The Challenge of Small-Scale Turbulence in Planetary Boundary Layers

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Canary Islands (Gran Canaria), from www.wikipedia.org

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The Planetary Boundary Layer

The planetary boundary layer is the lower layer of the atmosphere, the layer that feels directly surface effects on time scales smaller than a day.

Normaly turbulent, because of wind shear or because of convection.

Canary Islands (Gran Canaria), from www.wikipedia.org

Planetary boundary layers are key for climate...

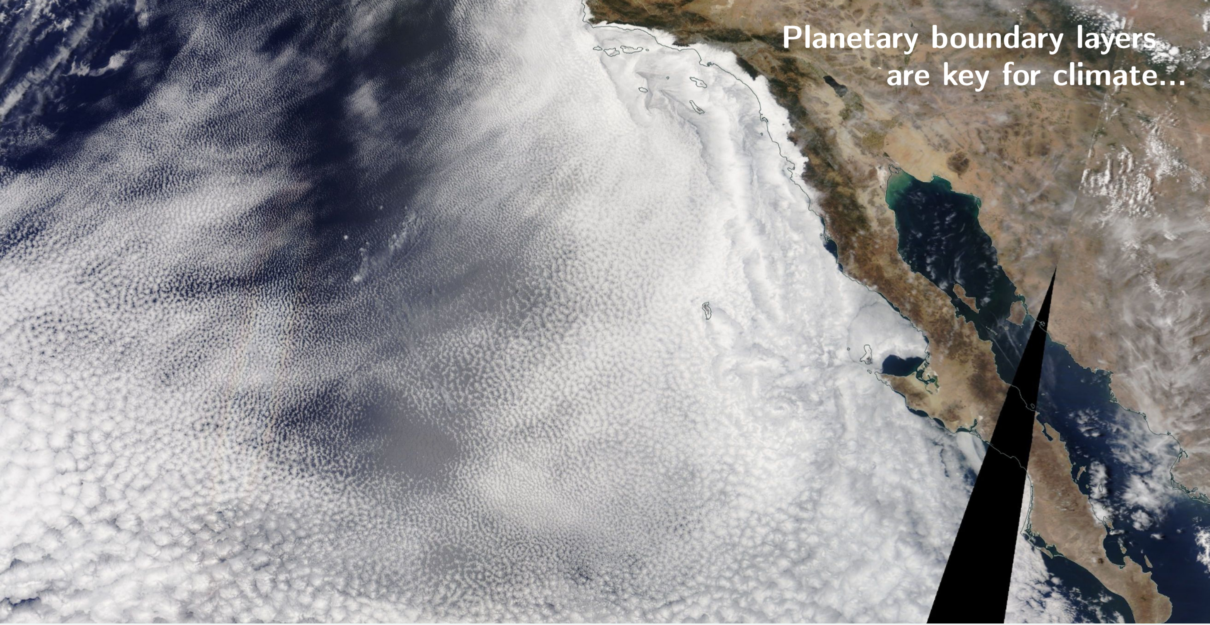


Image from NASA Worldview June 6th, 2017

... planetary boundary layers are crucial in meteorology ...

Photo by Peter Haas (left) and Abengoa Solar (right), from commons.wikimedia.org

...and are also a paradigm of multi-scale, complex fluid-dynamical systems.

Cloud breakup regime near the Canary Islands. Photo courtesy of C. Ansorge

Understanding Meter and Submeter Scales Remains a Challenge

In important cases, small scales affect the dynamics of the whole planetary boundary layer:

1. Near the surface: Effects of density stratification in the shear production of turbulence.
2. Near the PBL top: Effects of density stratification and cloud physics in entrainment.

Understanding this coupling between the small and the large scales remains a challenge that combines fluid mechanics and atmospheric processes. This challenge motivates our work.

Our analysis is based on theory and direct numerical simulations.

Key novelty: Reynolds numbers are becoming large enough to observe Reynolds number similarity. Production runs with grid sizes $2048^2 \times 1024$ to $5120^2 \times 2048$.

$\Rightarrow$ **HPC is providing data accurate enough for quantitative analysis.**

Outline

Turbulence Collapse in the Stable Boundary Layer

Work in collaboration with C. Ansorge

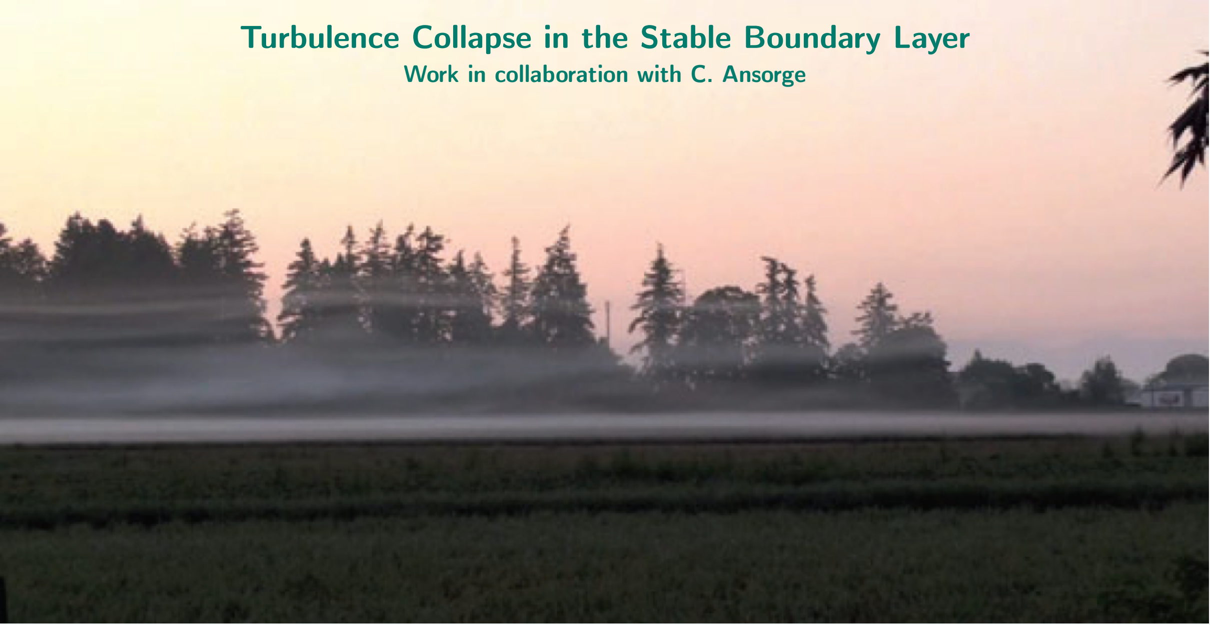
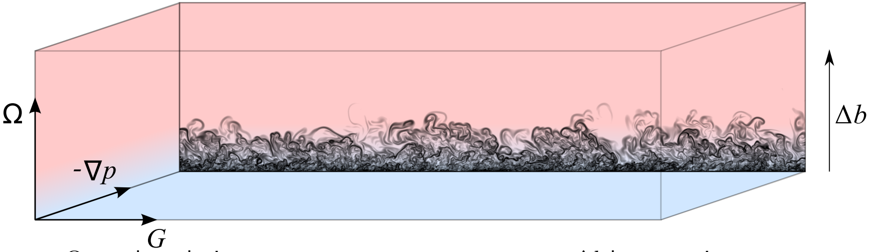


Photo from L. Mahrt (2014)

Physical Model: Stably Stratified Ekman Layer



Ω angular velocity;
G geostrophic wind velocity;
∇p geostrophic pressure gradient.

Δb buoyancy increment.

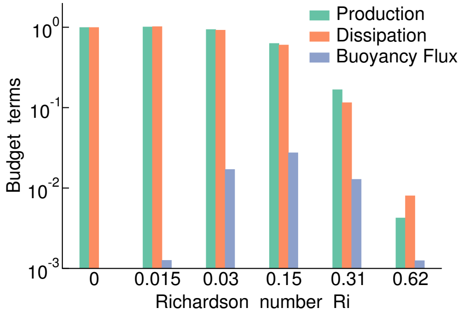
Two control parameters:

$$\text{Richardson number} = \frac{\text{buoyancy forces}}{\text{inertia forces}} \propto \Delta b$$

$$\text{Reynolds number} = \frac{\text{inertia forces}}{\text{viscous forces}} \propto \nu^{-1}$$

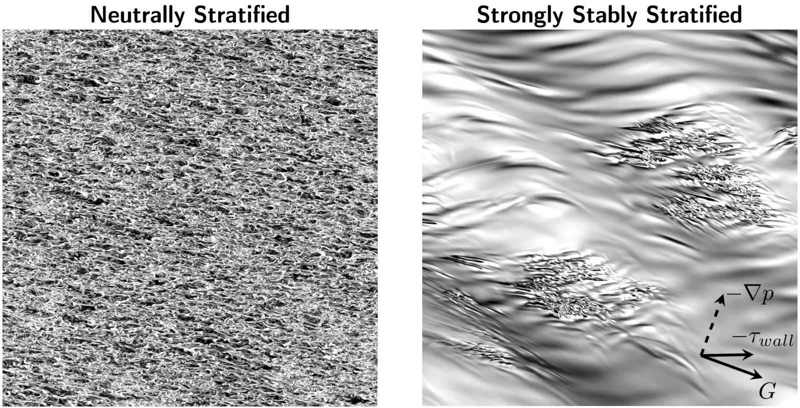
Model Reproduces Regimes Observed in Nature: Weakly, Intermediately, and Strongly Stratified

$$\frac{d}{dt}\int \mathrm{TKE}\,dz = \text{Prod. - Diss. - Buoy.Flux}$$



Strongly stratified regime for Richardson numbers beyond $0.1 - 0.2$.

Spatial Intermittency During Turbulence Collapse Can Occur Without External Perturbations



Near-surface enstrophy. Only $1/3 \times 1/3$ of domain is shown.

...provided that large scales have enough space and time to develop.

Outline

1. Turbulence Collapse in the Stable Boundary Layer
2. **Entrainment Effects on Moisture Statistics**
3. Entrainment Reduction in Stratocumulus by Droplet Sedimentation
4. Direct Numerical Simulation of Stratocumulus-Topped Boundary Layers

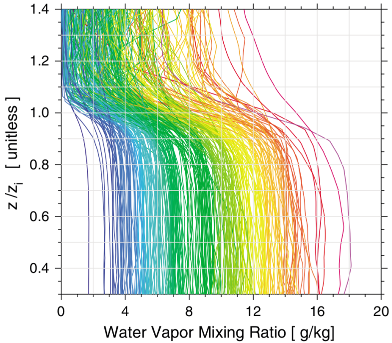
Entrainment Effects on Moisture Statistics

Work in collaboration with M. Puche, A. Haghshenas & C. C. van Heerwaarden

Photo from F. Le Blancq, Cloud Atlas.

Moisture field from DNS of 1000 m deep CBL resolved to 2 m.

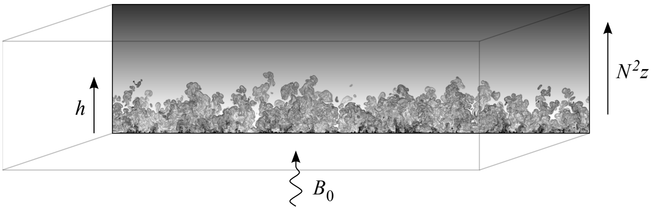
Aim: Generalize Previous Single-Case Studies on Moisture Statistics



Specific questions:

1. Obtain dependence on environmental conditions.
2. Obtain characteristic scales in entrainment zone and surface layer.

Physical Model: Free Convective Boundary Layer



B_0: surface buoyancy flux N^2: outer buoyancy gradient h: CBL depth

System depends only on Reynolds number ($Pr = 1$), and h/L_0, where

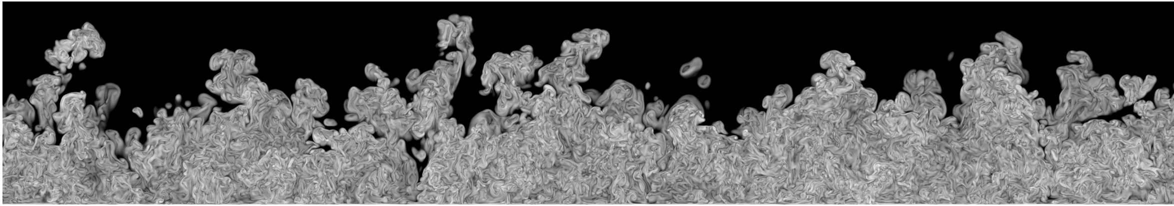
$$L_0 = (B_0/N^3)^{1/2}$$

is an Ozmidov scale. It provides a reference entrainment-zone thickness.

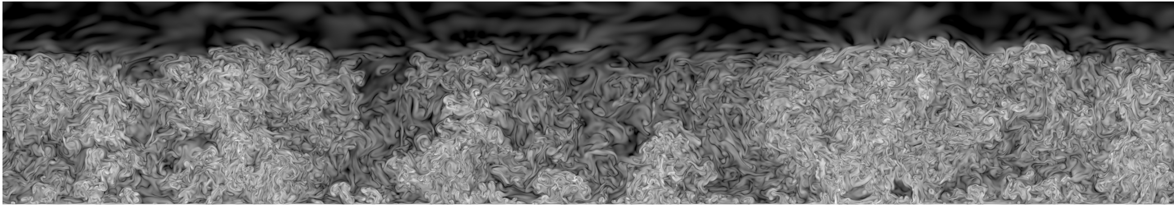
Typical atmospheric midday values: $L_0 \simeq 20 - 200$ m ($h/L_0 \simeq 5 - 50$).

Parameter h/L_0: Weak- and Strong Stratification Regimes

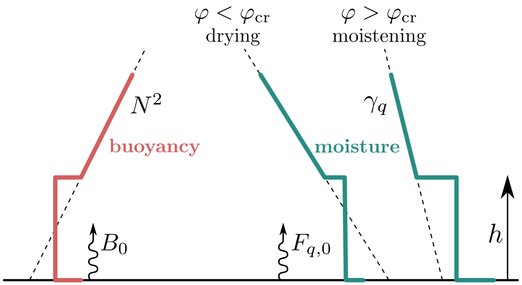
Weak Stratification Regime: low values of h/L_0 (below 1), unsteady.



Strong Stratification Regime: large values of h/L_0 (beyond 10–15), quasi-steady.



Defining an Appropriate Moisture Parameter



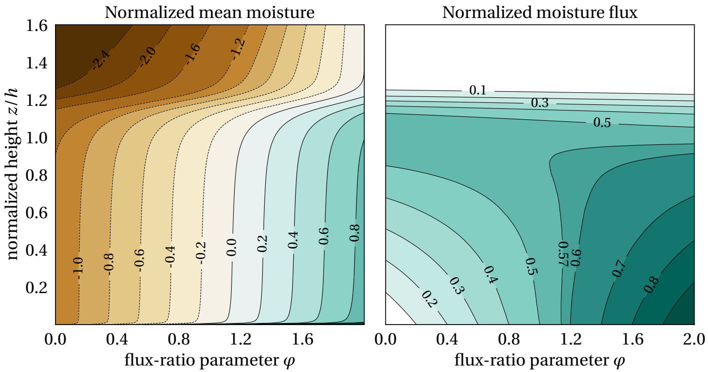
$\{B_0, F_{q,0}\}$	surface buoyancy & moisture fluxes
$\{-N^2, \gamma_q\}$	buoyancy & moisture lapse rates
h	CBL depth
φ	Flux-ratio parameter (surface moistening vs. entrainment drying)

Besides the Reynolds number and h/L_0, moisture introduces only one parameter. We choose:

$$\varphi = 2F_{q,0}/(F_{q,0} + F_{q,1}) \ ,$$

where $F_{q,1} \equiv (\gamma_q L_0)(N L_0)$ is a reference entrainment flux.

Mean Properties: Drying-to-Moistening Transition at $F_{q,0} \approx F_{q,1}$ ($\varphi \simeq 1$).

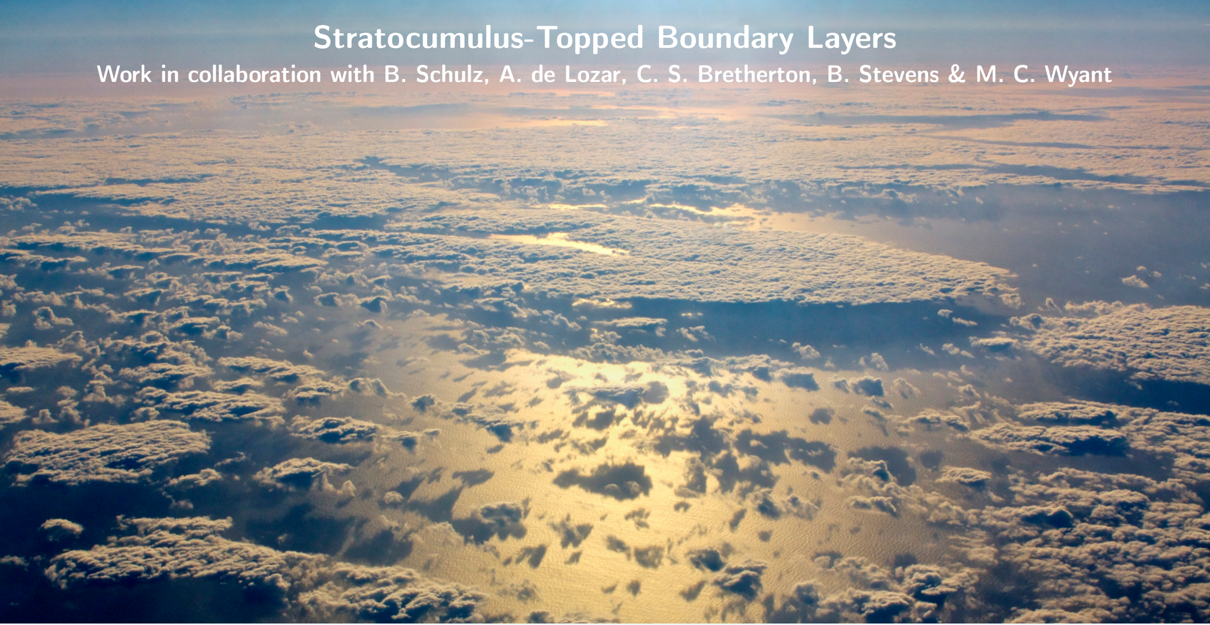


Drying-to-moistening transition occurs when the surface moisture flux $F_{q,0}$ becomes comparable with the reference entrainment flux in drying conditions $F_{q,1} \equiv (\gamma_q L_0)(N L_0)$.

Outline

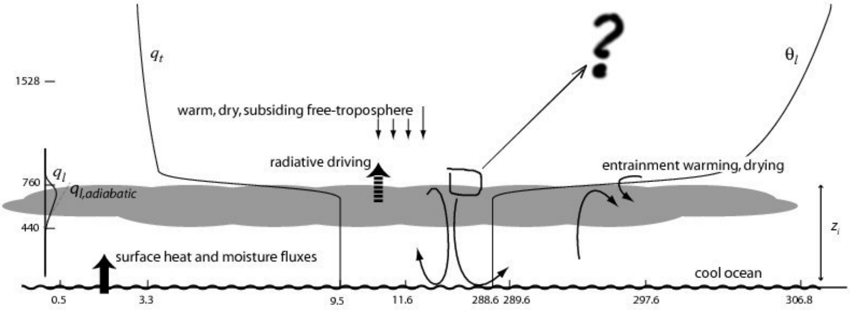
Stratocumulus-Topped Boundary Layers

Work in collaboration with B. Schulz, A. de Lozar, C. S. Bretherton, B. Stevens & M. C. Wyant



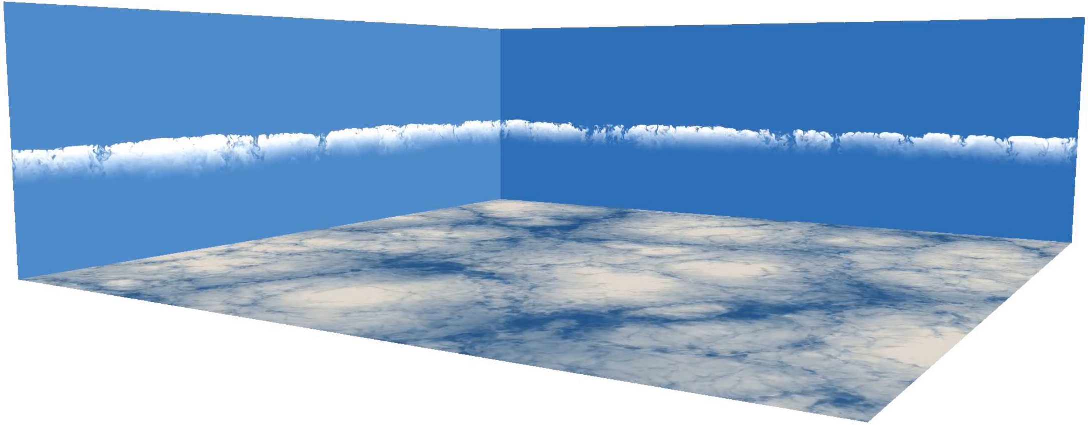
Cloud breakup regime near the Canary Islands. Photo courtesy of C. Ansorge

Small-scale Processes at the Top of Stratocumulus Are Key

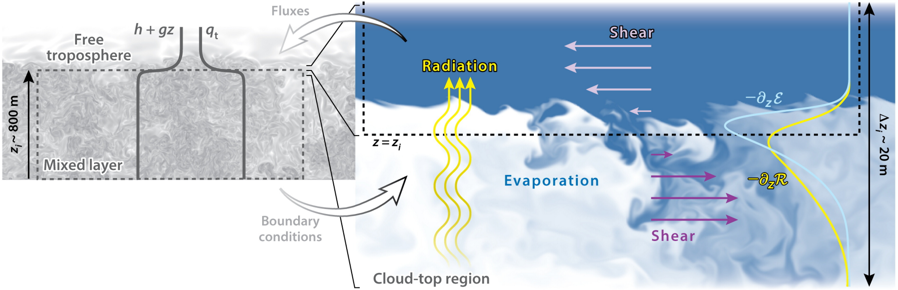


1. Longwave radiative cooling
2. Evaporative cooling
3. Turbulent entrainment across a stably stratified region
4. Droplet sedimentation (cloud microphysics)

1 m resolution DNS of 800 m deep stratocumulus-topped boundary layer



Quantifying Cloud-Top Mixing: The Mean Entrainment Velocity



Mixed-layer analysis needs the mean entrainment velocity

$$w_\mathrm{e} \equiv \frac{\mathrm{d}z_i}{\mathrm{d}t} - \langle w \rangle_{z_i} \ .$$

Cloud-top analysis of meter and submeter-scale phenomena provides it.

Governing Equations in Eulerian Framework

Disperse and dilute multi-phase flow (liquid volume fraction 10^{-6}) with small Stokes numbers ($< 10^{-2}$) and moderate settling numbers (≈ 0.5).

Anelastic approximation to Navier-Stokes equations plus:

$$
\begin{aligned}
\text{enthalpy} \quad & \rho_{\mathrm{ref}} \mathrm{D}_t h = \nabla \cdot [\rho \kappa_h \nabla h - \rho \mathbf{j}_\mu (h_\ell - h)] - \nabla \cdot (\rho \mathbf{j}_\mathrm{r}) \;, \\
\text{total water} \quad & \rho_{\mathrm{ref}} \mathrm{D}_t q_\mathrm{t} = \nabla \cdot [\rho \kappa_\mathrm{v} \nabla q_\mathrm{t} - \rho \mathbf{j}_\mu (1 - q_\mathrm{t})] \;, \\
\text{liquid water} \quad & \rho_{\mathrm{ref}} \mathrm{D}_t q_\ell = \nabla \cdot [\rho \kappa_\mathrm{v} \nabla q_\ell - \rho \mathbf{j}_\mu (1 - q_\ell)] + (\partial_t \rho q_\ell)_{\mathsf{con}} \;.
\end{aligned}
$$

Cloud processes to be modeled:

1. Radiative flux $\rho \mathbf{j}_\mathrm{r}$.
2. Rate of phase change $(\partial_t \rho q_\ell)_{\mathsf{con}}$: Latent heat effects.
3. Transport flux $\rho \mathbf{j}_\mu$: Droplet sedimentation.

Cloud-Top Integral Analysis Provides Expression for w_e

Evolution equation for the buoyancy b (normalized density anomaly) can be derived from the linearized equations of state:

$$D_t b = \nabla\cdot[\kappa_h \nabla b - \mathbf{j}_\mu (b_\ell - b)] - \beta_h \nabla\cdot\mathbf{j}_\mathrm{r} + \beta_{q_\ell} (\partial_t q_\ell)_{\mathsf{con}} \ .$$

(β_i are thermodynamic partial derivatives.)

Integral analysis from inversion height z_i upwards yields analytical expressions to calculate w_e:

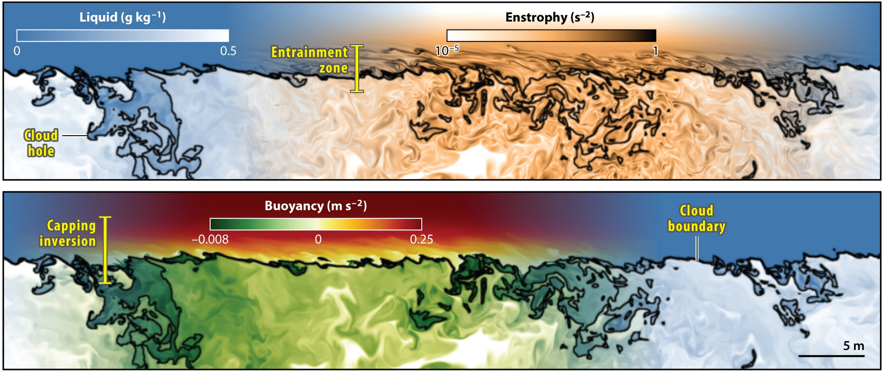
$$w_\mathrm{e}(\Delta b)_{z_i} \simeq -\langle w'b'\rangle_{z_i} + \beta_h(\Delta j_\mathrm{r})_{z_i} - \beta_{q_\ell}\int_{z_i}^{z_\infty} (\partial_t q_\ell)_{\mathsf{con}}\,\mathrm{d}z - g\langle|j_\mu|\rangle_{z_i}$$

$$\Rightarrow \quad w_\mathrm{e} = (w_\mathrm{e})_\mathrm{mix} + (w_\mathrm{e})_\mathrm{rad} + (w_\mathrm{e})_\mathrm{eva} + (w_\mathrm{e})_\mathrm{sed}$$

(g is the magnitude of the gravity acceleration.)

Resolving Meter and Submeter Scales at the Cloud Top

Cloud Boundary + Turbulence Interface + Capping Inversion



Example of the need for this resolution: Reduction of w_e by droplet sedimentation.

Model for Gravitational Settling of Droplets: Assumed Droplet-Size Distribution

Since the transport flux is

$$\rho \mathbf{j}_\mu = \rho q_\ell [\overline{d^5}/(\overline{d^3} d_0^2)] \mathbf{u}_{s,0} = \rho_0 q_{\ell,0} (n/n_0)(\overline{d^5}/d_0^5) \mathbf{u}_{s,0} \ ,$$

we need a model for the 5.-order moment of the droplet-size distribution, and then either the 3.-order moment or the cloud-droplet number density.

Following previous work, we assume a log-normal distribution with a constant number density, which leads to

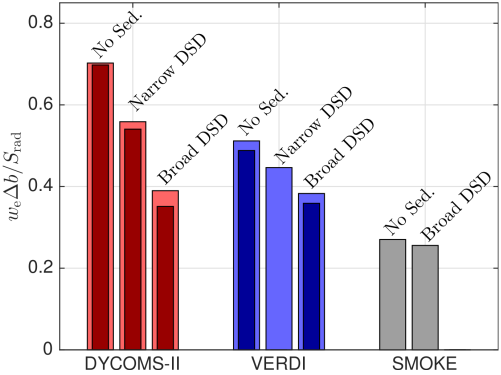
$$\overline{d^5}/(\overline{d^3} d_0^2) = \exp[5\sigma^2](q_\ell / q_{\ell,0})^{2/3} \ .$$

We consider a narrow distribution ($\sigma_g \simeq 1.0$) and a broad one ($\sigma_g \simeq 1.5$), where $\sigma_c = \exp(\sigma)$.

What is the effect of small-scale turbulence?

Ackerman et al. (2004), Bretherton et al., (2007)

Droplet Sedimentation Can Reduce Entrainment Significantly



1. It depends on the meteorological conditions.
2. It depends on droplet-size distribution.
3. **Almost 50% reduction of w_e, 2–3 times larger than previously reported.**

Two Contributions from Droplet Sedimentation to Entrainment Velocity

Integral analysis yields analytical expressions to calculate w_e:

$$w_\mathrm{e} = (w_\mathrm{e})_\mathrm{mix} + (w_\mathrm{e})_\mathrm{rad} + (w_\mathrm{e})_\mathrm{eva} + (w_\mathrm{e})_\mathrm{sed} \ .$$

Two contributions:

1. Direct contribution: Increase of mean buoyancy for $z > z_i$ by removal of droplets translates into a negative $(w_\mathrm{e})_\mathrm{sed}$

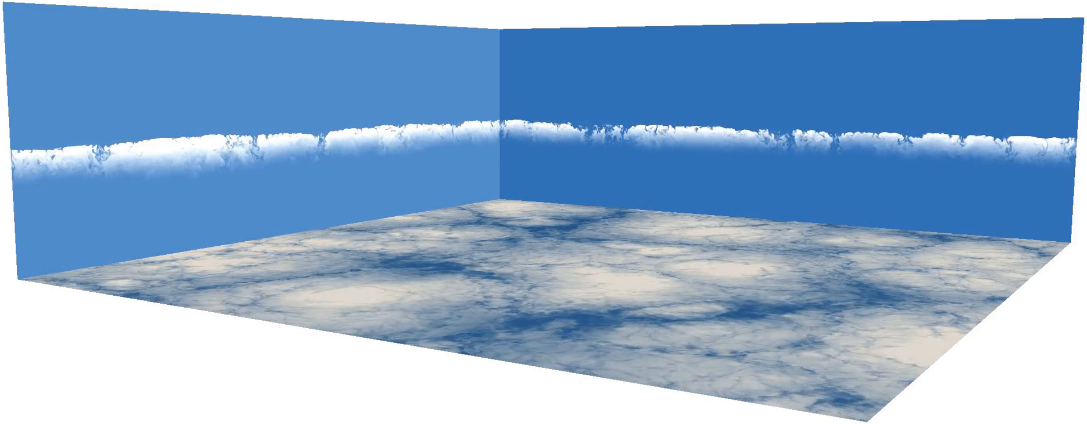
   $$(w_\mathrm{e})_\mathrm{sed} = -g\langle|j_\mu|\rangle/(\Delta b)_{z_i} \propto q_\ell \overline{d^5}/\overline{d^3} \propto n\overline{d^5}$$

   Responsible for almost 30% of the reduction.

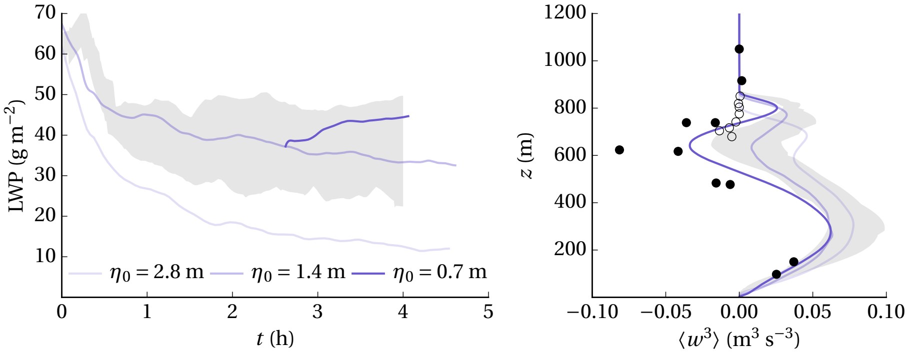
2. Indirect contribution: Changes in $(w_\mathrm{e})_\mathrm{mix} + (w_\mathrm{e})_\mathrm{rad} + (w_\mathrm{e})_\mathrm{eva}$. In particular, reduction of cloud-top cooling because of removal of droplets.

Outline

1 m resolution DNS of 800 m deep stratocumulus-topped boundary layer

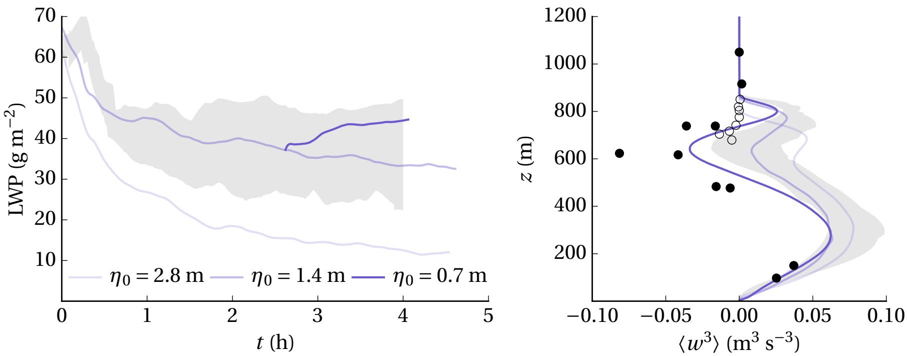


Approaching Reynolds Number Similarity



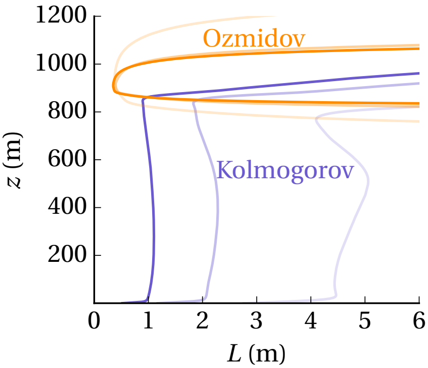
1. A Kolmogorov scale of $\simeq 1.4$ m reproduces the central distribution of LES models.
2. A Kolmogorov scale of $\simeq 0.7$ m reproduces more that 70% of measured LWP, about 90% of skewness of vertical velocity.

Approaching Reynolds Number Similarity



1. A Kolmogorov scale of $\simeq 1.4$ m reproduces the central distribution of LES models.
2. A Kolmogorov scale of $\simeq 0.7$ m reproduces more that 70% of measured LWP, about 90% of skewness of vertical velocity. **Why?**

Resolving the Ozmidov Scale in the Cloud-Top Region



Re_0	η_0	$(L_{Oz}/\eta)_{ct}$
2000	2.8 m	1.5
5000	1.4 m	2.7
12500	0.7 m	3.7

We start to represent motions smaller than the Ozmidov scale, which is the lower bound of length scales strongly influenced by stable stratification.

Summary & Conclusions

Meter and submeter scales can be key for the dynamics of planetary boundary layers

Near the surface:

Turbulence collapse in stable boundary layers can occur intermittently in space without external perturbations.

Near the boundary-layer top:

Droplet sedimentation can reduce substantially cloud-top mixing: better characterization of droplet-size distribution needed.

Laboratory experiments, field measurements, and numerical simulations are reaching the accuracy necessary to solve long-standing problems