Turbulence in Marine Cumulus and Stratocumulus Clouds: Observations and Large-Eddy Simulation

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Outline

- Motivation
- RICO: Cumulus (Cu)
- DYCOMS-II flight 1: Stratocumulus (Sc)
  - Temperature forcing due to evaporation/condensation
  - Advection: `mpdata3`/`mpdatm3`
  - ϵ as a funtion of height and LWC (observations and grid-dependency)
- Conclusions

Motivation

- Why are we interested in the dissipation rate of TKE in clouds?

- An important scaling parameter:
  - $l \sim u^3/\epsilon$
  - $\eta = \left(\nu^3/\epsilon\right)^{1/4}$
  - $\lambda = \sqrt{\frac{\nu u^2}{\epsilon}}$
  - etc.

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  - etc.
- Parametrization of cloud processes, for example:
  - Entrainment at the top of Sc: $\epsilon \propto \frac{\sigma_w^3}{l_i}$ (Zeman and Tennekes, 1977)
  - Cumulus entrainment rate: $\lambda_{\mathrm{c}} \simeq f(w, B, \epsilon)$ (Lu et al., 2016)
  - Microphysics, e.g., "eddy hopping" and droplet growth: $E = \left(\frac{L\epsilon}{C_E}\right)^{2/3}$ (Grabowski and Abade, 2017)
  - What is the value of ϵ?

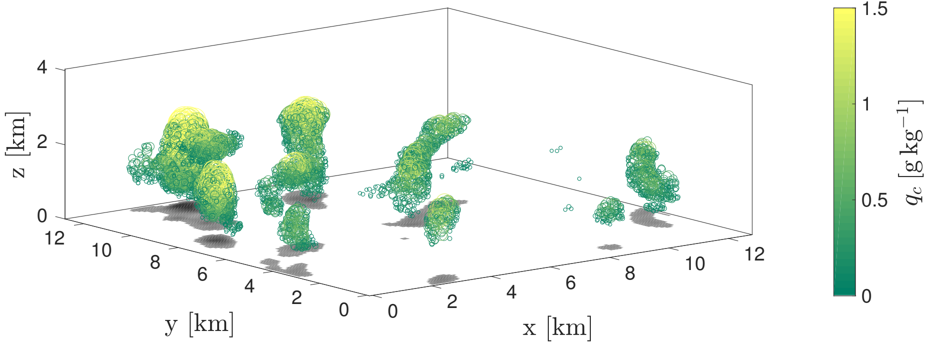
High-resolution observational studies of ϵ in Sc and shallow Cu

Study	Reported values of $\epsilon\,[\mathrm{m^2 s^{-3}}]$	Comments
Siebert et al. (2006), BBC2	10×10^{-3} (2×10^{-3})	Cu, $z = 760 \pm 20$ m, values are based on 1-sec segments in (outside) clouds.
Siebert et al. (2006), INSPECTRO2	5×10^{-3} (8×10^{-3})	Cu, $z = 1540 \pm 40$ m, as above.
Ma et al. 2018, RICO	3.9×10^{-3} (0.4×10^{-3})	Cu, values are based on all flight legs in (outside) clouds.
Siebert et al. (2010), Kiel 07	0.29×10^{-3}	MSc, $\sim$30 m below cloud top.
Katzwinkel et al. (2012), Kiel 07	$\sim 10^{-3}$	MSc, porpoises through cloud top (see their figure 3 for vertical profiles).
Fang et al. (2014)	1.2×10^{-3}	CSc (see their figures 4 and 5 for vertical profiles and diurnal variation of ϵ).
Jen-La Plante et al. (2016), POST	0.81×10^{-3} (0.19×10^{-3})	MSc, values from CTMSL (TISL) averaged over 8 flights.

Ma et al. 2018 (in preparation) analyse measurements from ASTEX, DYCOMS-II, EPIC, RICO, and POST with focus on ϵ.

RICO - marine shallow cumulus

Snapshot from EULAG simulation ($t = 24$ h)



- Standard RICO setup ($100 \times 100 \times 40\,\mathrm{m}^3$, as in van Zanten et al., 2011).
- "TKE" subgrid-scale model and no precipitation.
- Modified temperature forcing (F_θ).

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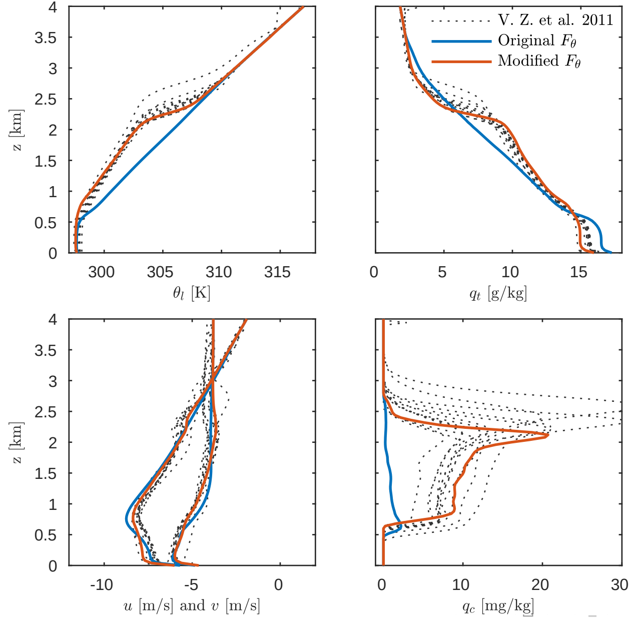

Temperature forcing due to condensation/evaporation

$$\boxed{\theta' = \theta - \theta_e}$$

	Original	Modified
1.	$\theta' = \theta' + \mathtt{F}_{\theta'}\Delta\mathtt{t}$	$\theta' = \theta' + \mathtt{F}_{\theta'}\Delta\mathtt{t}$
2.	$\theta' = \mathtt{mpdata}(\theta')$	$\theta' = \mathtt{mpdata}(\theta')$
3.	$\theta = \mathtt{mpdata}(\theta) + \mathtt{mpdata}(\mathtt{F}_\theta) * \Delta\mathtt{t}$	
4.	$\Delta\mathtt{q_c} = \mathtt{f}(\theta, \ldots)$	$\Delta\mathtt{q_c} = \mathtt{f}(\theta' + \theta_\mathtt{e}, \ldots)$
5.	$\mathtt{F}_\theta = \Delta\mathtt{q_c}\frac{\mathtt{L}\theta_\mathtt{e}}{\mathtt{c_p T_e}} * \frac{1}{\Delta\mathtt{t}}$	$\mathtt{F}_{\theta'} = \Delta\mathtt{q_c}\frac{\mathtt{L}\theta_\mathtt{e}}{\mathtt{c_p T_e}} * \frac{1}{\Delta\mathtt{t}}$
6.	$\theta = \theta + \mathtt{F}_\theta * \Delta\mathtt{t}$	
7.	$\theta' = \theta' + \mathtt{F}_\theta * \Delta\mathtt{t}$	$\theta' = \theta' + \mathtt{F}_{\theta'} * \Delta\mathtt{t}$
8.	$\mathtt{F}_{\theta'} = \mathtt{F}_\theta$	
9.	$\theta = \theta' + \theta_\mathtt{e}$	

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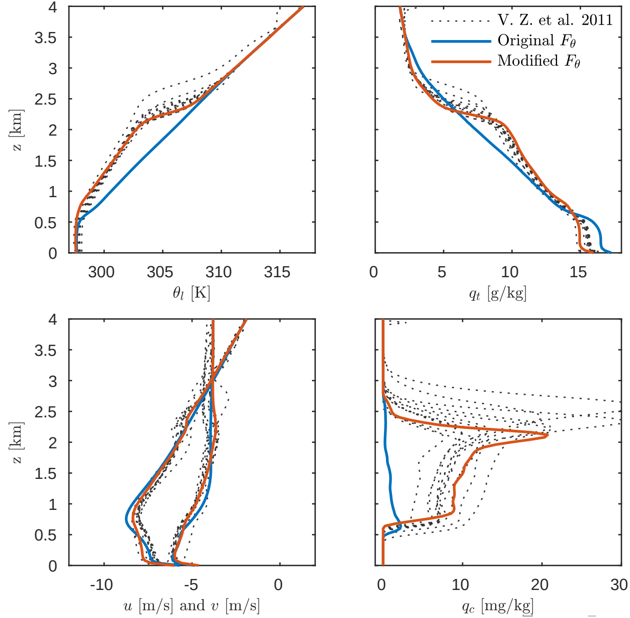

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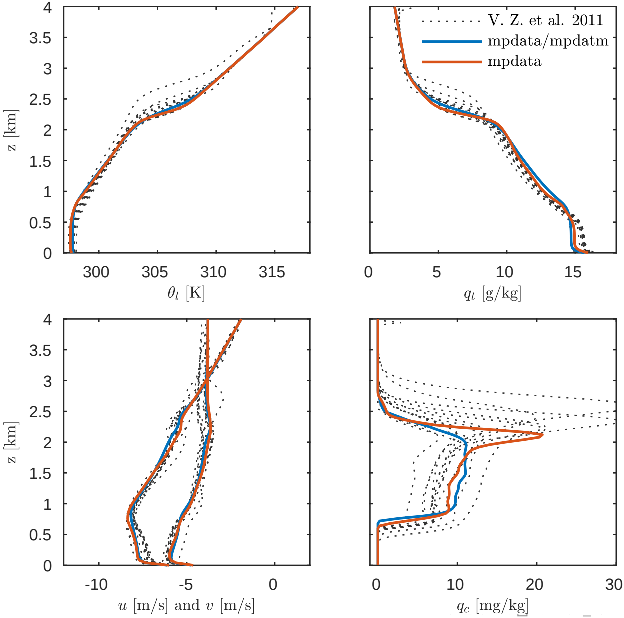
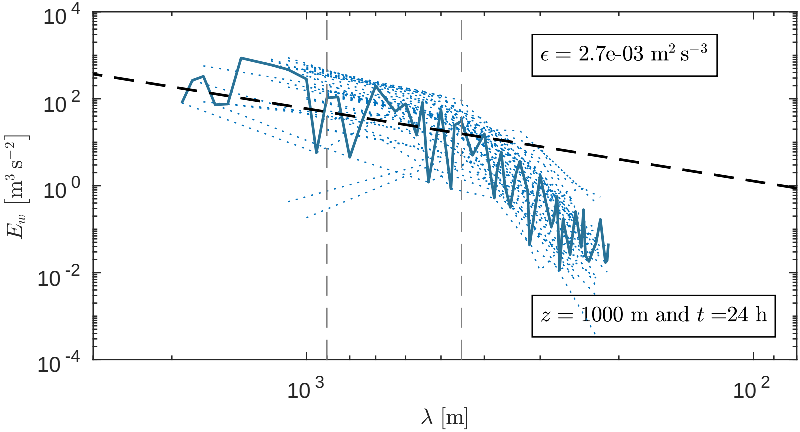


Calculation of dissipation rate ϵ (cloudy segments)

$$E_w(k) = C_1 \epsilon^{2/3} k^{-5/3}$$



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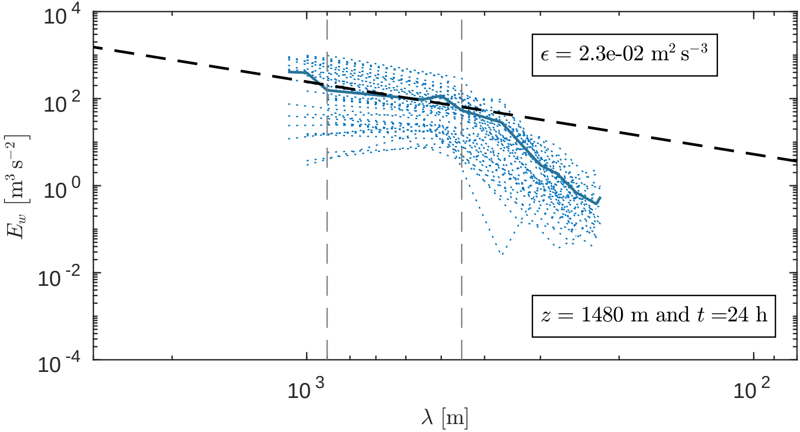

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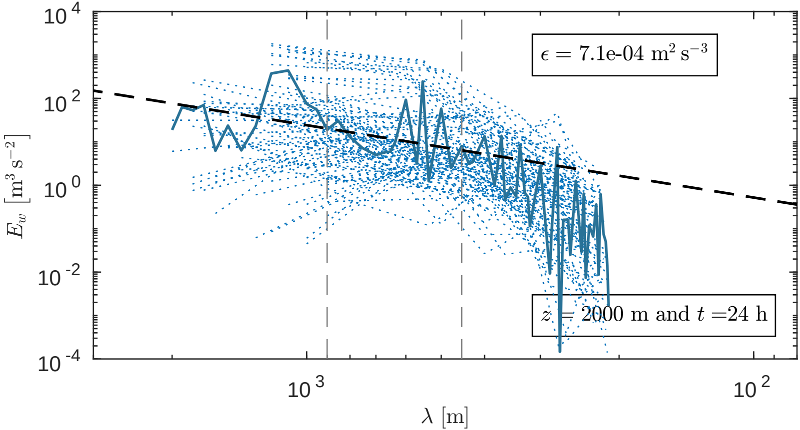
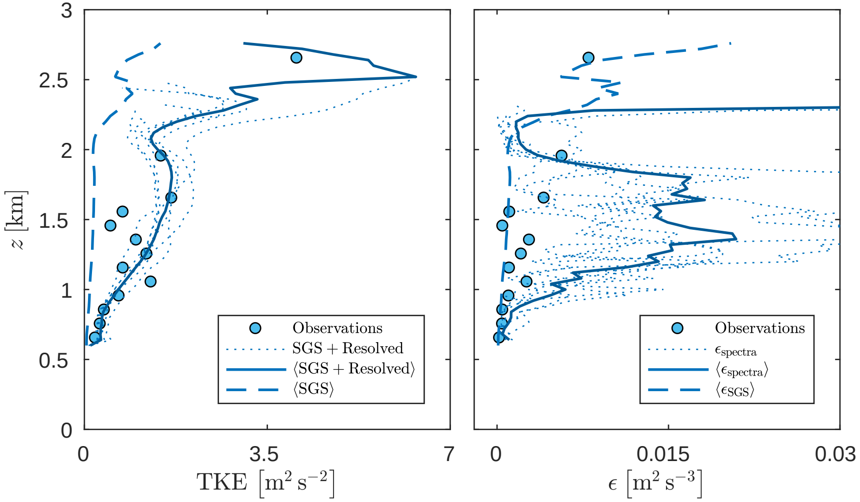


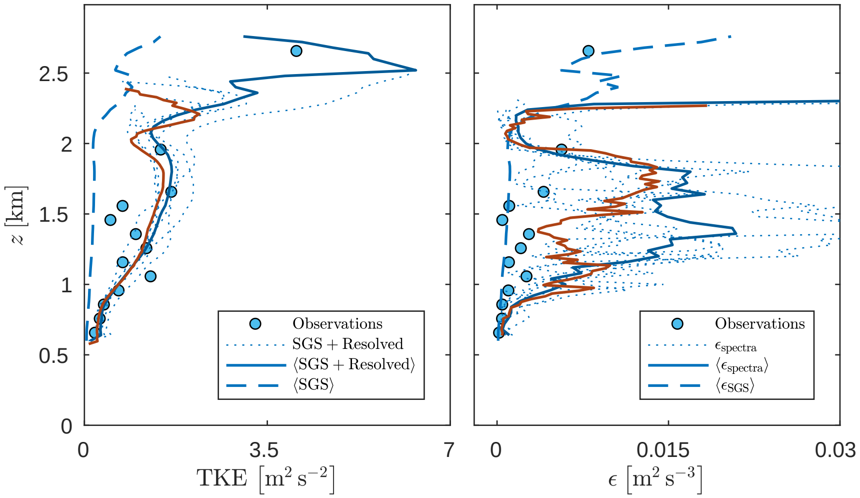
Vertical profiles of TKE and ϵ (cloudy segments)

Observations and LES ($100 \times 100 \times 40\,\mathrm{m}^3$)

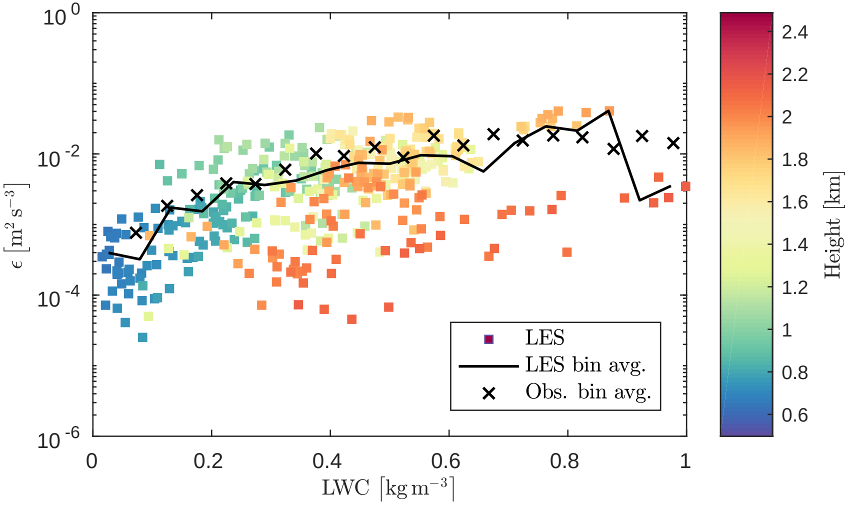


Vertical profiles of TKE and ϵ (cloudy segments)

Observations and LES ($100 \times 100 \times 40\,\mathrm{m}^3$ and $50 \times 50 \times 20\,\mathrm{m}^3$)

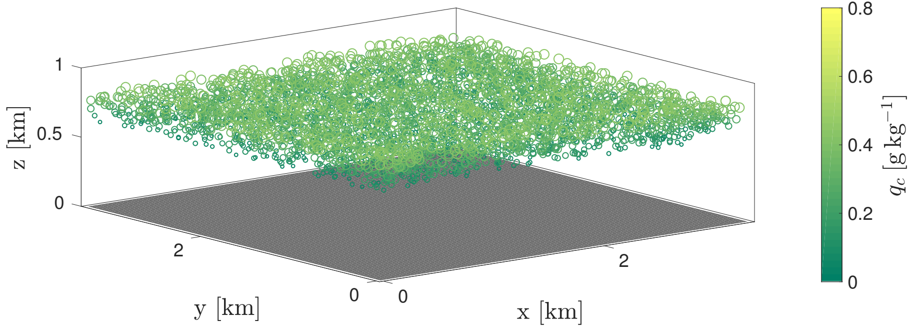


Dissipation rate vs. liquid water content



DYCOMS-II flight 1 - marine stratocumulus

Snapshot from EULAG simulation ($t = 0$ min, cloud cover = 100%)



- Standard setup ($35 \times 35 \times 5\,\mathrm{m}^3$, as in Stevens et al., 2005).
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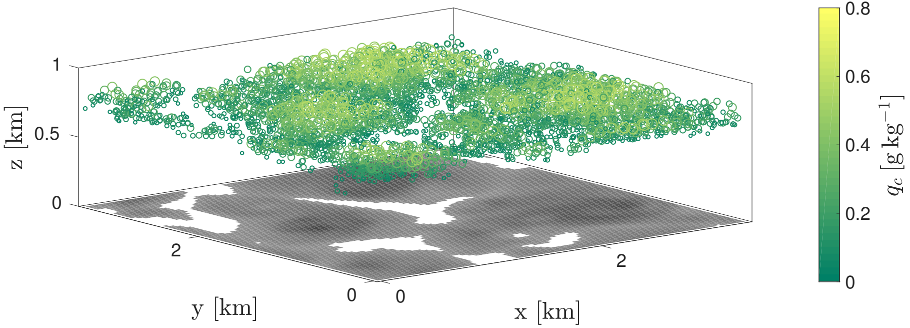
DYCOMS-II flight 1 - marine stratocumulus

Snapshot from EULAG simulation ($t = 60$ min, cloud cover = 96%)



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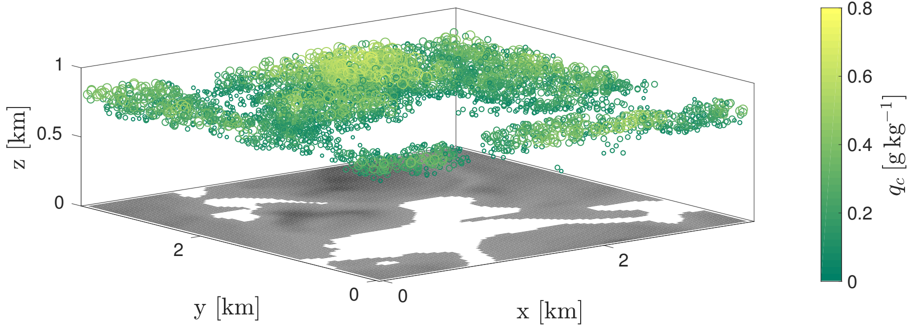
DYCOMS-II flight 1 - marine stratocumulus

Snapshot from EULAG simulation (t = 120 min, cloud cover = 92%)



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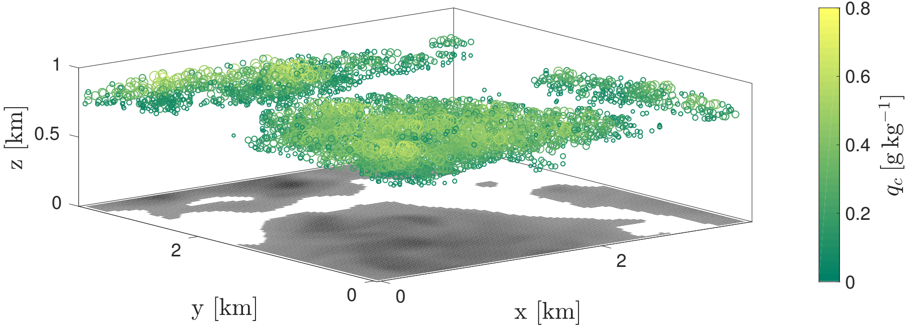
DYCOMS-II flight 1 - marine stratocumulus

Snapshot from EULAG simulation (t = 240 min, cloud cover = 83%)



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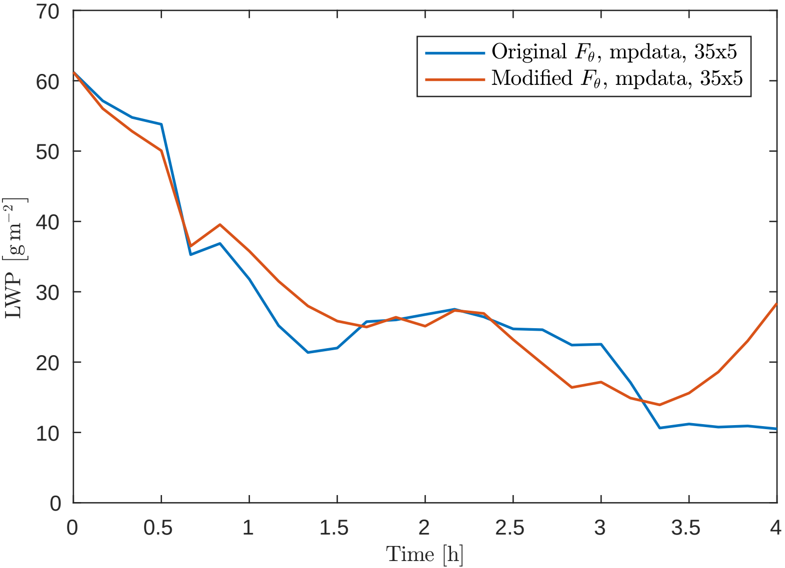
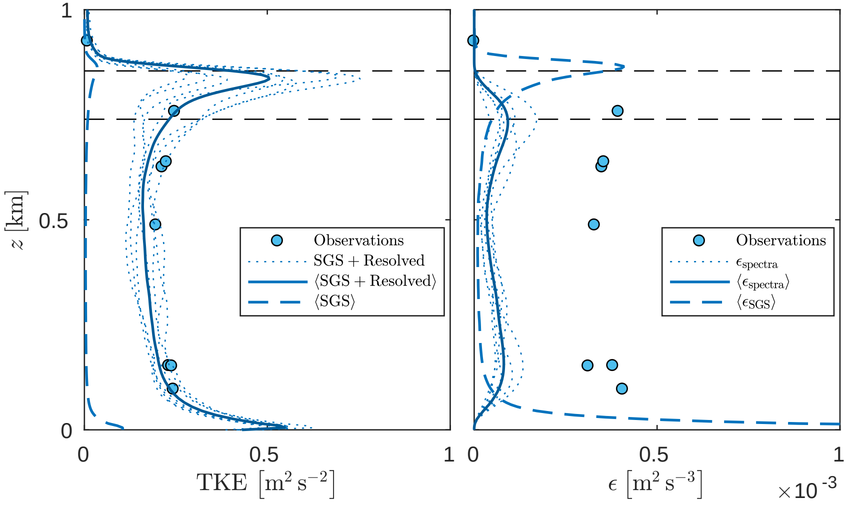
DYCOMS-II flight 1 - marine stratocumulus

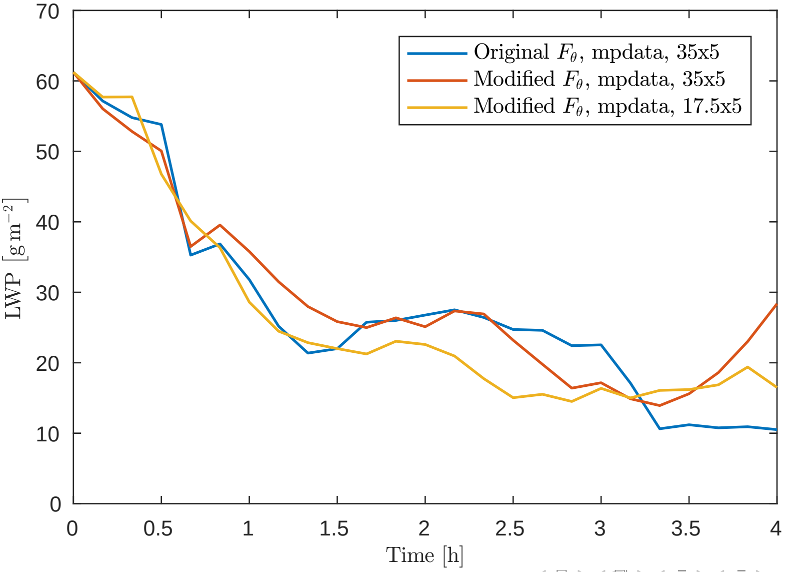


Vertical profiles of TKE and ϵ

Observations and LES ($35 \times 35 \times 5\ \mathrm{m}^3$)

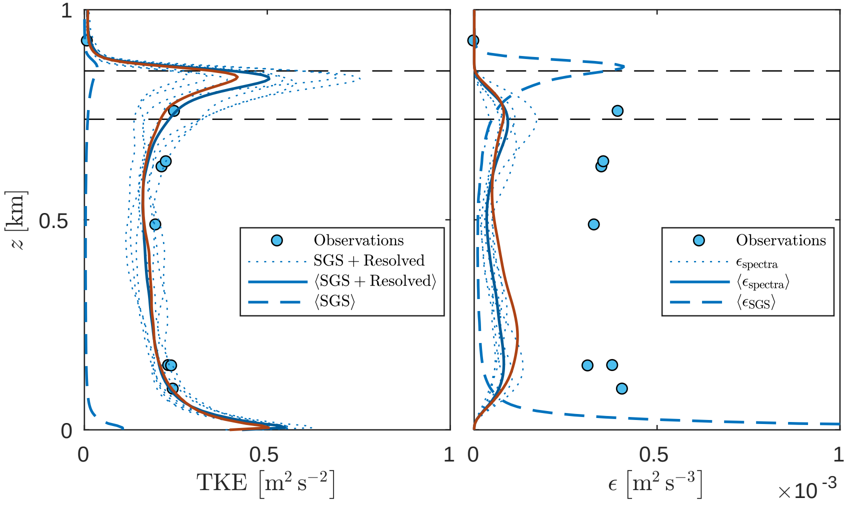


DYCOMS-II flight 1 - marine stratocumulus



Vertical profiles of TKE and ϵ

Observations and LES ($35 \times 35 \times 5\,\mathrm{m}^3$ and $17.5 \times 17.5 \times 5\,\mathrm{m}^3$)



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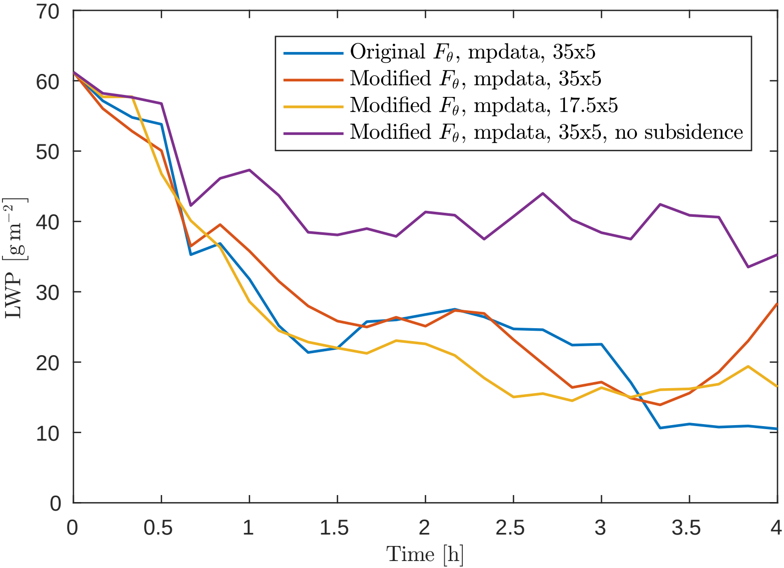
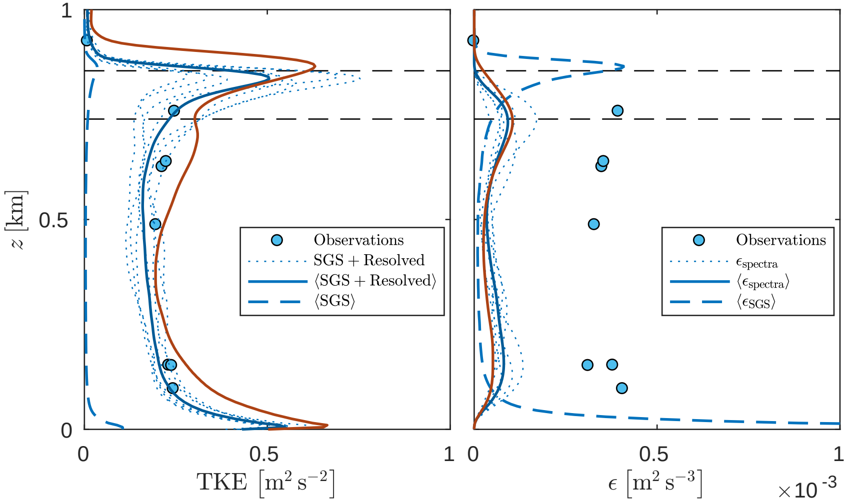


Vertical profiles of TKE and ϵ

Observations and LES (with and without subsidence)



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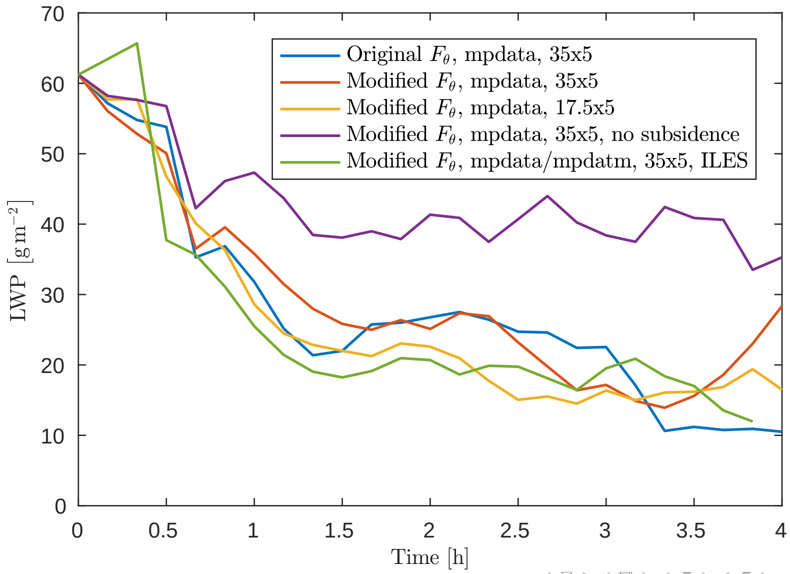
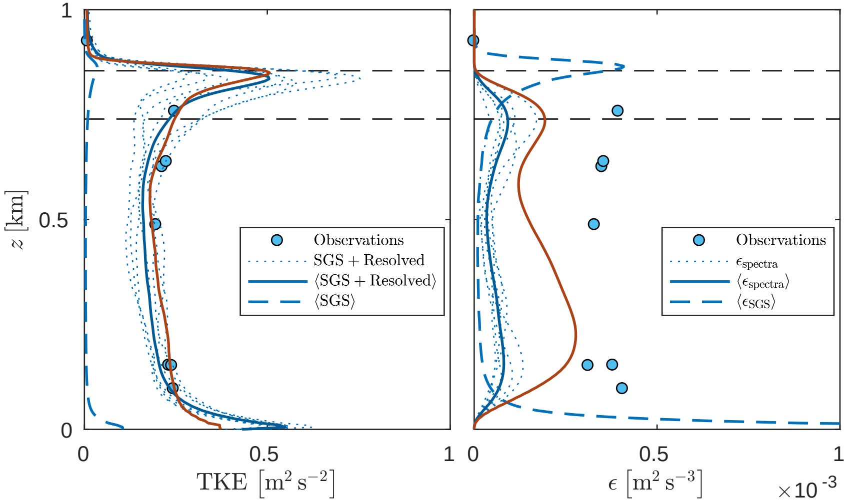


Vertical profiles of TKE and ϵ

Observations and LES (mpdata LES and mpdata/mpdatm ILES)



Conclusions

- Agreement with previously published Cu LES results (e.g. RICO and BOMEX) is obtained with modified F_θ.
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Thank you for your attention

Fang, M., Albrecht, B. A., Ghate, V. P., and Kollias, P. (2014). Turbulence in continental stratocumulus, part ii: Eddy dissipation rates and large-eddy coherent structures. *Boundary-layer meteorology*, 150(3):361–380.

Grabowski, W. W. and Abade, G. C. (2017). Broadening of cloud droplet spectra through eddy hopping: Turbulent adiabatic parcel simulations. *Journal of the Atmospheric Sciences*, 74(5):1485–1493.

Jen-La Plante, I., Ma, Y., Nurowska, K., Gerber, H., Khelif, D., Karpinska, K., Kopec, M. K., Kumala, W., and Malinowski, S. P. (2016). Physics of Stratocumulus Top (POST): turbulence characteristics. *Atmos. Chem. Phys.*, 16:9711–9725.

Katzwinkel, J., Siebert, H., and Shaw, R. A. (2012). Observation of a self-limiting, shear-induced turbulent inversion layer above marine stratocumulus. *Bound.-Layer Meteor.*, 145:131–143.

Lu, C., Liu, Y., Zhang, G. J., Wu, X., Endo, S., Cao, L., Li, Y., and Guo, X. (2016). Improving parameterization of entrainment rate for shallow convection with aircraft measurements and large-eddy simulation. *Journal of the Atmospheric Sciences*, 73(2):761–773.

Siebert, H., Lehmann, K., and Wendisch, M. (2006). Observations of small-scale turbulence and energy dissipation rates in the cloudy boundary layer. *Journal of the atmospheric sciences*, 63(5):1451–1466.

Siebert, H., Shaw, R. A., and Warhaft, Z. (2010). Statistics of small-scale velocity fluctuations and internal intermittency in marine stratocumulus clouds. *Journal of the Atmospheric Sciences*, 67(1):262–273.

Stevens, B., Moeng, C.-H., Ackerman, A. S., Bretherton, C. S., Chlond, A., de Roode, S., Edwards, J., Golaz, J.-C., Jiang, H., Khairoutdinov, M., Kirkpatrick, M. P., Lewellen, D. C., Lock, A., Müller, F., Stevens, D. E., Whelan, E., and Zhu, P. (2005). Evaluation of Large-Eddy Simulations via Observations of Nocturnal Marine Stratocumulus. *Mon. Wea. Rev.*, 133:1443–1462.

van Zanten, M. C. et al. (2011). Controls on precipitation and cloudiness in simulations of trade-wind cumulus as observed during RICO. *J. Adv. Model. Earth Syst.*, 3:M06001.

Zeman, O. and Tennekes, H. (1977). Parameterization of the turbulent energy budget at the top of the daytime atmospheric boundary layer. *Journal of the Atmospheric Sciences*, 34(1):111–123.