom boundary layer.* Proceedings of the Fifth International Symposium on Environmental Hydraulics.
- Taylor J.R., and S. Sarkar (2007). *Near-wall modeling for LES of an oceanic bottom boundary layer*. Proceedings of the Fifth International Symposium on Environmental Hydraulics.
- Taylor J.R., and S. Sarkar (2007). *Large eddy simulation of a stratified benthic boundary layer.* Turbulence and Shear Flow Phenomena-5 Proceedings.
- Taylor J.R., S. Sarkar, and V. Armenio (2005) *Open channel flow stratified by a surface heat flux*. Turbulence and Shear Flow Phenomena-4 Proceedings.