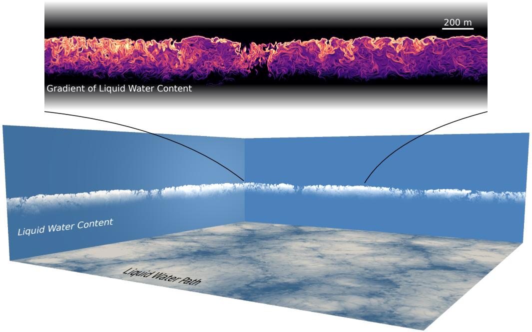
DNS and LES for Simulating Stratocumulus: Better Together

Juan Pedro Mellado, Chris Bretherton, Bjorn Stevens, Matt Wyant



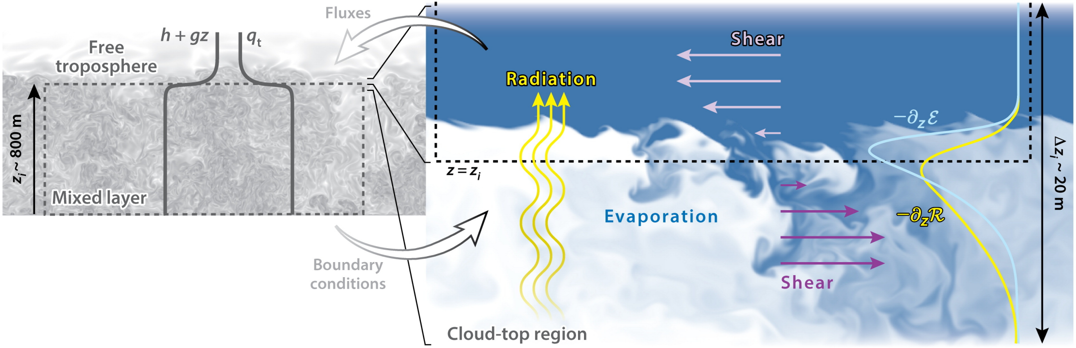
Max-Planck-Institut für Meteorologie
JÜLICH FORSCHUNGSZENTRUM
UNIVERSITY of WASHINGTON
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Workshop on Eulerian vs. Lagrangian Methods for Cloud Microphysics, Jagiellonian University Cracow | April 15-17, 2019

Importance and Challenges of Stratocumulus

- Stratocumulus are important for Earth's radiative energy balance: A small percent increase in area coverage could offset a 2 K warming (Randall, 1980).
- However, characterizing their sensitivity to environmental conditions remains a challenge (Lilly, 1968; Wood, 2012).
- When appropriately tuned, LES shows skill in process studies and climate change sensitivity studies, but quantitative prediction remains difficult (Stevens et al., 2005).
- This difficulty is mainly attributed to an inadequate representation of cloud-top entrainment.
- In stratocumulus, entrainment is not only driven by the large turbulent motions but also by radiative and evaporative cooling in a thin layer of a few meters.

Meter-Scale Processes at the Top of Stratocumulus Are Key



from Mellado (2017)

DNS and LES: Two Sides of the Same Coin

PBL depths of 1 km and velocity fluctuations of 1 m s^{-1} yield a length scale ratio of large turbulent motions to small dissipative ones of $O(10^6)$ (Reynolds number $O(10^8)$).

In LES, the Navier-Stokes equations are low-pass filtered and a subgrid-scale model is introduced, on the basis that large turbulent motions account for most of the vertical fluxes and are less universal, whereas the effect of the small turbulent motions is easier to model.

In DNS, we solve the Navier-Stokes equations with a larger viscosity, on the basis that those equations are an exceptionally good model and we understand their terms relatively well.

In practice, both DNS and LES are restricted to low-to-moderate Reynolds numbers, or low to moderate scale separation.

Both DNS and LES rely on Reynolds number similarity, the experimental observation that relevant properties of turbulent flows become practically independent of the Reynolds number when this parameter surpasses some critical value $O(10^4)$.

Cloud-Top Entrainment: A Challenge for DNS and LES

Problems appear when the grid spacing is not inside the inertial range of the turbulence cascade, as occurs in the inversion atop stratocumulus clouds.

Parcel arguments imply that large-eddy updrafts can penetrate a distance commensurate with

$$\delta_{EZ} = w_{\mathsf{rms}}^2/\Delta b$$

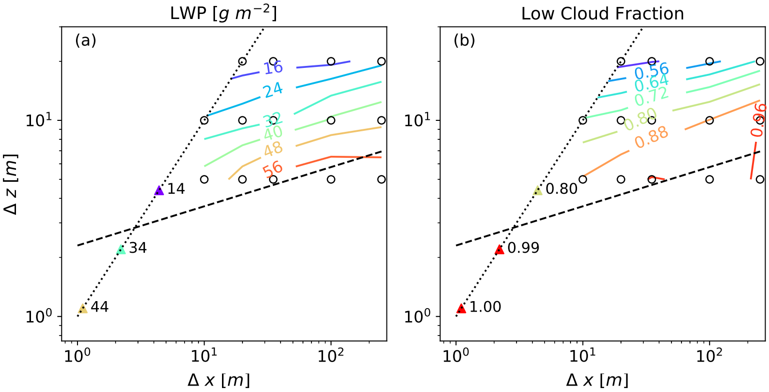
above the mean inversion height. It is commonly assumed that it is necessary to resolve this penetration distance to simulate a reasonable entrainment rate.

For $\Delta b \simeq 0.2$ m s^{-2} (7 K temperature jump), one finds $\delta_{EZ} \simeq 5$ m.

Indeed, LES with 5 m vertical grid spacing show skill in simulating stratocumulus, but when tuned by choosing an appropriate grid aspect ratio in the cloud top region.

Dependence of LES on Grid Spacing Used to Match the LWP

Case RF01 of DYCOMS-II field campaign:



Circles indicate LES (SAM). Triangles indicate DNS. Dashed lines indicate tuned aspect ratio.

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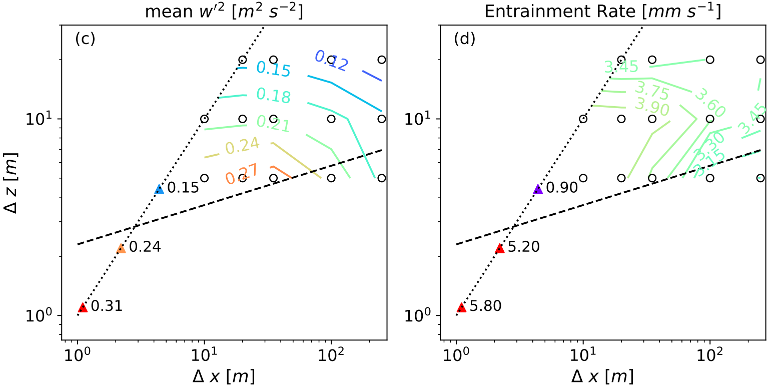

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We Need to Represent the Ozmidov Scale, Not Only the Penetration Depth

We must go to a scale much finer than δ_{EZ} before reaching the inertial range of the turbulence cascade. This scale is the Ozmidov scale (Dougherty, 1961; Ozmidov, 1965)

$$\delta_{Oz} \equiv (\varepsilon/N^3)^{1/2} \, .$$

For the typical conditions considered before, one obtains $\delta_{Oz} \simeq 0.5$ m, about 10 times smaller than $\delta_{EZ} \simeq 5$ m.

This estimate is supported by observational studies (Katzwinkel et al., 2012; Jen-La Plante et al., 2016) and DNS studies (Mellado et al., 2014), which report an interval $\delta_{Oz} \simeq 0.3$-4 m, depending on the environmental conditions.

Submeter scales seem necessary for grid spacing convergence.

Using DNS to Study Stratocumulus

Besides its dependence on the grid spacing (or effective Reynolds number), LES results also depend on the subgrid-scale model and on the numerical scheme, which makes interpretation of results and intra-model comparisons difficult.

We are trying to use DNS instead.

DNS also depends on the effective Reynolds number, but it removes the variability introduced by the subgrid-scale model and on the numerical scheme in LES.

Reducing biases associated with mixing allow to isolate biases associated with other phenomena such as microphysics.

Governing Equations for DNS 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.

Drew (1980), Mellado et al. (2010), de Lozar & Mellado (2013)

DNS Removes Turbulence Model, But Microphysics Model Remain

For instance, let us consider droplet sedimentation. Since the sedimentation transport flux is

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

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.

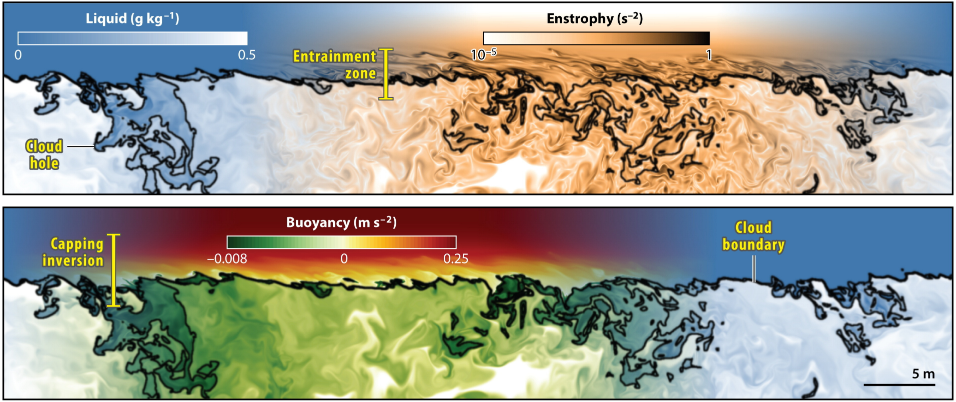
Following previous work (Ackerman et al., 2004; Bretherton et al., 2007), we assume a log-normal distribution with a constant number density, which leads to

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

and we ask the following question:

Do results change when the grid spacing is below the Ozmidov scale?

Local Domain Around the Cloud Top to Reach 20 cm Grid Spacing

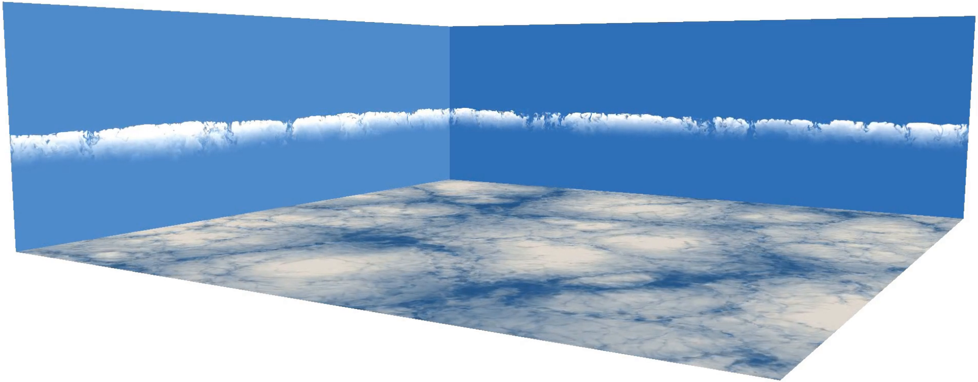


→ see Bernhard's talk.

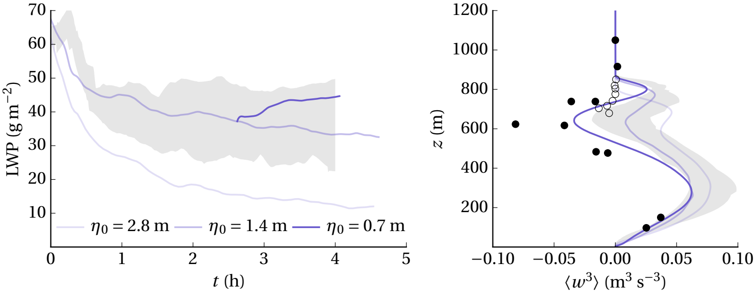
But what is the skill of DNS when simulating the whole stratocumulus-topped boundary layer, and not only a domain of a few hundred meters at the cloud top?

First Direct Numerical Simulation of a Stratocumulus-Topped Boundary Layer

Liquid Field from DNS at Reynolds number 10^4 (800 m deep boundary layer resolved to 1 m)

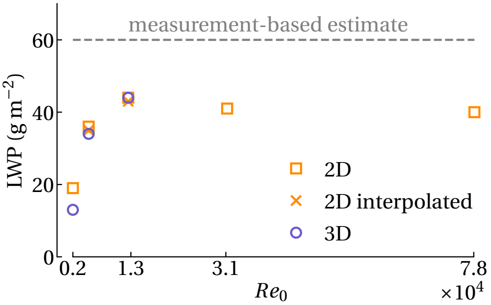


DNS Reproduce Measurements Without Tuning



A Kolmogorov scale of about 1 m reproduces the central distribution of LES models (Stevens et al., 2005), reproduces more that 70% of measured LWP, about 90% of skewness of vertical velocity.

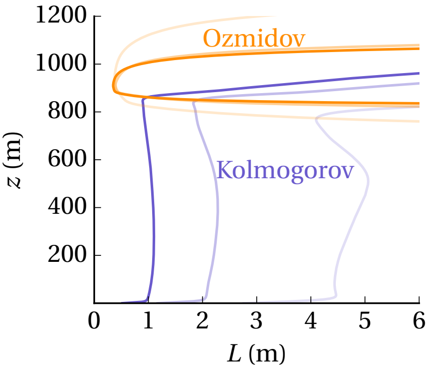
Approaching Reynolds Number Similarity



Independence of Reynolds number (grid spacing) is just around the corner.

We can distinguish between biases due to mixing and biases due to misrepresentation of other processes.

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

Combining DNS with LES and field studies could accelerate current lines of stratocumulus research. LES allows faster and more holistic studies, which can identify sensitive processes such as cloud-top entrainment. DNS can be more suited to study those processes.

We have shown that DNS starts to show Reynolds number similarity, and one way to interpret this result is in terms of the ratio between the Ozmidov and Kolmogorov scale.

DNS reduces uncertainty regarding mixing to one parameter, the Reynolds number.

DNS can test whether LES can correctly capture the sensitivity of large-scale properties to changes in the environmental conditions despite not resolving the underlying processes.

How to best represent the microphysics in such a DNS framework?