Impact of turbulence representation on deep convective clouds

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Introduction

Turbulence: extensively studied in the atmospheric boundary layer

**Convective clouds** associated with **strong turbulence**: instabilities, updraft, downdraft, gravity waves …

- Idealized **Large-Eddy Simulations** of deep convection
- Characterization of **turbulence** inside convective clouds, not enough subgrid turbulence. Verrelle, Ricard, Lac, 2015 QJRMS
- Evaluation and improvement of **turbulence parameterization** in Cloud-Permitting Models o(1 km)
LES of deep convective clouds

Configuration with Meso-NH:

1.5 order 3D turbulence scheme: prognostic TKE (Cuxart et al, 2000) with Deardorff mixing length

One-moment microphysical scheme: ICE3 (ice, cloud, rain, graupel, snow)

\[ \frac{\partial e}{\partial t} = - \frac{1}{\rho_{dref}} \frac{\partial (\rho_{dref} e u_i)}{\partial x_j} - \frac{u_i u_j}{\theta_{vref}} \frac{\partial u_i}{\partial x_j} + \frac{g}{\theta_{vref}} \frac{u_i}{u_j} \theta' v' + \frac{1}{\rho_{dref}} \frac{\partial}{\partial x_j} \left( C_T \rho_{dref} L e^{1/2} \frac{\partial e}{\partial x_j} \right) - C_e \frac{e^{3/2}}{L} \]

Dynamical production

Thermal production

Dissipation

Lac et al 2018 GMD
LES of deep convective clouds

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1.5 order 3D turbulence scheme: prognostic TKE (Cuxart et al., 2000) with Deardorff mixing length

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Dynamical production

\[
\frac{\partial e}{\partial t} = - \frac{1}{\rho_{dref}} \frac{\partial (\rho_{dref} e u_i)}{\partial x_j} - \frac{u_i' u_j'}{\theta_{vref}} \frac{\partial u_i}{\partial x_j} + \frac{g}{\theta_{vref}} u_3' \theta_v' + \frac{1}{\rho_{dref}} \frac{\partial}{\partial x_j} \left( C_T \rho_{dref} L e^{1/2} \frac{\partial e}{\partial x_j} \right) - C_e \frac{e^{3/2}}{L}
\]

Thermal production

Dissipation

Initial conditions:

Unstable conditions from: (Weisman and Klemp, 1982)
Moderate wind shear

LES: \( \Delta x = \Delta y = \Delta z = 50 \) m

Cloud contour \((\text{ri} + \text{rc} > 0.001 \text{ g/kg})\)

Horizontal cross sections of vertical velocity (m/s) at 6 km AGL t=175 min
LES of deep convective clouds

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1.5 order 3D turbulence scheme: prognostic TKE (Cuxart et al, 2000) with Deardorff mixing length

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Unstable conditions from: (Weisman and Klemp, 1982)
Moderate wind shear

Dynamical production

Thermal production

Dissipation

LES: \( \Delta x = \Delta y = \Delta z = 50 \text{ m} \)

Horizontal cross sections of vertical velocity (m/s) at 6 km AGL t=175 min
Well developed cumulonimbus with a strong updraft and many eddies.
Characterization of turbulence inside convective clouds

- LES: reference simulation (50-m grid spacing)
Characterization of turbulence inside convective clouds

- LES: reference simulation (50-m grid spacing)
- Computation of reference fields at coarser resolutions $\Delta x$ (500 m, 1 km, 2 km) by averaging LES fields
- Mean filtering by boxes of size $\Delta x$ (Honnert et al. 2011, Shin and Hong, 2013, Moeng 2014 ...)

Computation of terms at $\Delta x$:

\[
\overline{w^{\Delta x}}, \overline{u^{\Delta x}}, \overline{w^{\Delta x}}, \overline{r_{np}^{\Delta x}}, \overline{\theta_l^{\Delta x}}, ...
\]
Characterization of turbulence inside convective clouds

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Computation of terms at $\Delta x$:

$$\vec{u}_i^t = (\vec{u}_i - \overline{\vec{u}_i}^\Delta x)$$
Characterization of turbulence inside convective clouds

- LES: reference simulation (50-m grid spacing)
- Computation of reference fields at coarser resolutions $\Delta x$ (500m, 1 km, 2 km) by averaging LES fields
- Mean filtering by boxes of size $\Delta x$ (Honnert et al. 2011, Shin and Hong, 2013, Moeng 2014 …)

**Computation of terms at $\Delta x$:**

$$u_i^t = (u_i - \bar{u}_i^{\Delta x})$$

**Computation of subgrid terms at $\Delta x$:**

- Turbulent fluxes:
  $$\overline{u_i^tu_j^t}^{\Delta x} = \left(u_i - \bar{u}_i^{\Delta x}\right)\left(u_j - \bar{u}_j^{\Delta x}\right)\Delta x + \int u_i^t u_j^t \Delta x$$
- Variances:
  $$\overline{u'^2 v'^2}^{\Delta x}, \overline{w'^2}^{\Delta x}, \overline{r'_{np}}^{\Delta x}, \overline{\theta'^2}^{\Delta x}, \ldots$$
- Subgrid TKE:
  $$\overline{\epsilon_{ref}}^{\Delta x} = \frac{1}{2} \left( \overline{u'^2}^{\Delta x} + \overline{v'^2}^{\Delta x} + \overline{w'^2}^{\Delta x} \right)$$
Characterization of turbulence inside convective clouds

Vertical cross sections: subgrid TKE (m²/s²) computed from the LES at different Δx (500 m, 1 km and 2 km) at t=175 min

- strong turbulence inside the cloud
- subgrid TKE increases with coarser resolutions
Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux computed from the LES at different $\Delta x$ (500 m, 1 km and 2 km) at $t=175$ min
Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux computed from the LES at different $\Delta x$ (500 m, 1 km and 2 km) at $t=175$ min

$\Delta x=500$ m

$\Delta x=1$ km

$\Delta x=2$ km

$\rightarrow$ strong positive heat flux inside the cloud
Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux computed from the LES at different $\Delta x$ (500 m, 1 km and 2 km) at $t=175$ min

$\Delta x=500$ m

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$\rightarrow$ strong positive heat flux inside the cloud
Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux computed from the LES at different \( \Delta x \) (500 m, 1 km and 2 km) at \( t=175 \) min

- \( \Delta x=500 \text{ m} \)
- \( \Delta x=1 \text{ km} \)
- \( \Delta x=2 \text{ km} \)

\[ \frac{w' \theta'_l}{\partial \theta_l}{\partial z} > 0 \]

\[ (m \text{ s}^{-1} \text{ K}) \]

\[ (K^2 \text{ s}^{-1}) \]

→ strong positive heat flux inside the cloud

→ countergradient areas inside the cloud

→ coherent structures in the updraft

→ nonlocal turbulence, analogy with the boundary layer
Evaluation of turbulence parameterizations

Off-line evaluation: computation of parameterized fluxes from the LES at $\Delta x \rightarrow \overline{w'\theta'_i}$
Evaluation of turbulence parameterizations

Off-line evaluation: computation of parameterized fluxes from the LES at $\Delta x \rightarrow w'\theta_i^l$

**Kgrad**

Cuxart et al., 2000

CBR scheme

$L$ mixing length of Bougeault-Lacarrere 1989

Based on K gradient:

$$w'\theta_i^l = -K \frac{\partial \theta_i}{\partial z}$$

Using K gradient:

$$\frac{w'\theta_i^l}{\Delta x} = -\frac{2}{3C_p\rho} \phi_i^x L \sqrt{c_{ref}} \frac{\partial \theta_i}{\partial z}$$
Evaluation of turbulence parameterizations

Off-line evaluation: computation of parameterized fluxes from the LES at $\Delta x \rightarrow w'\theta'_{\Delta x}$

**Kgrad**

Cuxart et al, 2000  
CBR scheme

Based on $K$ gradient:

$$w'\theta'_{\Delta x} = -\frac{2}{3C_p\theta} \phi_i \Delta x L \sqrt{c_{ref} \Delta x} \frac{\partial \theta_i}{\partial z}$$

$L$ mixing length of Bougeault-Lacarrere 1989

**Hgrad**

Moeng et al, 2010

Based on product of horizontal gradients:

$$w'\theta'_{\Delta x} = C_{\Delta x} \left( \frac{\partial \bar{w} \Delta x}{\partial x} \frac{\partial \bar{\theta}_i}{\partial x} + \frac{\partial \bar{w} \Delta x}{\partial y} \frac{\partial \bar{\theta}_i}{\partial y} \right)$$

Related to a mass flux (Moeng, 2014)
Evaluation of turbulence parameterizations

Off-line evaluation: computation of parameterized fluxes from the LES at $\Delta x \rightarrow w' r'_n p$

### $K_{\text{grad}}$

**Cuxart et al, 2000**

CBR scheme

$$\frac{w' r'_n p}{\Delta x} = -\frac{2}{3C_{pr}} \phi_i \Delta x L \sqrt{e_{re,f}^{\Delta x}} \frac{\partial r_{np}^{\Delta x}}{\partial z}$$

L mixing length of *Bougeault-Lacarrere 1989*

based on $K$ gradient:

$$w' r'_n p = -K \frac{\partial r_{np}}{\partial z}$$

### $H_{\text{grad}}$

**Moeng et al, 2010**

$$\frac{w' r'_n p}{\Delta x} = C_{\Delta x} \left( \frac{\partial w^{\Delta x}}{\partial x} \frac{\partial r_{np}^{\Delta x}}{\partial x} + \frac{\partial w^{\Delta x}}{\partial y} \frac{\partial r_{np}^{\Delta x}}{\partial y} \right)$$

based on product of horizontal gradients:

$$w' r'_n p = C \left( \frac{\partial w}{\partial x} \frac{\partial r_{np}}{\partial x} + \frac{\partial w}{\partial y} \frac{\partial r_{np}}{\partial y} \right)$$

related to a flux mass (*Moeng, 2014*)
Evaluation of turbulence parameterizations

Off-line evaluation: using LES fields at $\Delta x = 1$ km

Mean vertical profiles inside convective clouds at $t=175$ min

→ $K_{\text{grad}}$ underestimates these two fluxes compared to REF
→ $H_{\text{grad}}$ increases these two fluxes and represents the positive heat flux in mid-troposphere
Evaluation of turbulence parameterizations

**Online** evaluation: simulations with $\Delta x = 2$ km

- **Mean vertical profiles inside convective clouds at t=175 min**

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**REF (LES)**

- $K_{\alpha x} = 4 \Delta x^2/12$
- $H_{\alpha x} = 3 \Delta x^2/12$

- Better representation of these two fluxes with **Hgrad** approach compared to the **Kgrad** approach
Evaluation of turbulence parameterizations

Online evaluation: simulations with $\Delta x = 2$ km

Mean vertical profiles inside convective clouds at $t=175$ min

→ more subgrid TKE and less intense vertical velocity with $H_{\text{grad}}$ compared to $K_{\text{grad}}$
→ better balance between resolved and subgrid parts
LES of deep convective clouds

- Generalization of previous results:
  Strauss, Ricard, Lac, Verrelle 2019 QJRMS (accepted)

- New LES (50-m grid spacing):
  - on a larger domain: 80x80 km²
  - during 4 hours:
    Population of clouds at different stages

- Off-line evaluation for vertical and horizontal thermodynamical fluxes and dynamical fluxes of 3 schemes:
  H-gradient formulation MOENG  K-gradient formulation CBR  K-gradient formulation SMAG

\[
\overline{u_i'r_{np}} \Delta x = - \left( \frac{c_s L}{P_r} \right)^2 D \sqrt{\max(0, 1 - \frac{Ri}{P_r})} \frac{\partial r_{np}}{\partial x_i} \Delta x
\]

\[
\overline{u_i'r_{np}} = - K \frac{\partial r_{np}}{\partial x_i}
\]

Smagorinsky, 1963
Evaluation of turbulence parameterization

Off-line evaluation \( u'v'_{\text{np}} \) (m s\(^{-1}\) kg kg\(^{-1}\))  
\( \Delta x = 1 \) km

Thermodynamical fluxes:  
Better distribution with Hgrad

Dynamical fluxes:  
Slightly better with Hgrad but better variances with CBR
Evaluation on real cases: HyMeX campaign over the Mediterranean area

- Online evaluation on IOP6 (24 September 2012)
  - heavy rainfall over Southern France (more than 150 mm/24h)
  - simulations with different horizontal resolutions: 2 km, 1 km and 500 m
  - new scheme applied above 2000 m (with c=3 for vertical fluxes of heat and moisture) → Hgrad runs
  - comparison with the current scheme → Kgrad runs
  - a convective line develops over the Massif Central, fastly moving eastward during the night and the morning
Impact on convective systems

Vertical cross section of radar reflectivity (dBZ) along the Falcon-20 trajectory during the morning (24 September 2012)

(Delanoë et al, 2013)

→ Good vertical extension of convective systems
→ Underestimation of reflectivity
→ Higher reflectivity in the upper part of the clouds with the Hgrad run
Turbulence inside convective systems

Subgrid TKE and cloud (gray shading) at 8000 m AGL - 10 UTC (24 September 2012)
Turbulence inside convective systems

Kgrad (Δx = 500 m) TKE

Hgrad (Δx = 500 m) TKE

Subgrid TKE and cloud (gray shading) at 8000 m AGL - 10 UTC (24 September 2012)
Turbulence inside convective systems

Kgrad ($\Delta x = 500$ m)

Hgrad ($\Delta x = 500$ m)

Subgrid TKE and cloud (gray shading) at 8000 m AGL - XX UTC (24 September 2012)
Turbulence and vertical velocity inside convective systems

Mean vertical profiles inside convective clouds between 21 UTC 23 September and 10 UTC 24 September 2012

→ more subgrid TKE with the Hgrad run compared to the Kgrad run
→ less intense vertical velocity in updraft cores (W > 5 m/s)
→ better balance between resolved and subgrid parts
Mean vertical profiles inside convective clouds between 21UTC 23 September and 10 UTC 24 September 2012

- More subgrid Thermal Production with the Hgrad run compared to the Kgrad run
- This explains the larger TKE with the Hgrad run, this induces more dynamical production (from TKE)
Hydrometeor mixing ratio

Mean vertical profiles between 21UTC 23 September and 00 UTC 24 September 2012

→ more ice, snow, and graupel with the Hgrad run compared to the Kgrad run
→ more developed anvils
Conclusion

- Characterization of turbulence from reference LES
  - strong subgrid TKE inside convective clouds
  - countergradient areas for turbulent fluxes due to coherent structures → nonlocal turbulence
- Off-line and online evaluations of turbulence parameterizations inside convective clouds
  - K-gradient formulations not suitable: too weak subgrid TKE and too strong vertical velocity
  - better representation with a parameterization based on horizontal gradients (Moeng et al, 2010)
    - better vertical turbulent fluxes of heat and water mixing ratio
    - better balance between subgrid and resolved parts
  - generalization: better vertical and horizontal turbulent fluxes of heat and moisture, slightly better dynamical covariances but better dynamical variances with CBR scheme
- Online evaluation of a new turbulence scheme on real cases of deep convection (IOP6 and IOP16)
  → Need for fine-scale observations of turbulence inside convective clouds (Feist et al, 2019)
Conclusion

EDR estimates from RASTA data for IOP5 (EXAEDRE field campaign)
10 October 2018: convection over the Gulf of Genoa

Ronan Houël (Master of Science, D. Ricard, J. Delanoë)
Conclusion

EDR estimates from RASTA data for IOP5 (EXAEDRE field campaign) 10 October 2018: convection over the Gulf of Genoa

Ronan Houël (Master of Science, D. Ricard, J. Delanoë)

Thank you for your attention
Turbulence inside convective systems

Kgrad ($\Delta x = 500 \text{ m}$)

Hgrad ($\Delta x = 500 \text{ m}$)

Subgrid TKE and cloud (gray shading) at 8000 m AGL - XX UTC (24 September 2012)
Turbulent fluxes inside convective systems

Mean vertical profiles inside convective clouds between 21 UTC 23 September and 10 UTC 24 September 2012

- $\overline{w'\theta'}$ (K m s$^{-1}$)
- $\overline{w'r'_{np}}$ (kg kg$^{-1}$ m s$^{-1}$)

Hgrad (2 km)
Kgrad (2 km)

→ more intense subgrid turbulent fluxes the Hgrad run compared to the Kgrad run
Time evolution of high cloud cover (Tb < 230 K)

Time evolution of high cloud cover between 00 UTC and 12 UTC 24 September 2012

Brightness temperature (K) 9:00 UTC

→ more anvils with Hgrad run compared to the Kgrad run
Time evolution of high cloud cover (Tb < 230 K)

Time evolution of high cloud cover between 00 UTC and 12 UTC 24 September 2012

Brightness temperature (K) 9:00 UTC

Hgrad (2 km)

→ more anvils with Hgrad run compared to the Kgrad run
Time evolution of high cloud cover (Tb < 230 K)

Time evolution of high cloud cover between 00 UTC and 12 UTC 24 September 2012

Observations

Brightness temperature (K) 9:00 UTC

→ more anvils with Hgrad run compared to the Kgrad run
→ more differences at 2 km resolution
→ underestimation in comparison with observations
Mean vertical profiles inside convective clouds between 00UTC 26 October and 00 UTC 27 October 2012

- more subgrid Thermal Production with the Hgrad run compared to the Kgrad run
- this explains the larger TKE with the Hgrad run, this induces more dynamical production (from TKE)
- For IOP6, there is a larger contribution of dynamical production than for IOP16 (strong wind shear)
Evaluation on real cases: HyMeX campaign over the Mediterranean area

- Evaluation on IOP16 (26 October 2012) and IOP6 (24 September 2012)
  - heavy rainfall over Southern France (more than 150 mm/24h)
  - 15-h and 24-h simulations with different horizontal resolutions: 2 km, 1 km and 500 m (initialization from AROME WMED reanalyses)
  - new scheme applied above 2000 m (with c=3) → Hgrad runs
  - comparison with the current scheme → Kgrad runs

IOP16: Brightness temperature (K) 9:30 UTC

IOP6: Brightness temperature (K) 7:00 UTC
12-h accumulated precipitation

→ Large rainfall accumulation over the orography (00 → 12 UTC)
12-h accumulated precipitation

→ Large rainfall accumulation over the orography (00 → 12 UTC)
12-h accumulated precipitation

- Large rainfall accumulation over the orography (00 - 12 UTC)
- Good location and precipitation pattern, propagating line
- Underestimation over the South Alps area
- Slight increase in precipitation with Hgrad run

Kgrad run (2 km) Mean: 3.16 mm

Hgrad run (2 km) Mean: 3.22 mm
12-h accumulated precipitation

- Large rainfall accumulation over the orography (00 → 12 UTC)
- Good location and precipitation pattern, propagating line
- Underestimation over the South Alps area
- Slight increase in precipitation with finer resolution
12-h accumulated precipitation

- Large rainfall accumulation over the orography (00 → 12 UTC)
- Good location and precipitation pattern, propagating line
- Underestimation over the South Alps area
- Slight increase in precipitation with finer resolution
24-h accumulated precipitation (IOP16)

Objectives scores

![Objectives scores graphs][1]

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[1]: #/file.png
12-h accumulated precipitation (IOP6)

Objectives scores

![Graphs showing Objectives scores for HGRAD and KGRAD, with different plots for POD, EAR, HSS, and Fbias against threshold (mm)].
Time evolution of high cloud cover (Tb < 230 K)

Time evolution of high cloud cover between 00 UTC and 12 UTC 24 September 2012

- more anvils with Hgrad run compared to the Kgrad run
- more differences at 2 km resolution
- underestimation in comparison with observations
Impact on convective systems

→ Good vertical extension of convective systems
→ Underestimation of reflectivity
→ Higher reflectivity in the upper part of the clouds with the Hgrad run
Turbulence inside convective systems

\[ \text{Kgrad (}\Delta x = 2 \text{ km)} \]

\[ \text{Hgrad (}\Delta x = 2 \text{ km)} \]

Subgrid TKE and cloud (gray shading) at 8000 m AGL - 11 UTC (26 October 2012)
Turbulence inside convective systems

Subgrid TKE and cloud (gray shading) at 8000 m AGL - 11 UTC (26 October 2012)
Turbulence inside convective systems

\[ K_{\text{grad}} (\Delta x = 2 \text{ km}) \]

\[ H_{\text{grad}} (\Delta x = 2 \text{ km}) \]
Turbulence inside convective systems

Kgrad (Δx = 2 km) and Hgrad (Δx = 2 km) at TKE.

Subgrid TKE and cloud (gray shading) at 8000 m AGL - XX UTC (24 September 2012).
Cold pools under convective systems IOP6

Vertical velocity at 600 m AGL
$\theta_v (K)$ at 10 m AGL 02:30 UTC

Kgrad ($\Delta x = 2$ km)

→ differences in cold pool extension
→ differences in lifting of the low-level inflow
Cold pools under convective systems IOP16

Vertical velocity at 600 m AGL $\theta_v$ (K) at 10 m AGL 11:00 UTC

$K_{\text{grad}} (\Delta x = 2 \text{ km})$

$H_{\text{grad}} (\Delta x = 2 \text{ km})$

→ differences in cold pool extension  
→ differences in lifting of the low-level inflow
24-h accumulated precipitation

- Large rainfall accumulation over the Sea and over the orography
- Overestimation over the Cévennes area
- Underestimation over the South Alps area
- Slight increase in precipitation with **Hgrad run**

**Kgrad run** (2 km) Mean: 12.62 mm

**Hgrad run** (2 km) Mean: 12.9 mm
Mean vertical profiles inside convective clouds between 00UTC 26 October and 00 UTC 27 October 2012

- More subgrid TKE with the Hgrad run compared to the Kgrad run
- Less intense vertical velocity in updraft cores (W > 5 m/s)
- Better balance between resolved and subgrid parts
Mean vertical profiles between 00UTC 26 October and 00 UTC 27 October 2012

- More ice, snow, and graupel with the Hgrad run compared to the Kgrad run
Evaluation on real cases: HyMeX campaign over the Mediterranean area

- Evaluation on IOP6 (24 September 2012)
  - heavy rainfall over Southern France (more than 150 mm/24h)
  - 15-h simulations with different horizontal resolutions: 2 km, 1 km and 500 m (initialization from AROME WMED reanalyses)
  - new scheme applied above 2000 m (with c=3) → Hgrad runs
  - comparison with the current scheme → Kgrad runs
Evaluation on real cases: HyMeX campaign over the Mediterranean area

- **Evaluation on IOP6 (24 September 2012)**
  - heavy rainfall over Southern France (more than 150 mm/24h)
  - 15-h simulations with different horizontal resolutions: **2 km, 1 km** and **500 m** (initialization from AROME WMED reanalyses)
  - new scheme applied above 2000 m (with c=3) → **Hgrad runs**
  - comparison with the current scheme → **Kgrad runs**
  - convection triggers over the Massif Central during the night

**Brightness temperature (K) 3:00 UTC**

**Radar reflectivity (dBZ) 3:00 UTC**
Evaluation on real cases: HyMeX campaign over the Mediterranean area

- Evaluation on IOP6 (24 September 2012)
  - Heavy rainfall over Southern France (more than 150 mm/24h)
  - 15-h simulations with different horizontal resolutions: 2 km, 1 km, and 500 m (initialization from AROME WMED reanalyses)
  - New scheme applied above 2000 m (with c=3) → Hgrad runs
  - Comparison with the current scheme → Kgrad runs
  - Convection triggers over the Massif Central during the night
  - A convective line develops, fastly moving eastward during the night and the morning

![Brightness temperature (K) 10:00 UTC](image1)

![Radar reflectivity (dBZ) 10:00 UTC](image2)
Configuration with Meso-NH (Lafore et al. 1997, Lac et al, 2018):

1.5 order turbulence scheme: pronostic TKE (Cuxart et al, 2000) with Bougeault-Lacarrère mixing length

One-moment microphysical scheme: ICE3 (ice, cloud, rain, graupel, snow)

Shallow convection scheme (2km, 1km)

Thermodynamical fluxes (thermal production) based on:

**K-gradient formulation**  \((Cuxart et al, 2000)\)

\[
\overline{w' \theta'_i} = -K \frac{\partial \overline{\theta_i}}{\partial z}
\]

\[K = A L e^{1/2}\]

**H-gradient formulation**  \((Moeng, 2014)\)

\[
\overline{w' \theta'_i} = C \left( \frac{\partial w}{\partial x} \frac{\partial \overline{\theta_i}}{\partial x} + \frac{\partial w}{\partial y} \frac{\partial \overline{\theta_i}}{\partial y} \right)
\]

\[C = c \Delta x^2/12\]

\[c = 3\]

\[
\overline{w' r'_{np}} = C \left( \frac{\partial w}{\partial x} \frac{\partial \overline{r_{np}}}{\partial x} + \frac{\partial w}{\partial y} \frac{\partial \overline{r_{np}}}{\partial y} \right)
\]
Evaluation of turbulence parameterization

REF LES  
**Vertical distribution at t=135 min**

Hgrad MOENG

**Off-line evaluation** $\overline{w'θ_l}$ (m s$^{-1}$ kg kg$^{-1}$)

Thermodynamical fluxes:
Better distribution with Hgrad
Evaluation of turbulence parameterization

Off-line evaluation: \( \overline{w'w'} \) (\( m^2 s^{-2} \))

Thermodynamical fluxes:
Better distribution with Hgrad

Dynamical fluxes:
Slightly better with Hgrad but better variances with CBR

Vertical distribution at t=135 min

REF LES
Hgrad MOENG
CBR
SMAG