On the Relevance of Droplet Sedimentation in Stratocumulus-Top Mixing

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Stratocumulus, Cloud Albedo and Earth's Energy Budget

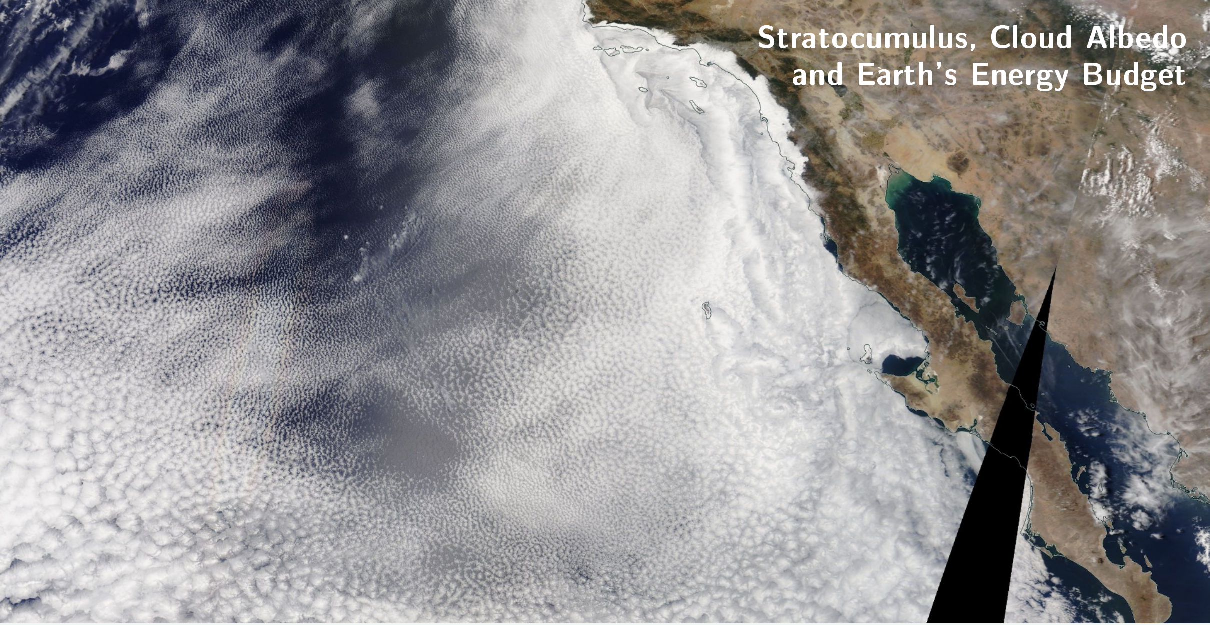
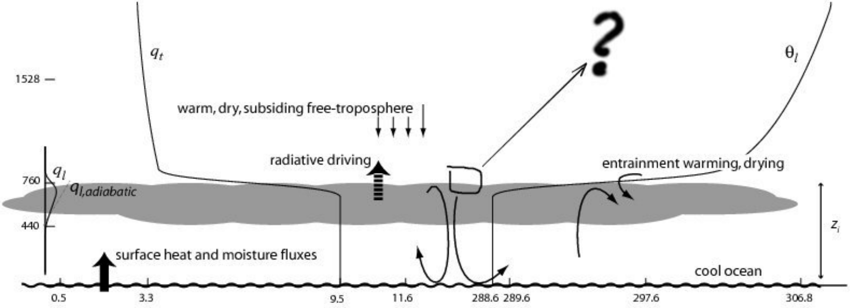


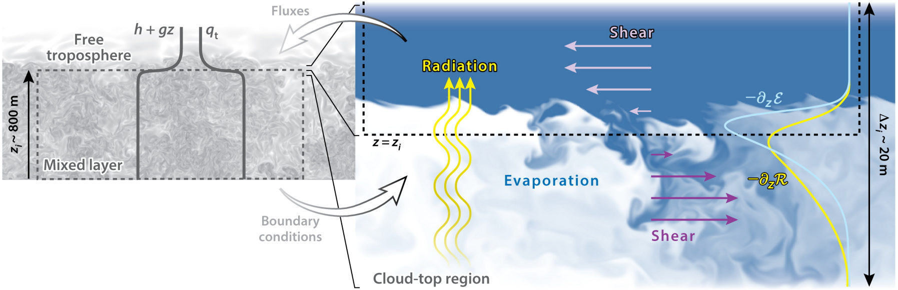
Image from NASA Worldview June 6th, 2017 | *Randall et al. (1984), Bony & Dufresne (2005)*

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)

Hierarchical Approach: Mixed layer $\leftrightarrow$ Cloud top



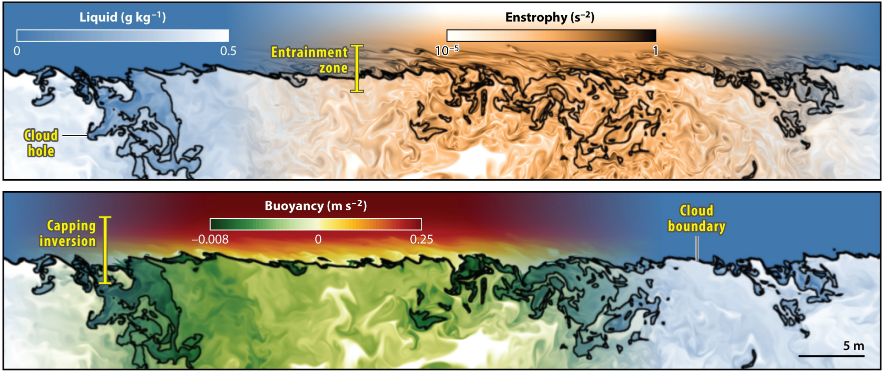
Mixed-layer analysis needs the mean entrainment velocity

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

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

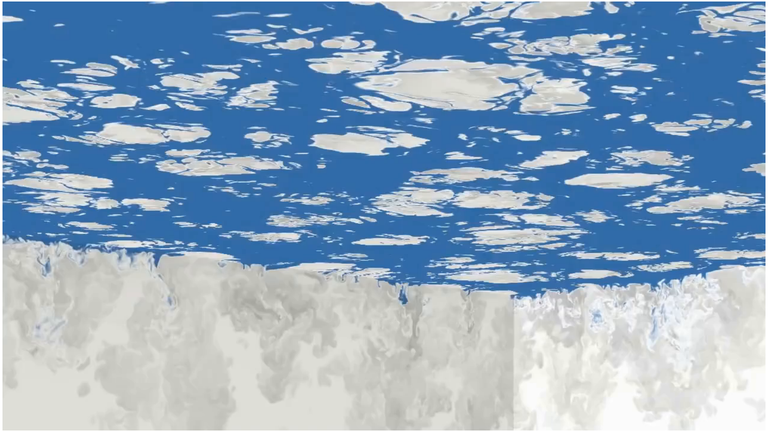
We Can Resolve Submeter Scales of Cloud-Top Structure As Observed in Measurements

Cloud Boundary + Turbulence Interface + Capping Inversion



Nicholls (1989), Gerber et al. (2005), Malinowski et al. (2013)

And We Can Partly Reproduce Large-Scale Properties



DNS of 150 m cloud top driven by radiative and evaporative cooling (DYCOMS-II RF01) resolved to 10 cm.

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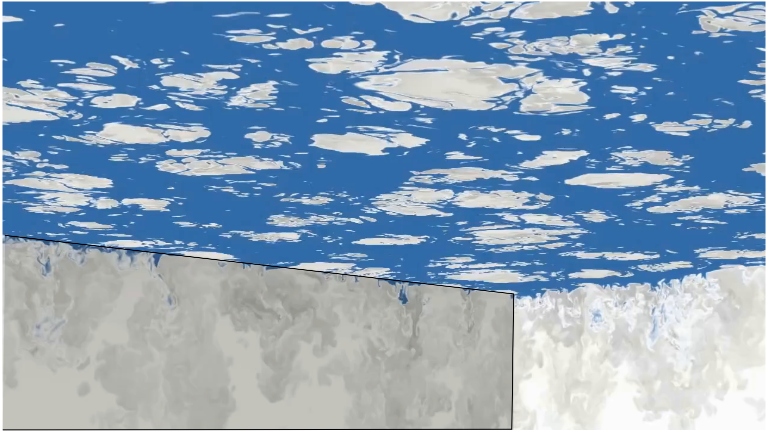

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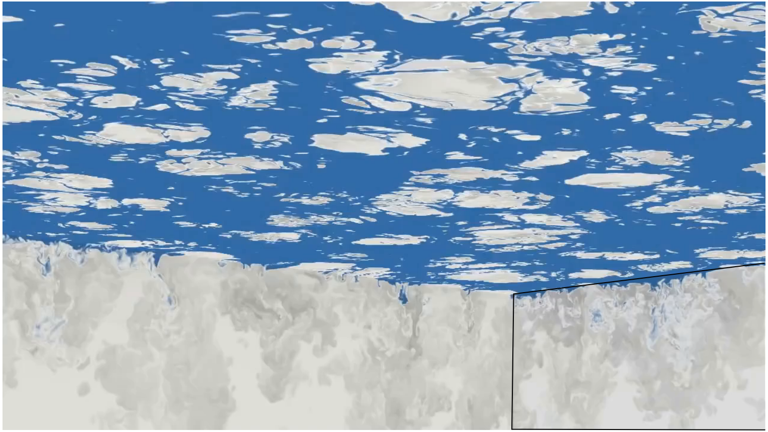

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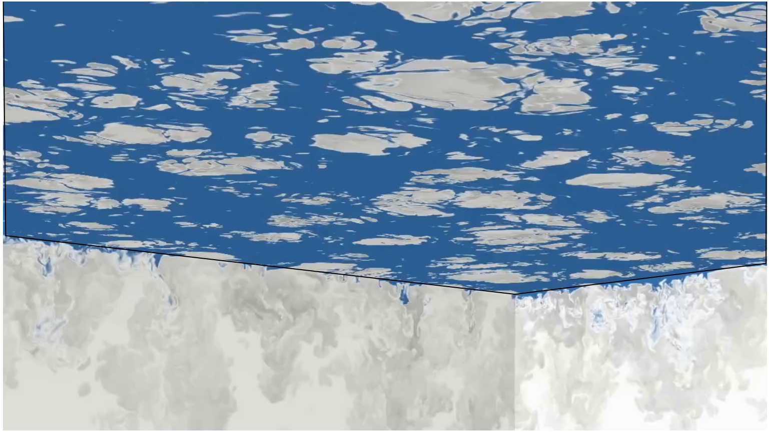

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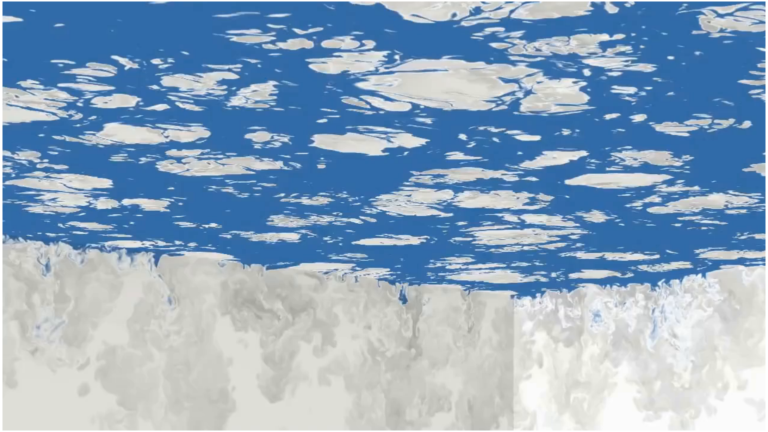

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Governing Equations in Eulerian Framework

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:

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

(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.)

Model for Gravitational Settling: 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.

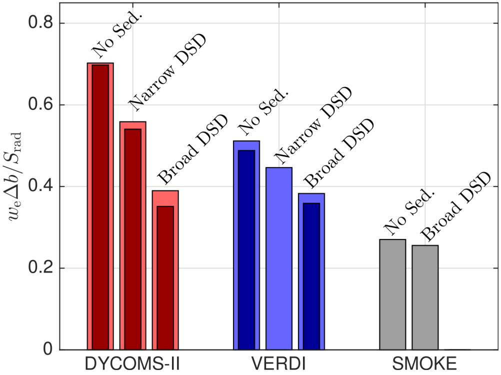
Following previous work, we assume a log-normal distribution with a constant number density, which leads to

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

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

What is the effect of small-scale turbulence?

Sedimentation Can Reduce Entrainment Significantly



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

Two Contributions from Settling 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.

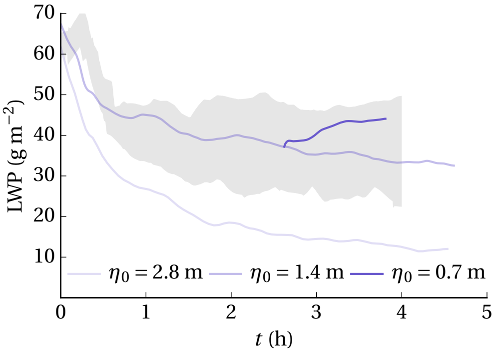
2. Indirect contribution: Changes in $(w_\mathrm{e})_\mathrm{mix} + (w_\mathrm{e})_\mathrm{rad} + (w_\mathrm{e})_\mathrm{eva}$. In particular, reduction of cloud-top cooling because of removal of droplets.

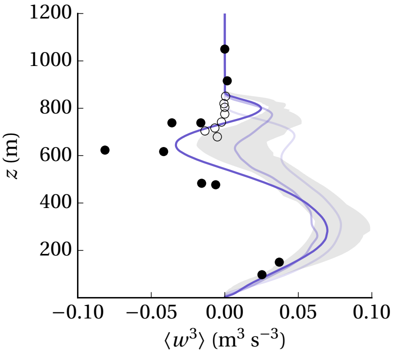
$\Rightarrow$ **Better characterization of droplet-size distribution needed.**

What is the skill of DNS to study the whole stratocumulus-topped boundary layer?

Work with C. S. Bretherton and B. Stevens.

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.

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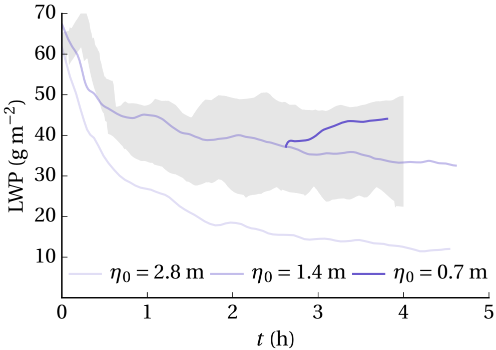
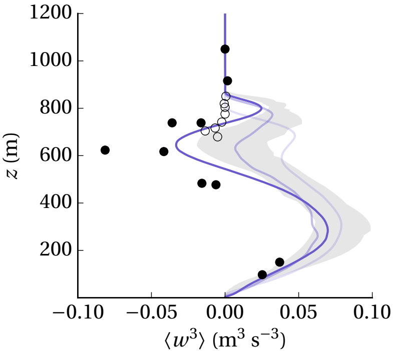
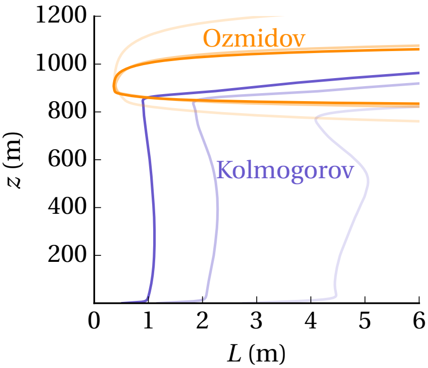




1. A Kolmogorov scale of $\simeq 1.4$ m reproduces the central distribution of LES models.
2. A Kolmogorov scale of $\simeq 0.7$ m reproduces more that 70% of measured LWP, about 90% of skewness of vertical velocity. **Why?**

Resolving the Ozmidov Scale in the Cloud-Top Region



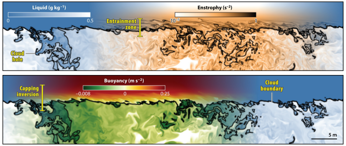
Re_0	η_0	$(L_{Oz}/\eta)_{ct}$
2000	2.8 m	1.5
5000	1.4 m	2.7
12500	0.7 m	3.7

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

Need to advance understanding of droplet-size distribution and microphysics effects in cloud boundaries near entrainment zones

Relevance of droplet sedimentation for cloud lifetime because of mixing effects (not only precipitation effects).



We can now complement laboratory experiments and field measurements with DNS.