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

Jesper Grønnegaard Pedersen

Institute of Geophysics, Faculty of Physics, University of Warsaw

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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”
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- Can we use LES to get improved understanding of e.g. entrainment?
- Smallest eddies involved: $\mathcal{O}(0.1) \text{ m}$
- Recent LES stratocumulus-topped boundary layer studies:
  - Horizontal grid spacing ($\Delta x$) between 5 and 120 m
  - Vertical grid spacing ($\Delta z$) between 2.5 and 25 m
- Even at $5 \times 5 \times 2.5 \text{ m}^3$ resolution we see grid-dependency (Yamaguchi et al., J. Atmos Sci., 2012)
ILES of the DYCOMS-II Flight 1 stratocumulus case using “babyEULAG” going down to resolutions of $10 \times 10 \times 10 \, \text{m}^3$ and $20 \times 20 \times 5 \, \text{m}^3$.
ILES of the DYCOMS-II Flight 1 stratocumulus case using “babyEULAG” going down to resolutions of $10 \times 10 \times 10 \text{m}^3$ and $20 \times 20 \times 5 \text{m}^3$.

- **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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  - Stronger inversion ⇒
  - Less entrainment ⇒
  - Increased cloud cover and LWP ⇒
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  - 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
- $3.5 \times 3.5 \times 1.5 \text{ km}^3$ domain with periodic lateral BC’s
- DYCOMS: $H_0 = 15 \text{ W m}^{-2}$, $Q_0 = 115 \text{ W m}^{-2}$, and $U_G = 8.9 \text{ m s}^{-1}$
- POST: $H_0 = 5 \text{ W m}^{-2}$, $Q_0 = 10 \text{ W m}^{-2}$, and $U_G = 8.6 \text{ m s}^{-1}$
- Longwave radiative cooling based on $q_c$
LWP* = ⟨⟨LWP⟩⟩_{4h-6h} / LWP_{initial}

\[ \Delta z = 5 \text{ m (DYCOMS)} \]
\[ \Delta z = 5 \text{ m (POST)} \]
\[ \Delta z = 10 \text{ m (DYCOMS)} \]
\[ \Delta z = 15 \text{ m (DYCOMS)} \]
DYCOMS-II Flight 1 @ $T = 0$ min

- $15 \times 15 \times 5m^3$
- $30 \times 30 \times 5m^3$

$z$ [km]

$0$  $0.7$  $1.4$

$x$ [km]

$0$  $0.8$  $1.6$  $2.4$  $3.2$

$q_c$ [g/kg]

$0$  $0.5$  $1$

$q_v$ [g/kg]

$1.5$  $4$  $6.5$  $9$
DYCOMS-II Flight 1 @ $T = 20$ min

\begin{align*}
\text{15} \times 15 \times 5 \text{m}^3 \\
\text{30} \times 30 \times 5 \text{m}^3
\end{align*}
DYCOMS-II Flight 1 @ $T = 40$ min

![Image of flight data](image-url)
DYCOMS-II Flight 1 @ $T = 60 \text{ min}$
DYCOMS-II Flight 1 @ $T = 120$ min

![Graph of flight data](image)

15 $\times$ 15 $\times$ 5m$^3$

30 $\times$ 30 $\times$ 5m$^3$

$z$ [km]

0 0.8 1.6 2.4 3.2

$x$ [km]

0 0.8 1.6 2.4 3.2

$q_c$ [g/kg]

0 0.5 1

$q_v$ [g/kg]

0 1.5 4 6.5 9
DYCOMS-II Flight 1 @ $T = 360$ min

15 $\times$ 15 $\times$ 5 m$^3$

30 $\times$ 30 $\times$ 5 m$^3$

$q_c$ [g/kg]

$q_v$ [g/kg]
DYCOMS-II Flight 1

The figure shows the time evolution of the average liquid water path (LWP) and cloud cover fraction for two different volumes: 15 × 15 × 5 m³ (blue line) and 30 × 30 × 5 m³ (red line). The LWP is measured in units of g m⁻², and the cloud cover fraction is normalized to a value of 1. The time is represented in hours (h).
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 $\Rightarrow$ reduced cloud-top cooling $\Rightarrow$ reduced TKE production $\Rightarrow$ “decoupling” from surface layer (two maxima in $\langle w'w' \rangle$ profile)

\[ \begin{align*}
\text{Variance of vertical velocity} & \quad \langle w'w' \rangle \quad [m^2 s^{-2}] \\
\text{z [m]} & \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \\
\text{x [m]} & \quad 0 \quad 0.8 \quad 1.6 \quad 2.4 \quad 3.2 \quad 3.4 \\
\end{align*} \]

\[ \begin{align*}
15 \times 15 \times 5m^3 & \quad \Delta x = 15 m \quad \Delta x = 30 m \\
30 \times 30 \times 5m^3 & \\
\end{align*} \]
DYCOMS-II Flight 1 @ $T = 120$ min

Quasi-steady state: The cloud “recovers” but still signs of decoupling with $\Delta z = 15$ m
DYCOMS-II Flight 1 @ $T = 360$ min

End of simulation: Still decoupled

Variance of vertical velocity

$\langle w'w' \rangle [m^2 s^{-2}]$
DYCOMS-II Flight 1 @ $T = 60$ min and $z = 300$ m

\begin{align*}
&15 \times 15 \times 5 \text{m}^3 \\
&30 \times 30 \times 5 \text{m}^3
\end{align*}

\begin{align*}
\text{[m}^3\text{s}^{-2}] &
\begin{array}{c}
10^3 \\
10^2 \\
10^1 \\
10^0 \\
10^{-1} \\
10^{-2}
\end{array} \\
\lambda [\text{m}] &
\begin{array}{c}
10^3 \\
10^2 \\
10^1 \\
10^0 \\
10^{-1} \\
10^{-2}
\end{array}
\end{align*}
DYCOMS-II Flight 1 @ $T = 60 \text{ min}$ and $z = 840 \text{ m}$
DYCOMS-II Flight 1 @ $T = 60$ min and $z = 840$ m

$E_{u,v} - E_w$

$[m^3 s^{-2}]$

$\lambda [m]$
DYCOMS-II Flight 1 @ $T = 360$ min and $z = 840$ m
\[ \text{LWP}^* = \left\langle \left\langle \text{LWP} \right\rangle \right\rangle_{4h-6h} / \text{LWP}_{\text{initial}} \]
Initial conditions

DYCOMS-II Flight 1
15 × 15 × 5m³

POST Flight 13
15 × 15 × 5m³

\( z \ [\text{km}] \)

\begin{align*}
0 & \quad 0.7 & \quad 1.4 \\
0 & \quad 0.7 & \quad 1.4
\end{align*}

\( x \ [\text{km}] \)

\begin{align*}
0 & \quad 0.8 & \quad 1.6 & \quad 2.4 & \quad 3.2 \\
0 & \quad 0.8 & \quad 1.6 & \quad 2.4 & \quad 3.2
\end{align*}

\( q_c \ [\text{g/kg}] \)

\begin{align*}
0 & \quad 0.5 & \quad 1 \\
0 & \quad 0.5 & \quad 1
\end{align*}

\( q_v \ [\text{g/kg}] \)

\begin{align*}
0 & \quad 1.5 & \quad 4 & \quad 6.5 & \quad 9 \\
0 & \quad 1.5 & \quad 4 & \quad 6.5 & \quad 9
\end{align*}
POST Flight 13 @ $T = 20$ min

![Graph showing the distribution of $q_c$ and $q_v$ in two different volumes.](image)
POST Flight 13 @ \( T = 40 \) min

\[ 15 \times 15 \times 5 \text{m}^3 \]

\[ 30 \times 30 \times 5 \text{m}^3 \]

\( q_c \) [g/kg]

\( q_v \) [g/kg]

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POST Flight 13 @ $T = 60$ min

![Heatmaps showing temperature distributions over different volumes and sections.](image-url)
POST Flight 13 @ $T = 120$ min

![Graphs showing distribution of $q_c$ and $q_v$ for two different volumes: $15 \times 15 \times 5m^3$ and $30 \times 30 \times 5m^3$.](image)

J. G. Pedersen (IGF UW)
POST Flight 13 @ $T = 180$ min

![Graphs showing}$z$ and $x$ in 15x15x5m$^3$ and 30x30x5m$^3$ volumes with $q_c$ and $q_v$ scaling.
POST Flight 13 @ $T = 240$ min

![Diagram showing different volumes and their respective $q_c$ and $q_v$ values with color scales for $q_c$ and $q_v$.]
POST Flight 13 @ $T = 300$ min

\[ \begin{array}{c}
15 \times 15 \times 5 \text{m}^3 \\
30 \times 30 \times 5 \text{m}^3
\end{array} \]
POST Flight 13 @ $T = 300$ min

No decoupling in this case
$LWP^* = \langle \langle LWP \rangle \rangle_{4h-6h}/LWP_{initial}$

$\Delta z = 5$ m (DYCOMS)

$\Delta z = 5$ m (POST)
Future work

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

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

- 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
\[ \langle LWP \rangle \quad [\text{g m}^{-2}] \]

**30 \times 30 \times 10 \text{ m}^3**

\[ \langle LWP \rangle \quad [\text{g m}^{-2}] \]

**75 \times 75 \times 10 \text{ m}^3**

- MPDATA3 IMPLGW=0
- MPDATA3 IMPLGW=1
- MPDATM3 IMPLGW=0
- MPDATA3 IMPLGW=0
- MPDATA3 IMPLGW=1
- MPDATM3 IMPLGW=0