DIRECT NUMERICAL SIMULATION OF TURBULENT MIXING IN THE PLANETARY BOUNDARY LAYER

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AIM

We aim to advance our understanding of geophysical turbulence at meter and submeter scales.

We focus on planetary boundary layers (PBLs), in particular, on the entrainment zone and the surface layer, where small-scale turbulence can become significant for earth's susceptibility and predictability by modulating the fluxes between the atmosphere, land and ocean.

Our research is guided by particularly challenging PBL regimes, such as the stratocumulus-topped boundary layer or the stable boundary layer.

Stable boundary layer (Mahrt, 2014)

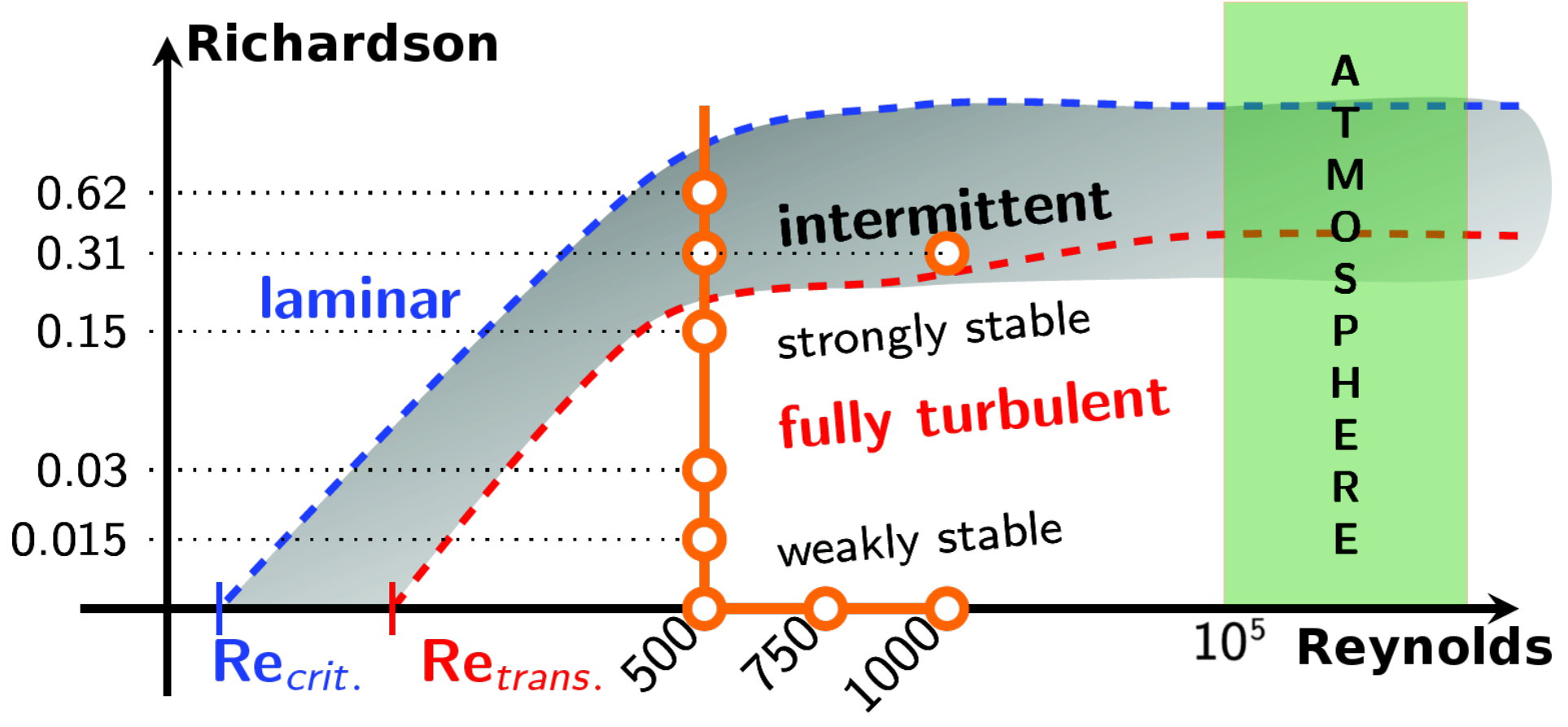
Broken stratocumulus (picture from C. Ansorge)

APPROACH

We systematically study how small-scale turbulence interacts with a reduced set of other phenomena, like density stratification, surface properties, radiative transfer or cloud processes.

We seek to

1. understand dominant balances among processes,
2. derive corresponding scaling laws and parametrizations, and
3. construct and uncover systematically the parameter space.



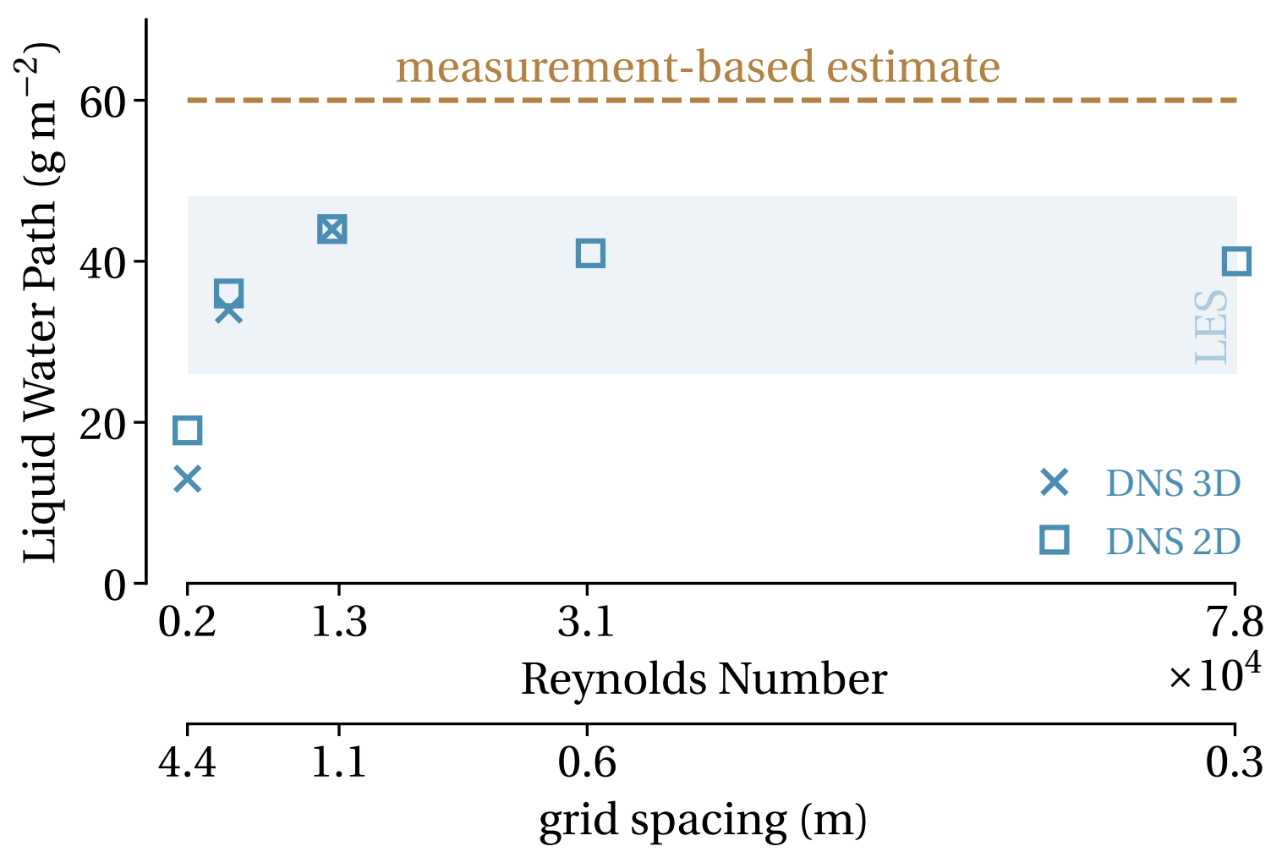
Parameter space of the stably stratified Ekman flow. Circles indicate cases that have been investigated.

DIRECT NUMERICAL SIMULATION

We solve the Navier–Stokes equations without turbulence parametrizations to obtain an accurate representation of all scales.

Although simulation Reynolds numbers are still much smaller than in nature,

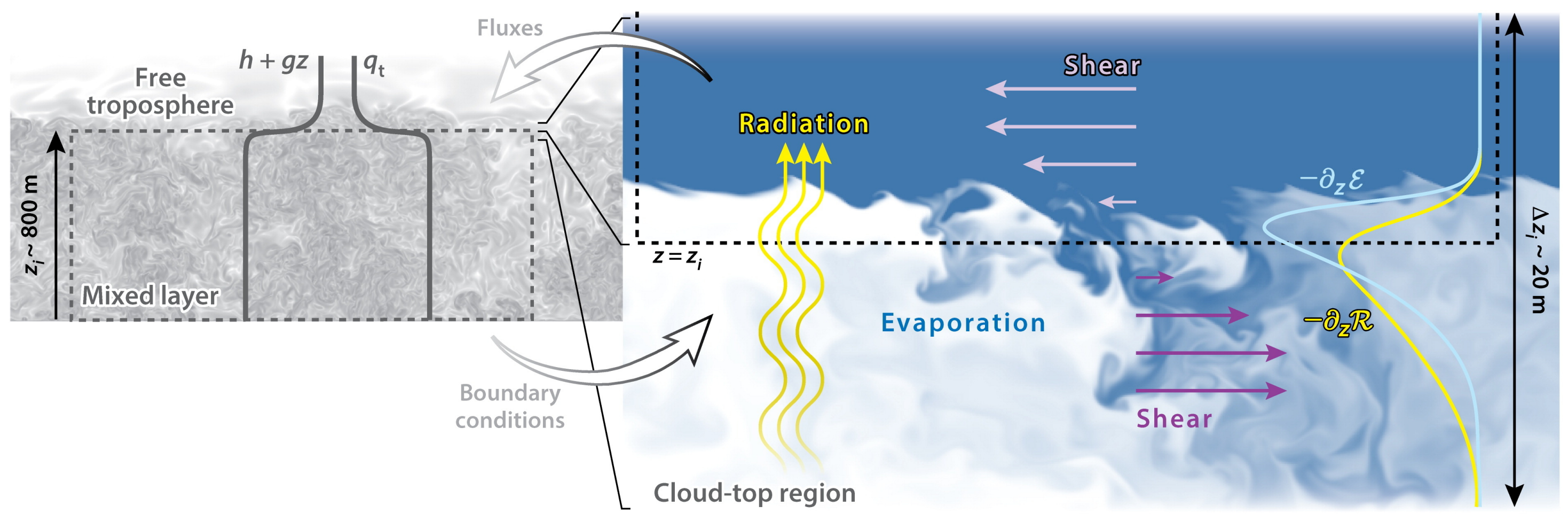
1. we reach sufficiently high Reynolds numbers for relevant turbulence properties to depend only weakly on them (Reynolds number similarity), and
2. we use sensitivity studies, without the uncertainty from turbulence parametrization or numerical error (grid convergence).



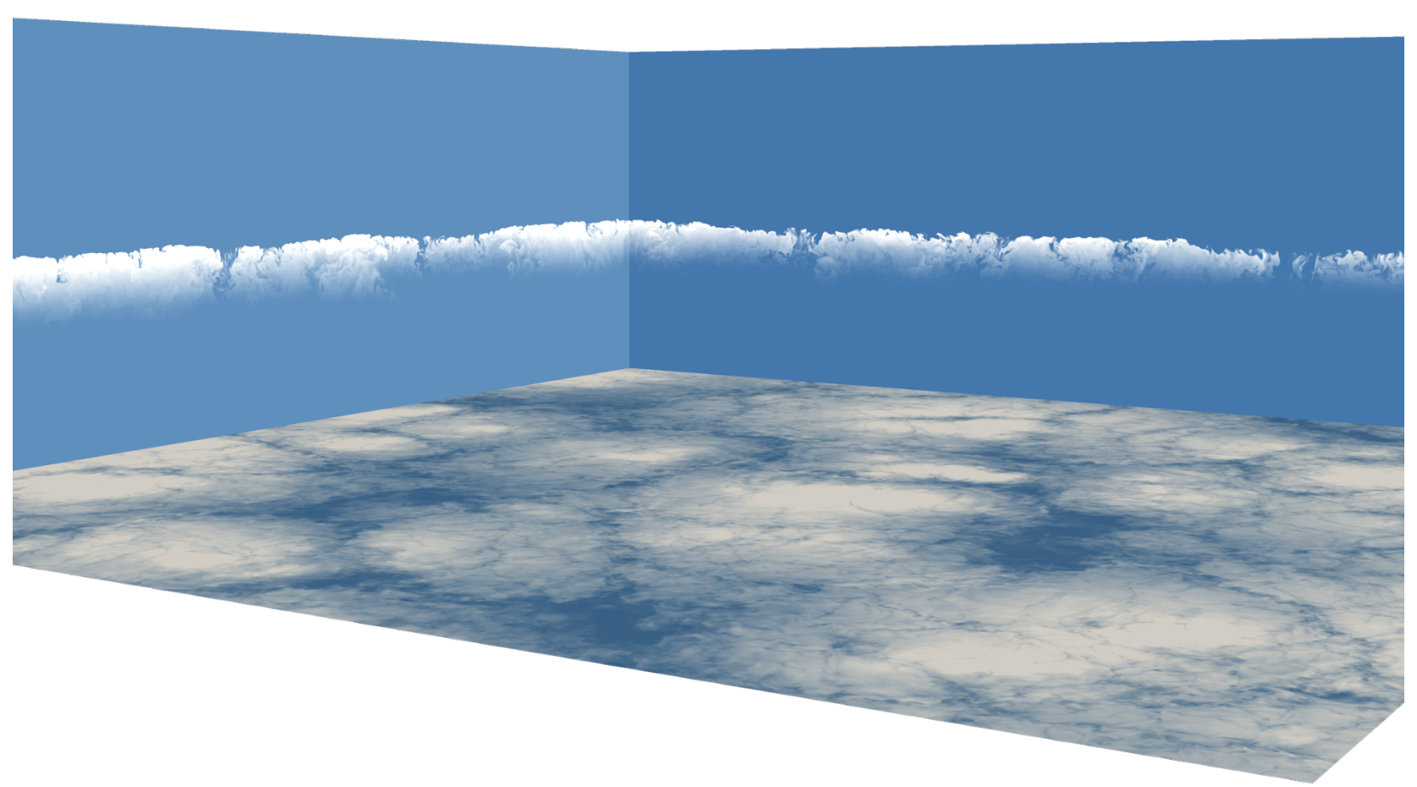
Grid convergence of cloud water per unit area in stratocumulus-topped boundary layers.

THE STRATOCUMULUS-TOPPED BOUNDARY LAYER

Modeled as a convective boundary layer that is forced by radiative and evaporative cooling at the cloud top. We combine global analysis of the boundary layer with local analysis of the cloud-top region.



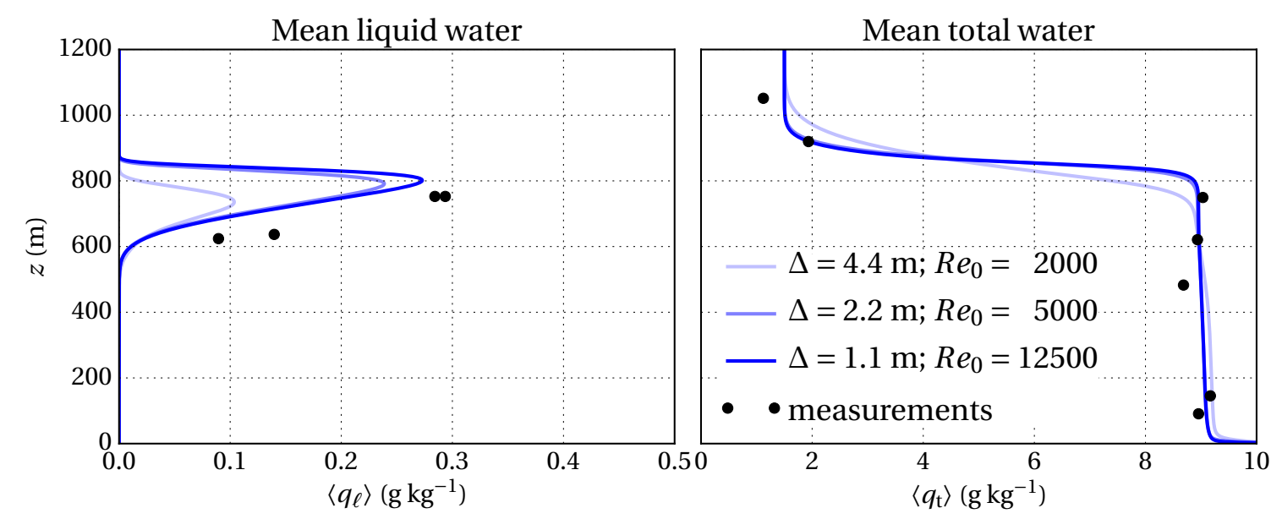
Sketch of the PBL (in gray) and cloud-top region (in color). Mixed layer provides boundary conditions for the cloud-top analysis, which in turn provides the fluxes for the mixed-layer analysis.



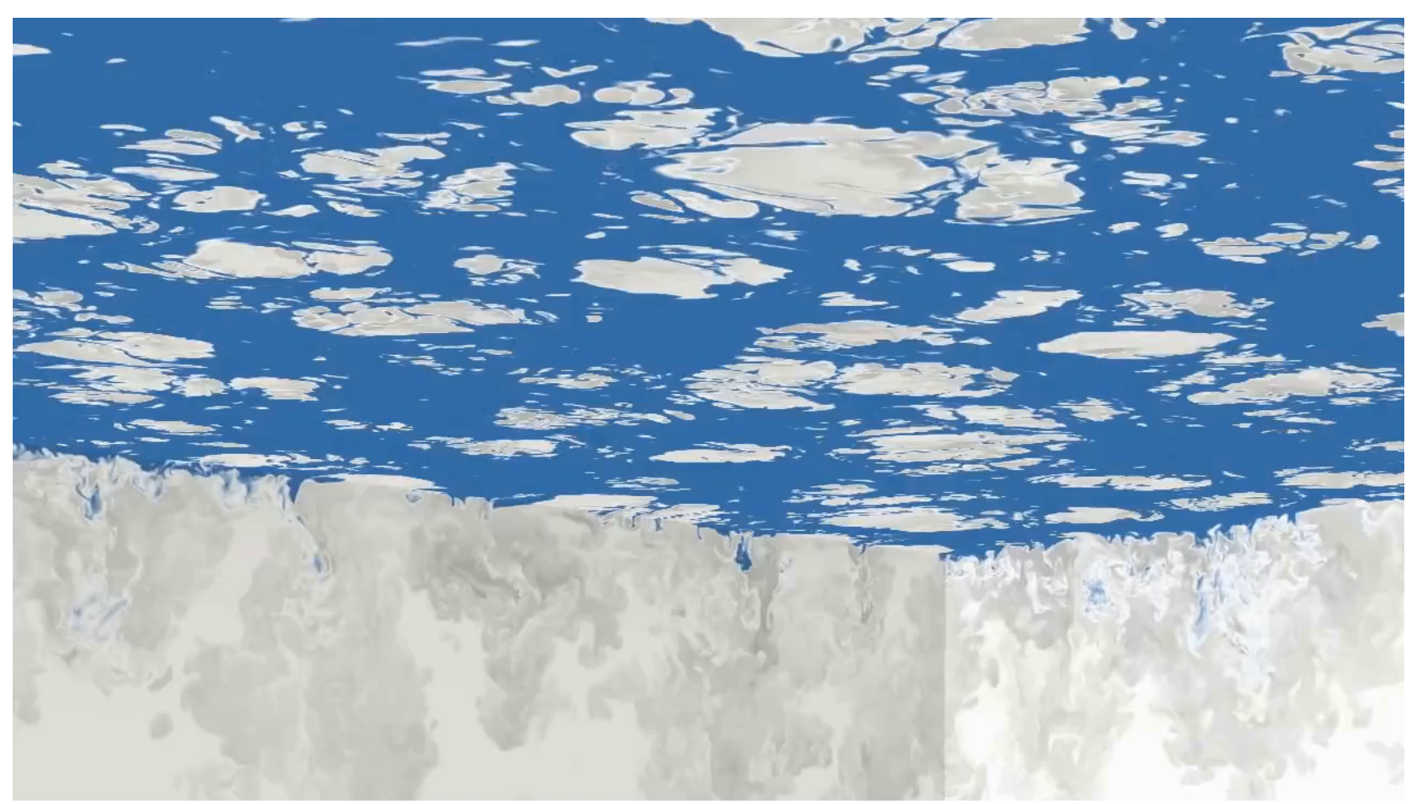
DNS of 5.6 km-wide stratocumulus-topped boundary layer (DYCOMS-II RF01) resolved to 1.1 m.

We have performed, for the first time, DNS of a stratocumulus-topped boundary layer. This allows us to reduce numerical artifacts in the representation of cloud-top mixing, cooling and microphysical effects, avoiding the ad-hoc tuning used in other simulation approaches [1,2].

We have considered the DYCOMS-II field campaign and investigated the dependence of results on the Reynolds number, matching all other DNS parameters to the atmospheric conditions.

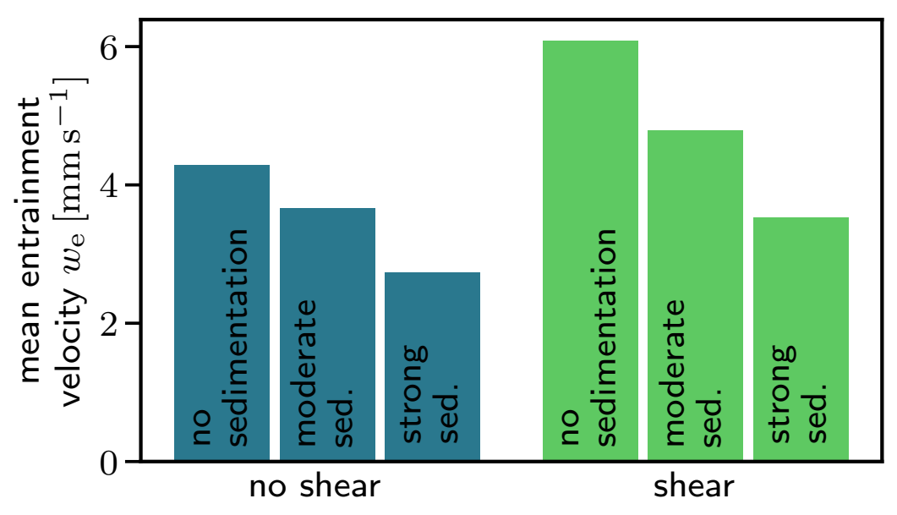


The difference between the two largest Reynolds numbers starts to be small enough to extrapolate part of the results to atmospheric conditions.

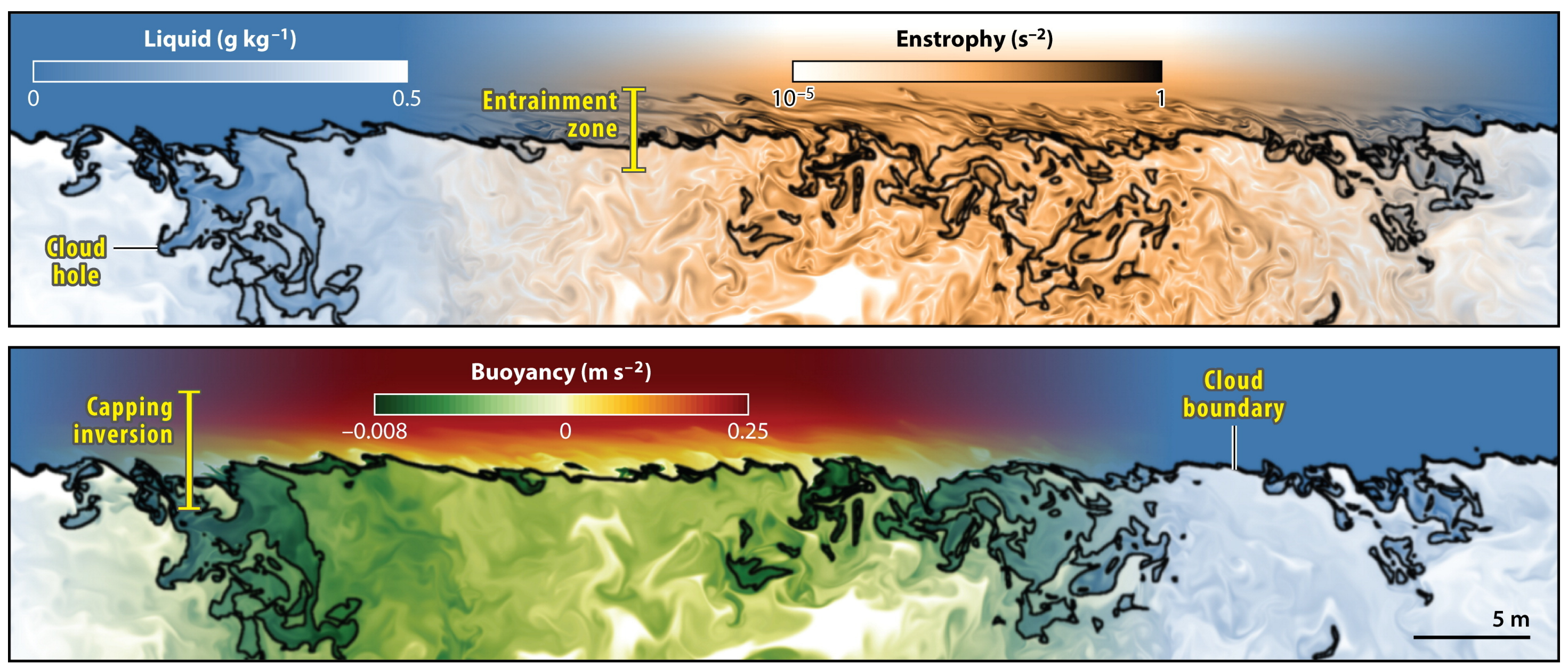


DNS of 150 m-thick cloud-top mixing layer (DYCOMS-II RF01) resolved to 10 cm.

We have derived a formulation to measure the contributions from mixing, radiation, evaporation and sedimentation to the mean entrainment velocity w_e.



We have found that the reduction of entrainment velocity by droplet sedimentation can be 2 to 3 times larger than previously conjectured [3]. One reason is the non-negligible contribution from mass loading, as falling droplets leave behind more buoyant air in the inversion. Moreover, the reduction of evaporative cooling as droplets fall out of the inversion is stronger than previously observed in large-eddy simulations, where excessive mixing by turbulence models and numerical artifacts may have partially masked this effect.



Cloud-top structure. Windows showing enstrophy and buoyancy overlie the liquid mass fraction.

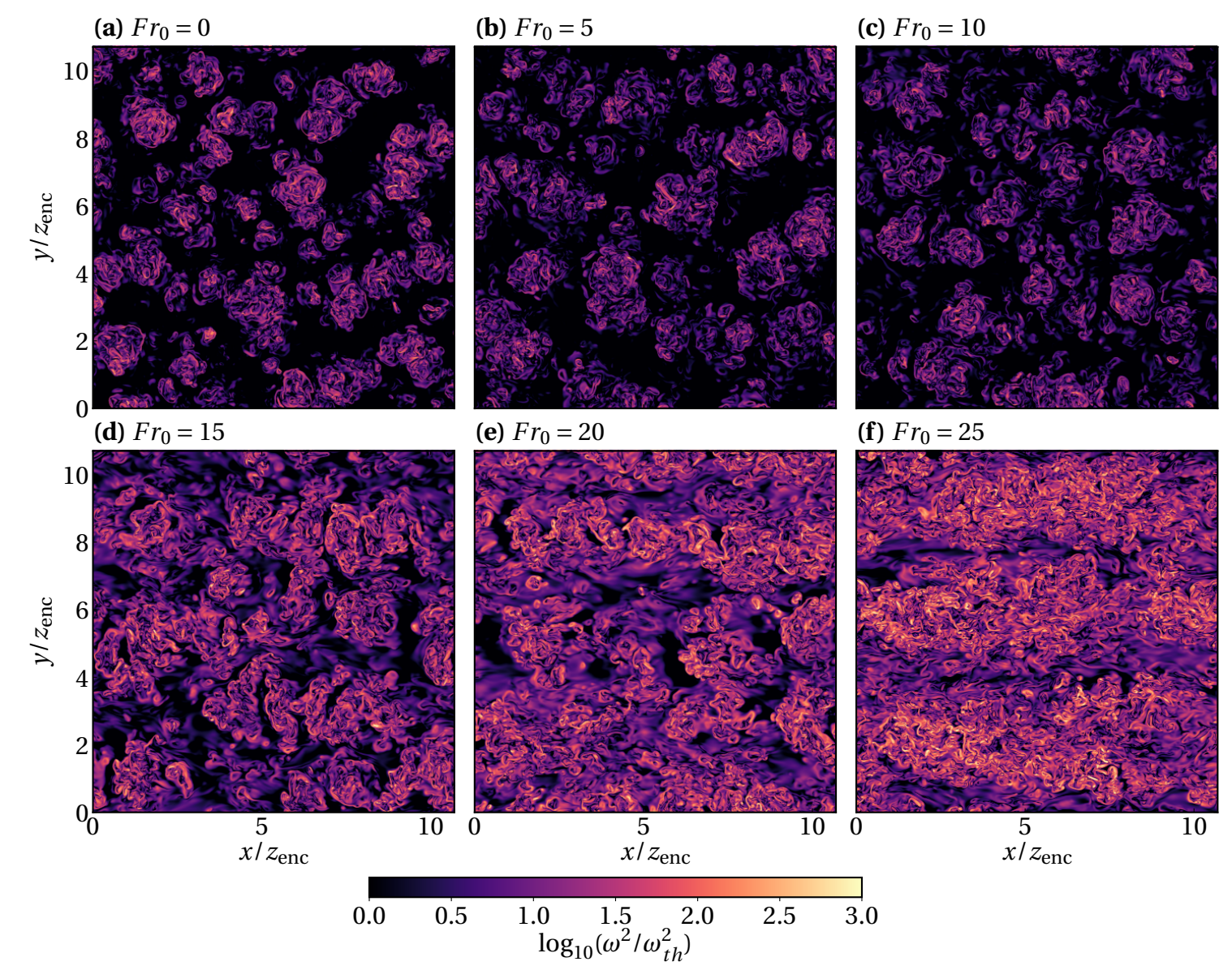
THE UNSTABLY STRATIFIED PLANETARY BOUNDARY LAYER

Modeled as a convective boundary layer that is forced by a mean surface buoyancy flux B_0 and that penetrates into a fluid with a mean buoyancy gradient N^2.

Different atmospheric conditions can be mapped into only two independent variables, h/L_0 and $Fr_0 = U_0/(NL_0)$, where h is the PBL depth, U_0 is the geostrophic wind velocity in the free atmosphere and

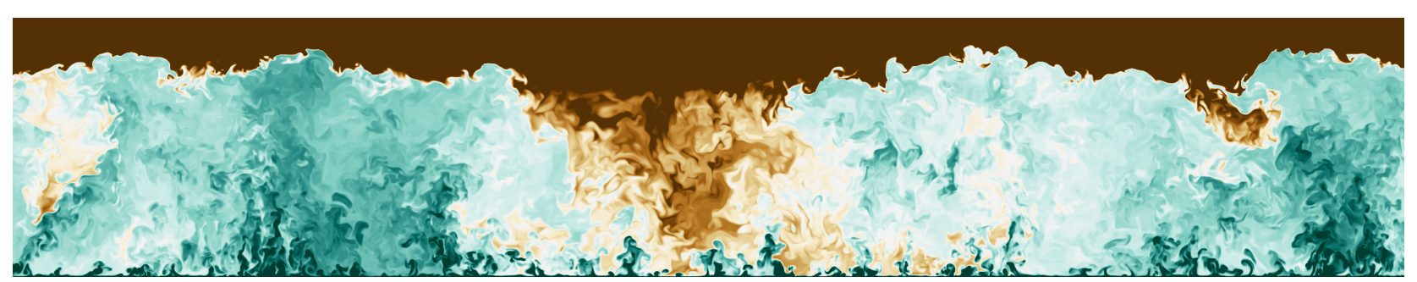
$$L_0 \equiv (B_0/N^3)^{1/2}$$

is the reference entrainment-zone thickness. For typical midday conditions over land, one finds $L_0 \simeq 20-200$ m and $Fr_0 \simeq 0-80$.



Horizontal cross-section of enstrophy in the entrainment zone at the top of the PBL.

The entrainment flux is key for the evolution of the PBL depth and mean properties. We have found that its variation with U_0 results from two competing effects: the initial decrease in the correlation between buoyancy and vertical velocity, and the increase in the turbulent area fraction. This result helps explaining the observed non-monotonic variation of entrainment flux with U_0 for weak winds [4].

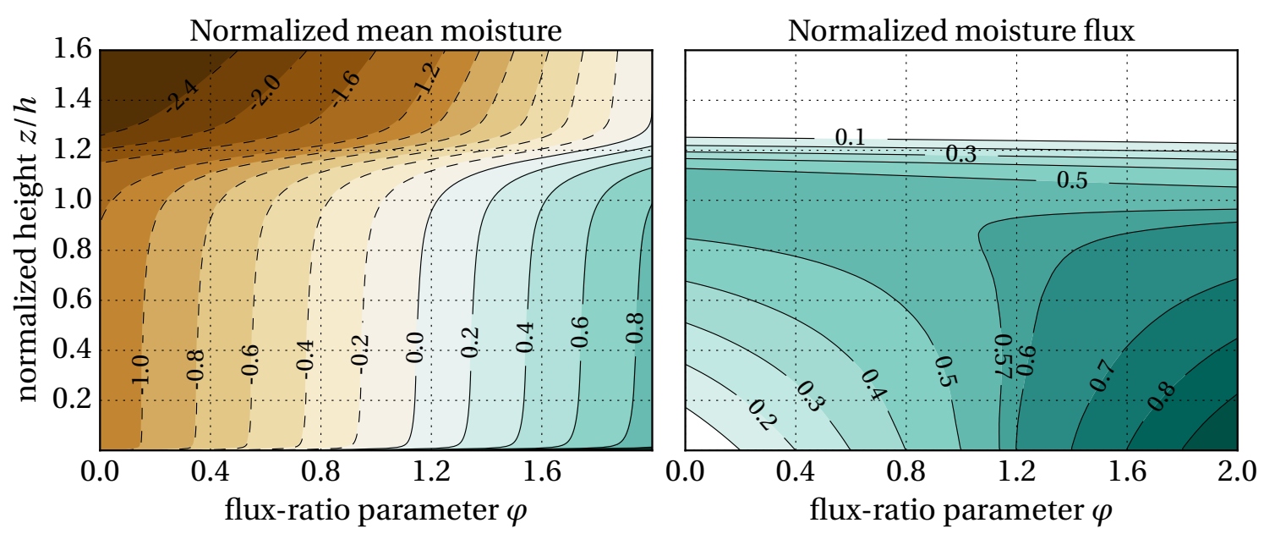


Moisture field from DNS of 1000 m-deep PBL at drying-to-moistening transition, resolved to 1 m.

The analysis of moisture statistics introduces only one additional parameter. We have shown that

$$F_{q,1} \equiv \gamma_q L_0 (B_0 L_0)^{1/3}$$

characterizes the entrainment flux, where γ_q is the free-atmosphere hydro-lapse rate, and that the ratio $\varphi \equiv (2F_{q,0})/(F_{q,0}+F_{q,1})$ characterizes the moisture regime, where $F_{q,0}$ is the surface moisture flux [5].



For $\varphi \approx 0$, the PBL dries because the flux of moisture out of the PBL (entrainment drying) dominates over the surface flux into the PBL (surface moistening). As φ increases, the PBL dries less rapidly because surface moistening increasingly compensates entrainment drying. The cross-over value $\varphi_{crit} \approx 1.16$ marks the transition between drying and moistening regimes. For $\varphi \approx 2$ we approach the pure moistening regime: $F_{q,1}$ is negligible compared to the surface moisture flux $F_{q,0}$, and $F_{q,0}$ fully characterizes the vertical flux.

THE STABLY STRATIFIED PLANETARY BOUNDARY LAYER

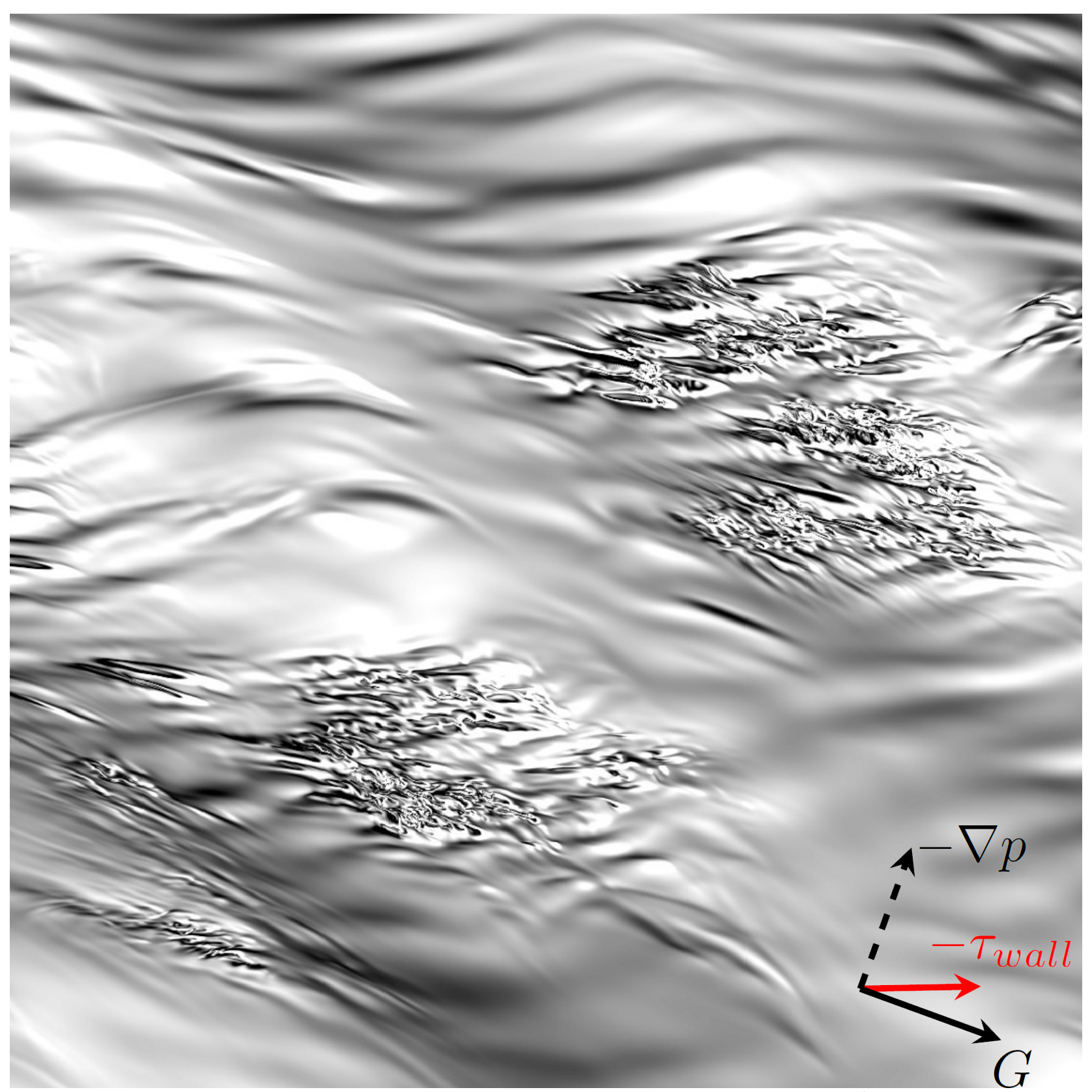
Modeled as an Ekman layer that is forced by a geostrophic wind G and a Coriolis parameter f, and with an imposed buoyancy difference Δb between the non-turbulent region above and the surface.

The parameter space is reduced to the Richardson number and the Reynolds number. By increasing the Richardson number, we study in a single configuration the three regimes of the stable boundary layer: weakly, intermediately, and strongly stratified.

Turbulence collapse occurs intermittently in space without the need of external triggers introducing this intermittency, provided that large-scale structures, several times the boundary-layer depth, have space and time to develop.

As stratification increases, order-of-one changes in the stable boundary layer are dominated by changes of the turbulence volume fraction, and stratification effects inside turbulent regions remain small [6]. This result suggests to parametrize intermittency factors separately from turbulent mixing.

This work is part of the PhD thesis of Dr. Ansorge, who was awarded the Otto Hahn Medal from the Max Planck Society.



Entrophy in a horizontal plane inside the logarithmic region. The lateral size is $\simeq 1/3$ Rossby radius.

[1] J. P. Mellado, Annu. Rev. Fluid Mech., 49, 145-169 (2017).
[2] J. P. Mellado, C. S. Bretherton, B. Stevens and M. C. Wyant, J. Adv. Model. Earth Syst., 10, 1421-1438 (2018).
[3] B. Schulz and J. P. Mellado, J. Adv. Model. Earth Syst., 11, 1830-1846 (2019).
[4] K. Fodor, J. P. Mellado and A. Haghshenas, Boundary-Layer Meteorol., 184, 463-477 (2022).
[5] J. P. Mellado, M. Puche and C. C. van Heerwaarden, Q. J. R. Meteorol. Soc., 143, 2403–2419 (2017).
[6] C. Ansorge and J. P. Mellado, J. Fluid Mech., 805, 611-635 (2016).

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