THE EFFECTS OF HORIZONTAL HETEROGENEITY ON THE DYNAMICS OF THE NOCTURNAL BOUNDARY LAYER ACROSS SCALES

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SURFACE MODELS

- Monin-Obukhov similarity theory (MOST) is a widely adopted approach to model the atmospheric surface layer (ASL) in large-eddy simulations (LES)
- MOST: assumes flow is stationary and horizontally homogeneous
- MOST: neglects effects from rotation, subsidence, and molecular exchange

$$\cancel{\frac{\partial \overline{u}}{\partial t}} + \cancel{\overline{u}\frac{\partial \overline{u}}{\partial x}} + \cancel{\overline{v}\frac{\partial \overline{u}}{\partial y}} + \cancel{\overline{w}\frac{\partial \overline{u}}{\partial z}} = \cancel{-\frac{\partial \overline{p}}{\partial x}} - \cancel{f(\overline{u} - U_g)} + \cancel{\frac{\partial \overline{\tau}_{xx}}{\partial x}} + \cancel{\frac{\partial \overline{\tau}_{xy}}{\partial y}} + \frac{\partial \overline{\tau}_{xz}}{\partial z} + \nu \cancel{\frac{\partial^2 \overline{u}}{\partial x \partial x}}$$

$$\downarrow$$

$$\frac{\partial \overline{\tau}_{xz}}{\partial z} = 0$$

- As a result, turbulent fluxes are assumed constant within the ASL

SURFACE MODELS

- End result is that vertical gradients of meteorological variables and their turbulence moments are universal functions of dimensionless height z/L when normalized by their corresponding ASL turbulence scales

$$\frac{\kappa z}{u_*}\frac{\partial \overline{u}}{\partial z} = \phi_m \qquad \frac{\kappa z}{\theta_*}\frac{\partial \overline{\theta}}{\partial z} = \phi_h$$

- Fluxes can then be parametrized using K-theory

$$\overline{\tau}_{xz} = K_m \frac{\partial \overline{u}}{\partial z} \qquad K_m = \frac{\kappa z u_*}{\phi_m}$$

- Standard procedure is to apply this locally or on average (e.g. Stoll and Porté-Agel 2006)

SURFACE MODELS

- Engineering
  - Piomelli et al. 1989 (phenomonological), Cabot and Moin 1999 (stochastic), Balaras et al. 1996 (explicit BL/RANS), Yang et al . 2015 (integrated BL)
- Atmospheric
  - Marusic et al. 2001 (correlate shear-stress with local velocity fluctuations), Bou-Zeid et al. 2005 (correlate shear-stress with filtered velocity), Anderson/Meneveau 2010, 2011 (displacement height, dynamic roughness), Shao et al. 2013 (power-law)

SURFACE MODELS

- The goal is to develop new models that account for stability and heterogeneity in atmospheric flows.
- Start at the basics - examine momentum and scalar budgets to understand under what conditions basic assumptions break down.
- Here, we will use DNS to examine the assumptions in basic building-block cases with the goal of moving toward stratified heterogeneous atmospheric boundary layer flows.

HOMOGENEOUS DNS

- Open-channel DNS data from He (2016) using HercuLES
- 2816 x 2048 x 256, Lx, Ly, Lz = 25, 10, 1
- $Re_\tau = 1000$, $Re_b \sim 10^5$
- Cases: neutral and stable ($Ri_\tau = 10^4$, $Ri_b \sim 1$)
- 4th-order space and time discretization
- No-slip/impermeability at the bottom, free-slip at top
- Fixed normalized temperatures at top and bottom
- Driven by constant external pressure gradient

HOMOGENEOUS DNS

- Start with momentum budget

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho_o}\frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 u_i}{\partial x_j^2}$$

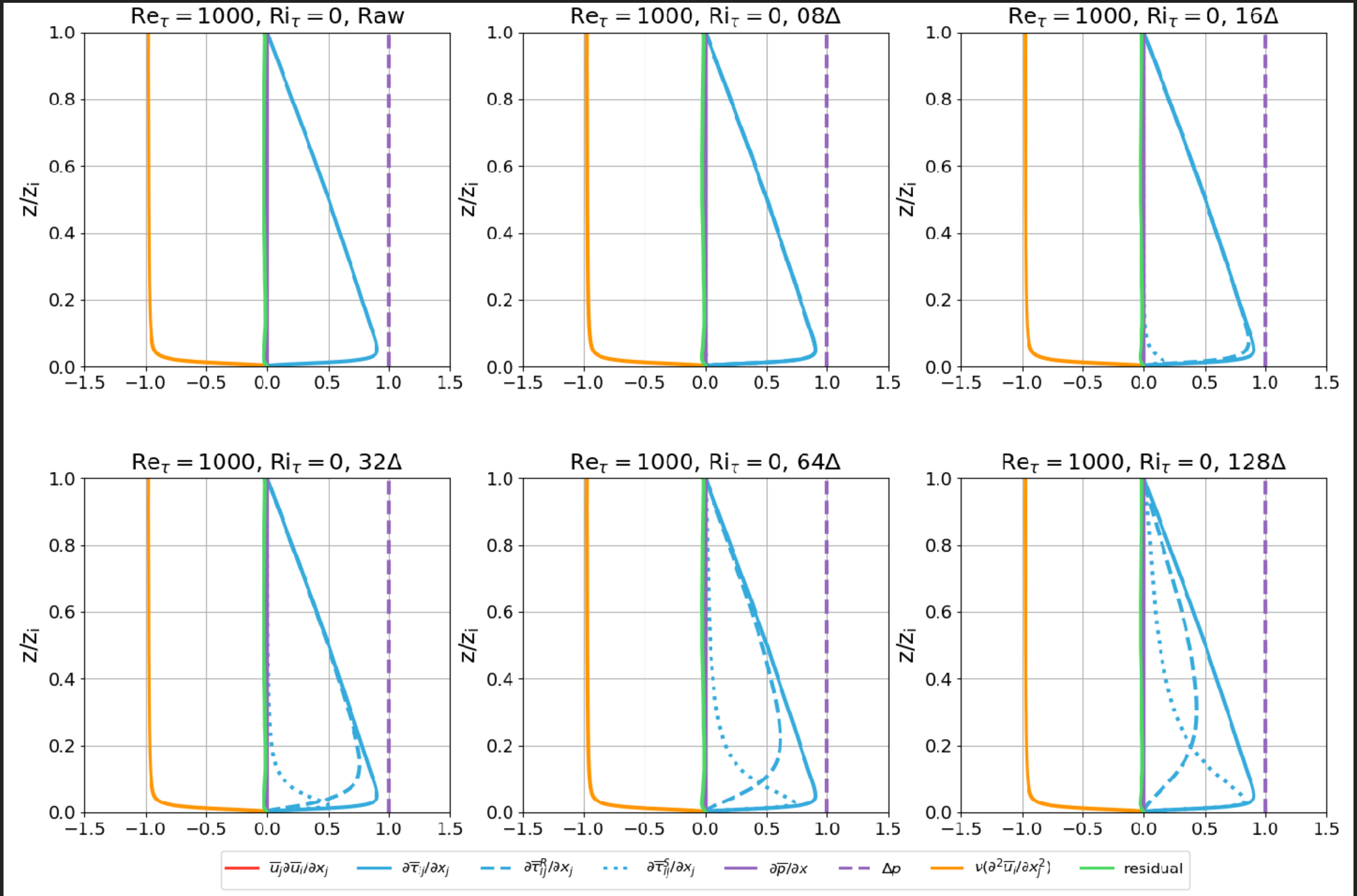
- Filter

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_j} - \frac{\partial \tau_{ij}^S}{\partial x_j} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2}$$

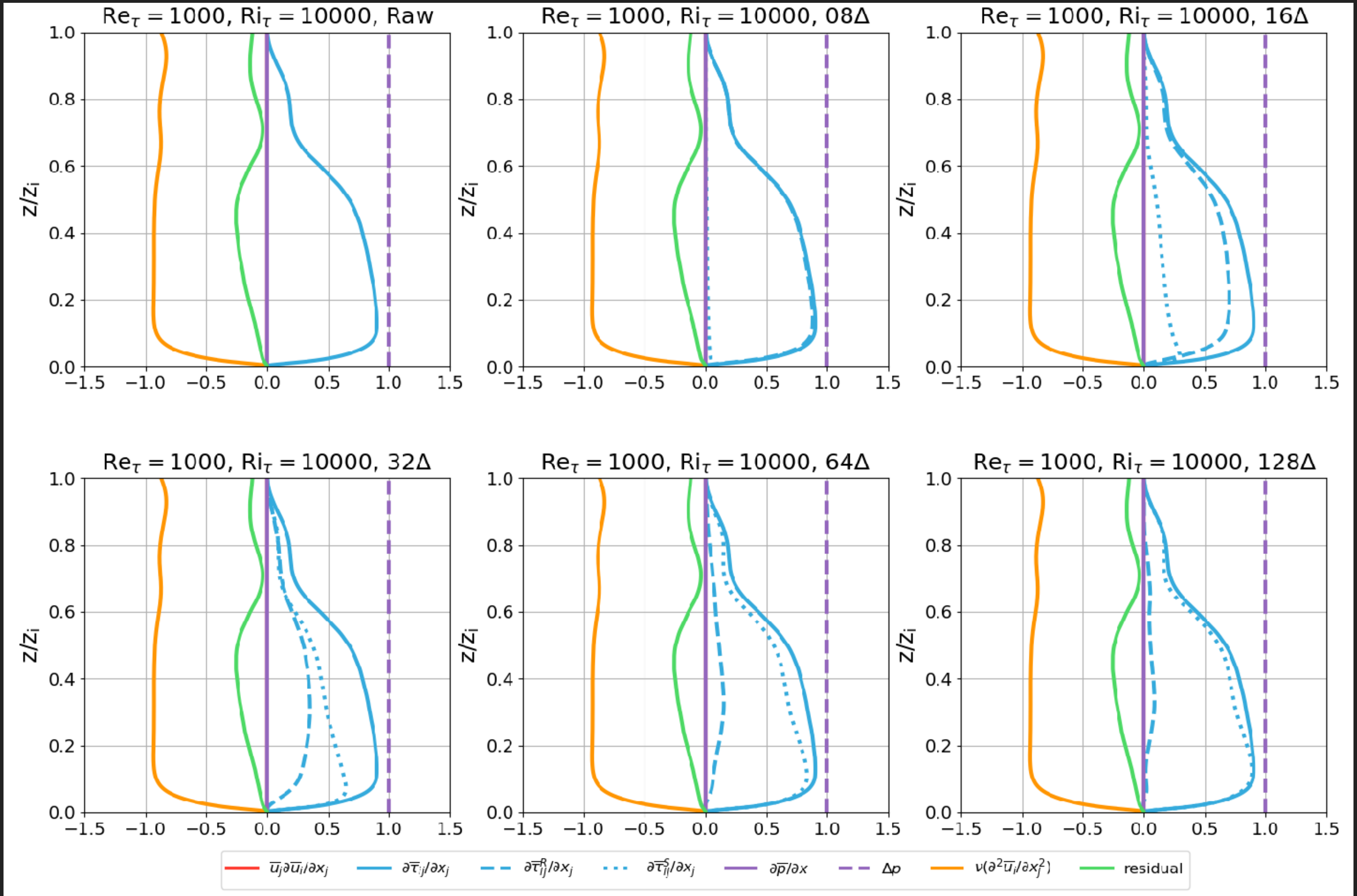
- Average then integrate vertically

$$\int (\overline{\text{time change}})dz = -\int (\overline{\text{advection}})dz - \int (\overline{\text{pressure gradient}})dz + \int (\overline{\text{stress gradient}})dz + \int (\overline{\text{friction}})dz$$

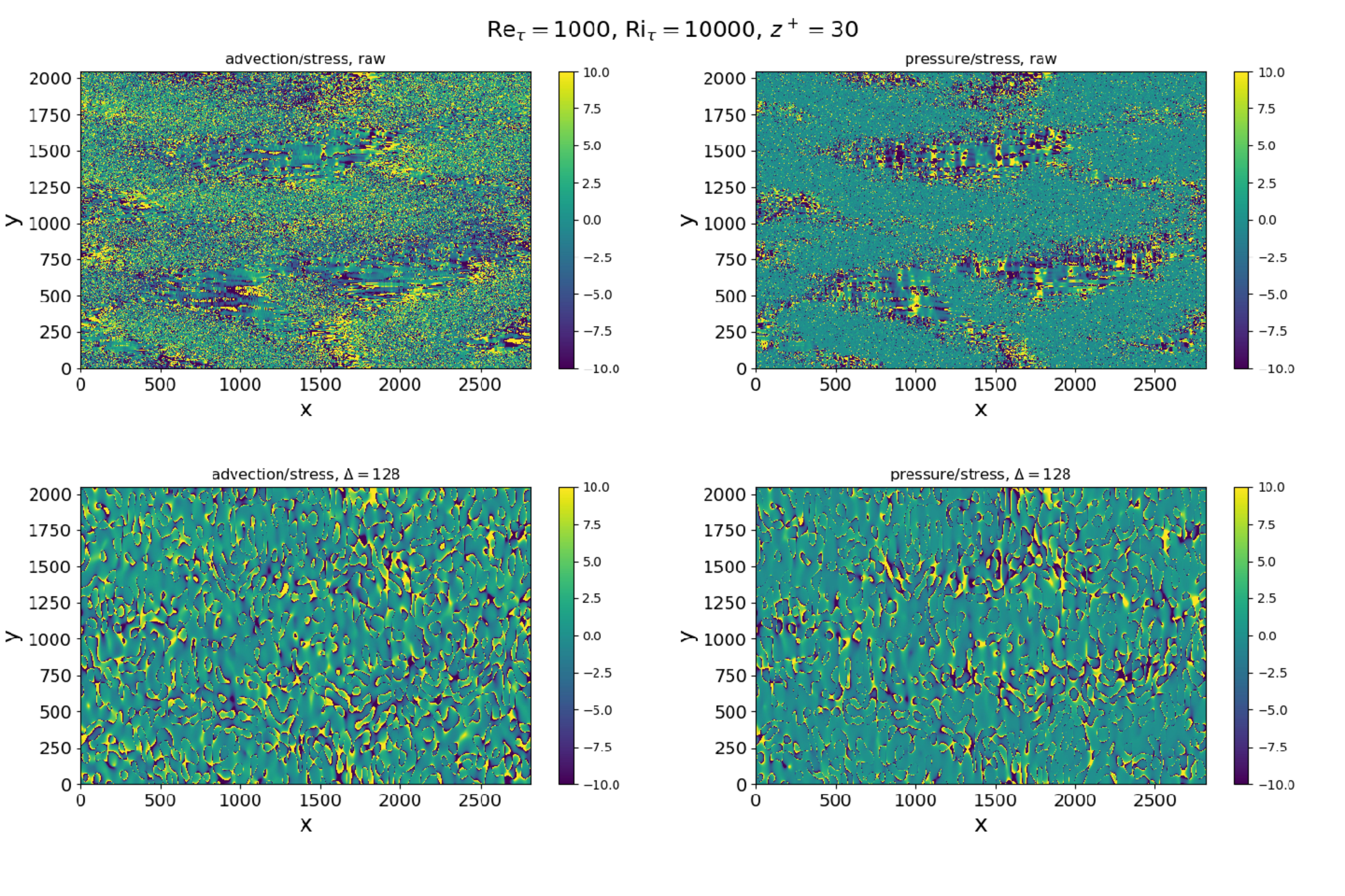
HOMOGENEOUS DNS (NEUTRAL): INTEGRATED MOMENTUM BUDGET



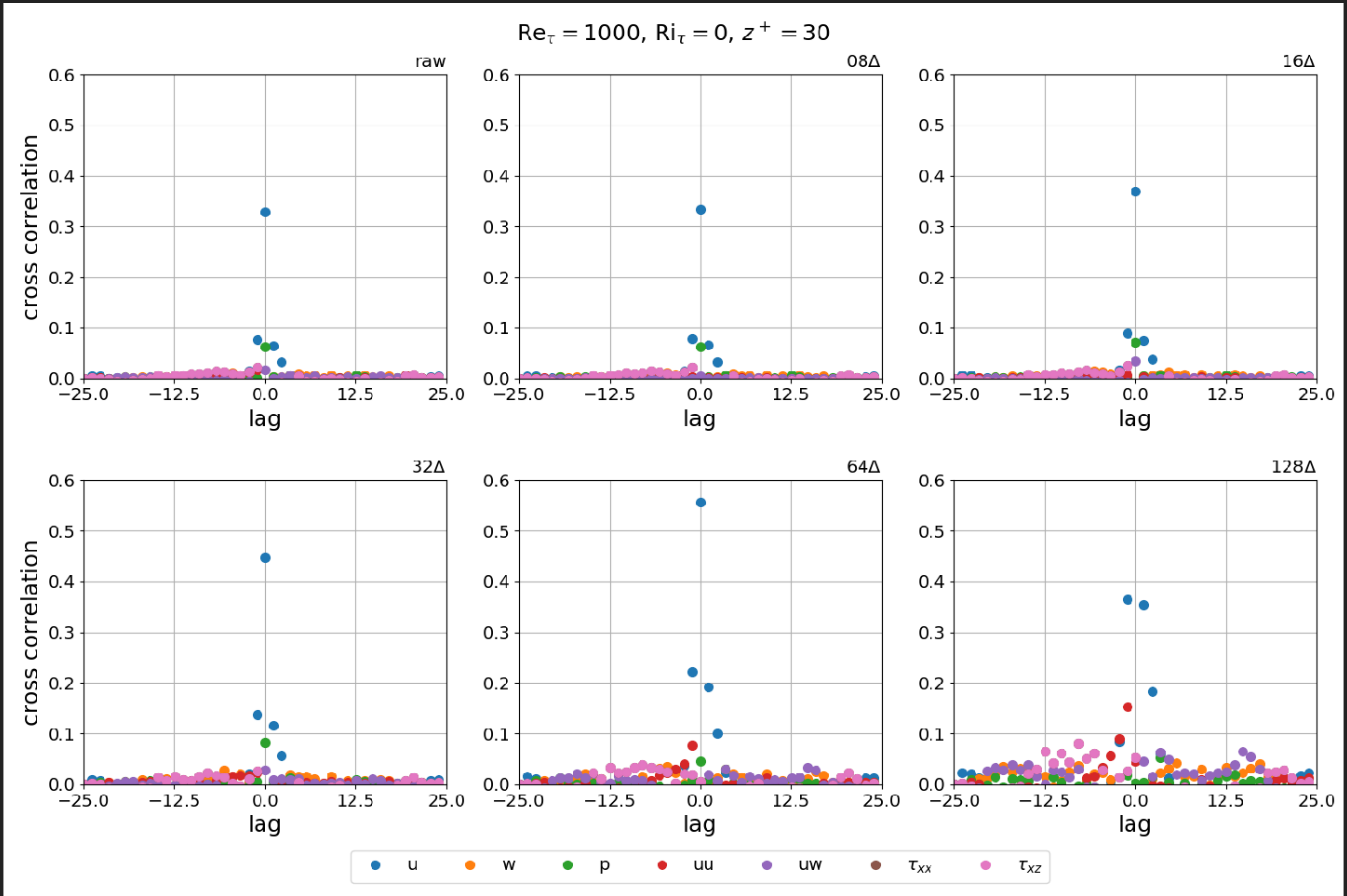
HOMOGENEOUS DNS (STABLE): INTEGRATED MOMENTUM BUDGET



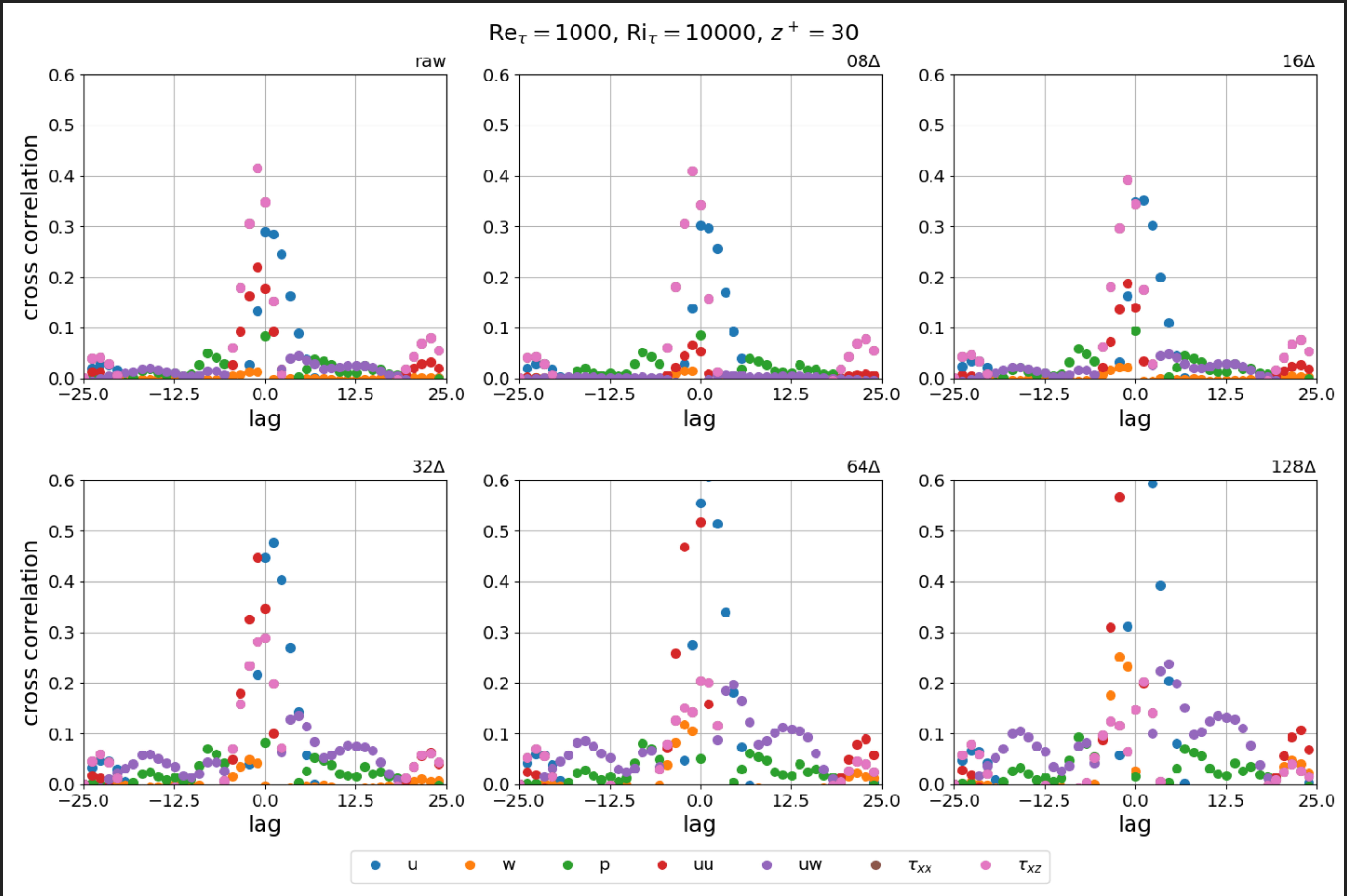
HETEROGENEOUS DNS (PATCHES): LOCAL AND INSTANTANEOUS



HOMOGENEOUS DNS (NEUTRAL): CROSS CORRELATION WITH SURFACE STRESS

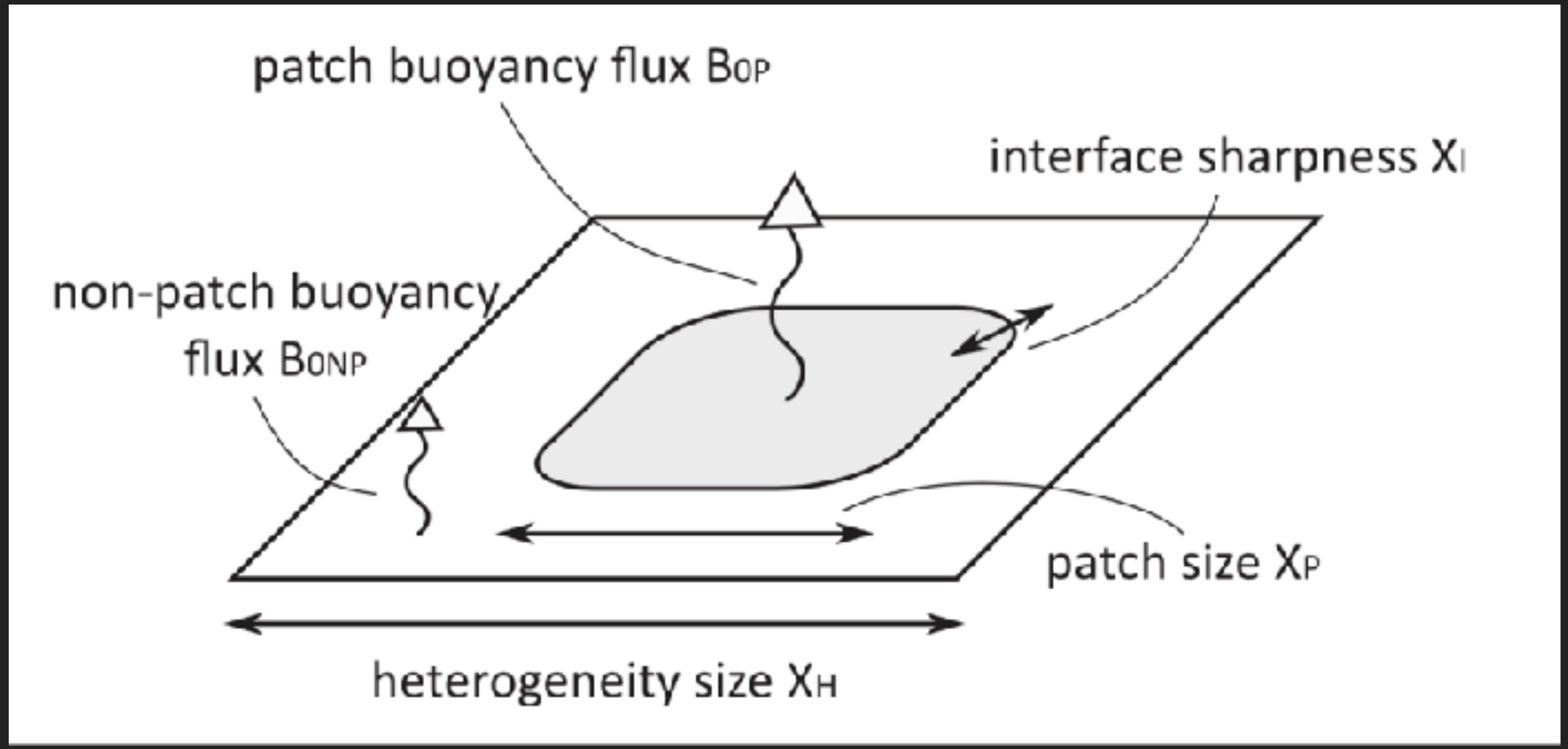


HOMOGENEOUS DNS (STABLE): CROSS CORRELATION WITH SURFACE STRESS

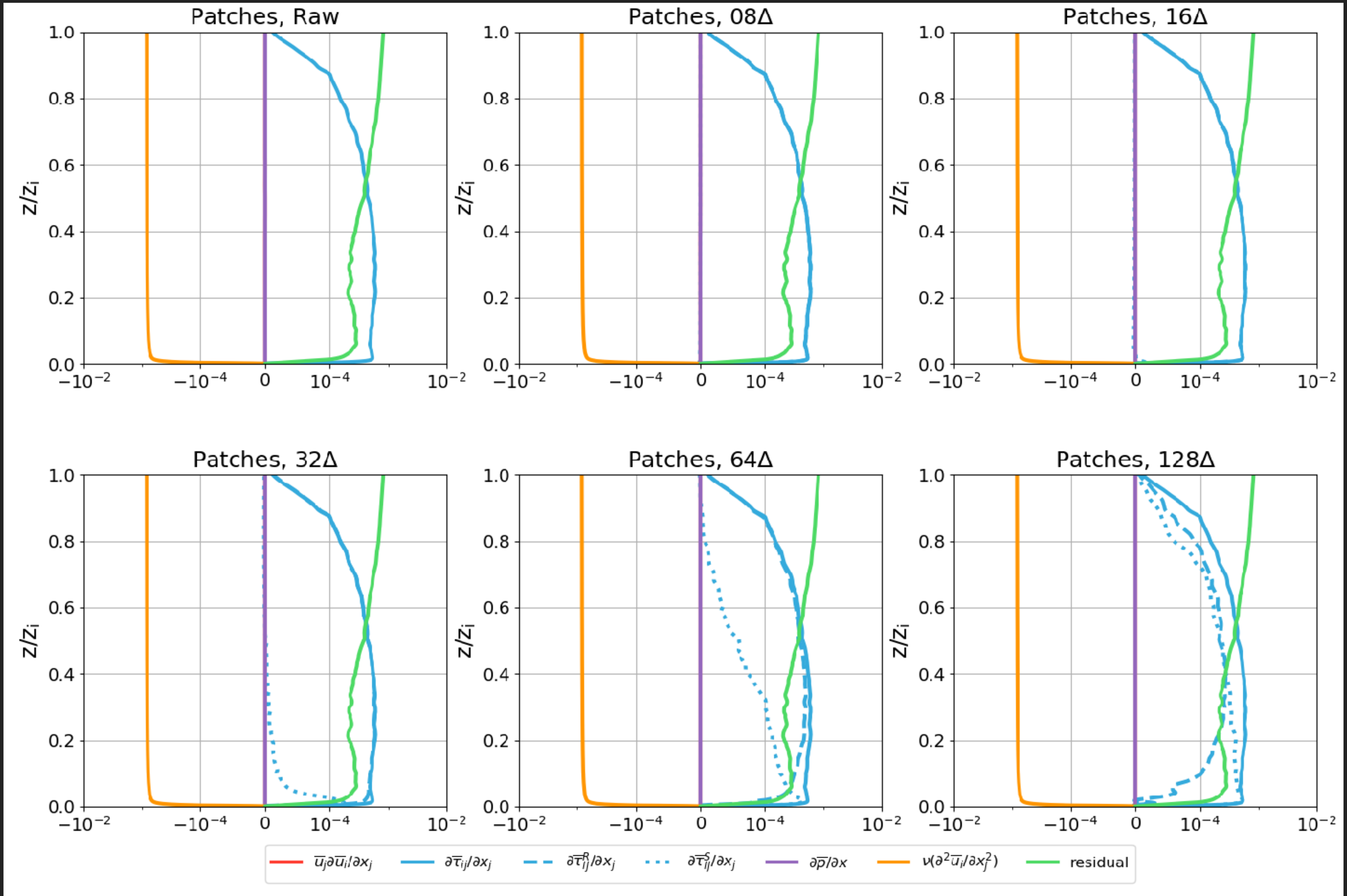


HETEROGENOUS DNS

- Couette flow similar to DNS reported in van Heerwaarden et al. (2014) using MicroHH
- 1024x1024x1024, Lx, Ly, Lz = 1, 1, 1.4
- 8x8 patches imposed with more strongly negative buoyancy fluxes than surroundings



HETEROGENEOUS DNS (PATCHES): INTEGRATED MOMENTUM BUDGET



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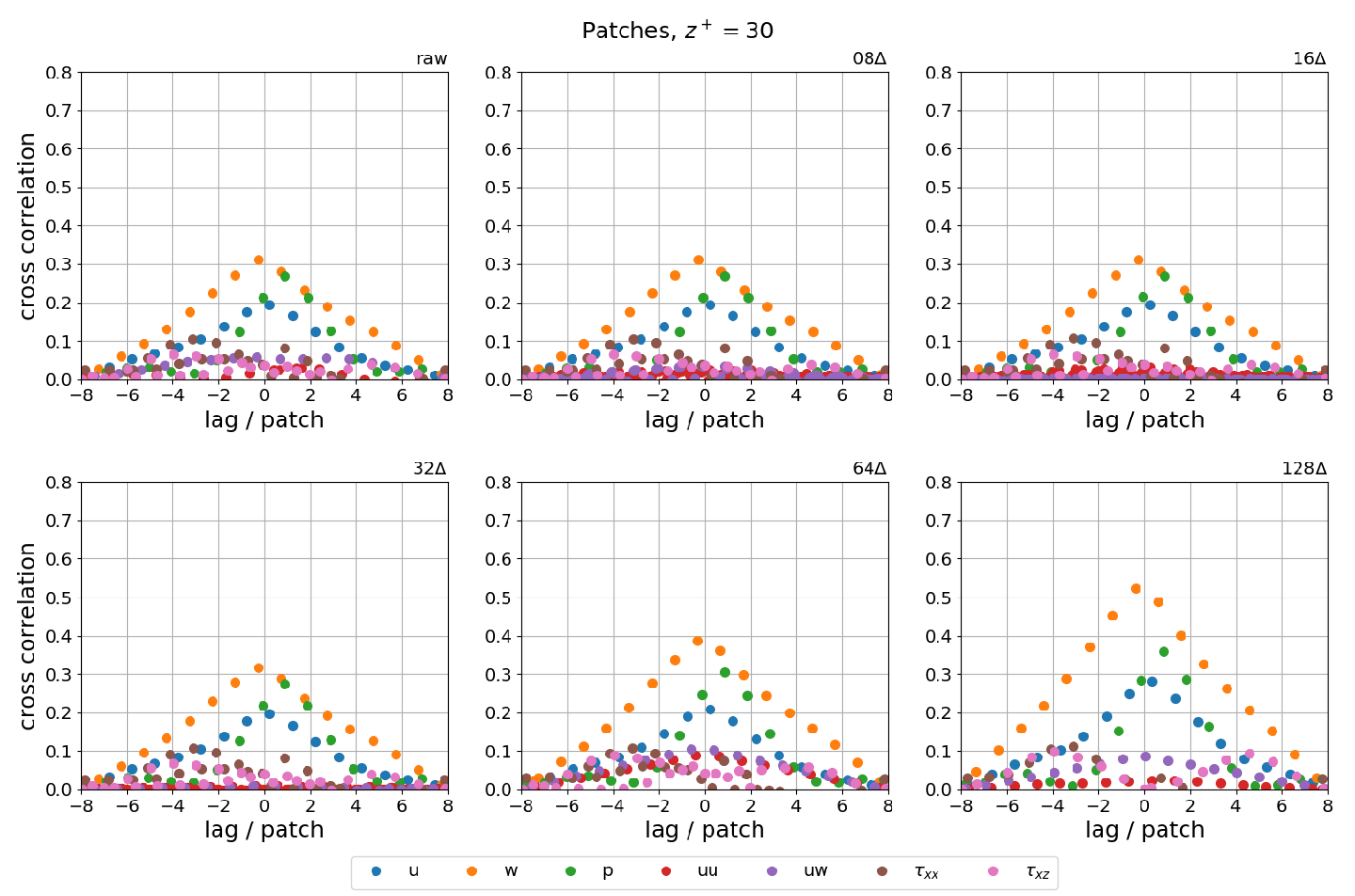

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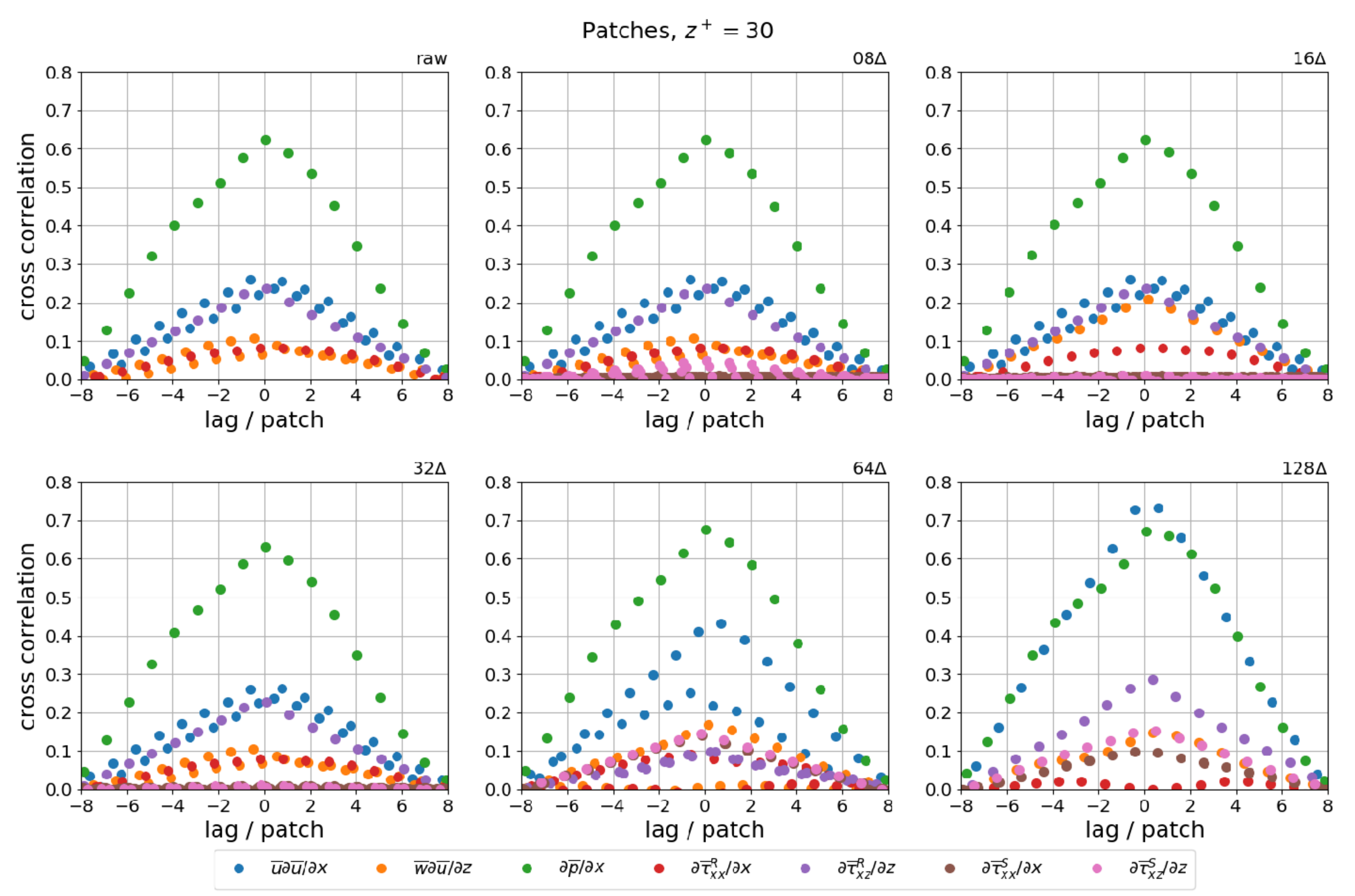

LET'S RECAP WHAT WE FOUND

- Integrated mean budgets look as expected and generally agree with MOST.
- Stability seemingly introduces unsteadiness even in the mean budget.
- Terms that are usually ignored become important locally and instantaneously in the presence of stratification and heterogeneity.
- In the case of surface thermal heterogeneity, pressure gradient and advection are most strongly correlated with surface stress.

WHAT IS NEXT?

- We need a way to account for the observed effects.
- We plan to run more DNS with a wider range of heterogeneities, including roughness
  - (24th AMS/BLT?).
- Formulate and evaluate new models from the momentum and thermal budgets based on DNS.