Cloud working week
16-18 January 2017, Toulouse, France

Didier Ricard, Antoine Verrelle, Christine Lac, Nicolas Rochetin
CNRM, (Météo-France CNRS), Toulouse, France

Representation of turbulence in simulations of deep convective clouds

Introduction

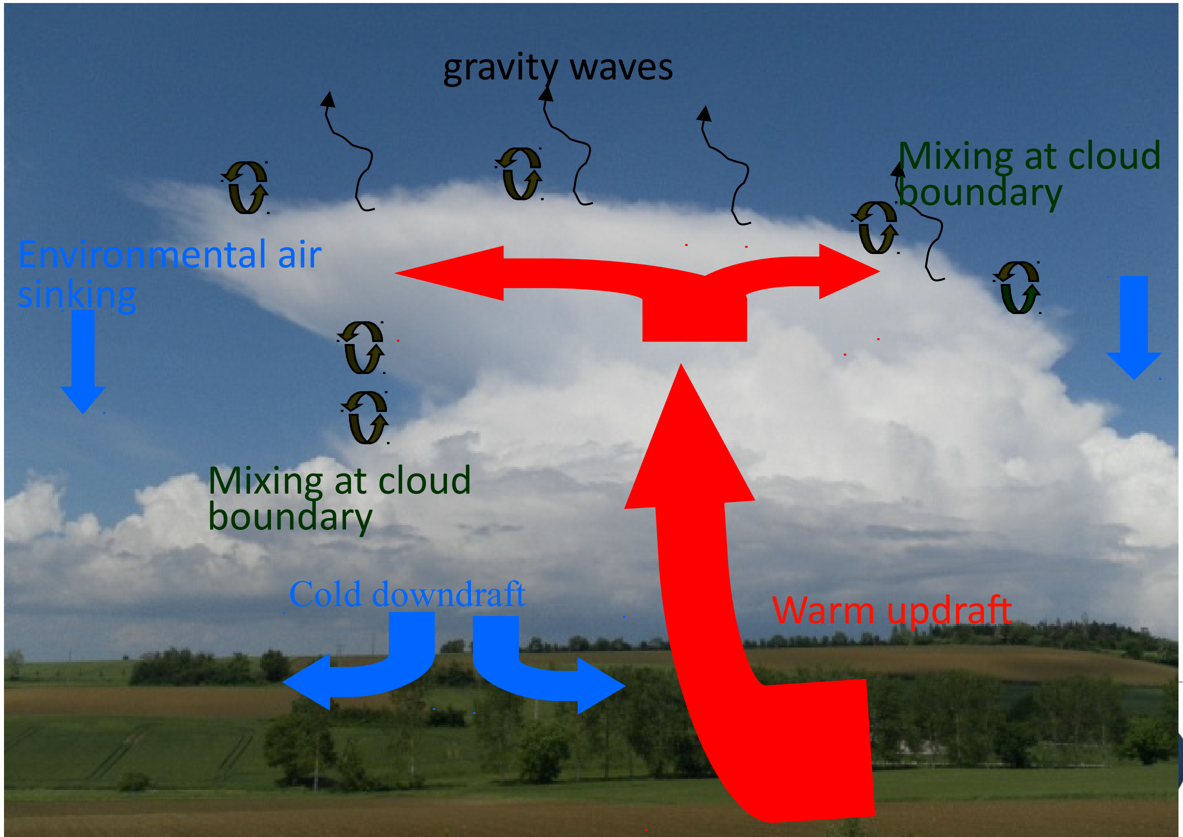
Turbulence: studied extensively in the atmospheric boundary layer

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

→ 1 - Idealized Large-Eddy Simulations of deep convection with the Meso-NH model

→ 2 - Characterization of turbulence inside convective clouds

→ 3 - Evaluation and improvement of turbulence parameterization



Configuration with Meso-NH:

1.5 order turbulence scheme: pronostic TKE (Cuxart et al. 2000) with Deardorff mixing length

one-moment microphysical scheme ICE3 (ice, cloud water, graupel, snow,rain)

no radiation scheme

no Coriolis force

surface fluxes: H, LE

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1 - LES of deep convective clouds

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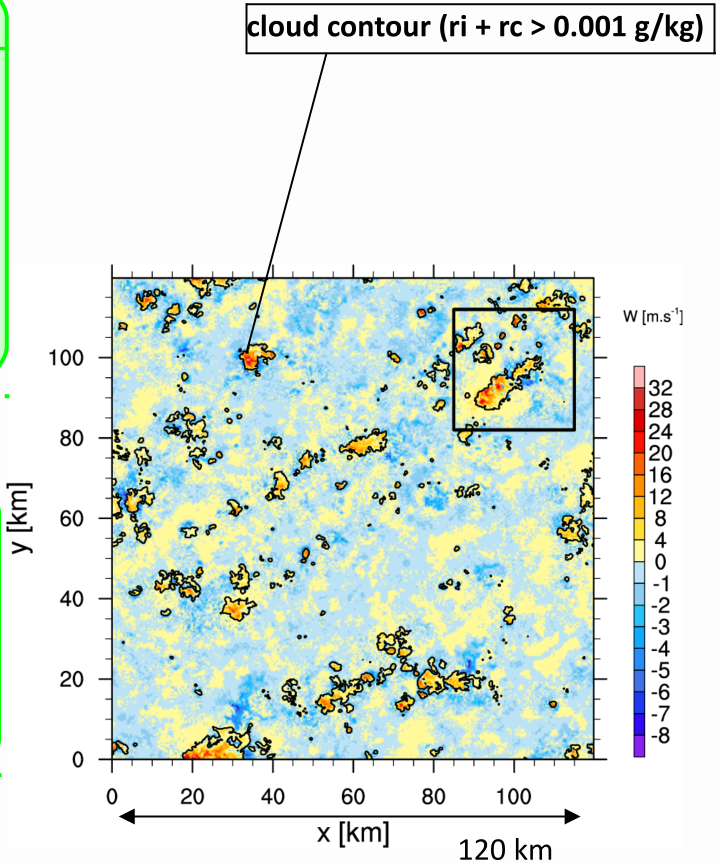
Initial conditions:

Unstable conditions from idealized profiles Weisman and Klemp (1982)

Moderate vertical wind shear

White noise on low-level θ

Horizontal cross section of vertical velocities (m/s) at 6 km AGL t= 175 min



$\Delta x, \Delta y$ = 200m Δz = 50m

600x600 points x 293 levels
~105 millions points

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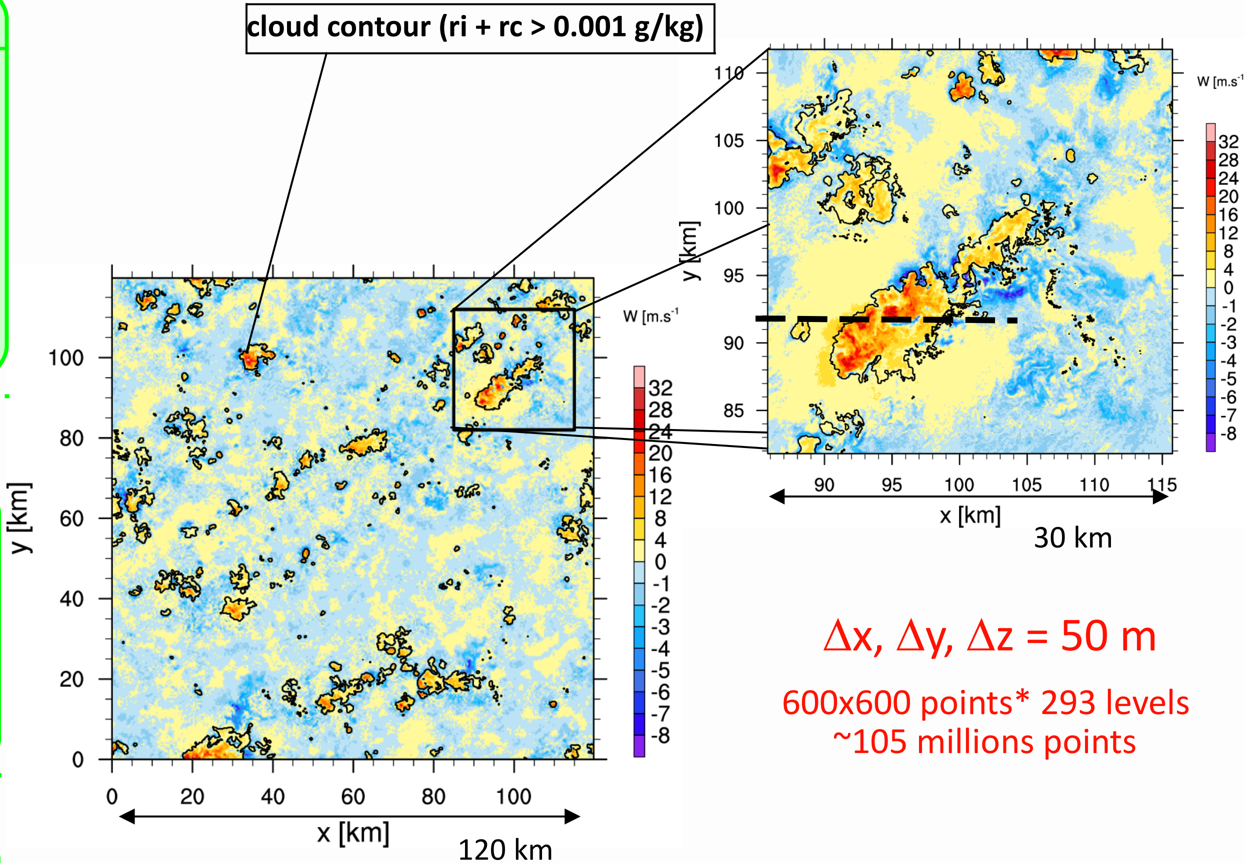
Grid-nesting configuration:

2 domains (one-way nesting)

Horizontal cross section of vertical velocities (m/s) at 6 km AGL t= 175 min



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Δx, Δy, Δz = 50 m

600x600 points* 293 levels
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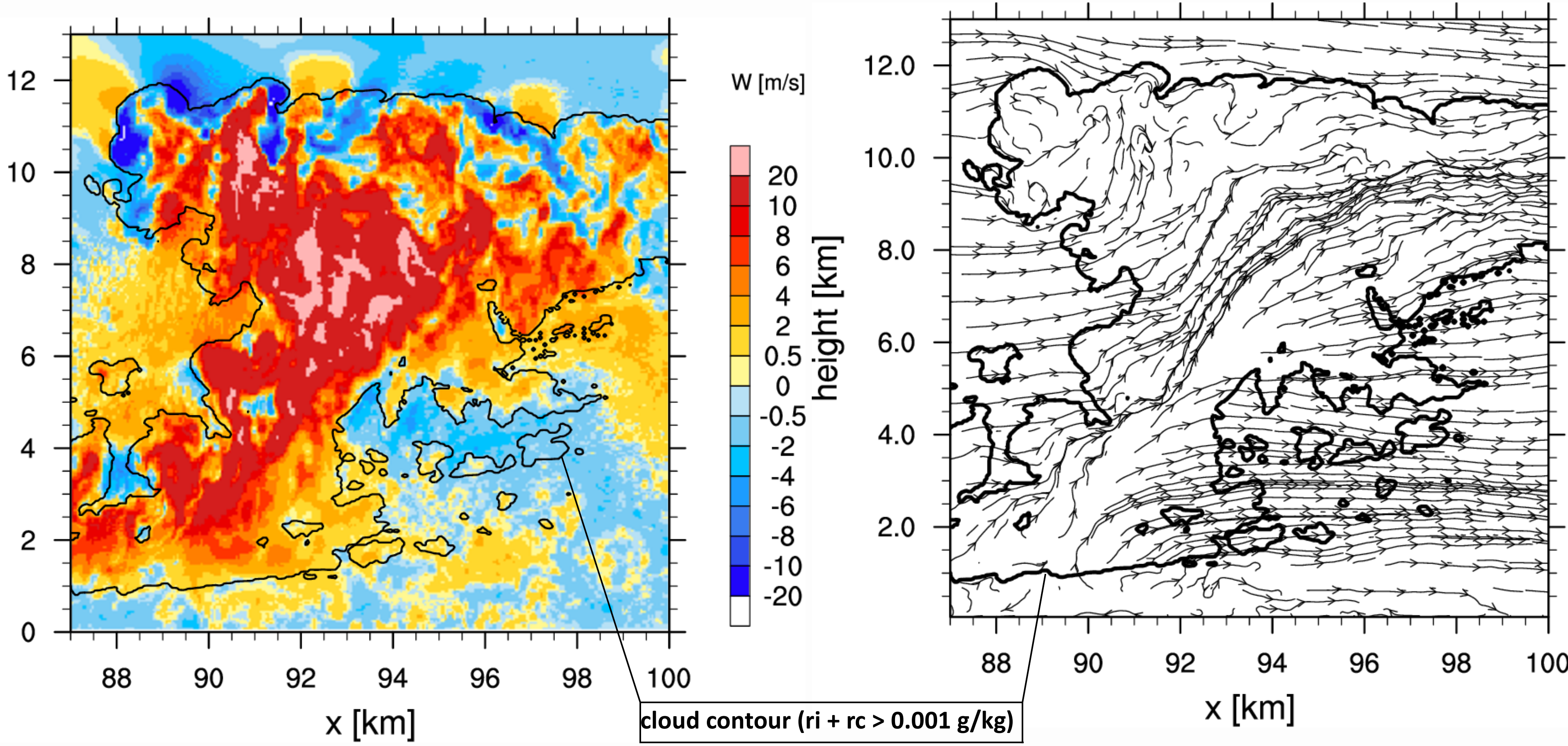
1 - LES of deep convective clouds

Vertical cross sections at 175 min: W (m/s)

Streamlines



→ well-developed cumulonimbus with a strong updraft and many eddies

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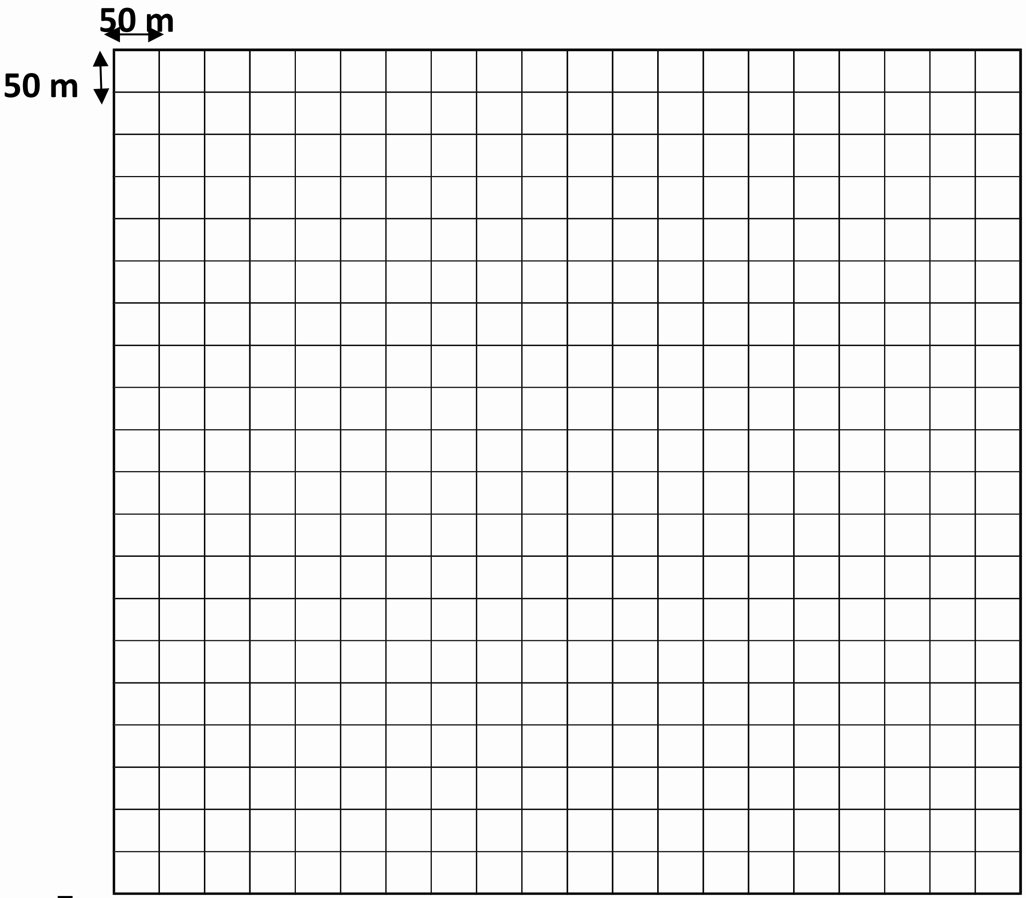
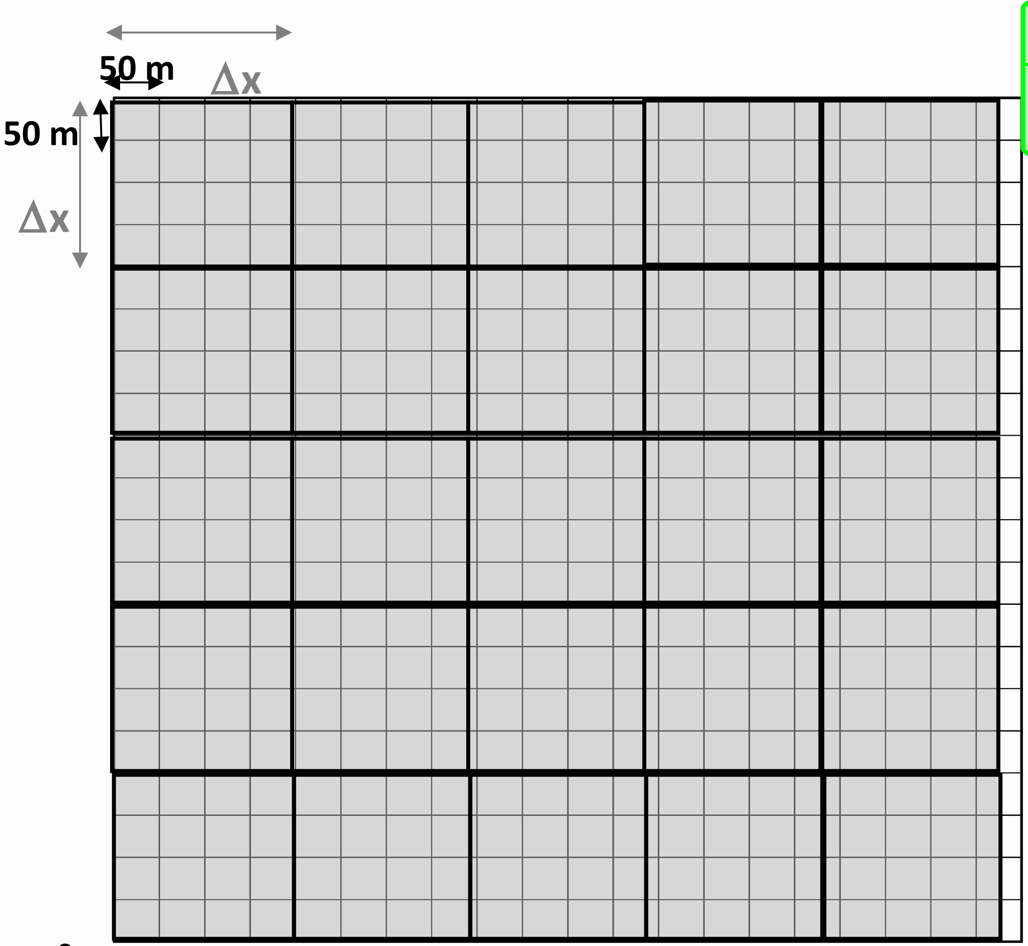
- LES: reference simulation (50-m grid spacing)



2 – Characterization of turbulence inside convective clouds

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



Computation of terms at Δx:

$$\overline{u}^{\Delta_x}, \overline{v}^{\Delta_x}, \overline{w}^{\Delta_x}, \overline{r_{np}}^{\Delta_x}, \overline{\theta_l}^{\Delta_x}, \ldots$$

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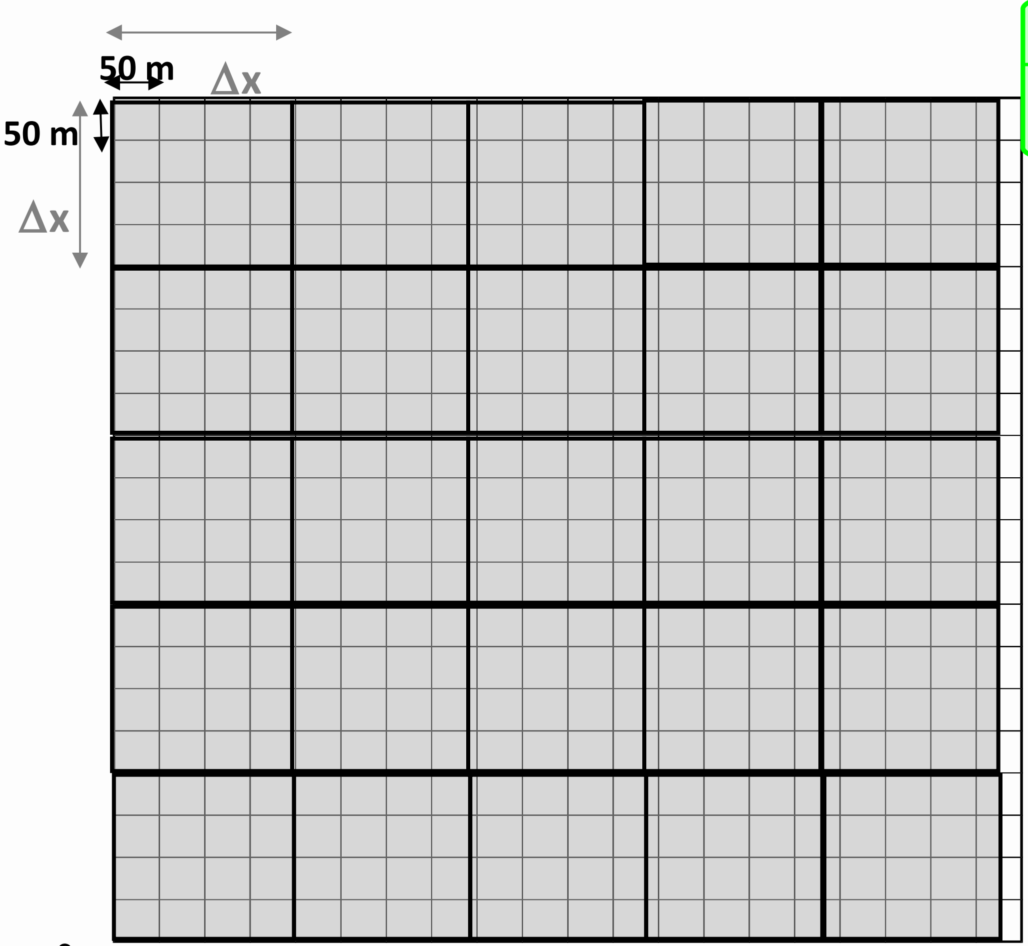

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$$\overline{u}^{\Delta x}, \overline{v}^{\Delta x}, \overline{w}^{\Delta x}, \overline{r_{np}}^{\Delta x}, \overline{\theta_l}^{\Delta x}, \ldots$$

$$u'_i = (u_i - \overline{u_i}^{\Delta x})$$

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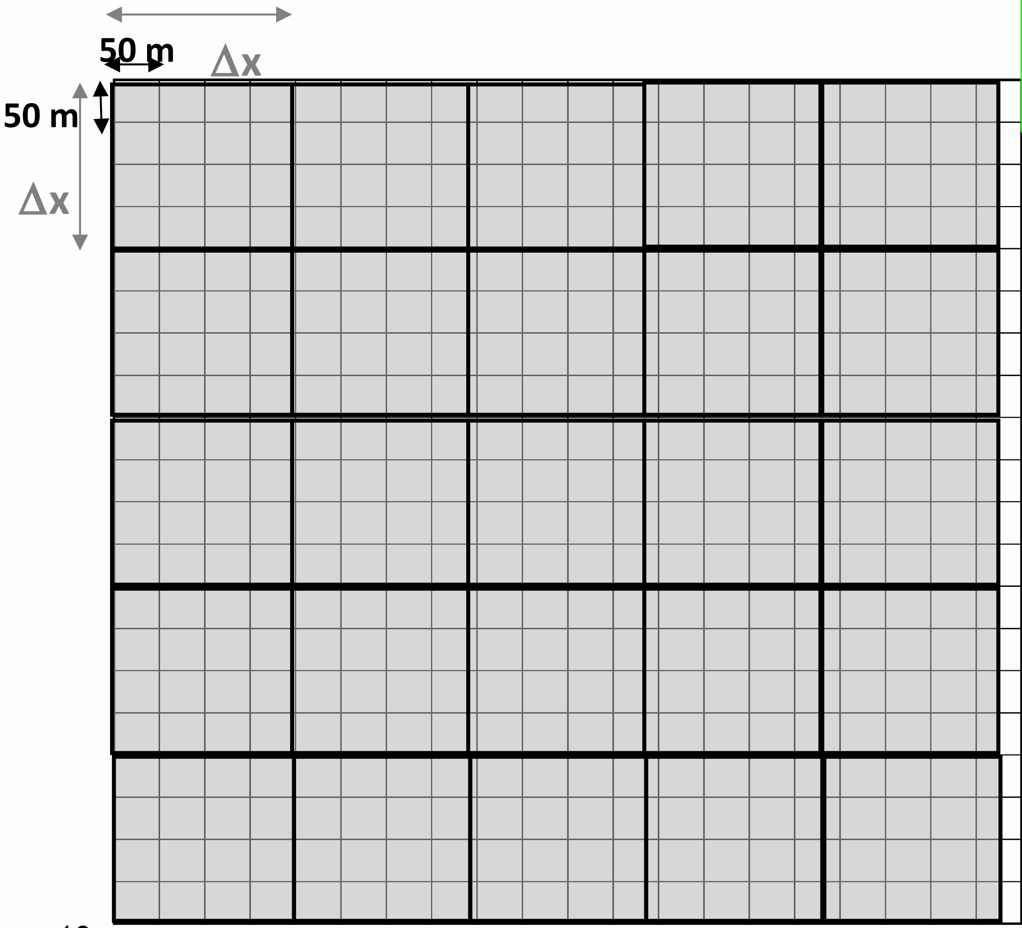


Computation of terms at Δx:

$$\overline{u}^{\Delta_x}, \overline{v}^{\Delta_x}, \overline{w}^{\Delta_x}, \overline{r_{np}}^{\Delta_x}, \overline{\theta_l}^{\Delta_x}, \ldots$$

$$u_i' = (u_i - \overline{u_i}^{\Delta_x})$$

Computation of subgrid terms at Δx:

- turbulent fluxes:

$$\overline{u'v'}^{\Delta_x}, \overline{u'w'}^{\Delta_x}, \overline{v'w'}^{\Delta_x}, \overline{w'r'_{np}}^{\Delta_x}, \overline{w'\theta'_l}^{\Delta_x}, \ldots$$

$$\overline{u'_i u'_j}^{\Delta_x} = \overline{(u_i - \overline{u_i}^{\Delta_x})(u_j - \overline{u_j}^{\Delta_x})}^{\Delta_x} + \overline{f^{u'_i u'_j}}^{\Delta_x}$$

- variances:

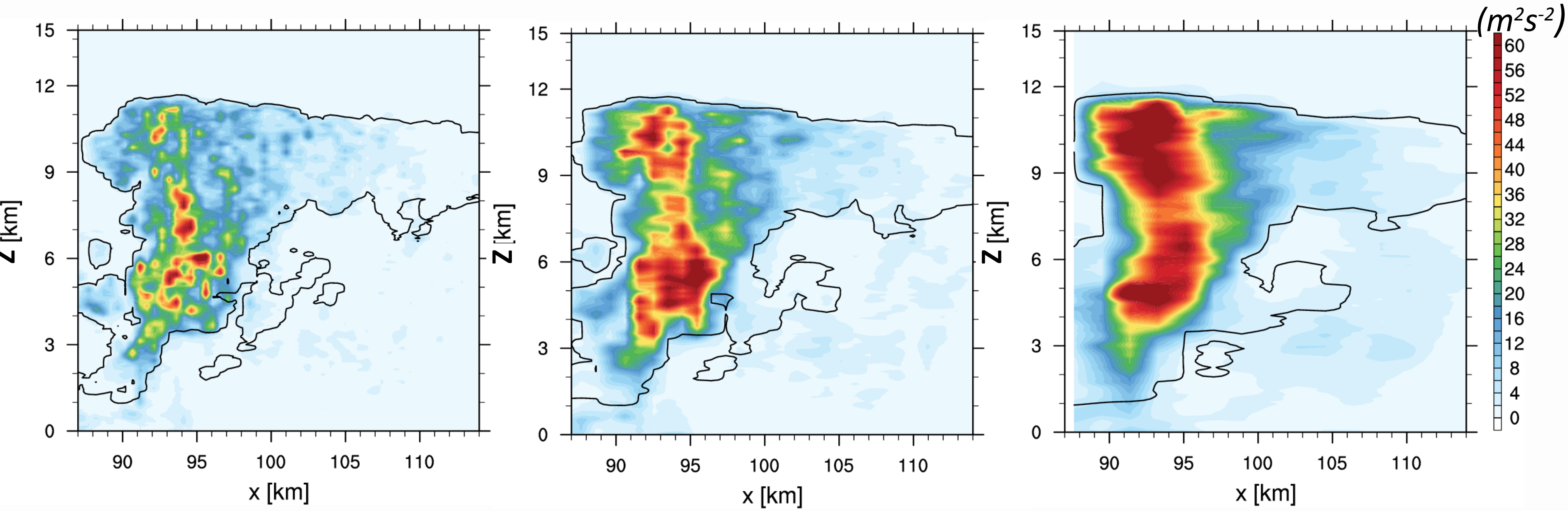
$$\overline{u'^2}^{\Delta_x}, \overline{v'^2}^{\Delta_x}, \overline{w'^2}^{\Delta_x}, \overline{r'^2_{np}}^{\Delta_x}, \overline{\theta'^2_l}^{\Delta_x}, \ldots$$

-TKE:

$$\overline{e}^{\Delta_x}_{ref} = \frac{1}{2}(\overline{u'^2}^{\Delta_x} + \overline{v'^2}^{\Delta_x} + \overline{w'^2}^{\Delta_x})$$

2 – Characterization of turbulence inside convective clouds

Vertical cross sections: TKE for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



$\overline{e}$ Δx=500m

$\overline{e}$ Δx= 1km

$\overline{e}$ Δx= 2km

→strong turbulence inside the cloud
→subgrid TKE increases with coarser resolutions

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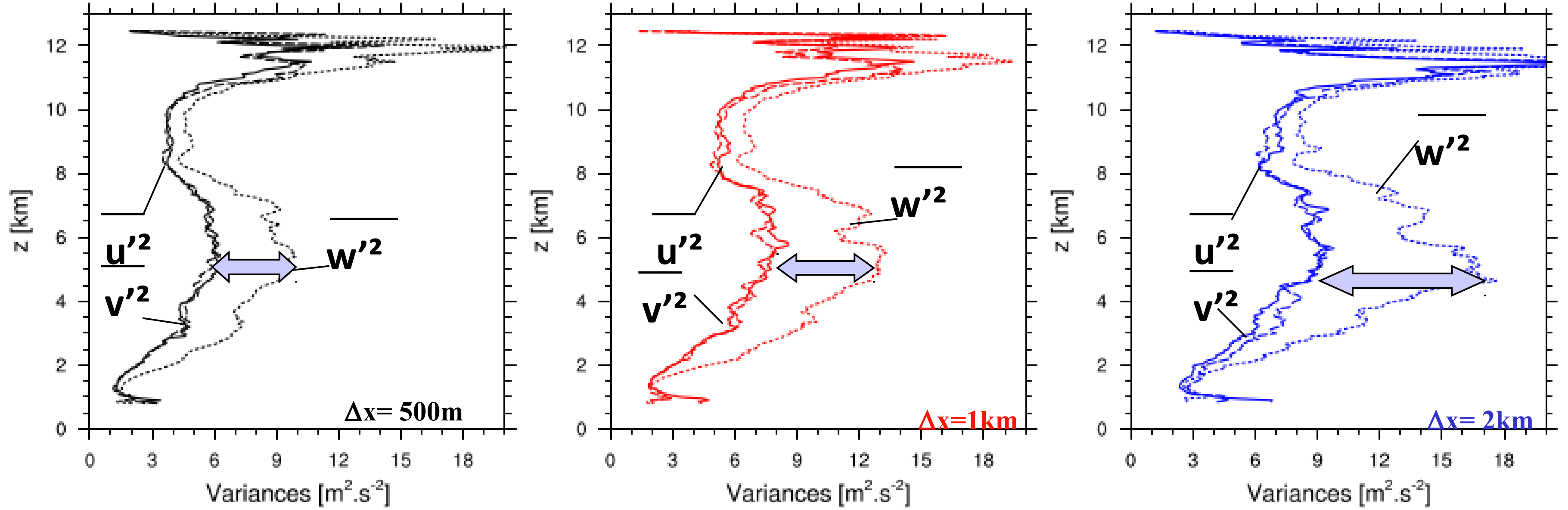
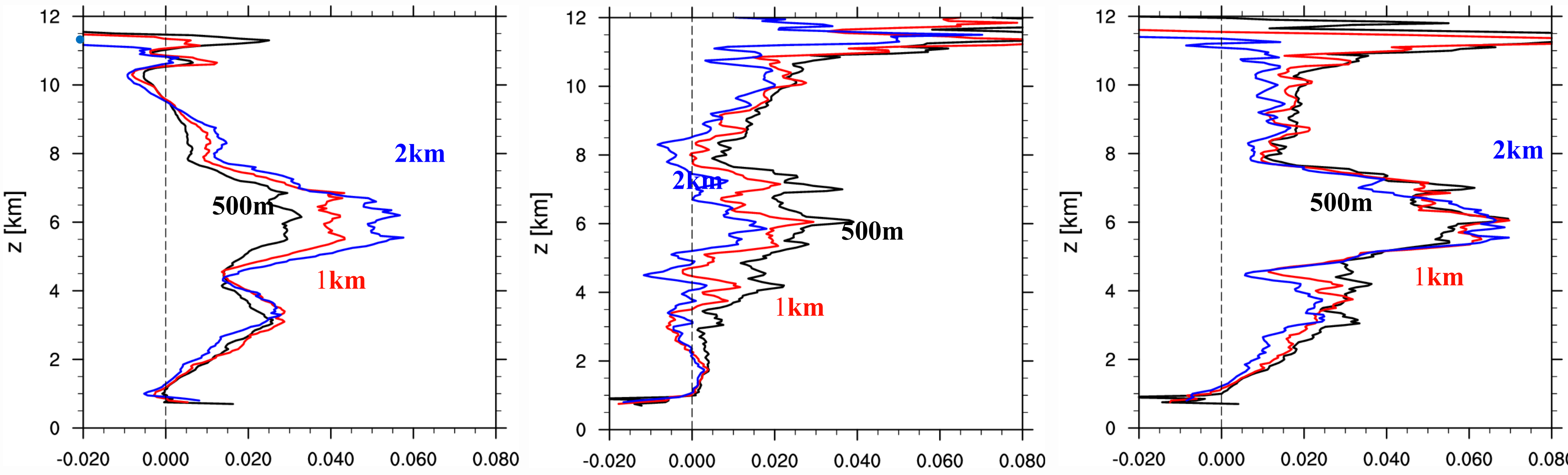
Vertical profiles: wind variances for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



→ variance of w is greater than variances of u and v: anisotropy
→ anisotropy increases with coarser resolutions

2 – Characterization of turbulence inside convective clouds

Vertical profiles: subgrid thermal and dynamical productions (m²/s³) for different Δx t= 175 min

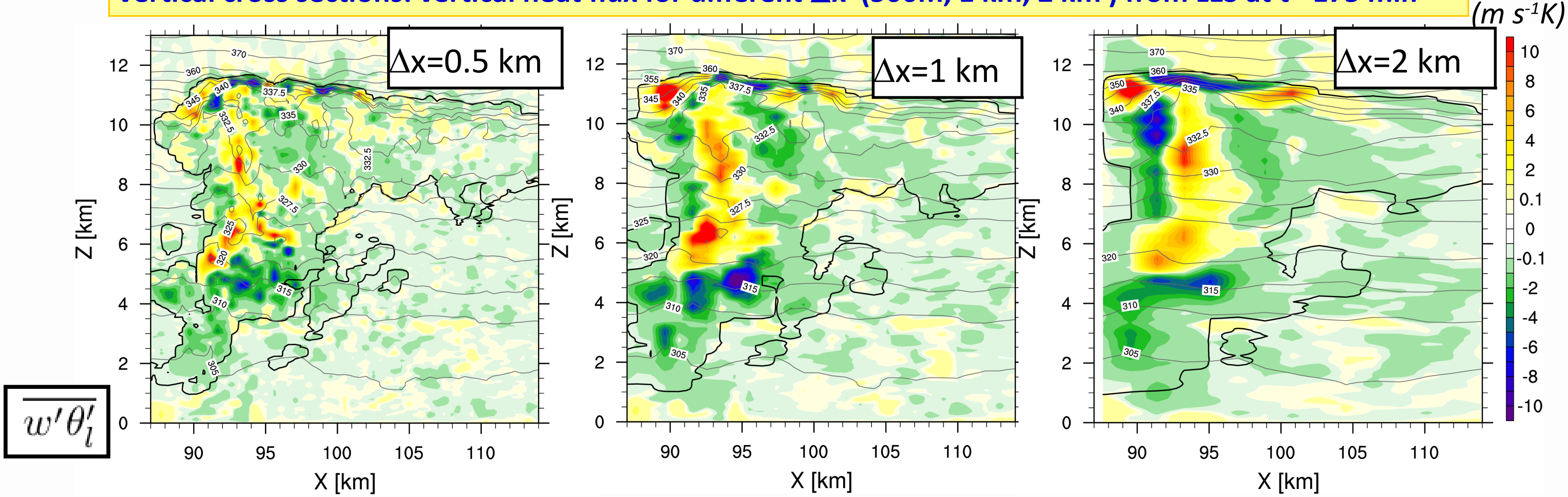


Thermal Production (TP) Dynamical Production (DP) TP + DP

- TP increases with coarser resolutions: 500m → 1km → 2km
- DP decreases with coarser resolutions (horizontal gradients)
- Sum seems quite similar (compensation between DP and TP?)

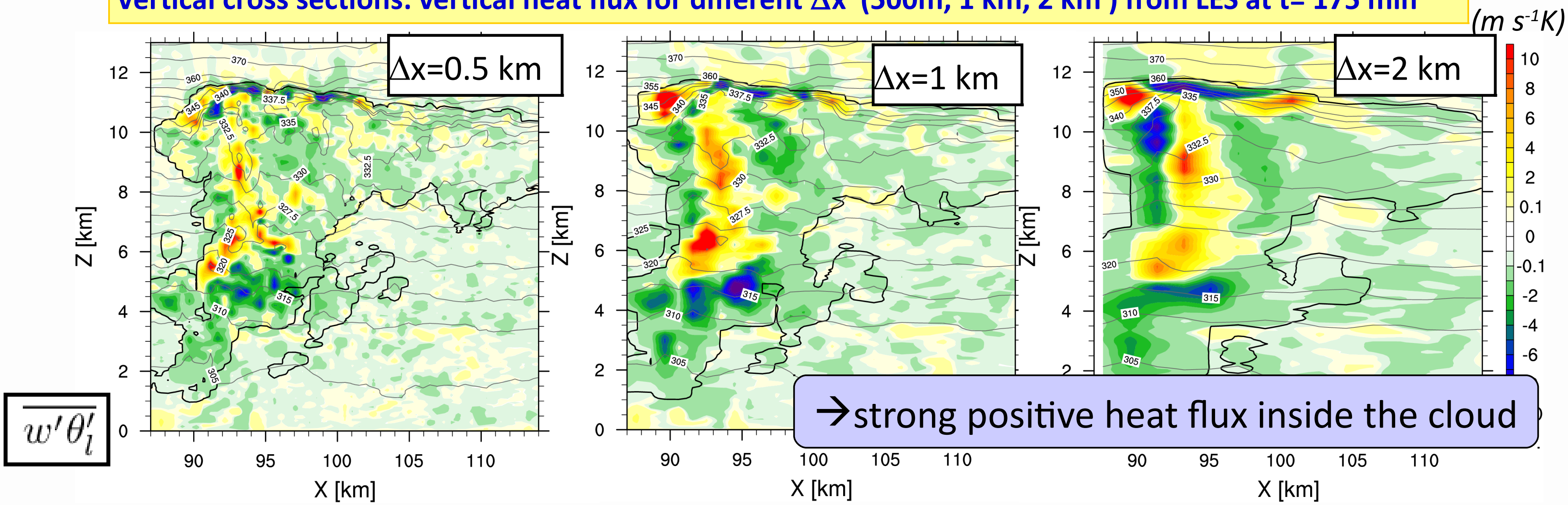
2 – Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



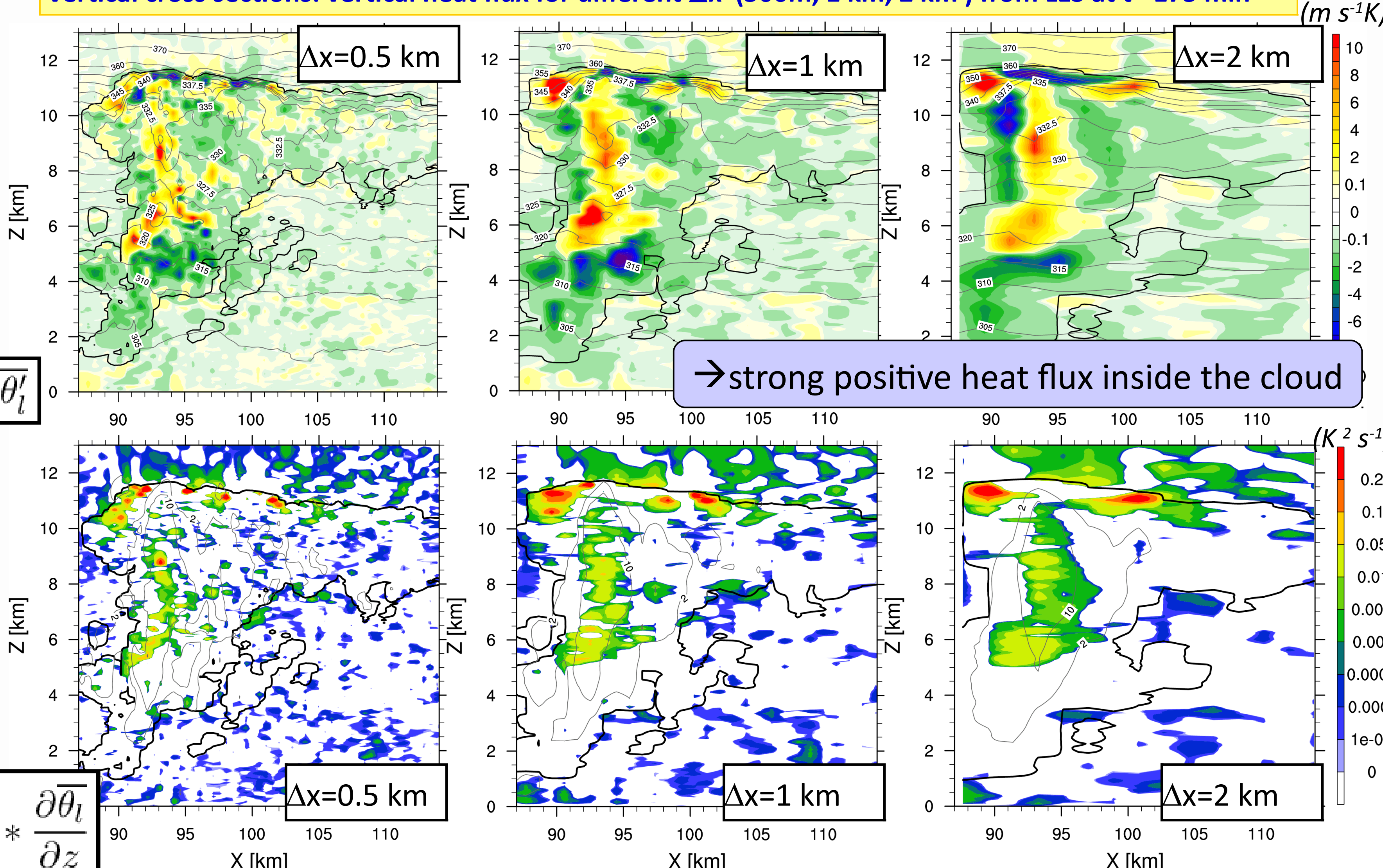
2 – Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



→strong positive heat flux inside the cloud

Vertical cross sections: vertical heat flux for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



$$\overline{w'\theta_l'}$$

→strong positive heat flux inside the cloud

$$\overline{w'\theta_l'} * \frac{\partial\overline{\theta_l}}{\partial z}$$

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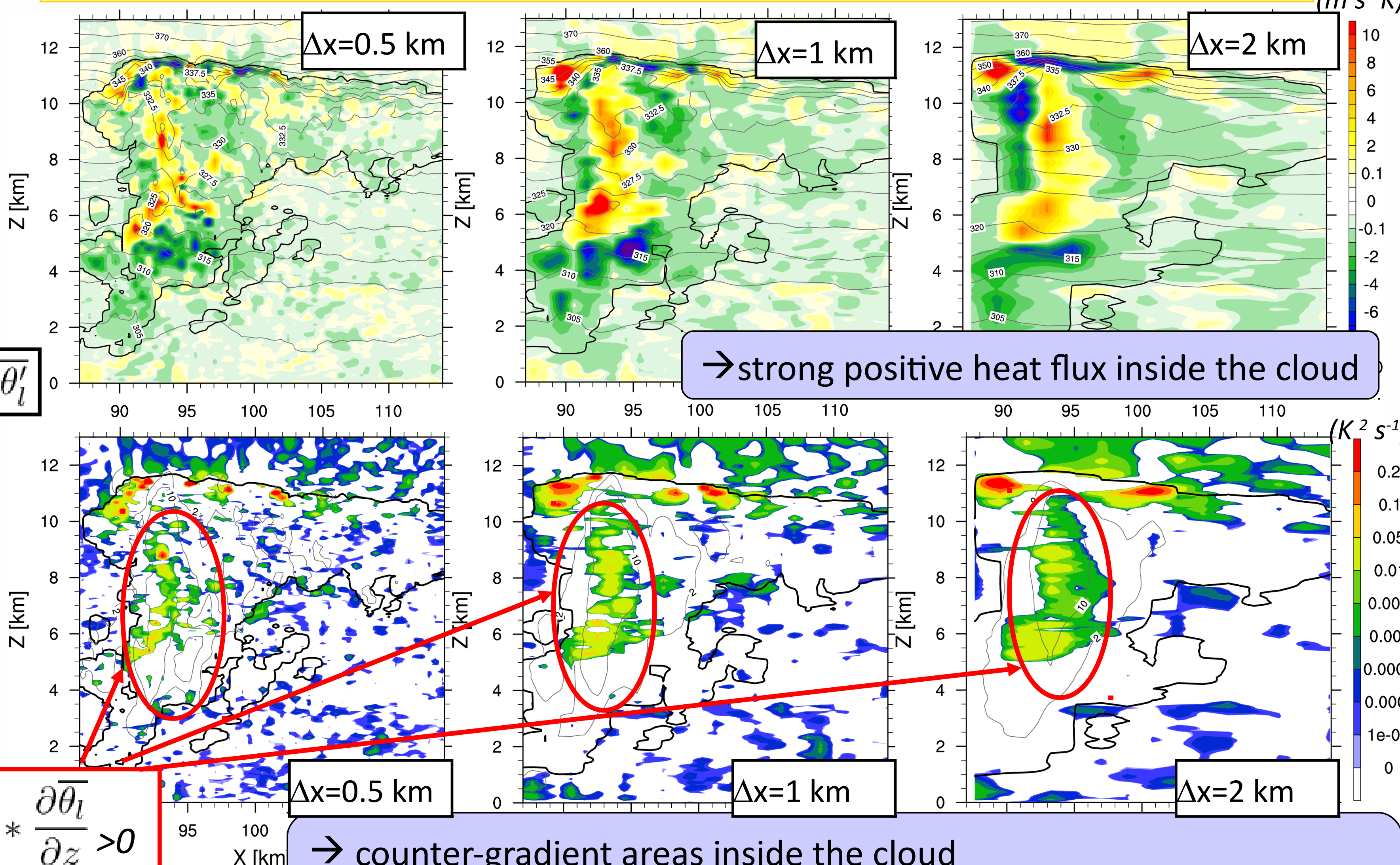
2 – Characterization of turbulence inside convective clouds

Vertical cross sections: vertical heat flux for different Δx (500m, 1 km, 2 km) from LES at t= 175 min



→strong positive heat flux inside the cloud

$\overline{w'\theta_l'} * \frac{\partial \overline{\theta_l}}{\partial z} > 0$

→ counter-gradient areas inside the cloud
→ coherent structures in the updraft
→ non-local turbulence, analogy with the convective boundary layer

3 – Evaluation of turbulence parameterization

Off-line evaluation: computation of parameterized fluxes from LES at Δx -> $\overline{w'\theta_l'}$

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Kgrad

Cuxart et al (2000)

$$\overline{w'\theta_l'}^{\Delta_x} = -\frac{2}{3C_{p\theta}}\overline{\phi_i}^{\Delta_x} L\sqrt{\overline{e}_{ref}^{\Delta_x}}\frac{\partial\overline{\theta_l}^{\Delta_x}}{\partial z}$$

based on K-gradient: $\overline{w'\theta_l'} = -K\frac{\partial\overline{\theta_l}}{\partial z}$

Off-line evaluation: computation of parameterized fluxes from LES at Δx -> $\overline{w'\theta'_l}$

Kgrad

Cuxart et al (2000)

$$\overline{w'\theta'_l}^{\Delta_x} = -\frac{2}{3C_{p\theta}}\overline{\phi_i}^{\Delta_x} L\sqrt{\overline{e}^{\Delta_x}_{ref}}\frac{\partial\overline{\theta_l}^{\Delta_x}}{\partial z}$$

based on K-gradient: $\overline{w'\theta'_l} = -K\frac{\partial\overline{\theta_l}}{\partial z}$

Hgrad

Moeng et al (2010)

$$\overline{w'\theta'_l}^{\Delta_x} = C_{\Delta_x}(\frac{\partial\overline{w}^{\Delta_x}}{\partial x}\frac{\partial\overline{\theta_l}^{\Delta_x}}{\partial x} + \frac{\partial\overline{w}^{\Delta_x}}{\partial y}\frac{\partial\overline{\theta_l}^{\Delta_x}}{\partial y})$$

based on horizontal gradients: $\overline{w'\theta'_l} = C(\frac{\partial\overline{w}}{\partial x}\frac{\partial\overline{\theta_l}}{\partial x} + \frac{\partial\overline{w}}{\partial y}\frac{\partial\overline{\theta_l}}{\partial y})$

related to a mass flux (Moeng, 2014)

Off-line evaluation: computation of parameterized fluxes from LES at Δx -> $\overline{w'r'_{np}}$

Kgrad

Cuxart et al (2000)

$$\overline{w'r'_{np}}^{\Delta_x} = -\frac{2}{3C_{pr}}\overline{\phi_i}^{\Delta_x} L\sqrt{\overline{e}_{ref}^{\Delta_x}}\frac{\partial \overline{r_{np}}^{\Delta_x}}{\partial z}$$

based on K-gradient: $\overline{w'r'_{np}} = -K\frac{\partial \overline{r_{np}}}{\partial z}$

Hgrad

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$$\overline{w'r'_{np}}^{\Delta_x} = C_{\Delta_x}\left(\frac{\partial \overline{w}^{\Delta_x}}{\partial x}\frac{\partial \overline{r_{np}}^{\Delta_x}}{\partial x} + \frac{\partial \overline{w}^{\Delta_x}}{\partial y}\frac{\partial \overline{r_{np}}^{\Delta_x}}{\partial y}\right)$$

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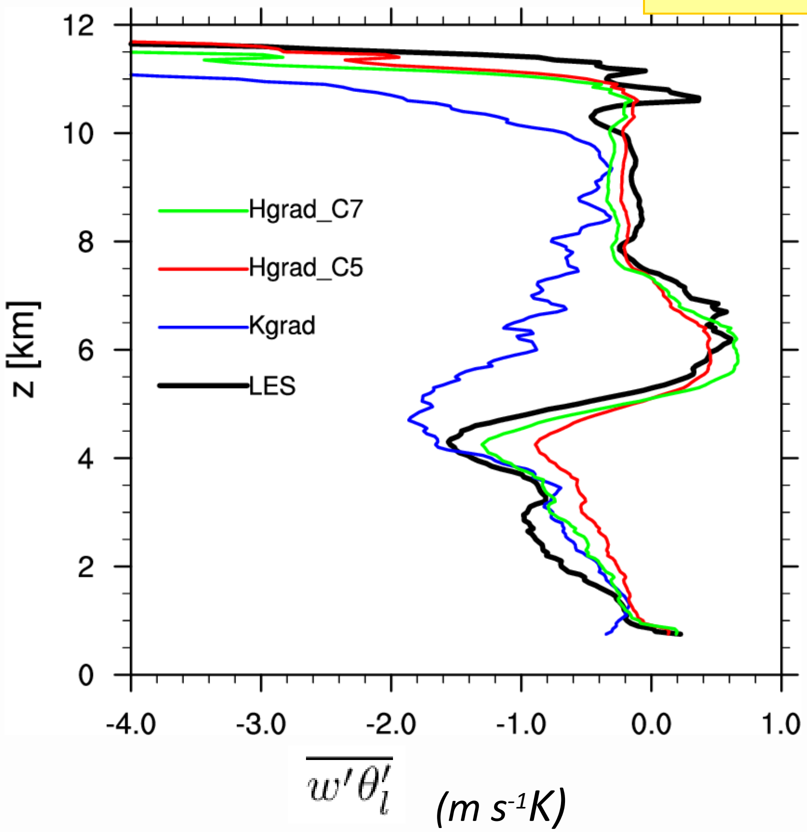
Off-line evaluation: using LES fields filtered at Δx = 1 km

Vertical profiles inside convective system t= 175 min



REF (LES)

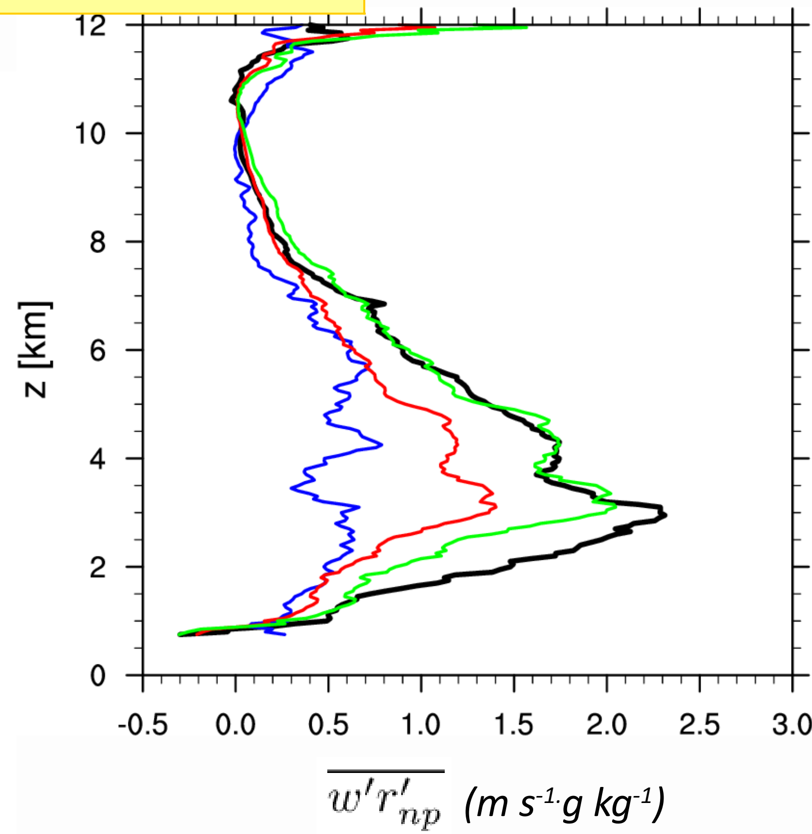
Kgrad

Hgrad

$C = 5\Delta x^2/12$

Hgrad

$C = 7\Delta x^2/12$



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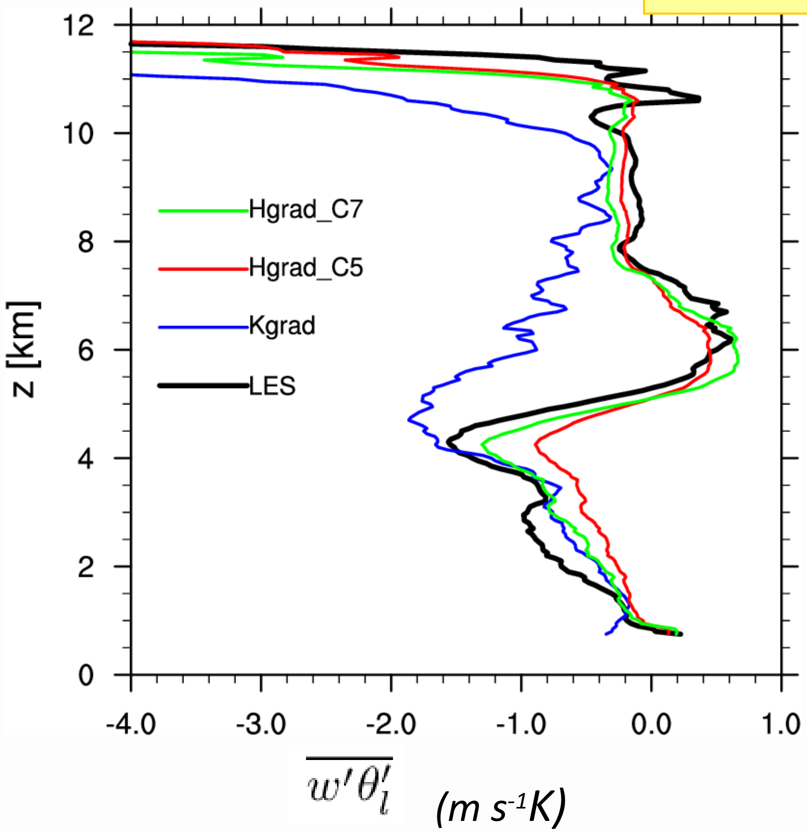

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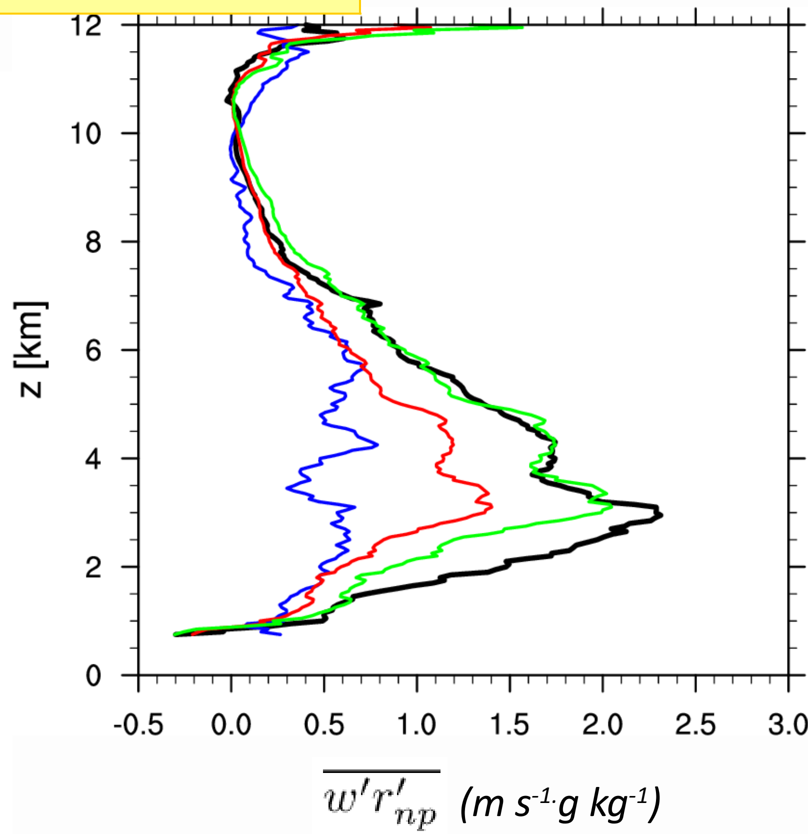
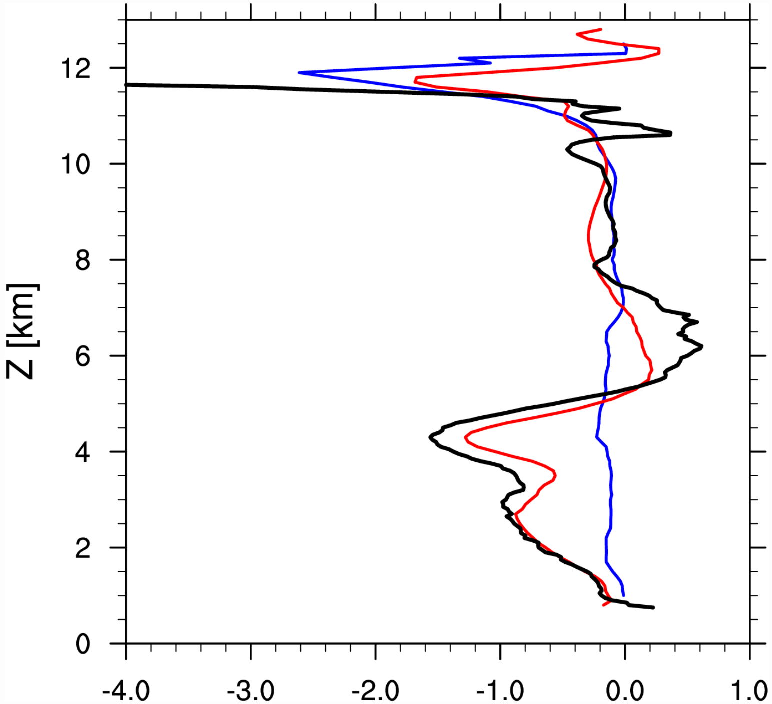


→ **Kgrad** underestimates these two fluxes compared to **REF**
→ **Hgrad** increases the fluxes and represents positive $w'\theta'_l$ in mid-troposphere

On-line evaluation: simulations with Δx = 1 km

Vertical profiles inside convective system t= 180 min



$\overline{w'\theta'_l}$ *(m s⁻¹K)*

REF (LES)

Kgrad

$$\overline{w's'} = -K\frac{\partial \overline{s}}{\partial z}$$

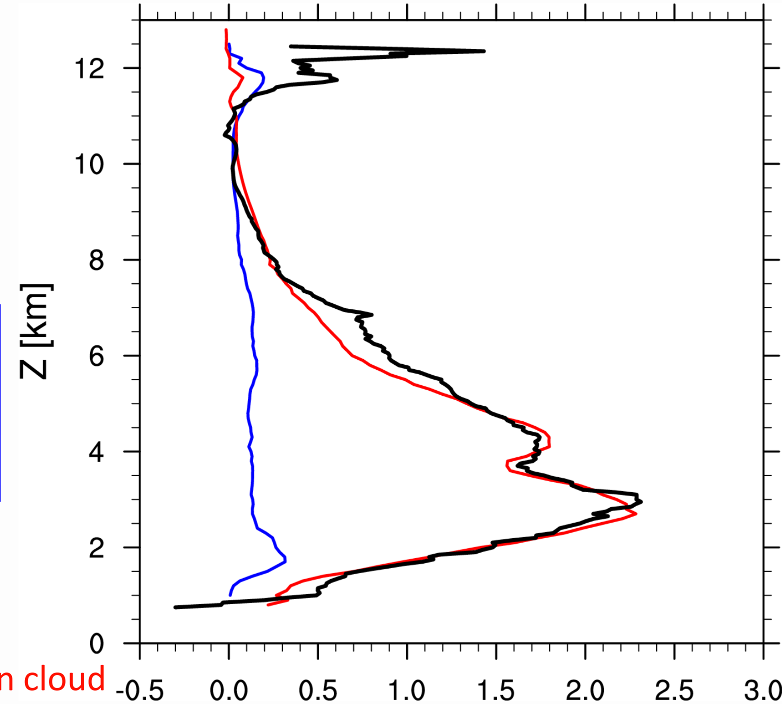
$$s = r_{np}, \theta_l$$

Hgrad

applied only in cloud

$$\overline{w's'} = C\left(\frac{\partial \overline{w}}{\partial x}\frac{\partial \overline{s}}{\partial x} + \frac{\partial \overline{w}}{\partial y}\frac{\partial \overline{s}}{\partial y}\right)$$

($C = 3\Delta x^2/12$) $s = r_{np}, \theta_l$



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

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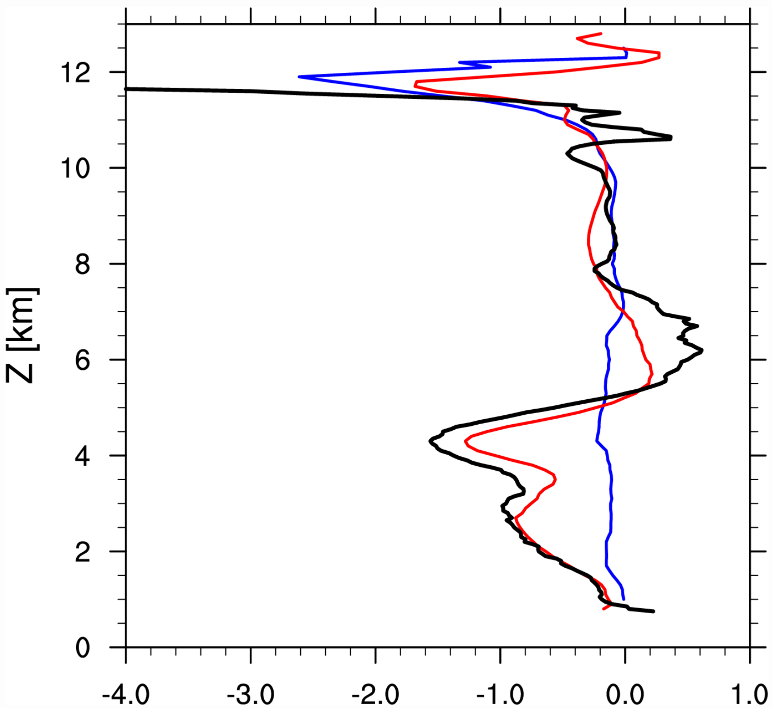
On-line evaluation: simulations with Δx = 1 km

Vertical profiles inside convective system t= 180 min



$\overline{w'\theta'_l}$ *(m s⁻¹K)*

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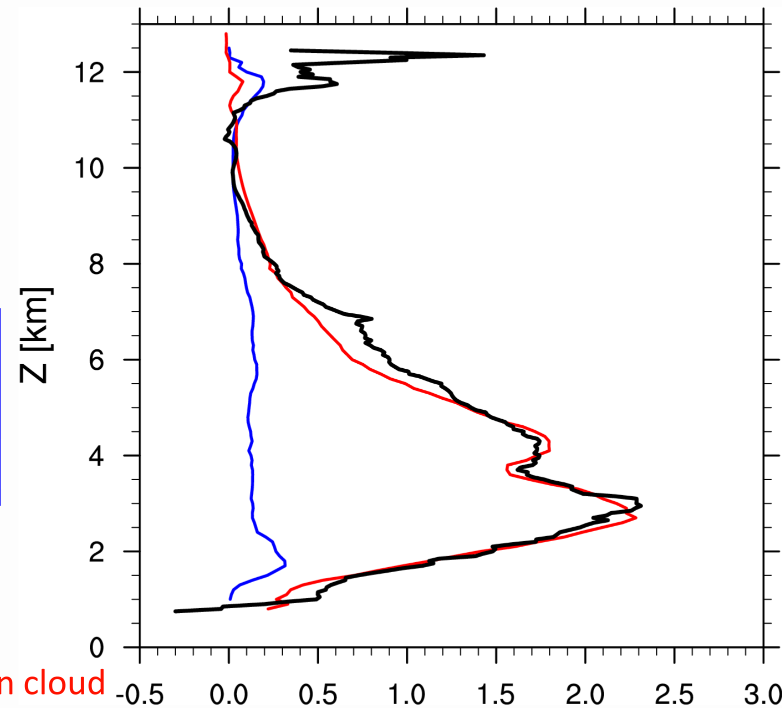

$\overline{w'r'_{np}}$ *($m\ s^{-1} g\ kg^{-1}$)*

→ better representation of those vertical turbulent fluxes with **Hgrad**

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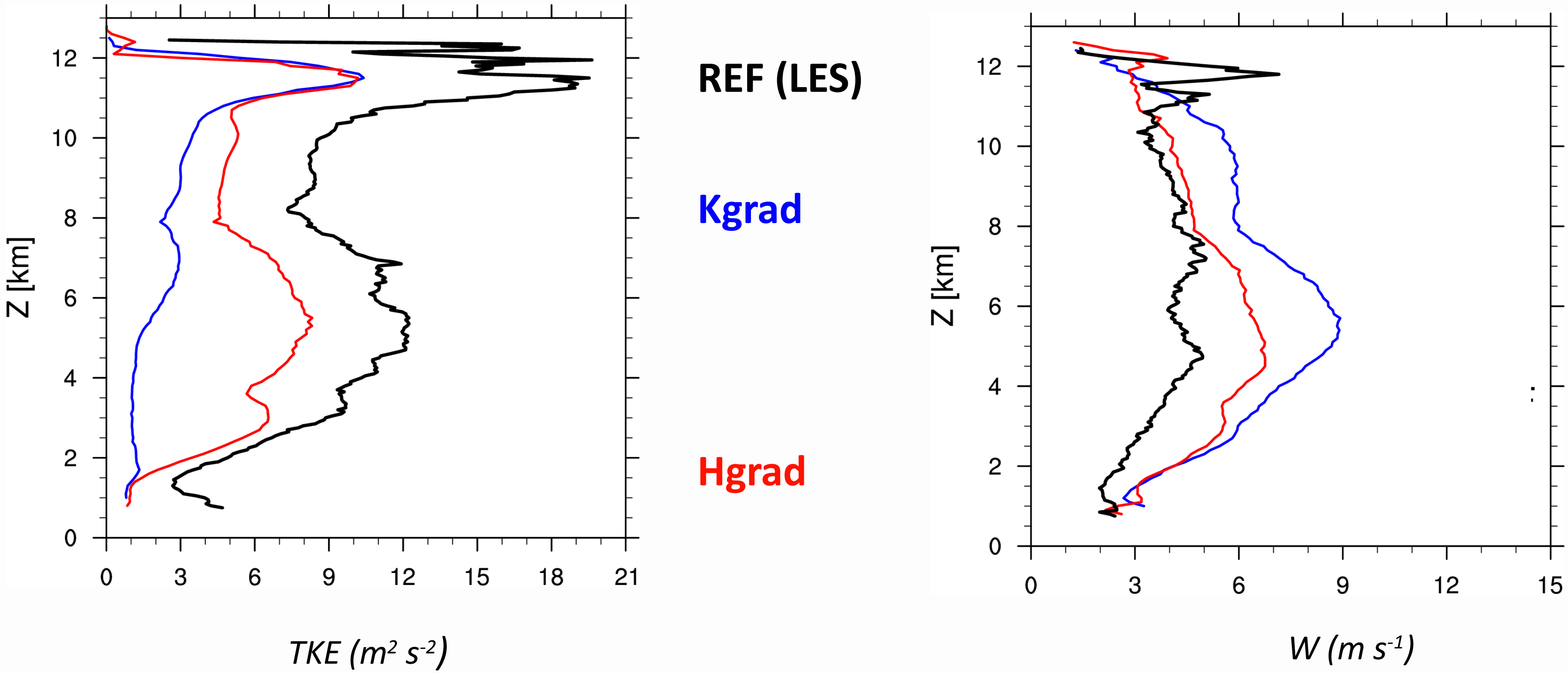
On-line evaluation: simulations with Δx = 1 km

Vertical profiles inside convective system t= 180 min



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On-line evaluation: simulations with Δx = 1 km

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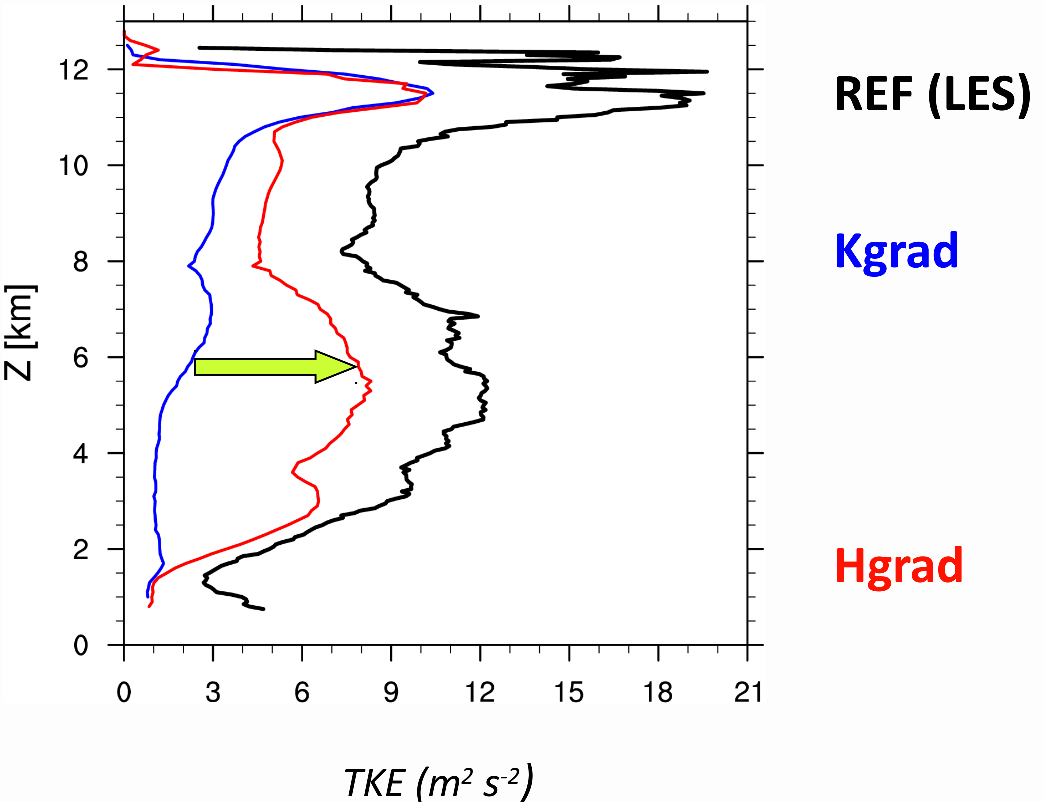
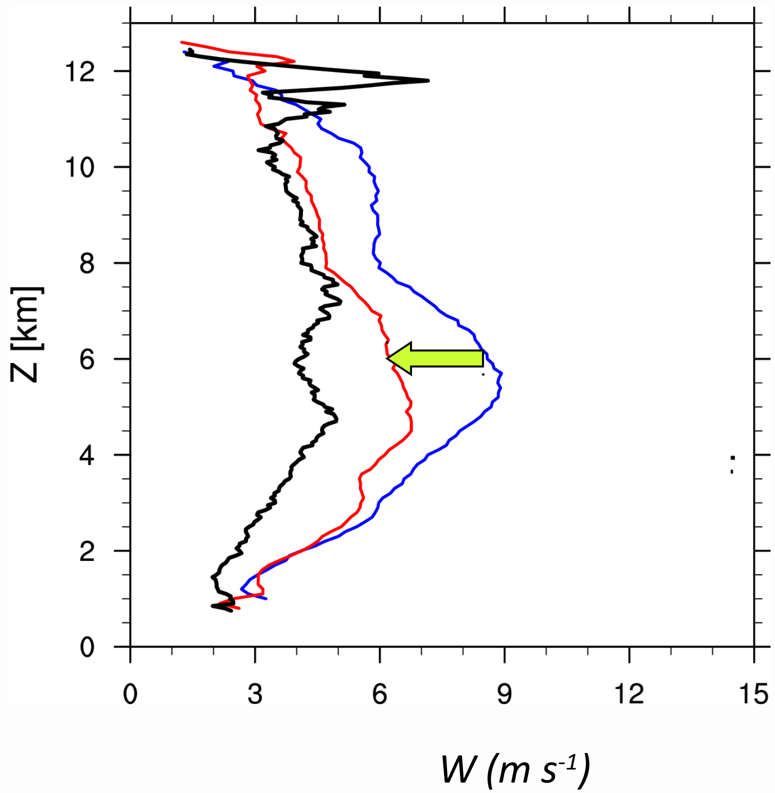


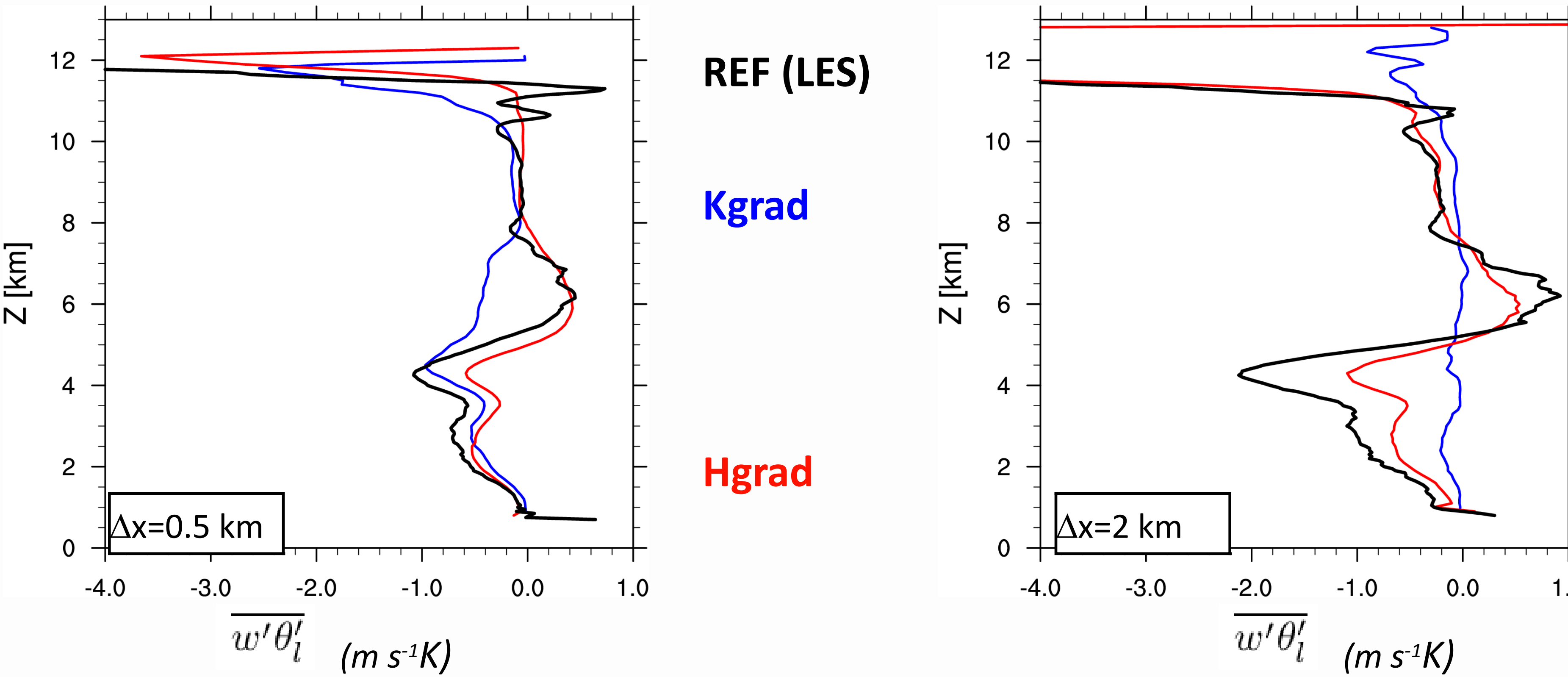


→ more TKE and weaker W for **Hgrad** compared to **Kgrad**
→ better balance between subgrid and resolved parts

3 – Evaluation of turbulence parameterization

On-line evaluation: simulations **with Δx = 0.5 km, 2 km**

Vertical profiles inside convective system t= 180 min



→ positive impact at 0.5 km and 2 km

Conclusion

- Characterization of turbulence from a reference LES:
  - strong TKE inside convective clouds, subgrid TKE increases with coarser resolutions, thermal production increases whereas dynamical production decreases
  - anisotropy increases with coarser resolutions
  - counter-gradient areas for turbulent fluxes due to coherent structures → non-local turbulence
- Evaluation of turbulence parameterization inside convective clouds
  - K-gradient formulation not suitable: too weak subgrid TKE and too strong W as shown in *Verrelle et al., 2015, QJRMS*
  - 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 → *Verrelle et al., Submitted to MWR*

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    - better vertical turbulent fluxes of heat and water mixing ratio
    - better balance between subgrid and resolved parts
      → *Verrelle et al., Submitted to MWR*

→ Next step:

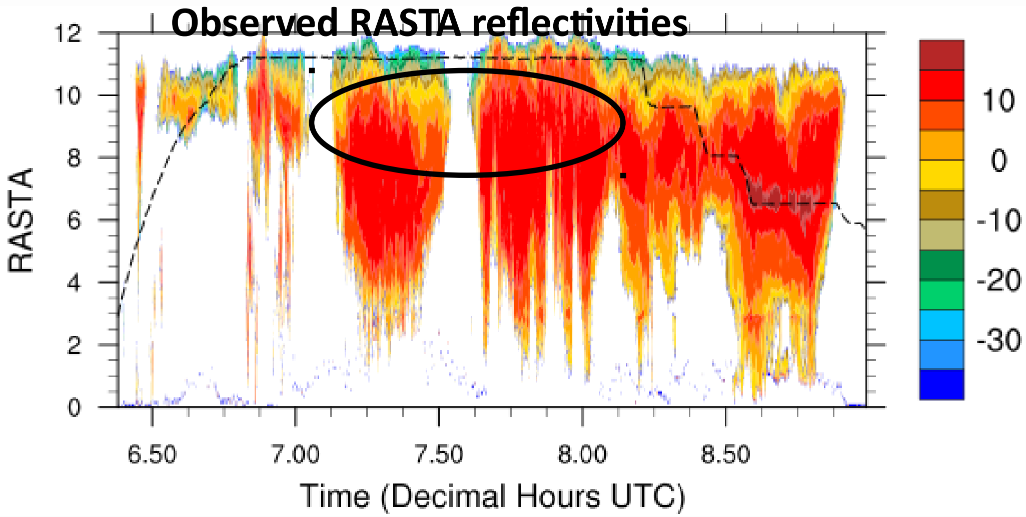
Evaluation of the new parameterization on real convective cases from HyMeX

→ at different horizontal resolutions (500m, 1km, 2km)

→ validation with comparison to observational datasets

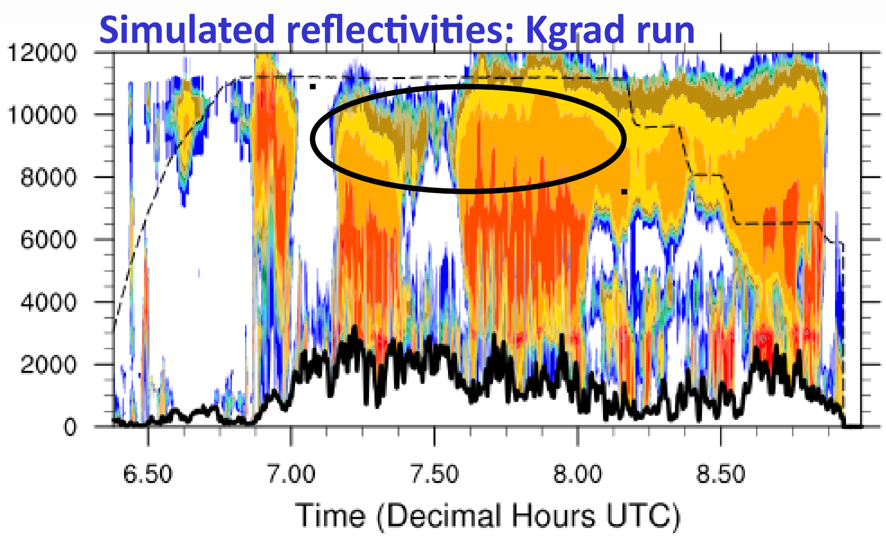
ANR Project

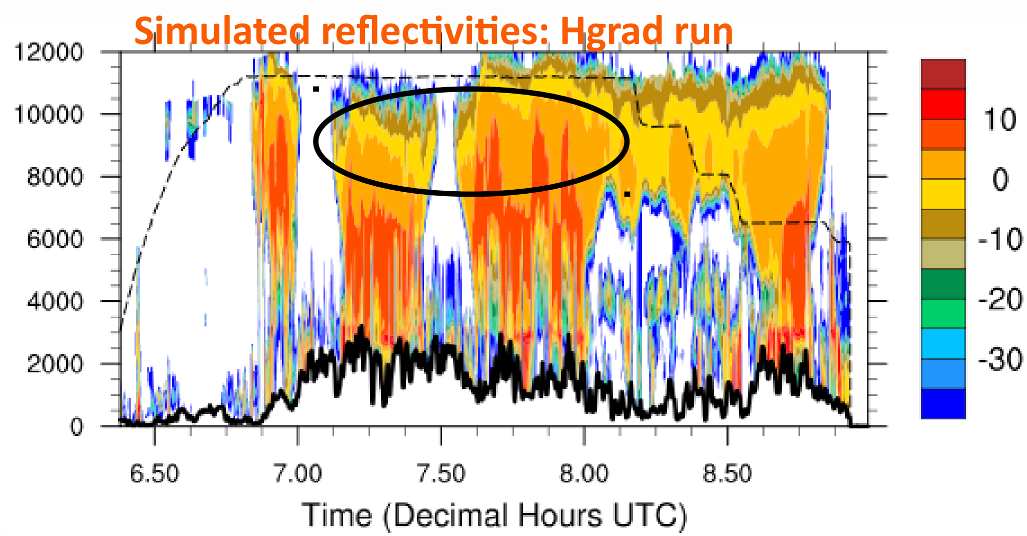
Conclusion



Radar reflectivities along Falcon-20 trajectory (dBZ) during IOP6 (24 september 2012)

Post-doc: Nicolas Rochetin





→Preliminary results: higher reflectivities in the upper part of the clouds with Hgrad due to more ice, snow and graupel

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Thank you for your attention!

Tensor: decomposed in 3 terms

$$\tau_{ws} = \left[\widetilde{\tilde{w}\tilde{s}} - \tilde{\tilde{w}}\tilde{\tilde{s}}\right] + \left[\underbrace{\widetilde{\tilde{w}s'} + \widetilde{w'\tilde{s}} - \tilde{\tilde{w}}\tilde{s'} - \tilde{w'}\tilde{\tilde{s}}}\right] + \left[\underbrace{\widetilde{w's'} - \tilde{w'}\tilde{s'}}\right]$$

L Leonard term (filtered variables) — ***C*** Cross term (interaction) — ***R*** Reynolds term (fluctuations)

$$L_{ws} = \widetilde{\tilde{w}\tilde{s}} - \tilde{\tilde{w}}\tilde{\tilde{s}} = \underbrace{\left(\frac{\Delta x^2}{12}\right)\left(\frac{\partial\tilde{w}}{\partial x}\frac{\partial\tilde{s}}{\partial x} + \frac{\partial\tilde{w}}{\partial y}\frac{\partial\tilde{s}}{\partial y}\right)}_{\text{Limited development}}$$

Bardina et al, 1980,
Clark et al 1979,
Chow et al, 2005

Moeng et al, 2010:

$$\tau_{ws} = \underbrace{L_{ws} + C_{ws}} + \underbrace{R_{ws}} = 2\underbrace{\left(\frac{\Delta x^2}{12}\right)\left(\frac{\partial\tilde{w}}{\partial x}\frac{\partial\tilde{s}}{\partial x} + \frac{\partial\tilde{w}}{\partial y}\frac{\partial\tilde{s}}{\partial y}\right)} - \underbrace{K\frac{\partial\tilde{s}}{\partial z}}$$

Mixte model

Moeng, 2014:

$$\overline{w's'} = \underbrace{A_1(w^u - w^d)(s^u - s^d)}_{\text{mass flux}}$$

$$\overline{w's'} = A_1 A_2\underbrace{\left(\frac{\partial\overline{w}}{\partial x}\frac{\partial\overline{s}}{\partial x} + \frac{\partial\overline{w}}{\partial y}\frac{\partial\overline{s}}{\partial y}\right)}$$

Off-line evaluation: computation of parameterized fluxes from LES at Δx -> $\overline{w'\theta_l'}$

CTRL

Cuxart et al (2000)

$$\overline{\overline{w'\theta_l'}}^{\Delta_x} = -\frac{2}{3C_{p\theta}}\overline{\phi_i}^{\Delta_x} L\sqrt{\overline{e}^{\Delta_x}_{ref}}\frac{\partial\overline{\overline{\theta_l}}^{\Delta_x}}{\partial z}$$

based on K-gradient: $\overline{w'\theta_l'} = -K\frac{\partial\overline{\theta_l}}{\partial z}$

TEST1

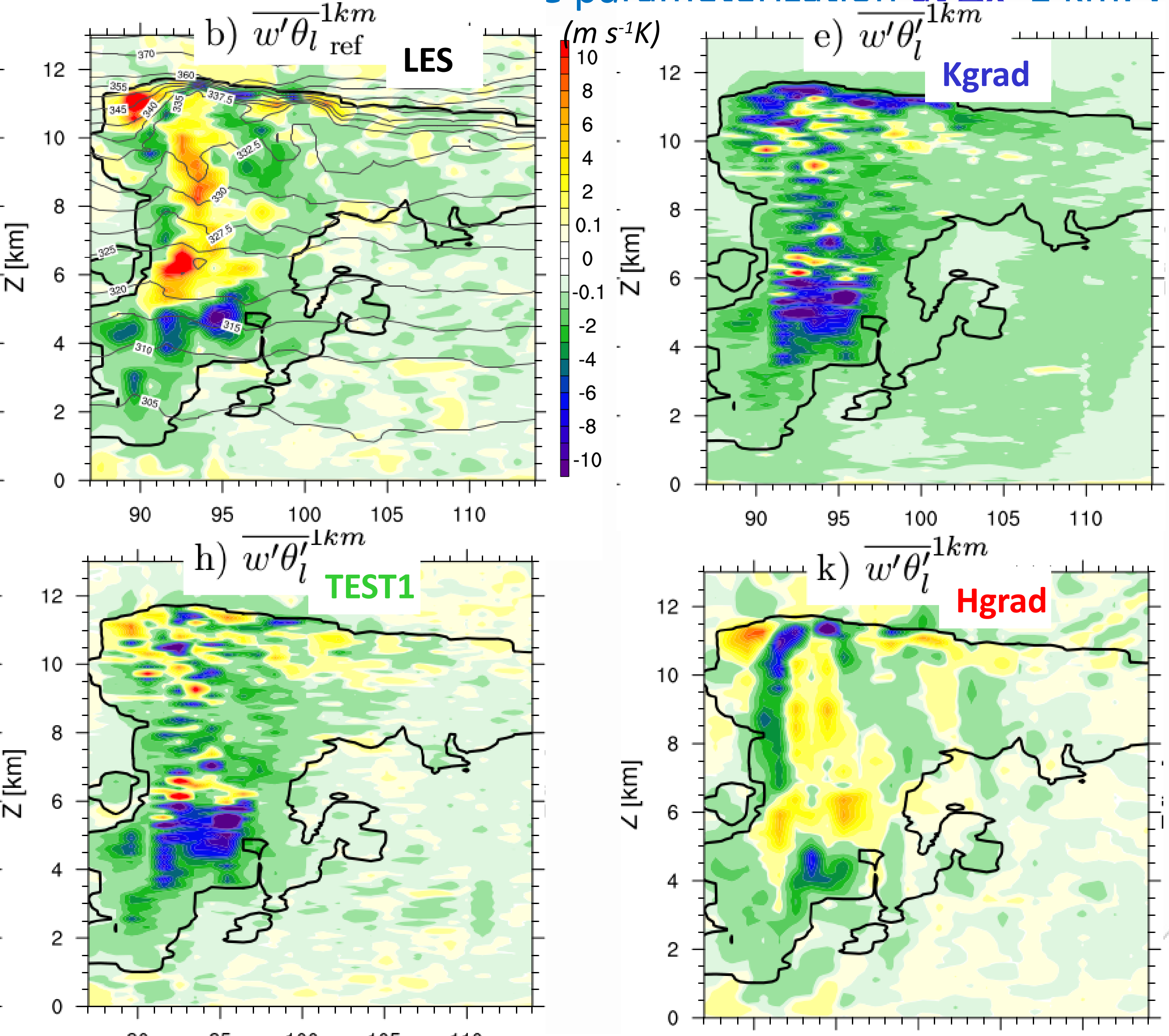
$$\overline{\overline{w'\theta_l'}}^{\Delta_x} = -\frac{L}{C_{p\theta}\sqrt{\overline{e}^{\Delta_x}_{ref}}}\left[\overline{w'^2}^{\Delta_x}\frac{\partial\overline{\overline{\theta_l}}^{\Delta_x}}{\partial z} - \frac{2}{3}\beta(E_\theta\overline{\theta_l'^2}^{\Delta_x} + E_r\overline{\theta_l' r_{np}'}^{\Delta_x})\right]$$

Zilitinkevich et al (1999)

based on K-gradient with a counter-gradient term: $\overline{w'\theta_l'} = -K(\frac{\partial\overline{\theta_l}}{\partial z} - \gamma)$

Characterization of turbulence inside convective clouds

- Evaluation of turbulence parameterization at Δx=1 km: vertical heat flux



→ positive flux inside the cloud
→ Better representation with horizontal gradient formulation

Δx=1km

METEO FRANCE

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