THE CHALLENGE OF SMALL-SCALE TURBULENCE IN PLANETARY BOUNDARY LAYERS

Juan Pedro Mellado, Katherine Fodor, Armin Haghshenas, Mona Karimi, Bernhard Schulz

Max Planck Institute for Meteorology, Bundesstr. 53, 20146, Hamburg

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)

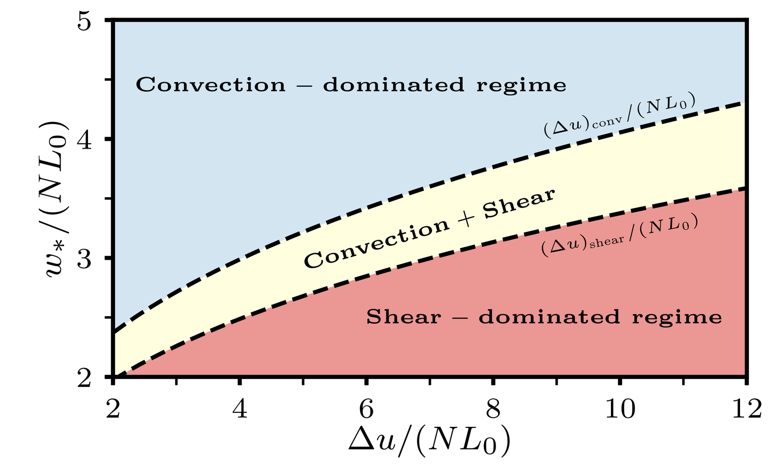
Broken stratocumulus (picture from C. Ansorge)

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
3. Construct and uncover systematically the parameter space



Parameter space of the unstable boundary layer. Δu indicates velocity difference across the PBL top, w_* indicates convective velocity.

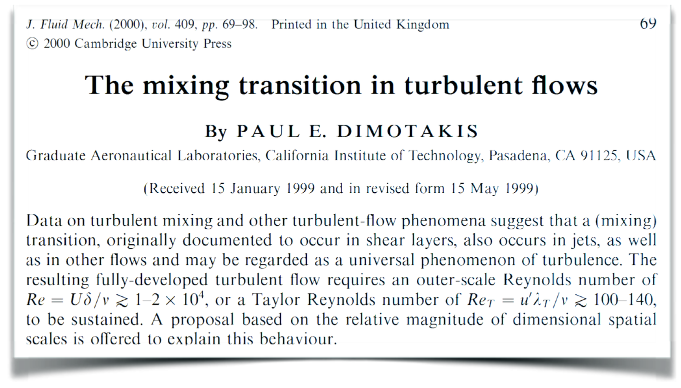
DIRECT NUMERICAL SIMULATION

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 use sensitivity studies, without the uncertainty from turbulence parametrization or numerical error (grid convergence).

Although computationally demanding (100 million core-hours between 2014 and 2017 at Jülich Supercomputing Centre), it is already feasible.



J. Fluid Mech. (2000), vol. 409, pp. 69–98. Printed in the United Kingdom 69
© 2000 Cambridge University Press

The mixing transition in turbulent flows

By PAUL E. DIMOTAKIS

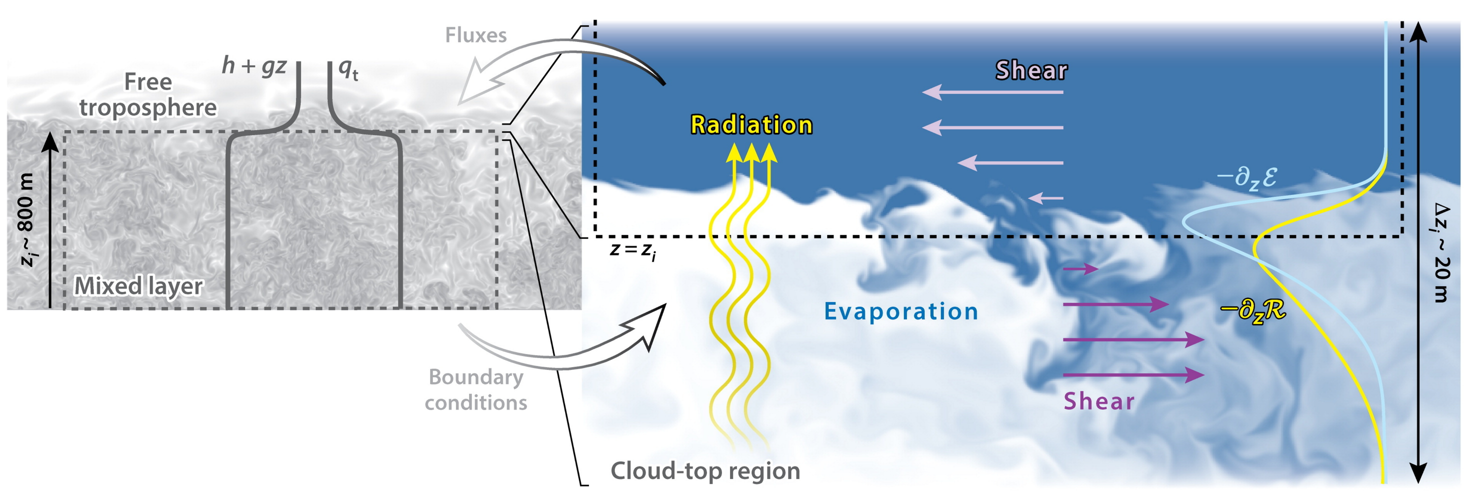
Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA 91125, USA

(Received 15 January 1999 and in revised form 15 May 1999)

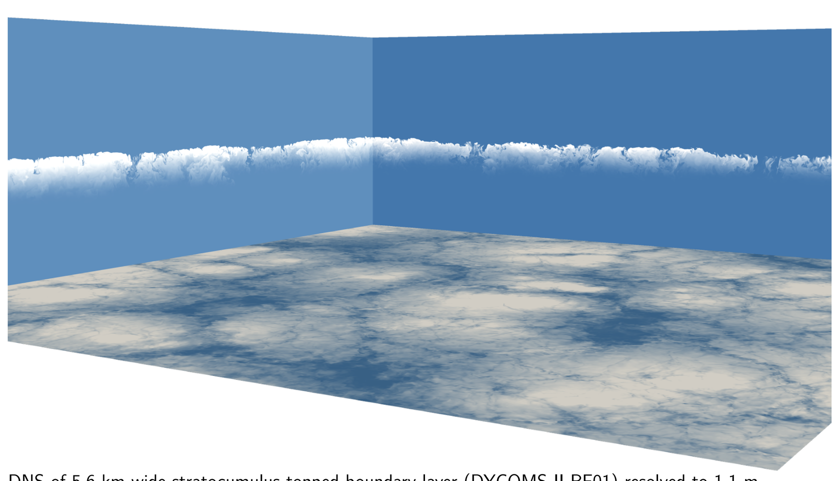
Data on turbulent mixing and other turbulent-flow phenomena suggest that a (mixing) transition, originally documented to occur in shear layers, also occurs in jets, as well as in other flows and may be regarded as a universal phenomenon of turbulence. The resulting fully-developed turbulent flow requires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

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.



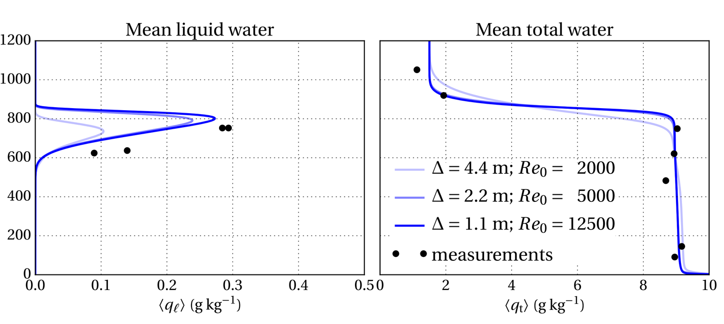
Sketch of the PBL (in gray) and cloud-top region (in color). Mixed layer provides boundary conditions for the cloud-top analysis, which in turn provides the fluxes for the mixed-layer analysis.



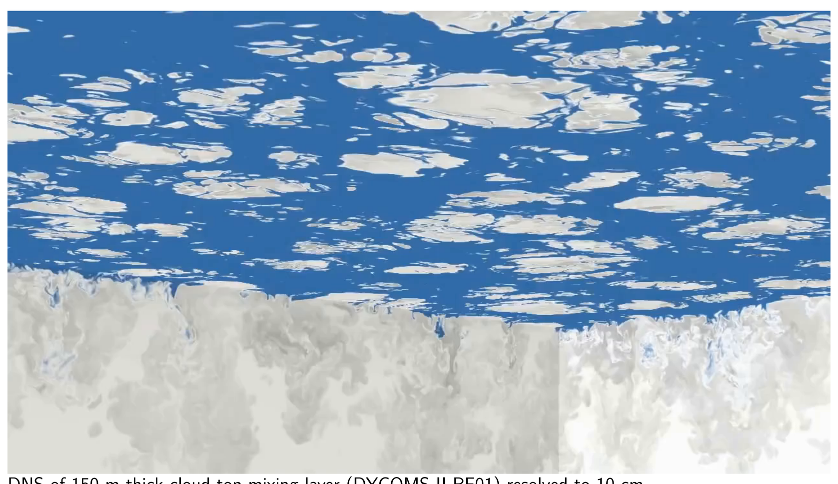
DNS of 5.6 km-wide stratocumulus-topped boundary layer (DYCOMS-II RF01) resolved to 1.1 m.

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 cooling, which are known to be detrimental in the analysis of the effects of droplet evaporation and gravitational settling [1,2].

We have considered RF01 of the DYCOMS-II field campaign and investigated the dependence of results on the Reynolds number, which is the only DNS parameter that does not match atmospheric conditions.

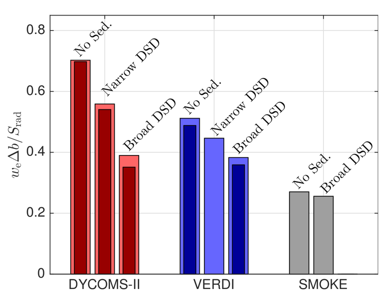


The difference between the two largest Reynolds numbers starts to be small enough to extrapolate part of the results to atmospheric conditions.

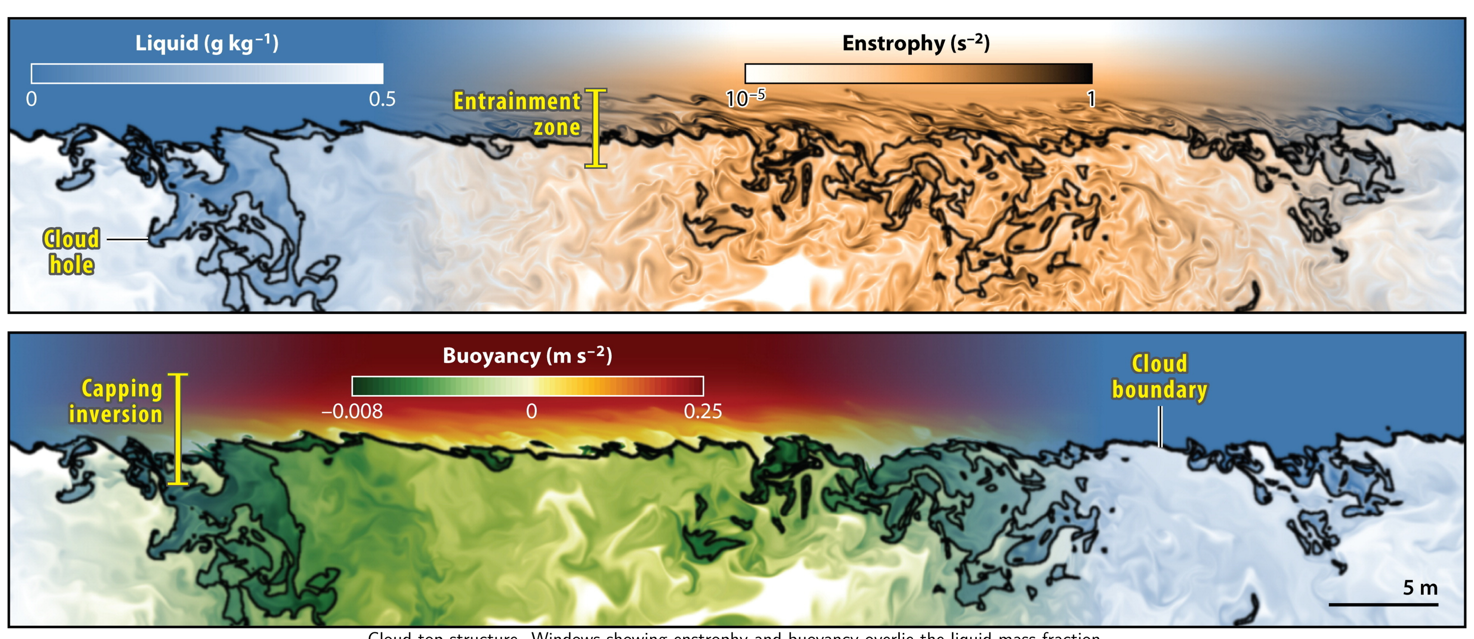


DNS of 150 m-thick cloud-top mixing layer (DYCOMS-II RF01) resolved to 10 cm.

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]. The reason is twofold. First, there is a non-negligible direct contribution from mass loading, as falling droplets leave behind more buoyant air in the inversion. Second, 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.

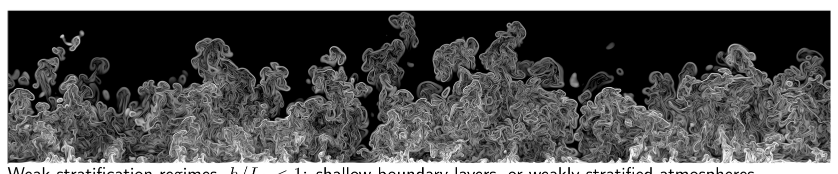


Cloud-top structure. Windows showing enstrophy and buoyancy overlie the liquid mass fraction.

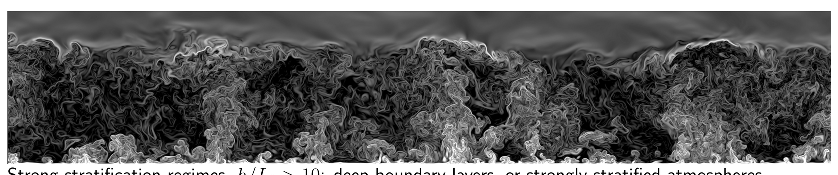
[1] J. P. Mellado, Annu. Rev. Fluid Mech., 49, 145-169 (2017).
[2] J. P. Mellado, C. S. Bretherton, B. Stevens, M. C. Wyant, J. Adv. Model. Earth Syst., (to be submitted).
[3] A. de Lózar and J. P. Mellado, J. Atmos. Sci., 74, 751-765 (2016).

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.



Weak stratification regimes, $h/L_0 < 1$: shallow boundary layers, or weakly stratified atmospheres.

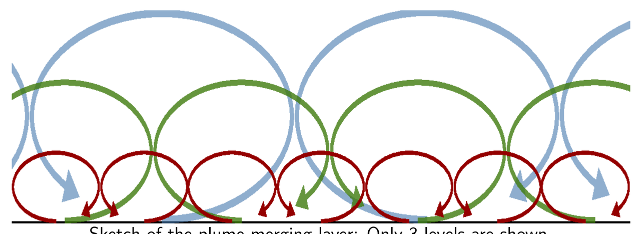


Strong stratification regimes, $h/L_0 > 10$: deep boundary layers, or strongly stratified atmospheres.

Different atmospheric conditions can be mapped into one single independent variable, h/L_0, the ratio of the boundary-layer thickness h to the reference length

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

Typical midday atmospheric values are $L_0 \simeq 20-200$ meters and $h/L_0 \simeq 5-50$. Physically, L_0 characterizes the entrainment-zone thickness.



Sketch of the plume-merging layer: Only 3 levels are shown.

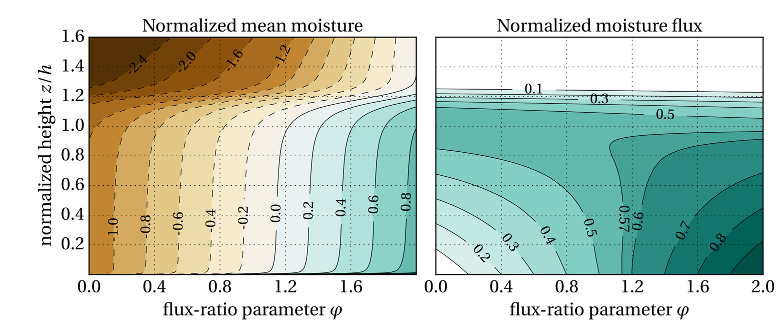
The near-surface region can be explained as a hierarchy of circulations that starts with small scales near the surface and ends with the large scales in the mixed layer: the plume merging layer [4]. The parameter h/L_0 modulates its vertical extent, but not its properties. Some properties follow Monin-Obukhov similarity theory, like the transfer law, but some others systematically deviate from that theory, like the variance.

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

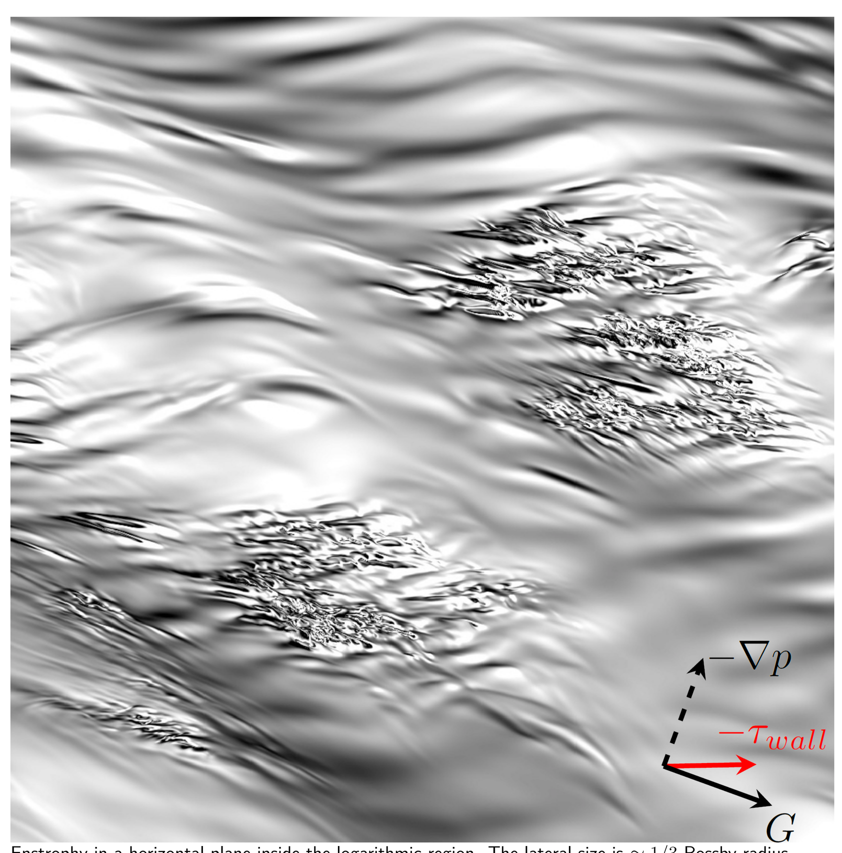
Modeled as an Ekman layer that is forced by a geostrophic wind G and a Coriolis parameter f, and with an imposed buoyancy difference Δb between the non-turbulent region above and the surface.

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.

[4] J. P. Mellado, C. C. van Heerwaarden and J. R. Garcia, Boundary-Layer Meteorol., 159, 69-95 (2016).
[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).

Max-Planck-Institut für Meteorologie

JÜLICH FORSCHUNGSZENTRUM

MAX-PLANCK-GESELLSCHAFT