Entrainment and anisotropic turbulence in large-eddy simulation of the stratocumulus-topped boundary layer

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Workshop on numerical and computational methods for simulation of all-scale geophysical flows
ECMWF 06.10.2016

Motivation

"Only small changes in the coverage and thickness of stratocumulus clouds are required to produce a radiative effect comparable to those associated with increasing greenhouse gases"
R. Wood, Stratocumulus Clouds, *Monthly Weather Review*, 2012

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- Can we use LES to get improved understanding of e.g. entrainment?
- Smallest eddies involved: $\mathcal{O}(0.1)$ m
- Recent LES stratocumulus-topped boundary layer studies:
  - Horizontal grid spacing (Δx) between 5 and 120 m
  - Vertical grid spacing (Δz) between 2.5 and 25 m
- Even at $5 \times 5 \times 2.5\,\mathrm{m}^3$ resolution we see grid-dependency (Yamaguchi et al., *J. Atmos Sci.*, 2012)

Pedersen et al., *J. Adv. Model. Earth. Syst.* 2016:

ILES of the DYCOMS-II Flight 1 stratocumulus case using "babyEULAG" going down to resolutions of $10 \times 10 \times 10\,\mathrm{m}^3$ and $20 \times 20 \times 5\,\mathrm{m}^3$.

Pedersen et al., *J. Adv. Model. Earth. Syst.* 2016:

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- **Decreasing horizontal grid spacing (reducing dx/dz)** ⇒
  Smaller-scale isotropic turbulence at the cloud top ⇒
  Increased entrainment (initially) ⇒
  Reduced cloud cover and LWP ⇒
  Poor agreement with measurements

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- **Decreasing vertical grid spacing** ⇒
  Stronger inversion ⇒
  Less entrainment ⇒
  Increased cloud cover and LWP ⇒
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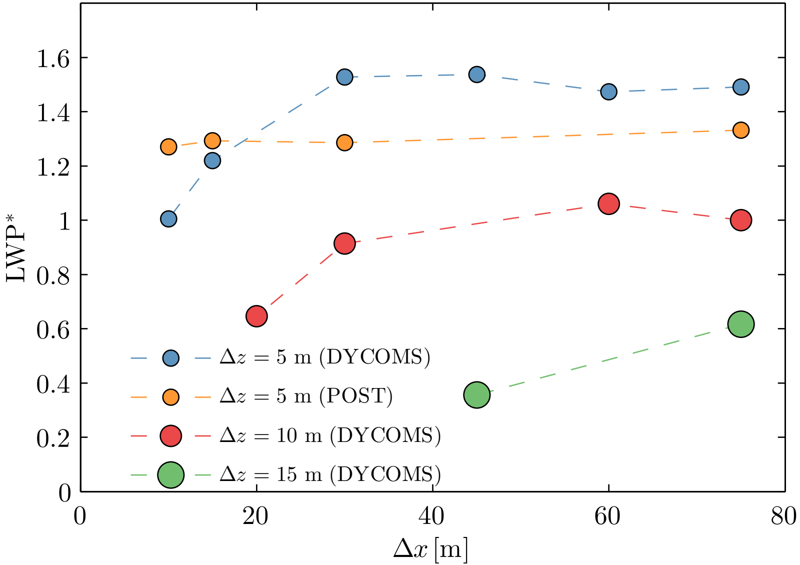
  Increased cloud cover and LWP ⇒
  Good agreement with measurements
- Increasing domain size has little effect

Simulation setup

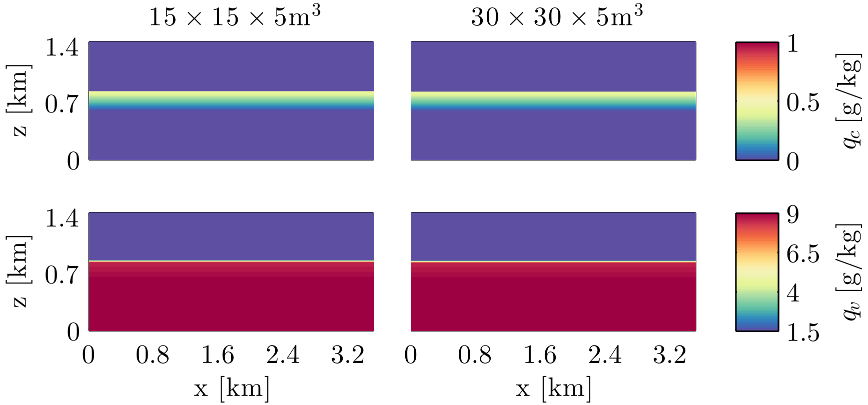
DYCOMS-II Flight 1 and POST Flight 13

- 3D
- Non-hydrostatic
- Anelastic
- No supersaturation
- No precipitation
- No explicit subgrid-scale model (ILES)
- MPDATA, IORD $= 2$
- IMPLGW $= 0$
- $3.5 \times 3.5 \times 1.5\,\mathrm{km}^3$ domain with periodic lateral BC's
- DYCOMS: $H_0 = 15\,\mathrm{W\,m^{-2}}$, $Q_0 = 115\,\mathrm{W\,m^{-2}}$, and $U_G = 8.9\,\mathrm{m\,s^{-1}}$
- POST: $H_0 = 5\,\mathrm{W\,m^{-2}}$, $Q_0 = 10\,\mathrm{W\,m^{-2}}$, and $U_G = 8.6\,\mathrm{m\,s^{-1}}$
- Longwave radiative cooling based on q_c

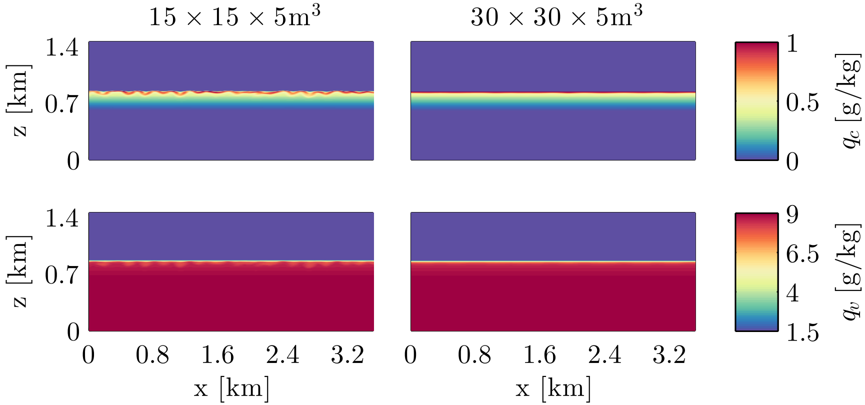
$\mathrm{LWP}^* = \langle\langle \mathrm{LWP} \rangle\rangle_{4\mathrm{h}-6\mathrm{h}} / \mathrm{LWP}_{\mathrm{initial}}$



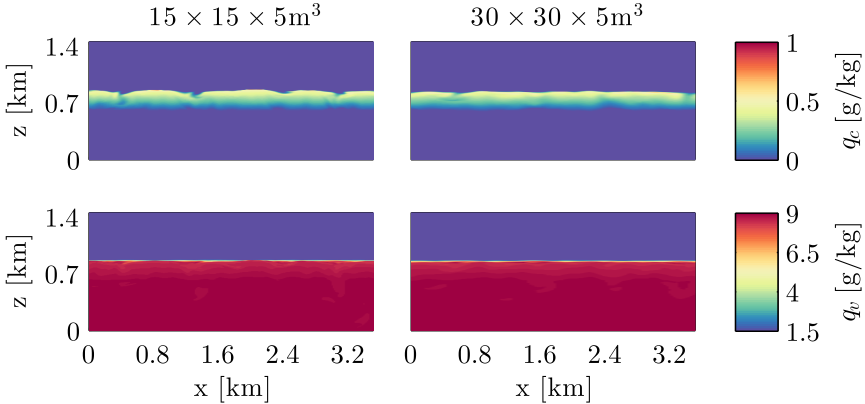
DYCOMS-II Flight 1 @ $T = 0$ min



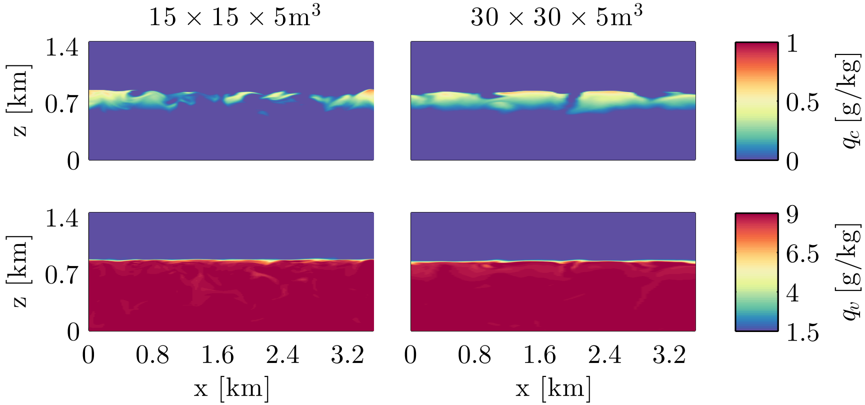
DYCOMS-II Flight 1 @ $T = 20$ min



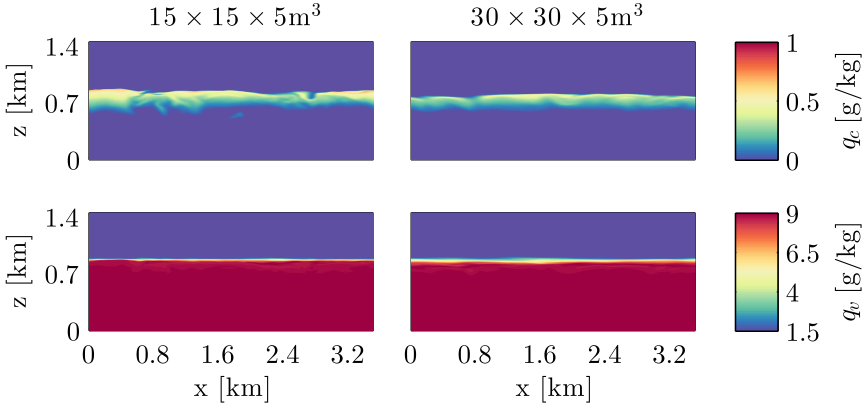
DYCOMS-II Flight 1 @ $T = 40$ min



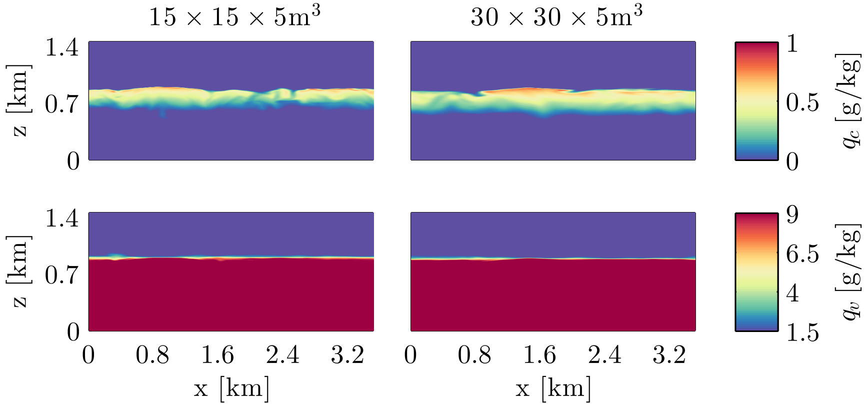
DYCOMS-II Flight 1 @ $T = 60$ min



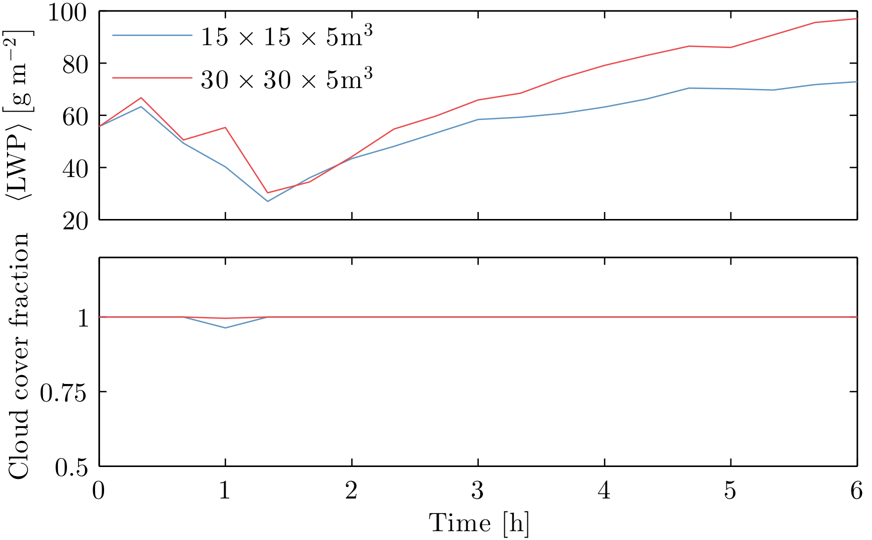
DYCOMS-II Flight 1 @ $T = 120$ min



DYCOMS-II Flight 1 @ $T = 360$ min

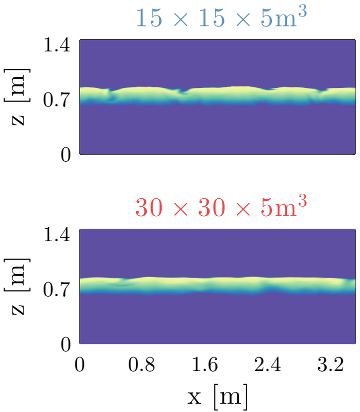


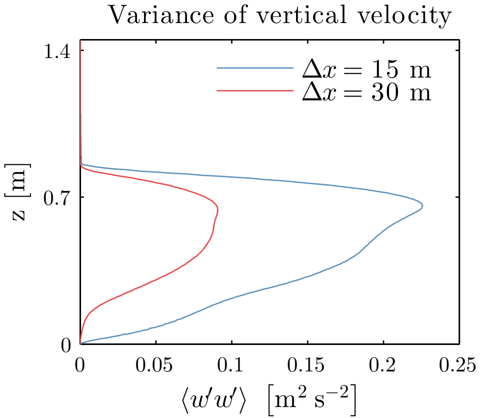
DYCOMS-II Flight 1



DYCOMS-II Flight 1 @ $T = 40$ min

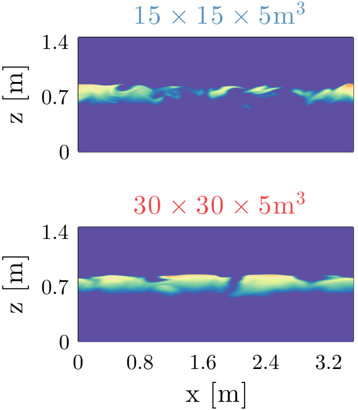
Small $\Delta x \Rightarrow$ large cloud-top $\langle w'w' \rangle \Rightarrow$ high entrainment rate $\Rightarrow$ dissolution of cloud

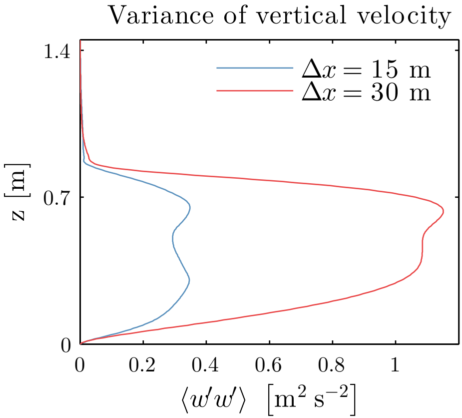




DYCOMS-II Flight 1 @ $T = 60$ min

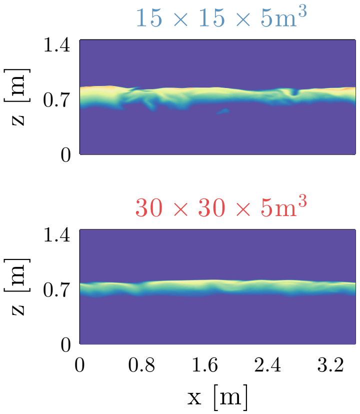
Dissolution of cloud ⇒ reduced cloud-top cooling ⇒ reduced TKE production ⇒ "decoupling" from surface layer (two maxima in $\langle w'w' \rangle$ profile)

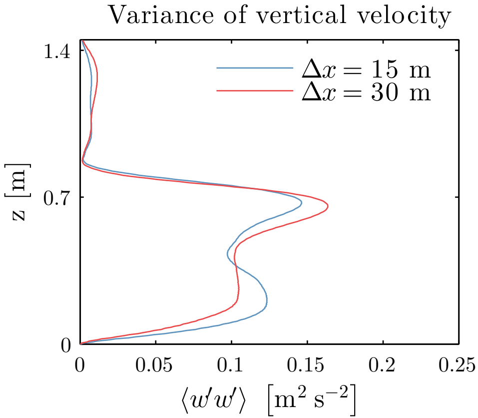




DYCOMS-II Flight 1 @ $T = 120$ min

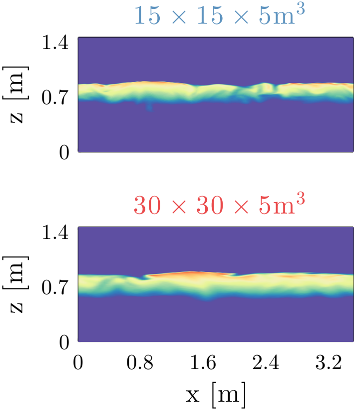
Quasi-steady state: The cloud “recovers” but still signs of decoupling with $\Delta z = 15$ m

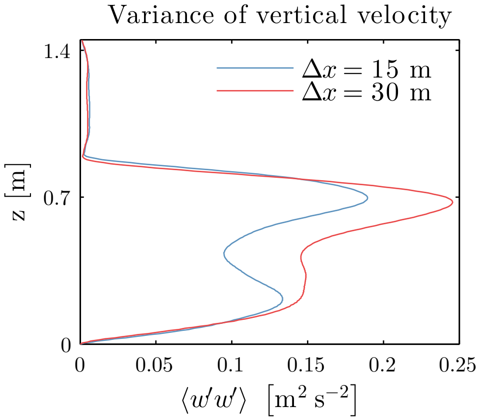



Variance of vertical velocity

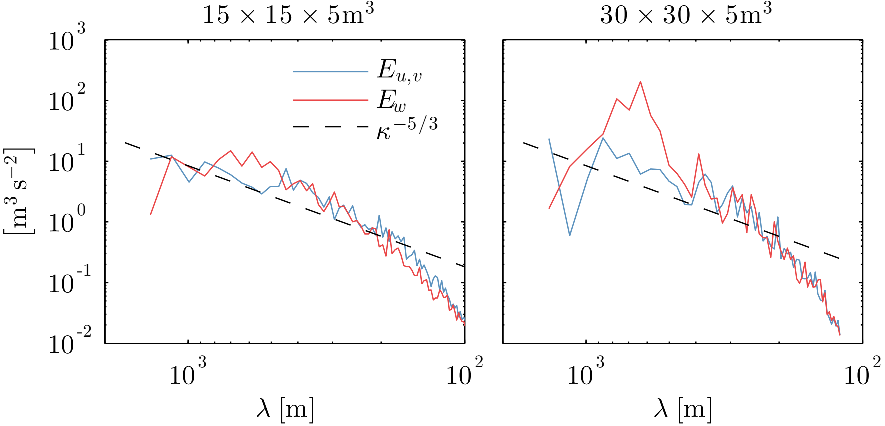
DYCOMS-II Flight 1 @ $T = 360$ min

End of simulation: Still decoupled

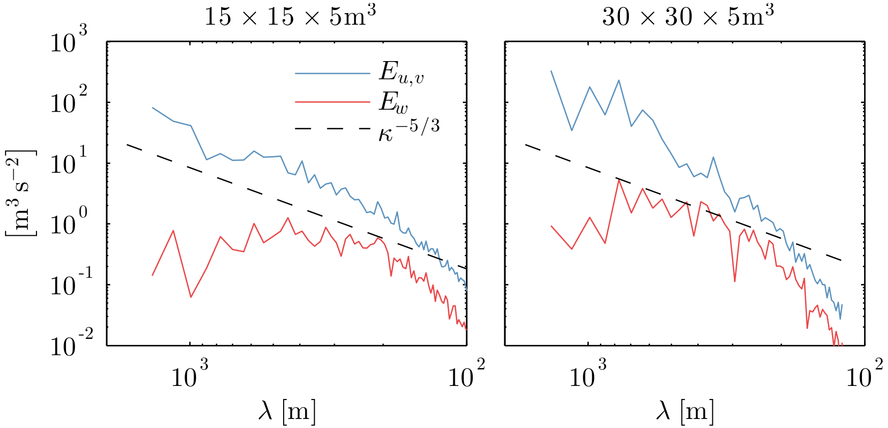




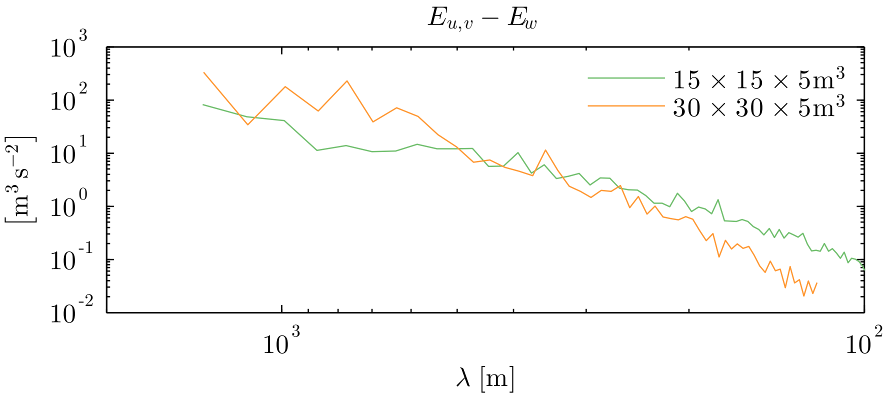
DYCOMS-II Flight 1 @ $T = 60$ min and $z = 300$ m



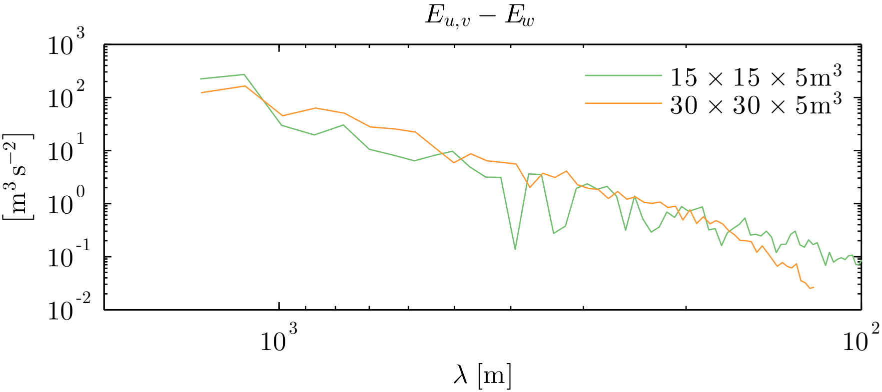
DYCOMS-II Flight 1 @ $T = 60$ min and $z = 840$ m



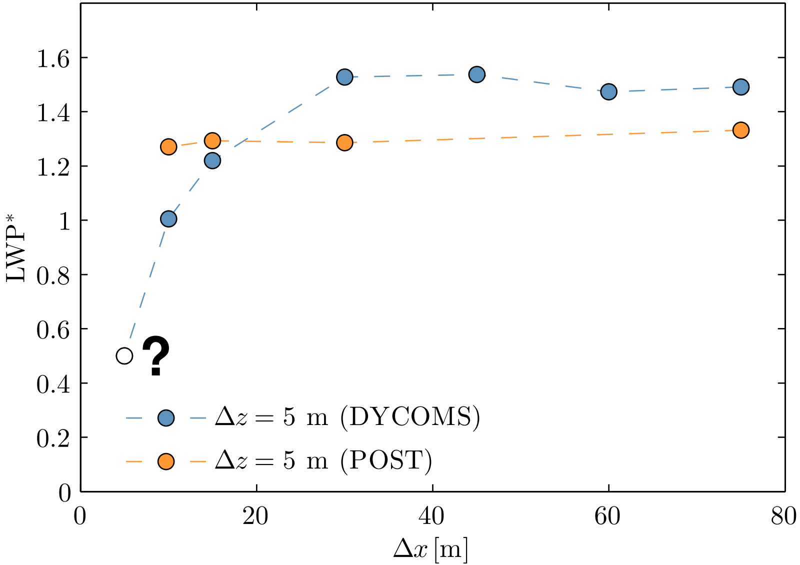
DYCOMS-II Flight 1 @ $T = 60$ min and $z = 840$ m



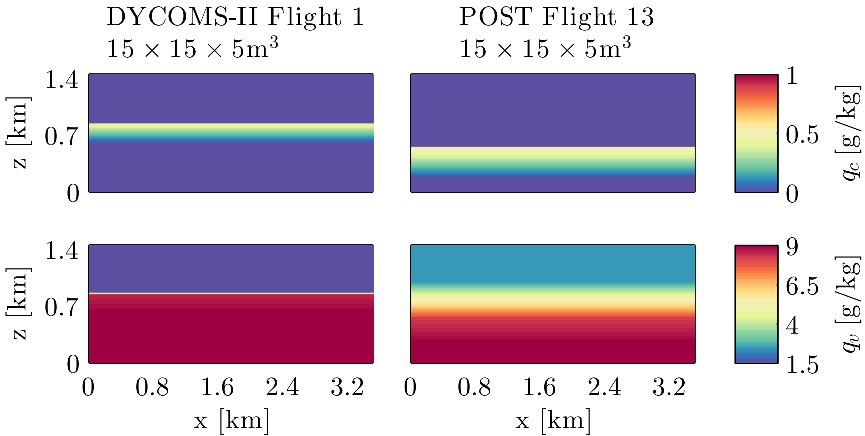
DYCOMS-II Flight 1 @ $T = 360$ min and $z = 840$ m



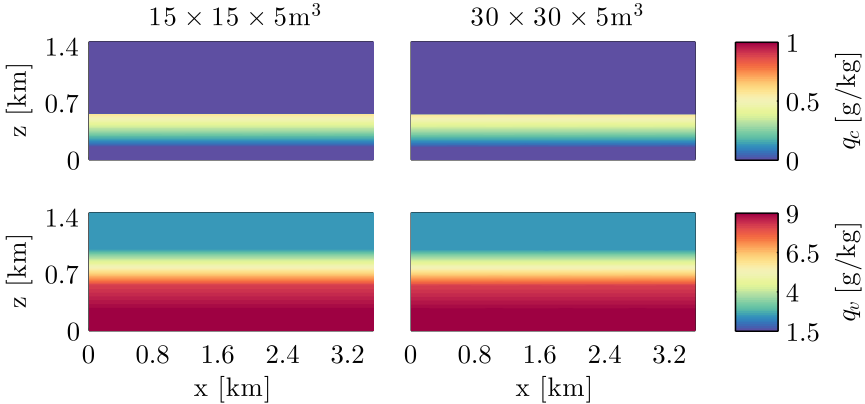
$\text{LWP}^* = \langle\langle \text{LWP} \rangle\rangle_{4\text{h}-6\text{h}} / \text{LWP}_{\text{initial}}$



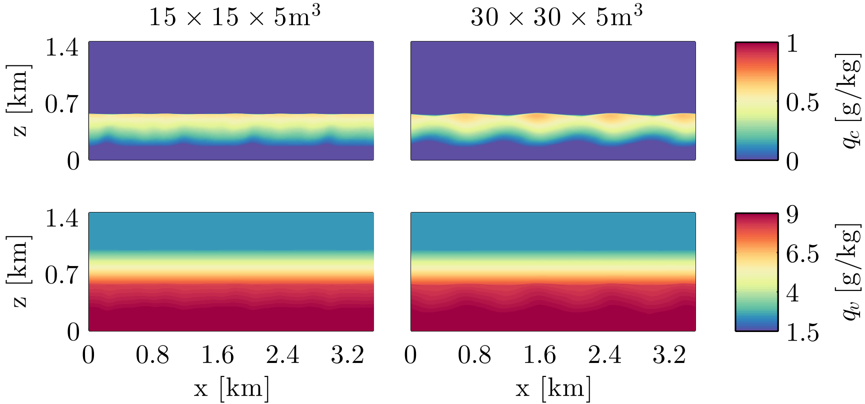
Initial conditions



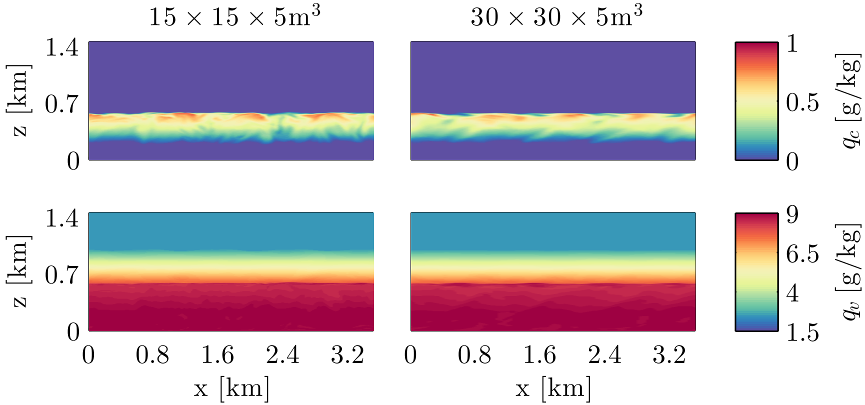
POST Flight 13 @ $T = 20$ min



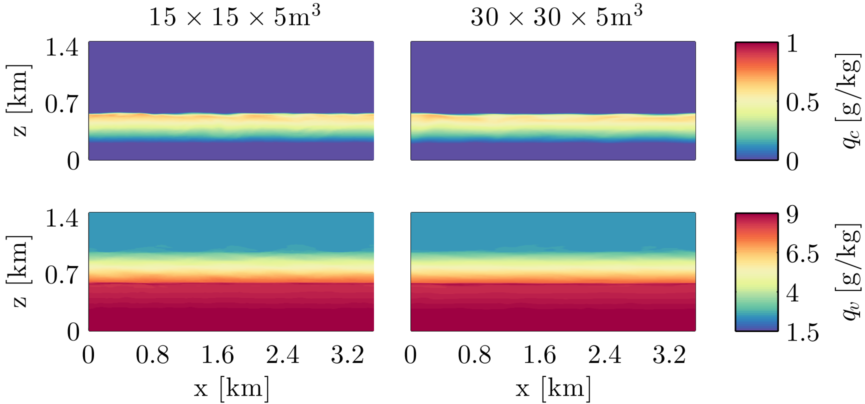
POST Flight 13 @ $T = 40$ min



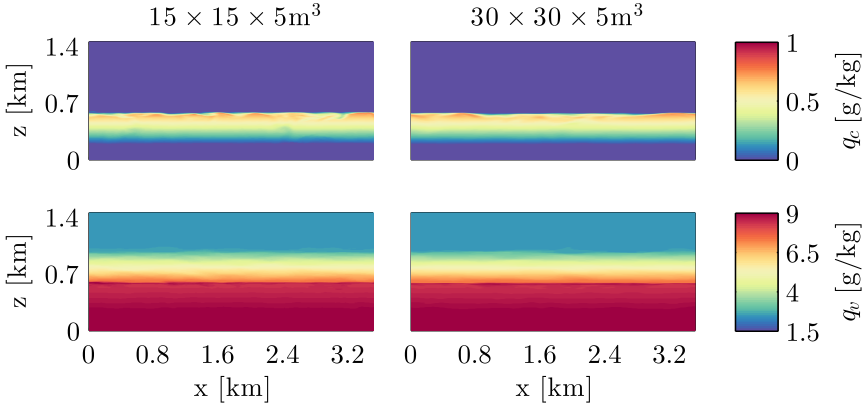
POST Flight 13 @ $T = 60$ min



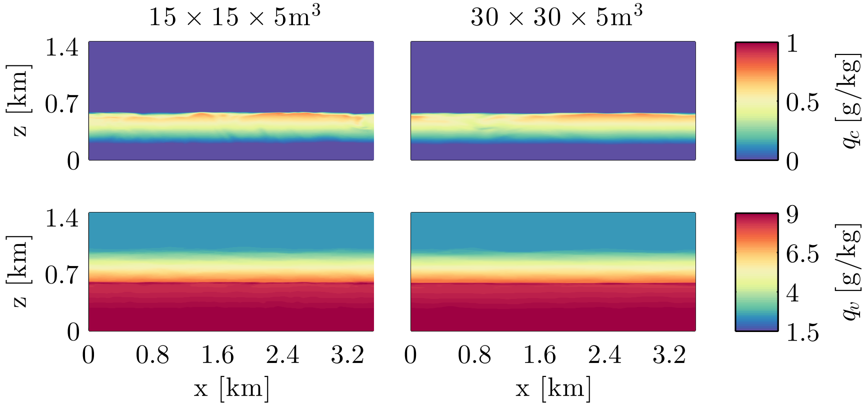
POST Flight 13 @ $T = 120$ min



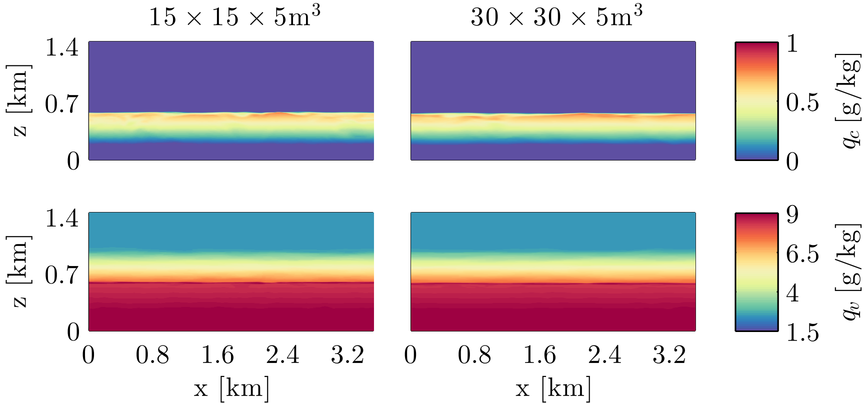
POST Flight 13 @ $T = 180$ min



POST Flight 13 @ $T = 240$ min

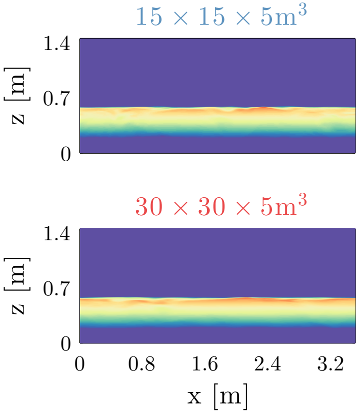


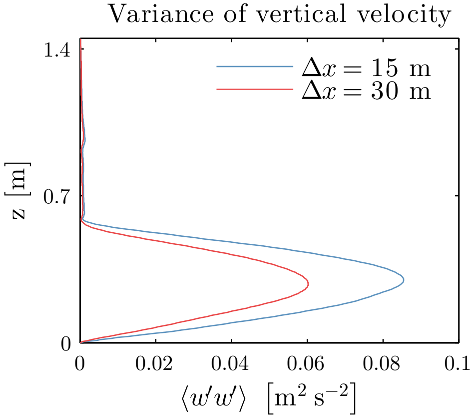
POST Flight 13 @ $T = 300$ min

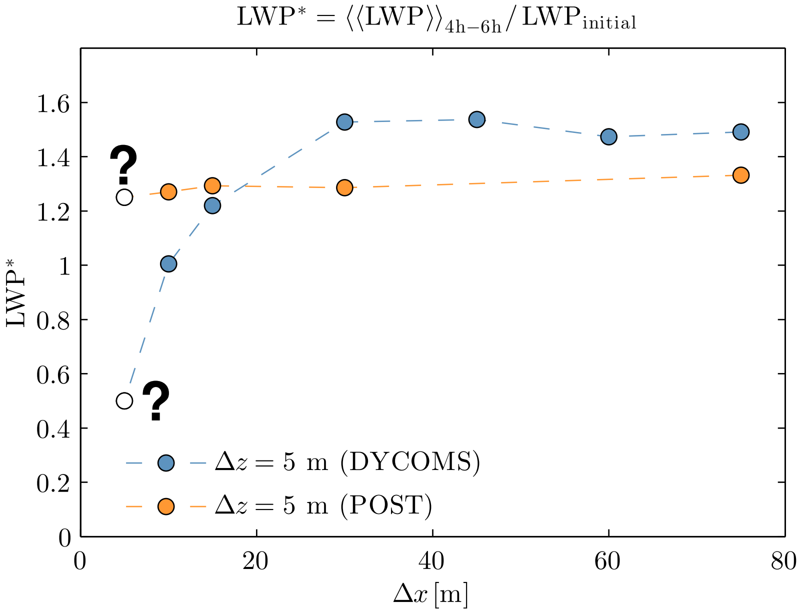


POST Flight 13 @ $T = 300$ min

No decoupling in this case







$$\mathrm{LWP}^* = \langle\langle \mathrm{LWP} \rangle\rangle_{4h-6h} / \mathrm{LWP}_{\mathrm{initial}}$$

Future work

- Increase resolution, e.g. to $5 \times 5 \times 5\,\mathrm{m}^3$ or $2.5 \times 2.5 \times 2.5\,\mathrm{m}^3$
  - Stratocumulus-top Ozmidov scale $L_O = \left(\epsilon/N^3\right)^{1/2} \simeq 0.5\,\mathrm{m}$ (Jen-La Plante et al., *Atmos. Chem. Phys.*, 2016)

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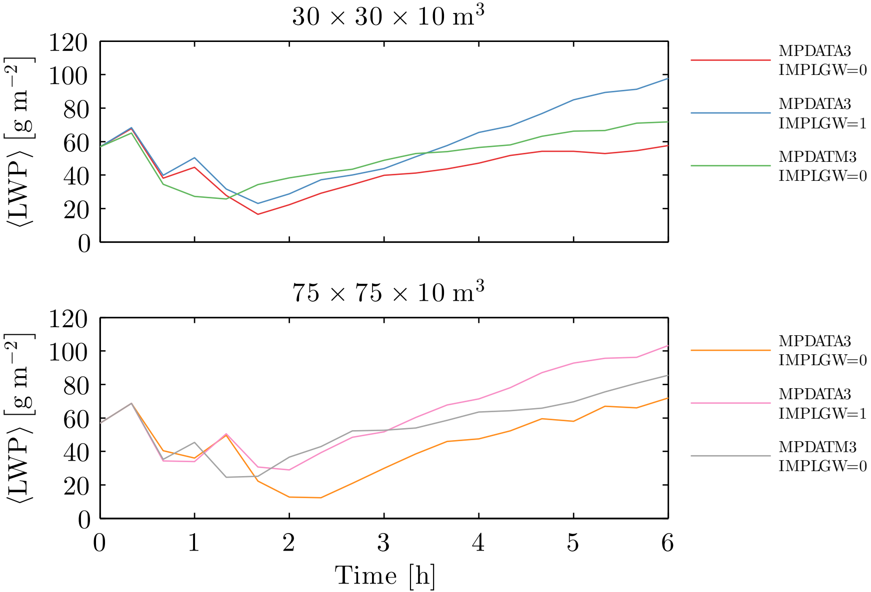
- Will we see the same dependencies using conventional LES?
  - $\tau_{ij} \propto L_{SGS} V_{SGS} S_{ij}$, but how to define L_{SGS} when $\Delta x \neq \Delta z$?
  - $L_{SGS} = \Delta x$
  - $L_{SGS} = \Delta z$
  - $L_{SGS} = (\Delta x \Delta y \Delta z)^{1/3}$

Thank you

Some other issues:

- IMPLGW 0/1
- MPDATA3/MPDATM3


30 × 30 × 10 m³
75 × 75 × 10 m³
⟨LWP⟩ [g m⁻²]
0
20
40
60
80
100
120
Time [h]
0
1
2
3
4
5
6
MPDATA3 IMPLGW=0
MPDATA3 IMPLGW=1
MPDATM3 IMPLGW=0