THE CHALLENGE OF SMALL-SCALE TURBULENCE IN PLANETARY BOUNDARY LAYERS

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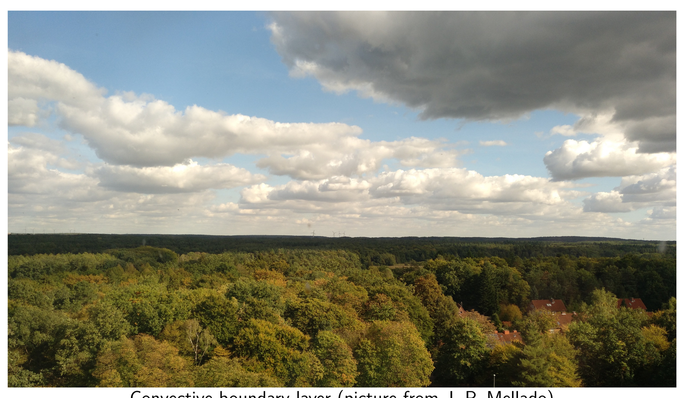
AIM

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.

During the last year, we have concentrated on the unstable PBL. In particular, we have investigated two aspects: the role of wind shear on entrainment, and the role of large coherent structures.



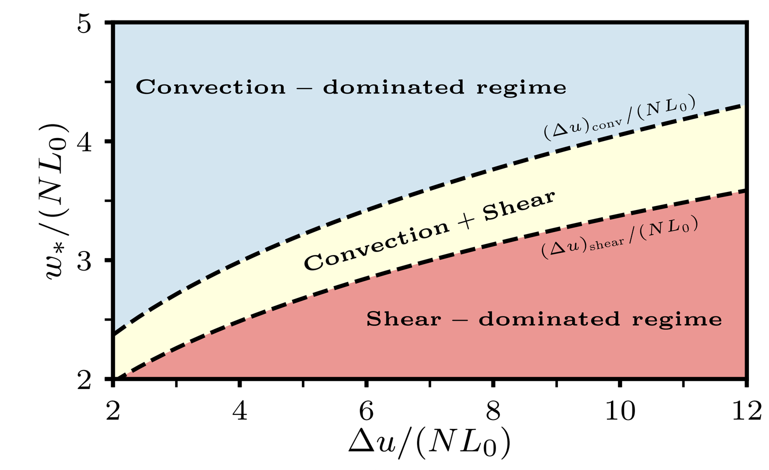
Convective boundary layer (picture from J. P. Mellado)

APPROACH

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

We seek to:

1. Understand dominant balances among processes
2. Derive corresponding scaling laws and parametrizations
3. Construct and uncover systematically the parameter space



Parameter space of the unstable PBL. Δu indicates velocity difference across the PBL top, w_* indicates convective velocity. From reference [1].

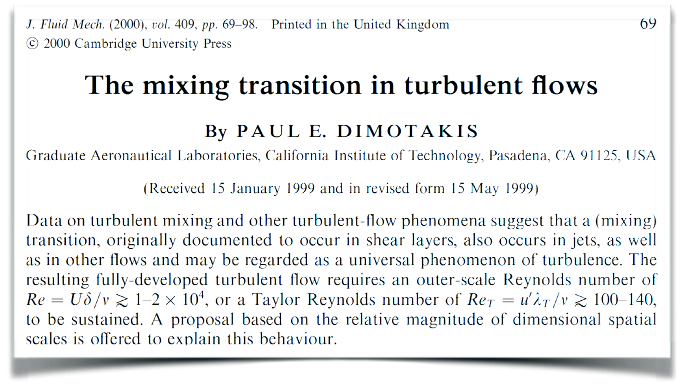
DIRECT NUMERICAL SIMULATION

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

Despite reaching the largest possible Reynolds numbers in simulations, values are still orders of magnitude smaller than in nature. However:

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

This approach is referred to as direct numerical simulation (DNS).



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The mixing transition in turbulent flows

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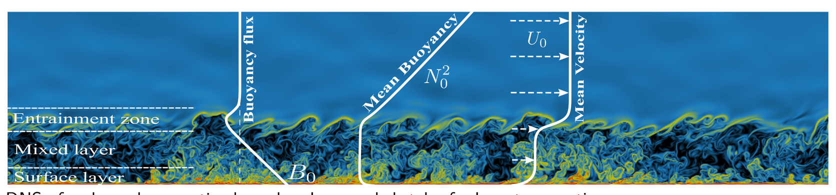
Data on turbulent mixing and other turbulent-flow phenomena suggest that a (mixing) transition, originally documented to occur in shear layers, also occurs in jets, as well as in other flows and may be regarded as a universal phenomenon of turbulence. The resulting fully-developed turbulent flow requires an outer-scale Reynolds number of $Re = U\delta/\nu \gtrsim 1\text{–}2 \times 10^4$, or a Taylor Reynolds number of $Re_T = u'\lambda_T/\nu \gtrsim 100\text{–}140$, to be sustained. A proposal based on the relative magnitude of dimensional spatial scales is offered to explain this behaviour.

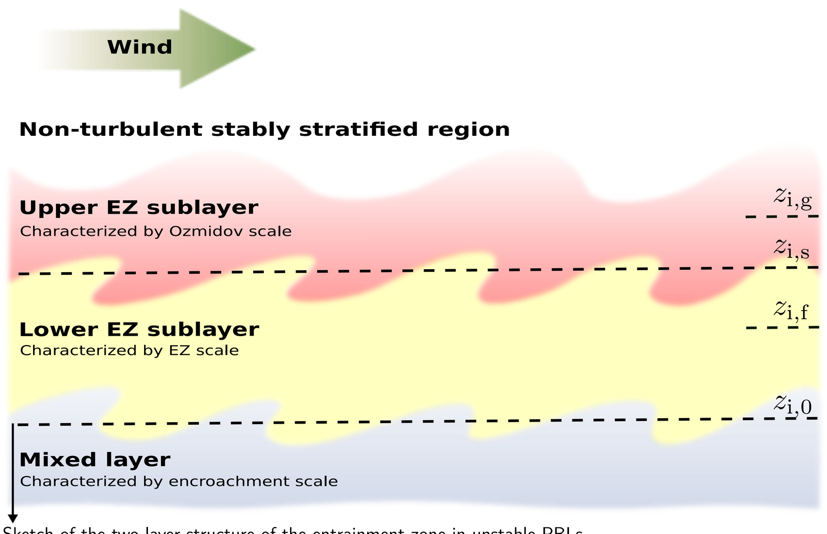
NEW RESULTS ABOUT WIND-SHEAR EFFECTS ON ENTRAINMENT IN UNSTABLE PLANTEARY BOUNDARY LAYERS

Local Scales in the Entrainment Zone



DNS of a sheared convective boundary layer and sketch of relevant properties.

Wind shear at the top of unstable PBLs has multiple effects on local and global properties. However, the intricacy of how wind shear interacts with the convective turbulence generated underneath and with the stable stratification imposed from above continues to challenge our ability to quantify its effects.



Sketch of the two-layer structure of the entrainment zone in unstable PBLs.

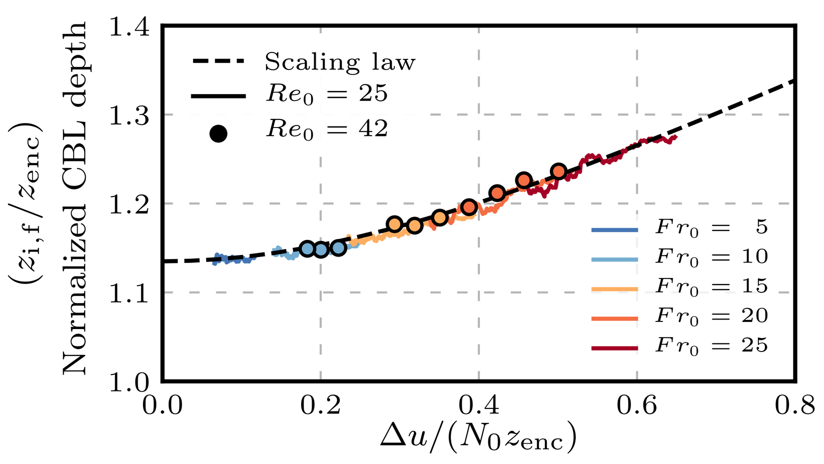
We have used DNS to show that shear mainly affects the lower sublayer of the entrainment zone. In particular, we have shown that the height of the minimum buoyancy flux, a proxy for the boundary-layer depth, can be approximated by

$$z_{\mathrm{i,f}} \simeq 0.94\, z_{\mathrm{enc}} + 0.8\, \Delta z_{\mathrm{i}} \ ,$$

where the entrainment-zone scale Δz_{i} can be obtained from the integral analysis of the budget equation for the turbulence kinetic energy. This analysis leads to

$$\frac{\Delta z_{\mathrm{i}}}{z_{\mathrm{enc}}} = 0.25 \sqrt{1 + 4.8 \left(\frac{\Delta u}{N_0 z_{\mathrm{enc}}} \right)^2} \ .$$

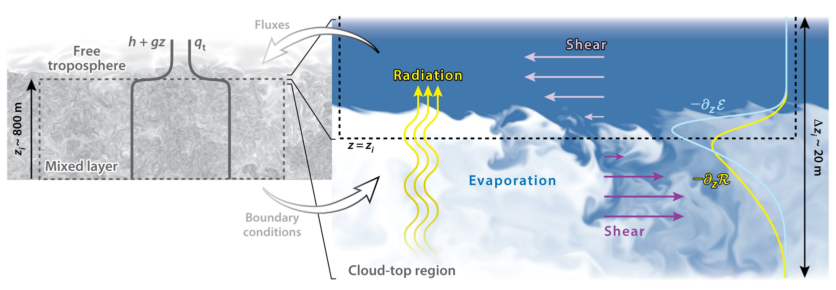
In this way, shear effects are quantified in terms of Δu, the velocity difference across the PBL top, and the encroachment height, z_{enc}, both of which can be calculated from the vertical profiles of buoyancy and streamwise velocity [1].



DNS data supports the derived scaling law for the height of minimum buoyancy flux.

As a first application, we have used these results to derive new zero-order bulk models. The advantage of these new models is that they are free from the singularity of previous ones [2].

Effects on Stratocumulus Clouds



Sketch of the PBL (in gray) and cloud-top region (in color).

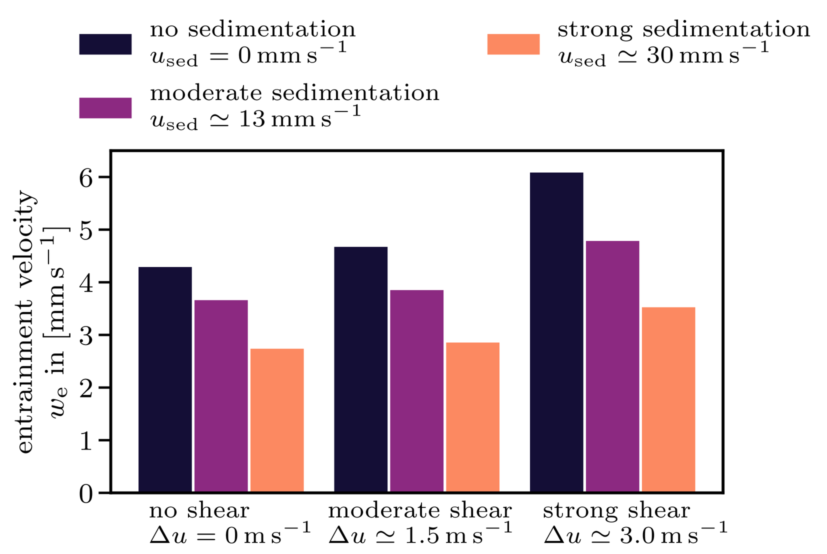
In cloud-topped PBLs, entrainment becomes even more important because it affects cloud-top radiative and evaporative cooling, two major sources of PBL turbulence. Wind shear has opposing effects:

- it enhances entrainment directly by local mixing and indirectly by enhancing evaporative cooling,
- it weakens entrainment indirectly by diluting the cloud, which reduces radiative cooling and hence in-cloud-turbulence.

We have provided estimates of the critical velocities at which these effects become important. By means of a local analysis and DNS data, we have found that:

- Only a wind shear with $(\Delta u)_{\min} \gtrsim 1 - 4$ m s^{-1} enhances entrainment. This result implies that cloud-top shear caused by convection cells is unlikely to modify mean entrainment properties.
- Only a wind shear with $(\Delta u)_{\max} \gtrsim 4 - 10$ m s^{-1} weakens entrainment. This result helps to explain why stratocumulus clouds often have smaller velocity jumps.

Outside of the interval $(\Delta u)_{\min} < \Delta u < (\Delta u)_{\max}$, there are no wind-shear effects, either because the wind shear is too weak or because there is no cloud anymore [3].



The effects of wind shear and droplet sedimentation can compensate each other.

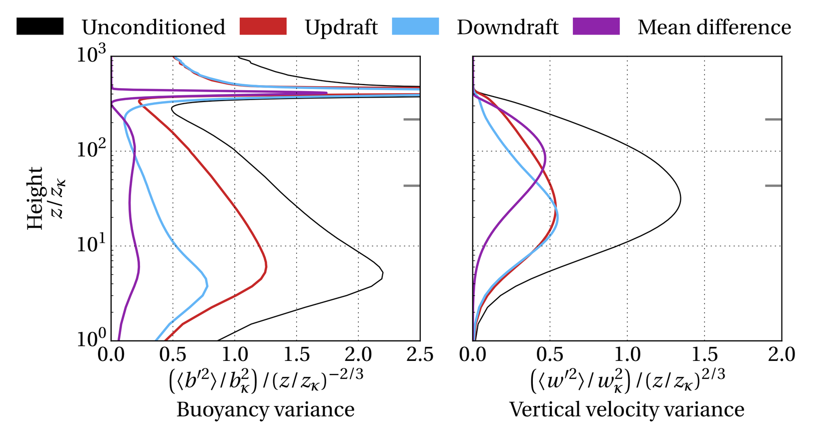
We have also studied the role of droplet sedimentation. Due to gravitational settling, droplets fall out of the entrainment zone and this causes a reduction of evaporative cooling and hence entrainment rates. We have showed that this effect can compensate wind-shear enhancement. The implication is that changes in the droplet size distribution can substantially affect cloud lifetimes not only because of its effect on rain formation, but also because of its effect on cloud-top entrainment. Therefore, a better characterization of the droplet size distribution is needed to accurately represent mixing effects on cloud lifetimes [4].

NEW INSIGHTS INTO UNSTABLE PLANETARY BOUNDARY LAYERS GAINED FROM CONDITIONAL ANALYSIS

Deviations from Monin–Obukhov Similarity Theory in Free Convection

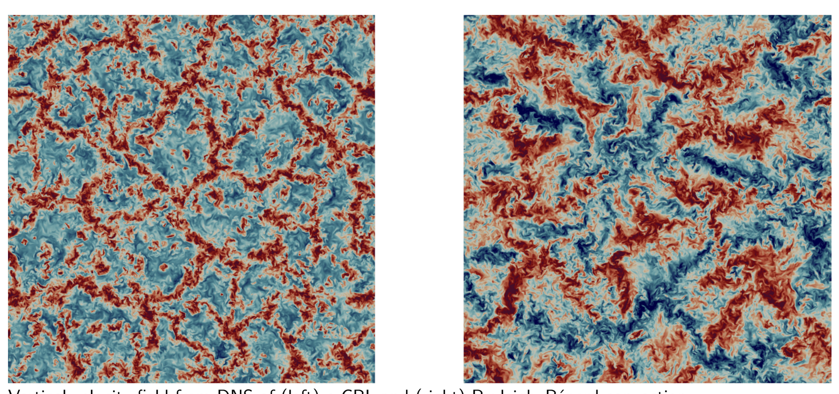
Moisture field from DNS of 1000 m-deep CBL at drying-to-moistening transition, resolved to 1 m.

Classical theory on the near-surface region makes predictions about how statistical properties change with height, but studies have shown that these predictions fail in free convective conditions. We test the hypothesis that deviations from this theory are due to large-scale downdrafts, which transport non-local properties to the surface layer and violate the assumption of no interaction with the outer layer.



By conditioning the flow into large-scale updraft and downdraft regions, we find the unexpected result that deviations from classical similarity theory occur not only in downdraft regions, but also in updraft regions. The updraft regions are at least as important as the downdraft regions, if not more so, for determining the near-surface behaviour and hence, the cause of departures from classical similarity theory is not as straightforward as has been hypothesised [5].

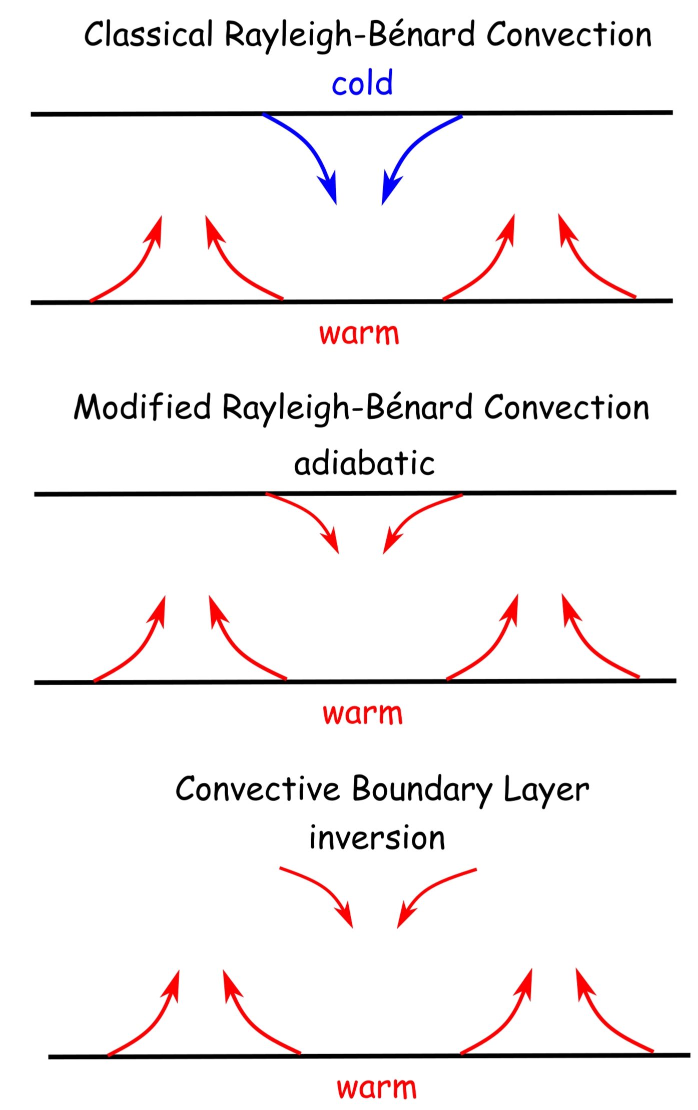
Rayleigh–Bénard Convection as a Model of the Unstable Atmospheric Surface Layer



Vertical velocity field from DNS of (left) a CBL and (right) Rayleigh-Bénard convection.

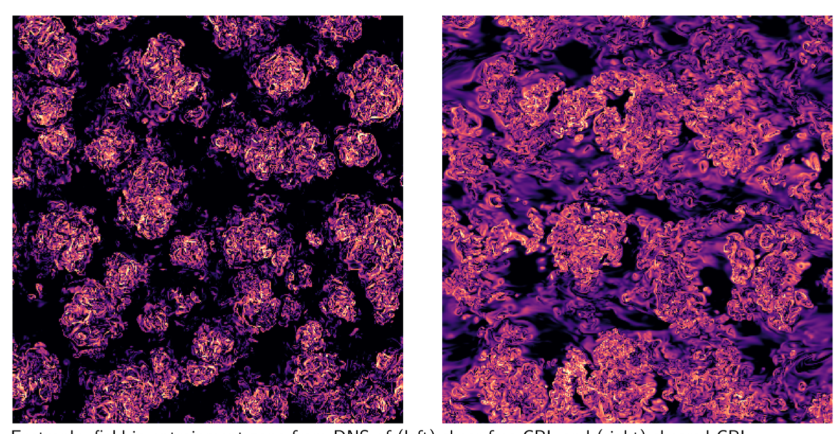
Rayleigh–Bénard convection is one of the most well-studied, canonical free convective flows. The large-scale circulation cells that form in that system bear a striking resemblance to those found in the CBL. However, differences in the upper boundary conditions between the two systems modify the large scales. How important are these differences for the near-surface behaviour?

We show that the cold, strong downdrafts in classical Rayleigh–Bénard convection notably modify the near-surface region compared to the convective boundary layer.



However, we also find that only a small change to the classical set up of Rayleigh–Bénard convection is needed for surface-layer properties to behave in a similar way to the CBL, namely by replacing the cooled upper plate with an adiabatic one [5].

Implications of External Intermittency for Understanding Shear Enhanced Entrainment



Enstrophy field in entrainment zone from DNS of (left) shear-free CBL and (right) sheared CBL.

Wind shear enhances the magnitude of the buoyancy flux at the CBL top. This is commonly associated with an increase in turbulent kinetic energy in the entrainment zone. However, this picture is complicated by the fact that the entrainment zone is not entirely turbulent, but also has large non-turbulent patches. What is the effect of wind shear on the properties of these different regions and how is that related to an increased entrainment flux?

By conditioning into turbulent and non-turbulent regions, we find that turbulent regions contribute by far the most to the entrainment buoyancy flux, but the flux itself within those regions does not increase under sheared conditions. Rather, the main cause of shear enhancement of the entrainment buoyancy flux is the increase in the turbulent area fraction [6].

[1] A. Haghshenas and J. P. Mellado, J. Fluid Mech., 858, 145-18 (2019).
[2] A. Haghshenas, J. P. Mellado and M. Hartmann, J. Atmos. Sci., 76, 3697-3715 (2019).
[3] B. Schulz and J. P. Mellado, J. Atmos. Sci., 75, 3245-3263 (2018).
[4] B. Schulz and J. P. Mellado, J. Adv. Model. Earth Syst., 11, 1830-1846 (2019).
[5] K. Fodor, J. P. Mellado and M. Wilczek, Boundary-Layer Meteorol., 172, 371-396 (2019).
[6] K. Fodor and J. P. Mellado, J. Atmos. Sci., (under review).

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