Large-eddy simulation of very stable boundary layers

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Motivation

Simulate **very** stable conditions using the buoyancy-adjusted stretch-vortex SGS model in LES with a novel LES model setup:

Surface fluxes dynamically computed by partially resolving the surface layer

Study of the:

1. SBL structure in very stable conditions with weak geostrophic winds
2. Turbulence structure and its energetic regimes

Large-eddy simulations

Initial and boundary conditions of second set of simulations

- $u_g = 1$ and 2 m s^{-1} (meridional component set to zero).
- Initial wind profile: Ekman solution.
- Initial potential temperature profile: uniform and equal to the reference temperature of 275 K up to 2 m, with an overlying stable lapse rate of 0.01 K m^{-1}.
- Surface cooling rates equal to 1 and 3 K h^{-1}.
- Surface fluxes dynamically computed by partially resolving the surface layer.
- Flat and smooth surface.
- Latitude: 70°N.
- Uniform and isotropic grid.
- Rayleigh damping layer imposed at the top of the domain (20%).
- Runs were carried out for 24 h of physical time (i.e., no diurnal cycle).

Large-eddy simulations

Table 2.2 Summary of the second set of simulations, where the surface fluxes were dynamically computed. "Run" shows the name of the simulation followed by geostrophic wind (u_g), surface cooling rate (C_r), number of grid points, grid resolution that is isotropic (Δ), surface friction velocity (u_*), surface heat flux (Q_*), Obukhov length (L), and height of the SBL (h). The bulk quantities correspond to a time average in $t = 14 - 15$ h.

Run	u_g ($\mathrm{m\,s^{-1}}$)	C_r ($\mathrm{K\,h^{-1}}$)	Grid points	Δ (m)	$u_* \times 10^{-2}$ ($\mathrm{m\,s^{-1}}$)	$Q_* \times 10^{-3}$ ($\mathrm{K\,m\,s^{-1}}$)	L (m)	h (h)
A1	1	1	$64^2 \times 80$	0.10	1.60	-0.519	0.55	4.00
A2	1	1	$128^2 \times 100$	0.10	1.59	-0.520	0.55	4.00
A3	1	1	$256^2 \times 150$	0.05	1.46	-0.453	0.48	3.20
B1	1	3	$64^2 \times 80$	0.10	1.11	-0.718	0.13	1.70
B2	1	3	$128^2 \times 100$	0.10	1.10	-0.716	0.13	1.70
B3	1	3	$256^2 \times 150$	0.05	1.08	-0.722	0.12	1.35
C1	2	3	$64^2 \times 100$	0.15	2.70	-2.20	0.64	6.45
C2	2	3	$128^2 \times 120$	0.15	2.70	-2.10	0.64	6.30
C3	2	3	$256^2 \times 200$	0.10	2.59	-2.00	0.60	5.50

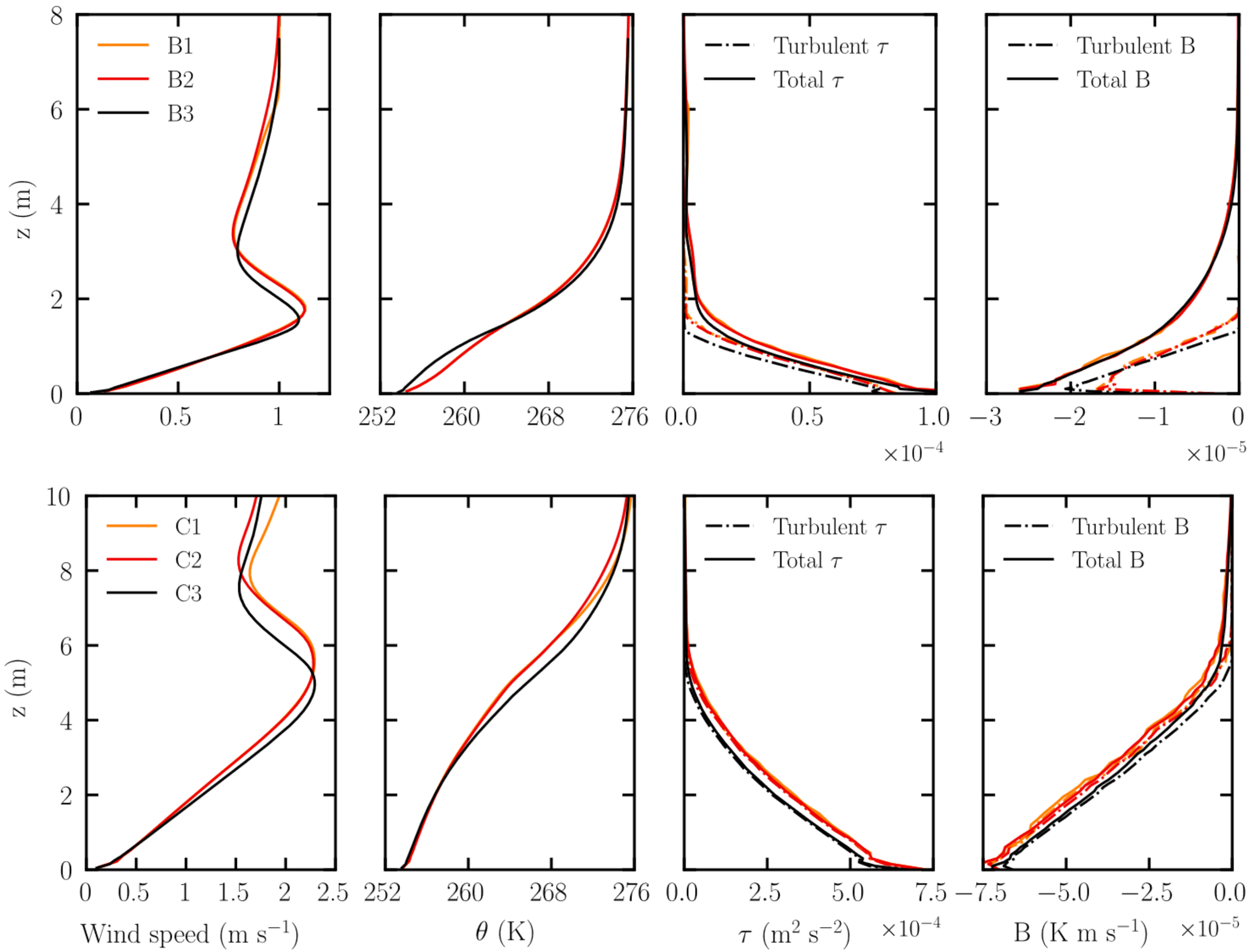
Sensitivity of the LES results

$\Delta_{B1} = \Delta_{B2} = 0.10$ m

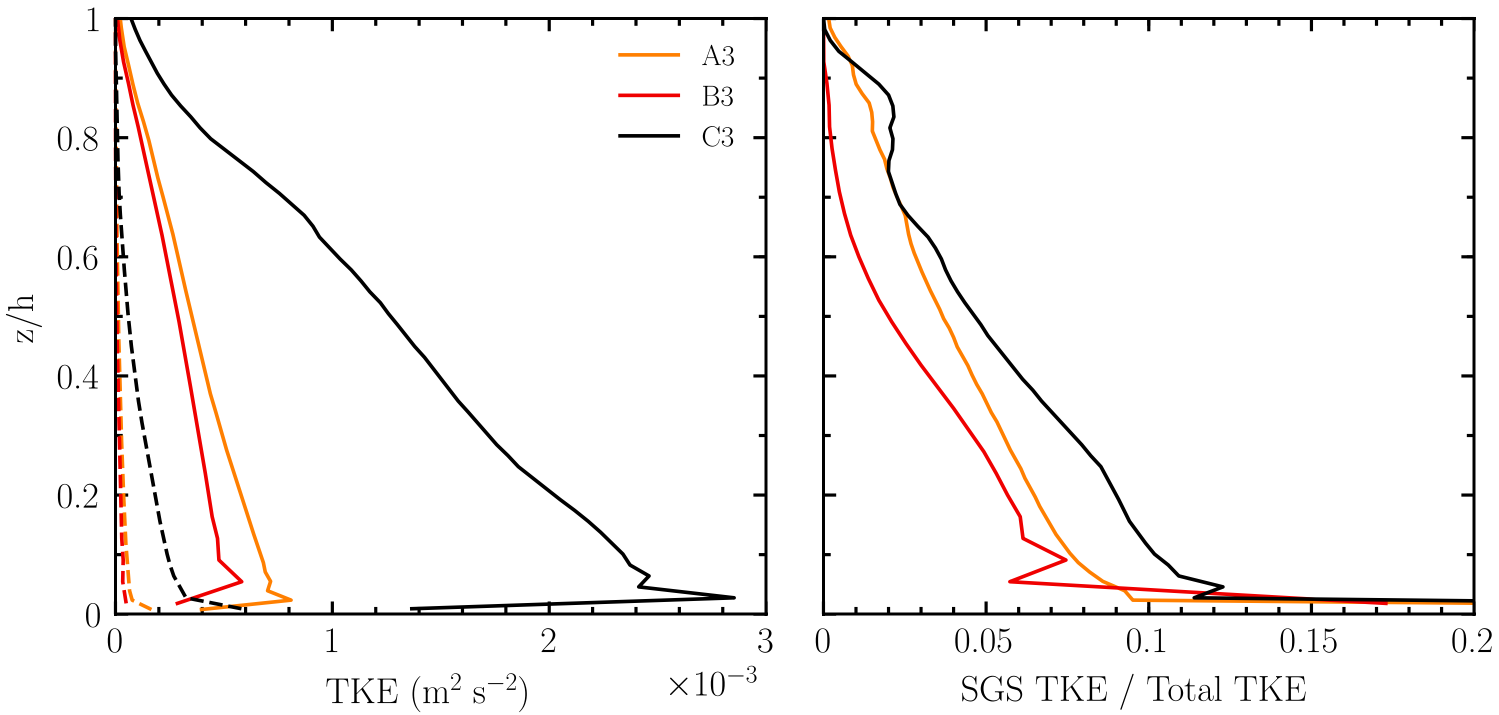
$\Delta_{B3} = 0.05$ m

$\Delta_{C1} = \Delta_{C2} = 0.15$ m

$\Delta_{C3} = 0.10$ m



Sensitivity of the LES results – Grid convergence



Overall, more than **90%** of TKE is **resolved.**

A: u100.100

B: u100.300

C: u200.300

SBL height estimation methods

Table 2.3 Boundary layer height estimated by the following five methods: (1) height at which the vertical turbulent momentum flux vanishes; (2) height of the low-level jet; (3) height at which $\partial\bar{\theta}/\partial z$ is a maximum; and, (4) height at which the total TKE reduces to 5% of its surface value. The values correspond to a time average in $t = 14 - 15$ h.

Run	h_τ (m)	h_j (m)	$h_{\nabla\theta}$ (m)	h_E (m)
A	2.84	3.10	3.25	3.20
B	1.21	1.55	1.35	1.35
C	4.74	5.00	5.00	5.50
GABLS1	179	178	212	215
$\text{GABLS4}_{0.25\,\text{m}}$	20	21.5	17	22

$h_E/L = 22/3.12 = 7$

for $t = 15 - 16$ h

- h_E is chosen for this study.

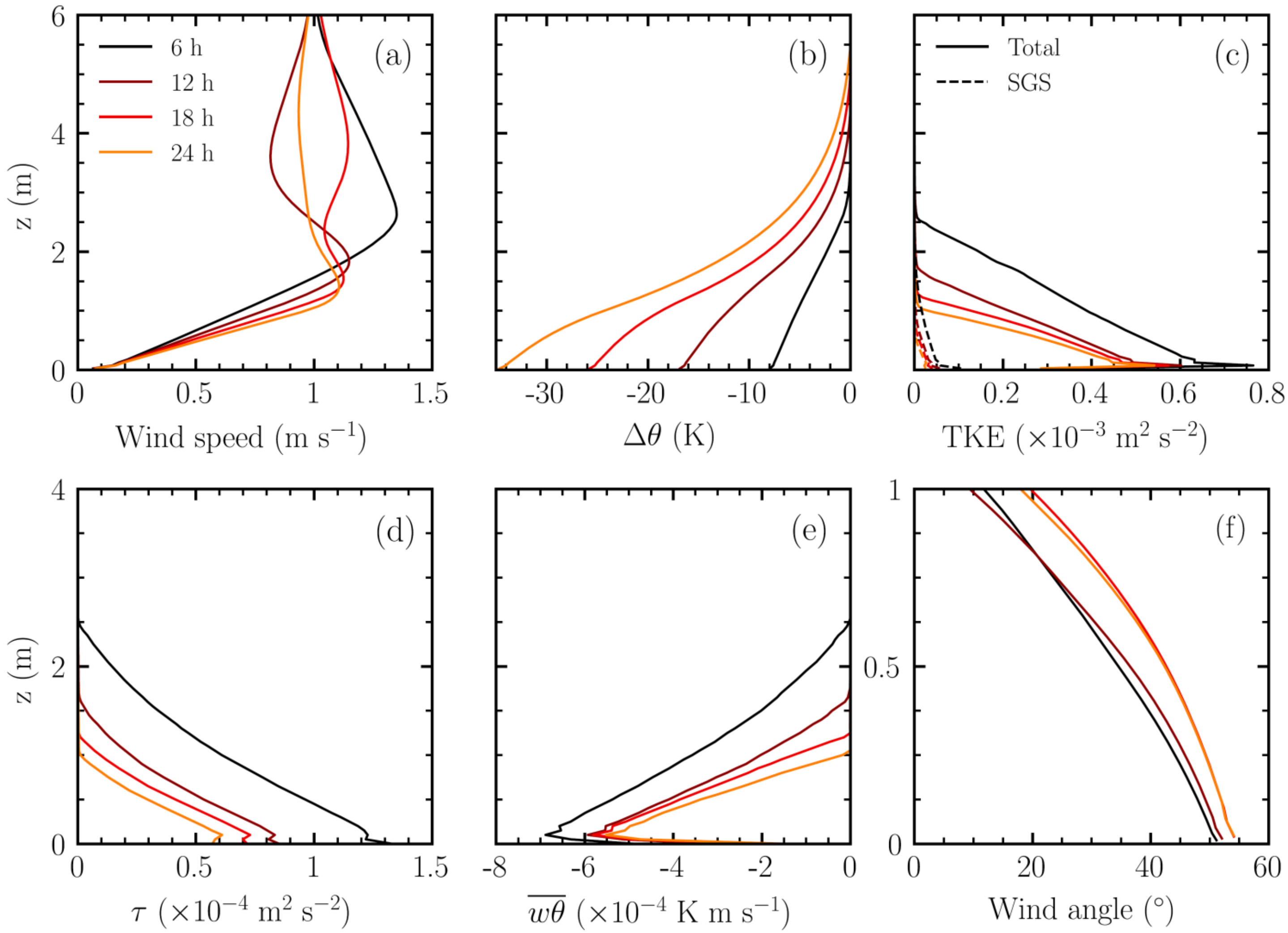
A: u100.100

B: u100.300

C: u200.300

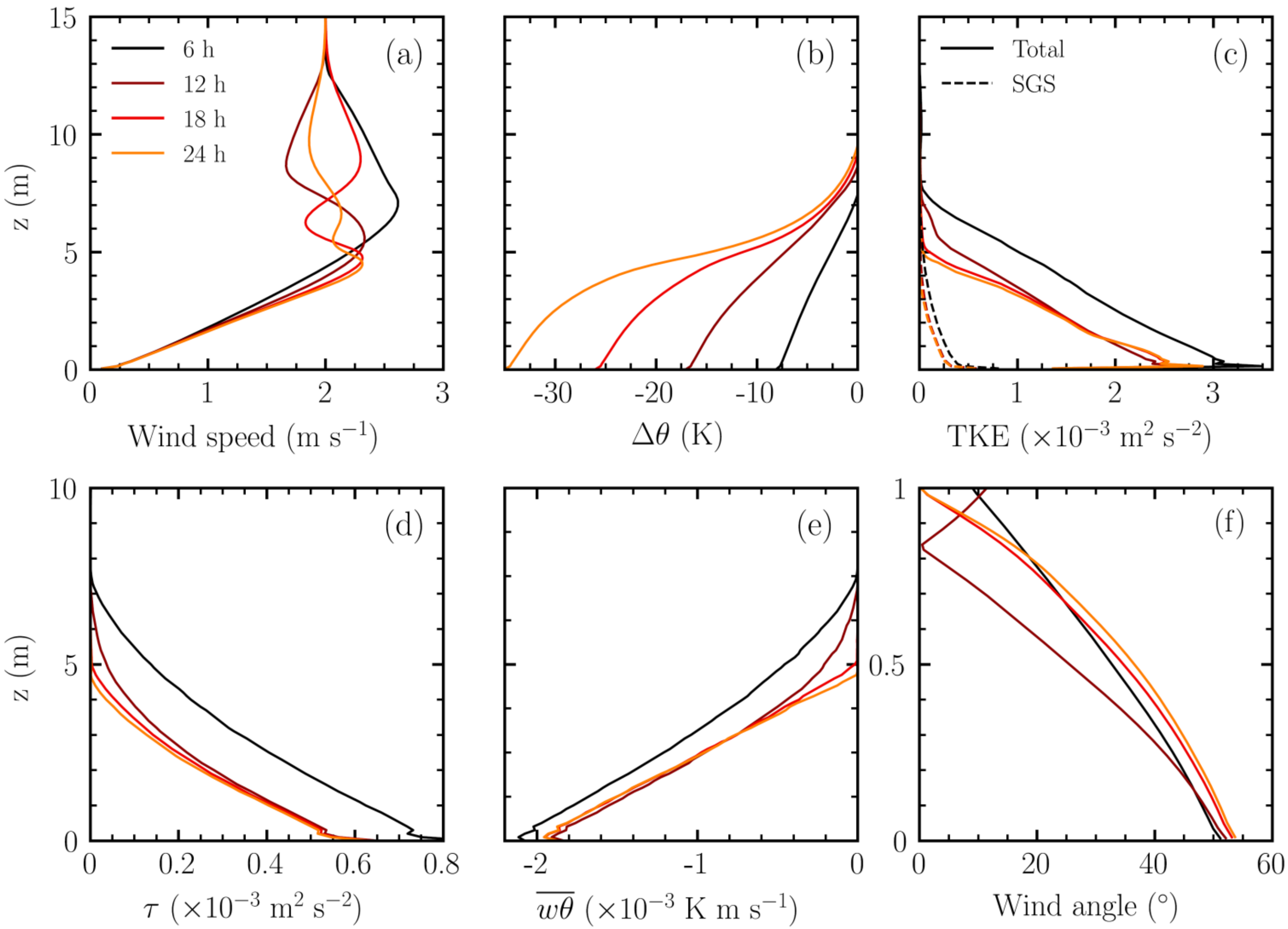
Temporal evolution of vertical profiles

Temporal evolution of simulation B ($u_g = 1\ \mathrm{m\,s^{-1}}$ and $C_r = 3\ \mathrm{K\,h^{-1}}$).



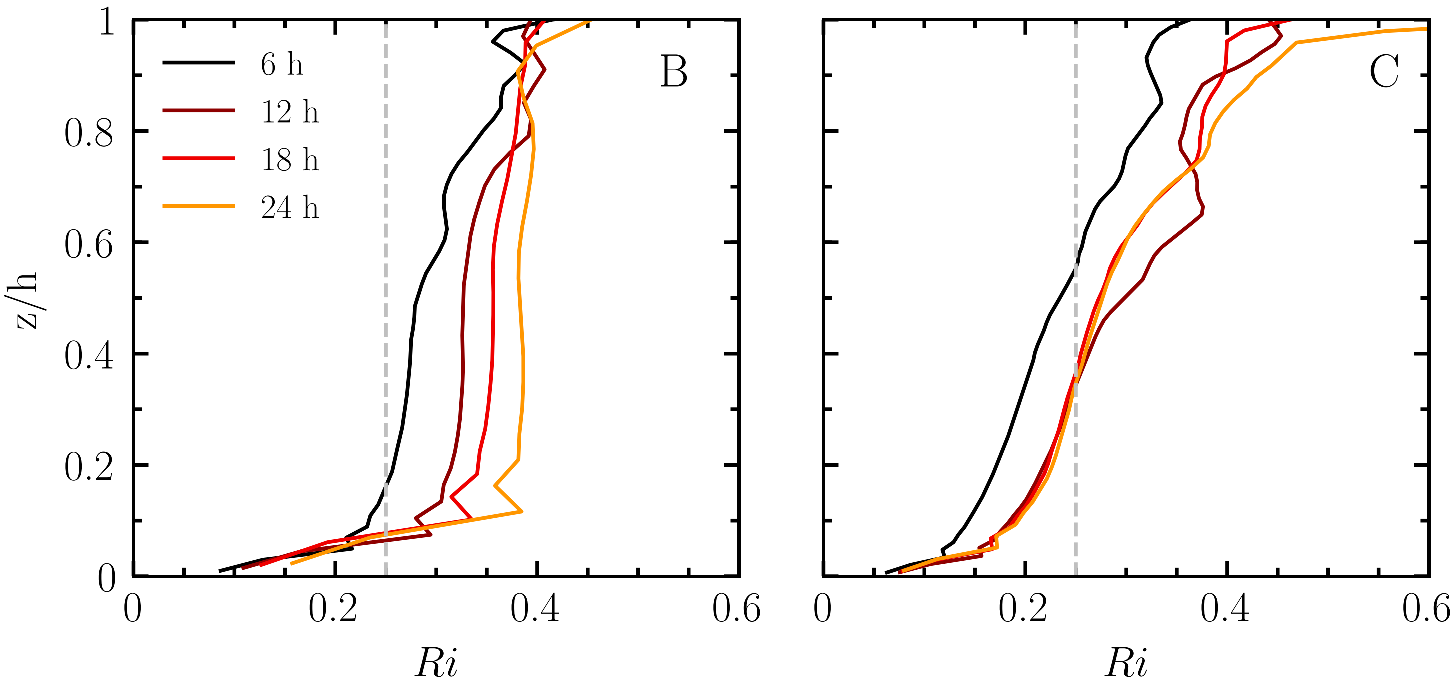
Temporal evolution of vertical profiles

Temporal evolution of simulation C ($u_g = 2\ \mathrm{m\,s^{-1}}$ and $C_r = 3\ \mathrm{K\,h^{-1}}$).

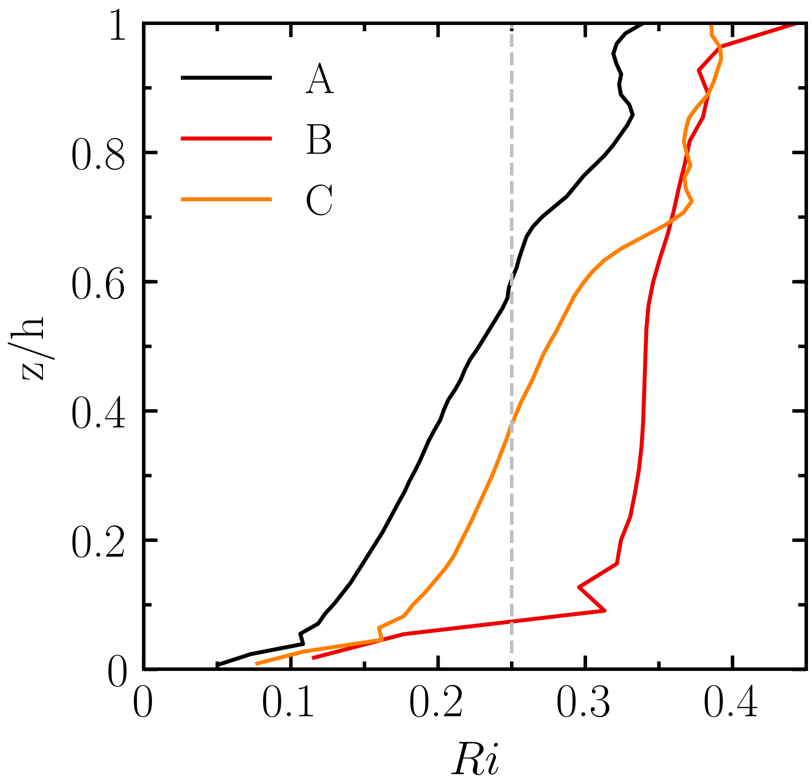


Temporal evolution of vertical profiles

Temporal evolution of Ri for simulations B ($u_g = 1$ m s^{-1} and $C_r = 3$ K h^{-1}), and C ($u_g = 2$ m s^{-1} and $C_r = 3$ K h^{-1}).



Gradient Richardson number



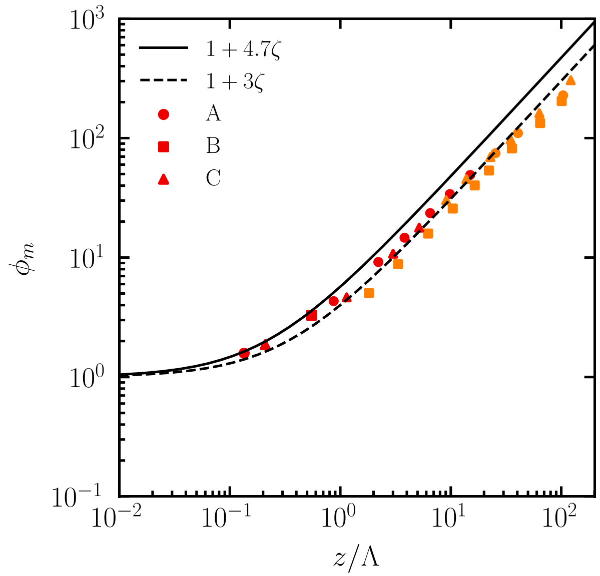
A: u100.100

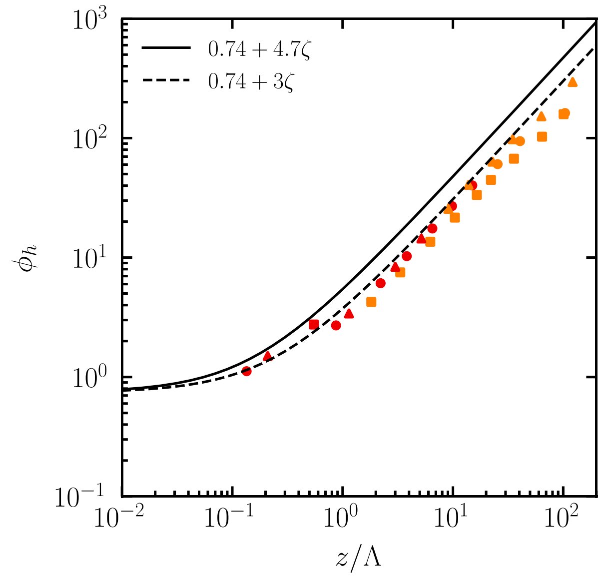
B: u100.300

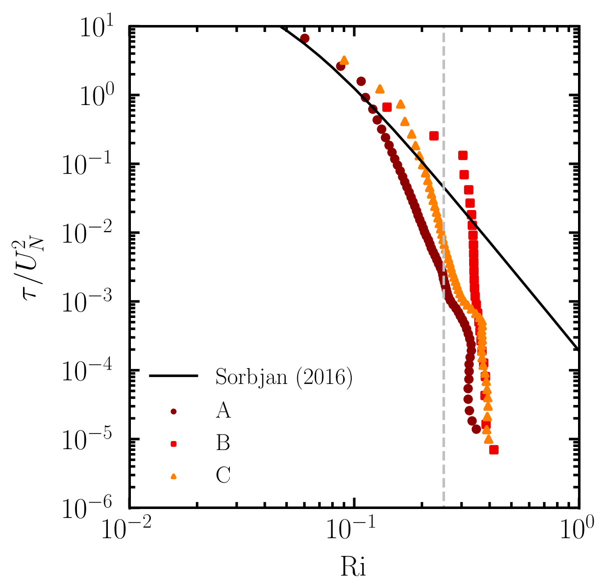
C: u200.300

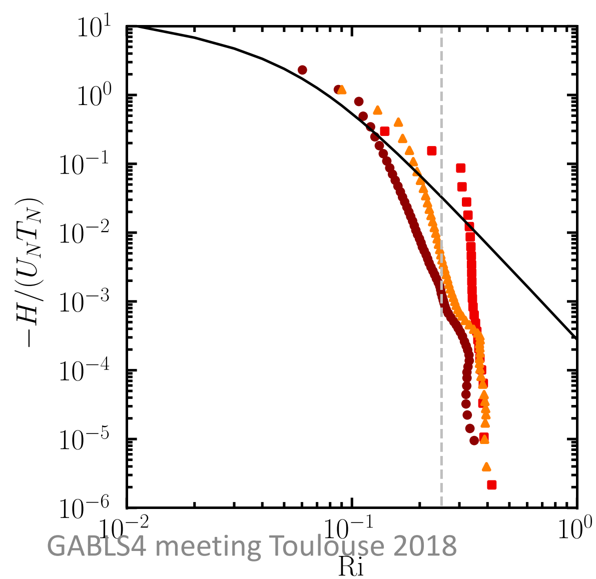
Stability: $B > C > A$

Scaling systems









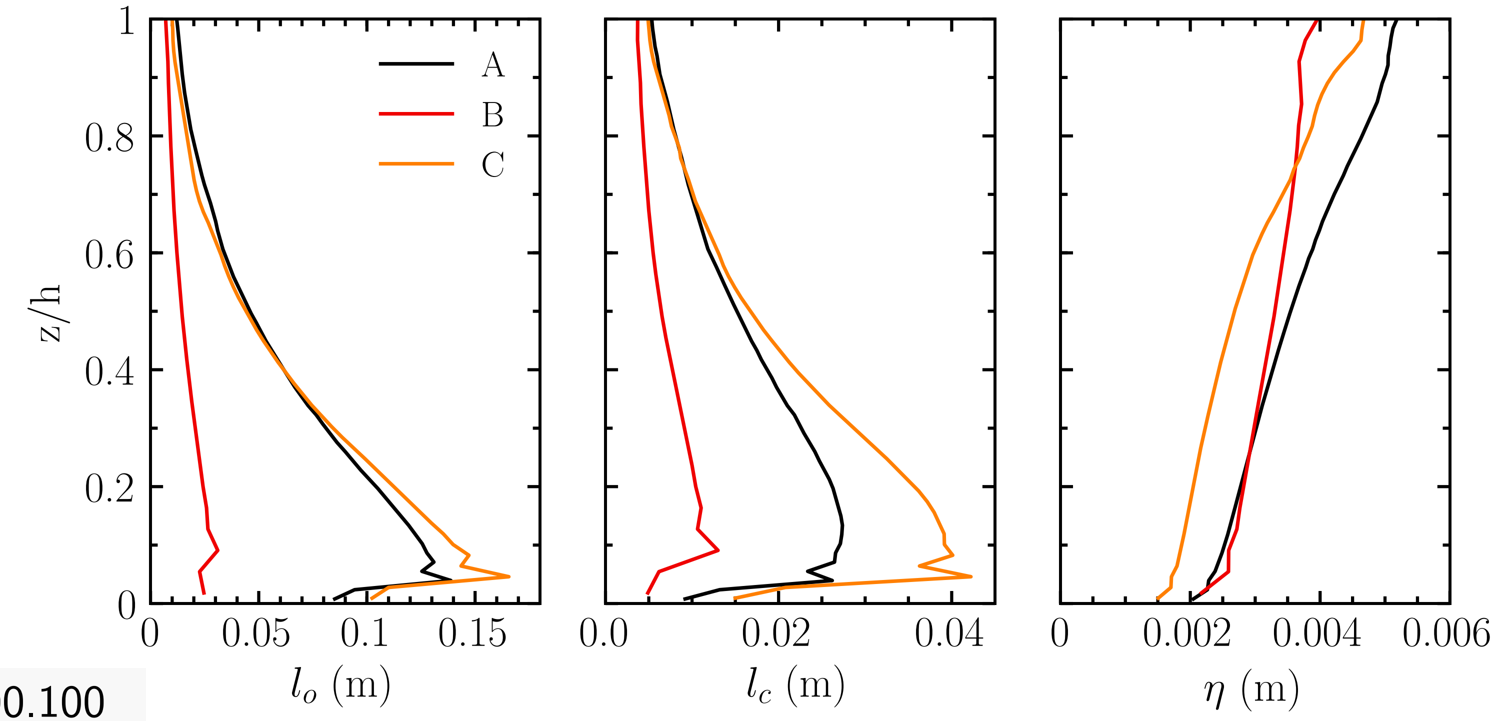
$$\frac{\tau}{U_N^2} = \frac{1}{Ri(1 + 300Ri^2)^{3/2}},$$
$$U_N = lN$$

$$\frac{-\overline{w'\theta'}}{U_N T_N} = \frac{1}{0.9Ri^{1/2}(1 + 250Ri^2)^{3/2}},$$
$$T_N = l\frac{\partial\bar{\theta}}{\partial z}$$

Length scales

- Dougherty-Ozmidov (l_o), Corrsin (l_c), and Kolmogorov (η) scales:

$$l_o = (\varepsilon/N^3)^{1/2} \qquad l_c = (\varepsilon/S^3)^{1/2} \qquad \eta = (\nu^3/\varepsilon)^{1/4}$$



A: u100.100

B: u100.300

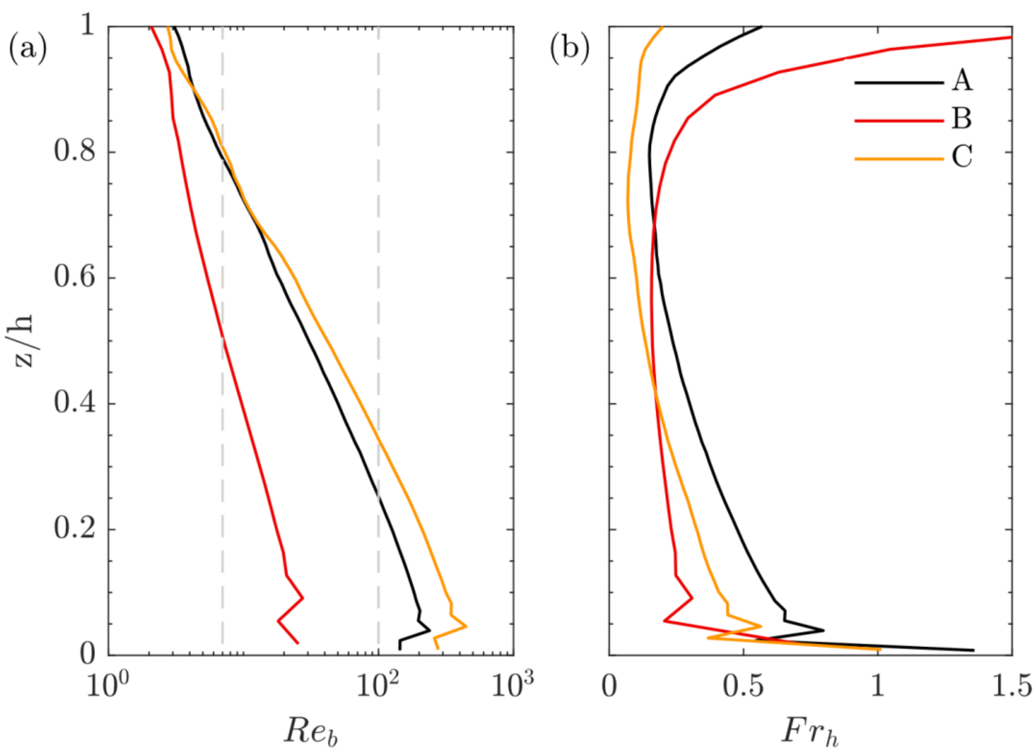
C: u200.300

Strongly stratified turbulence theory

- Strongly stratified turbulence regime without viscous effects (e.g. Billant and Chomaz 2001): $\boldsymbol{Re_b \gg 1}$ and $\boldsymbol{Fr_h \ll 1}$.

$$Re_b = \varepsilon/(\nu N^2) = (l_o/\eta)^{4/3}$$

$$Fr_h = \varepsilon/(N u_{rms}^2) = (l_o/L_h)^{2/3}$$



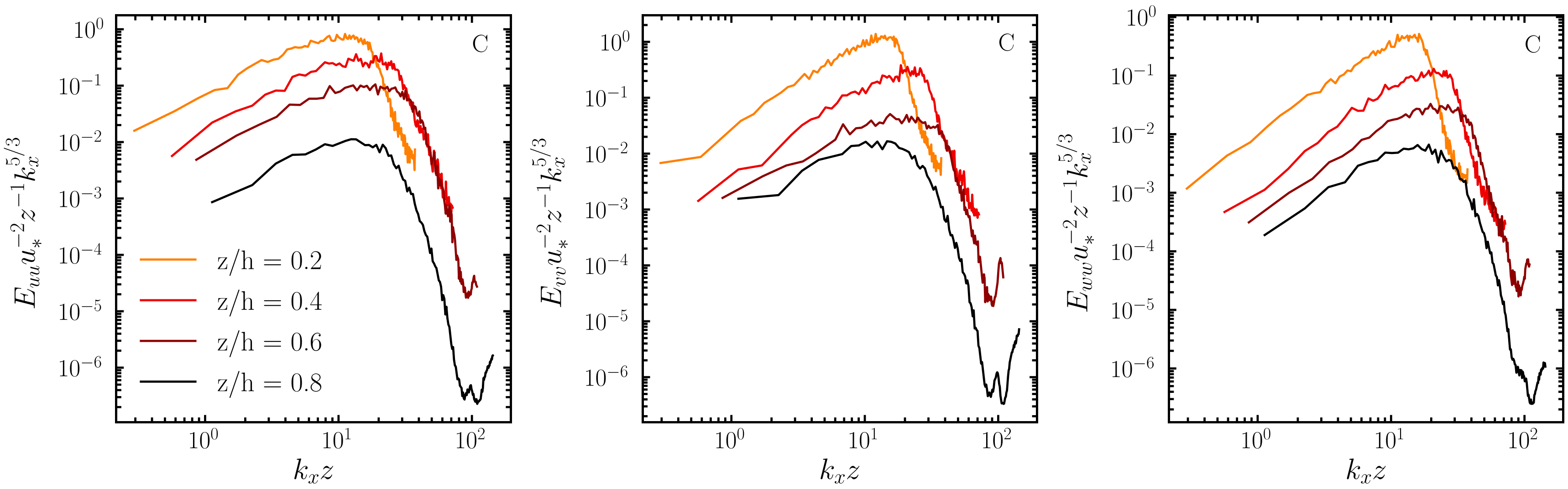
A: u100.100

B: u100.300

C: u200.300

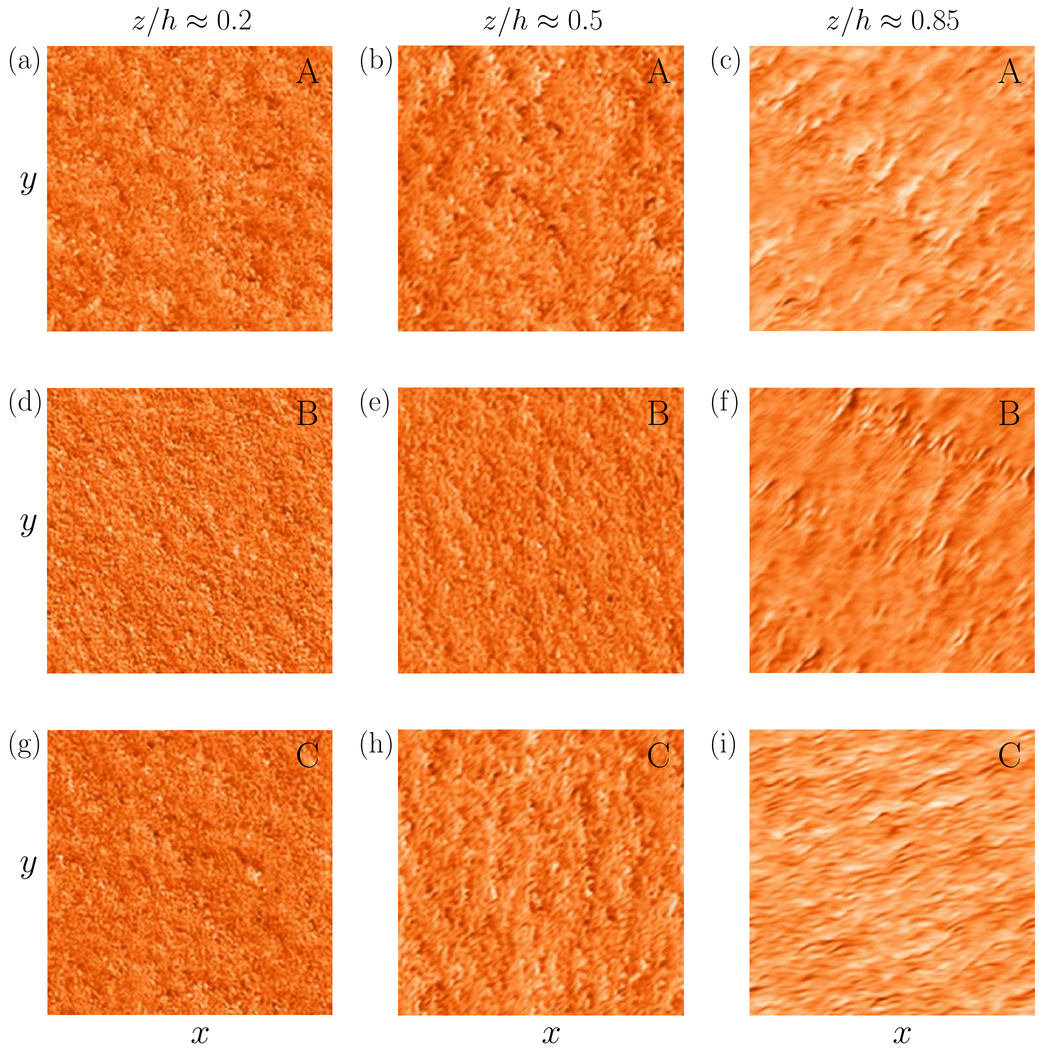
Spectra

- Compensated one-dimensional spectra of zonal, meridional and vertical wind components for simulation C (instant $t = 15$ h).



- $l_o < \Delta_x \rightarrow$ production, inertial and dissipation ranges correspond to anisotropic turbulence due to buoyancy effects.

Flow visualization



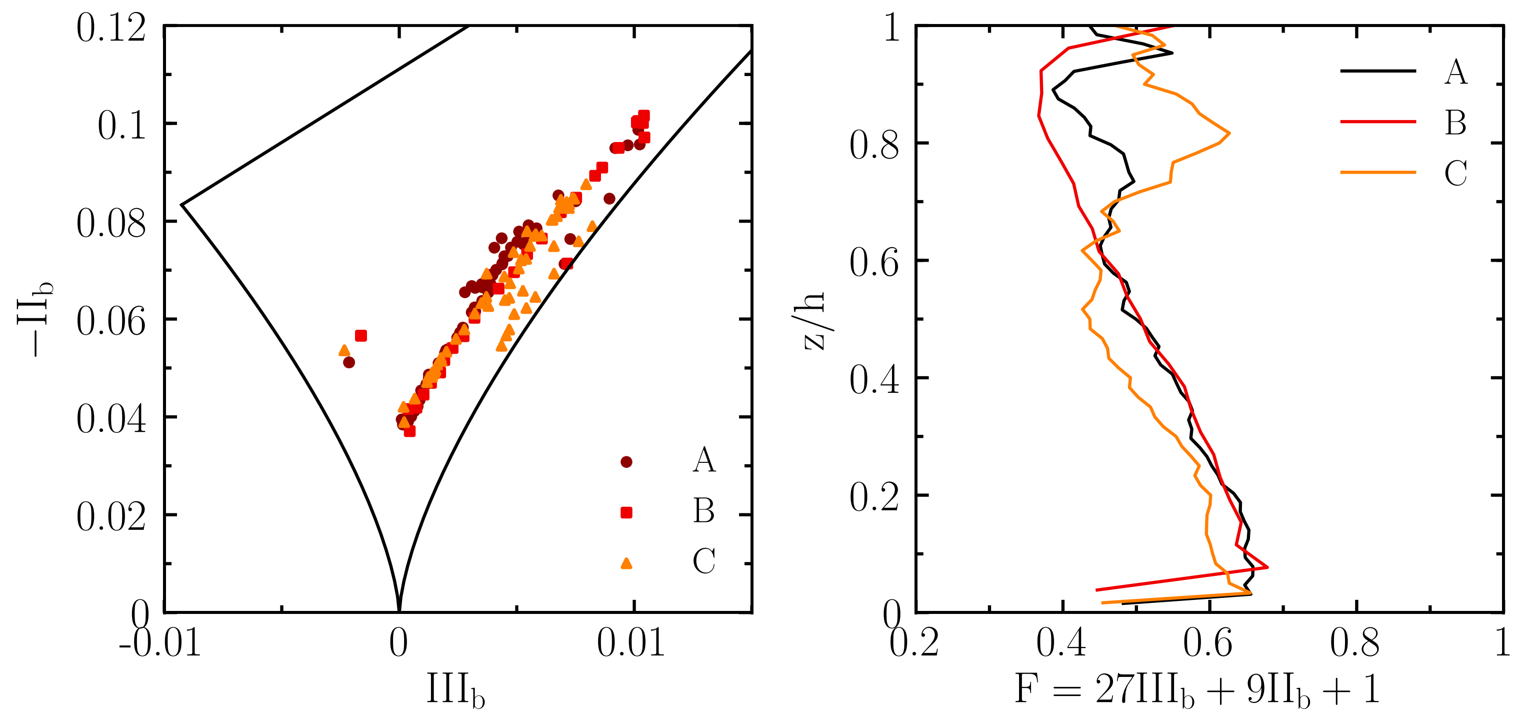
A: u100.100

B: u100.300

C: u200.300

Anisotropy invariant map

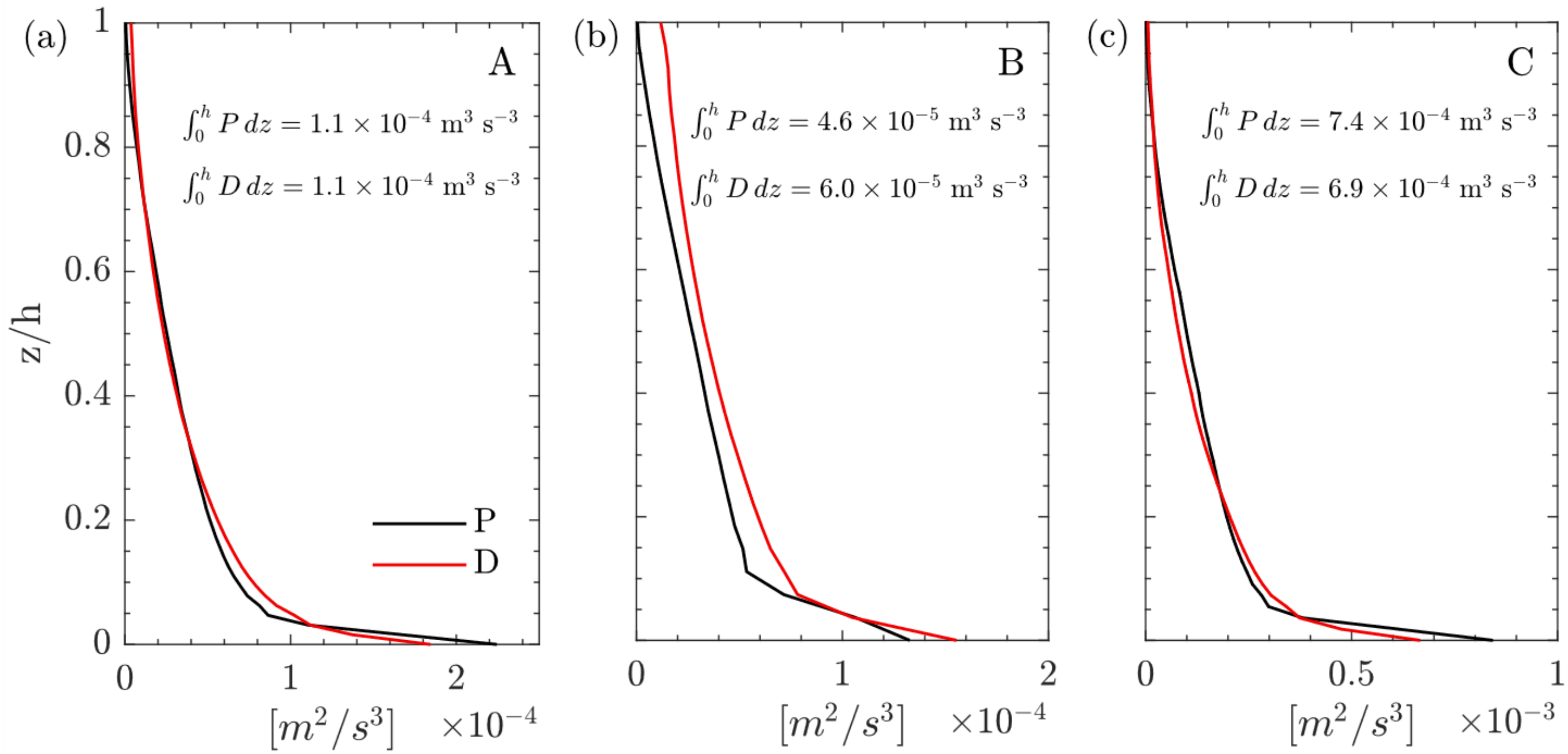
$$b_{ij} = \frac{\overline{u_i' u_j'}}{\overline{u_k' u_k'}} - \frac{\delta_{ij}}{3} \qquad II_b = -\frac{1}{2} b_{ij} b_{ji} \qquad III_b = \frac{1}{3} b_{ij} b_{jk} b_{ki}$$



- Flow is dominated by one component $\overline{u'u'}$ (cigar-shaped turbulence).

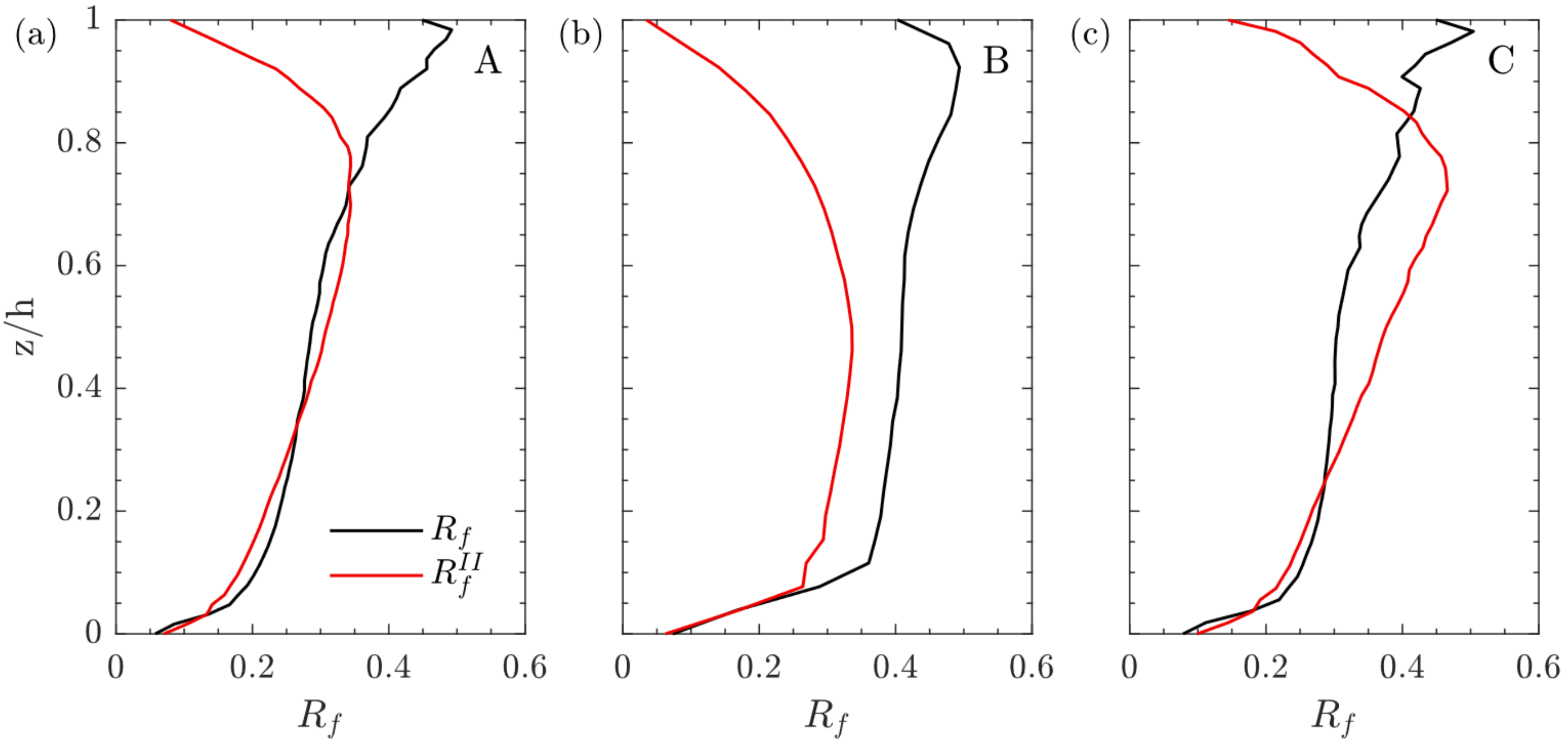
TKE budget

P – shear production of TKE
D – destruction of TKE by buoyancy and dissipation



Mixing efficiency

$$R_f = \frac{B}{P} \qquad R_f^{II} = \frac{B}{m} = \frac{B}{B + \varepsilon}$$



Conclusions

- Successful large-eddy simulations of very stable conditions ($h/L > 6$ and $Ri > 0.25$).
- LES is very computationally challenging because of very small time-steps and long-time integrations.
- Wind turning significant from the surface.
- Turbulent flows met the criteria of strongly stratified regime without viscous effects ($Re_b \gg 1$ and $Fr_h \ll 1$), except near the SBL top where the flow is viscously-dominated.
- Flow is very anisotropic.

Mixing efficiency