Convection Parameterization: Progress and Challenges

15 – 19 July 2019, Exeter, UK

Impact of turbulence representation on deep convective clouds

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Introduction

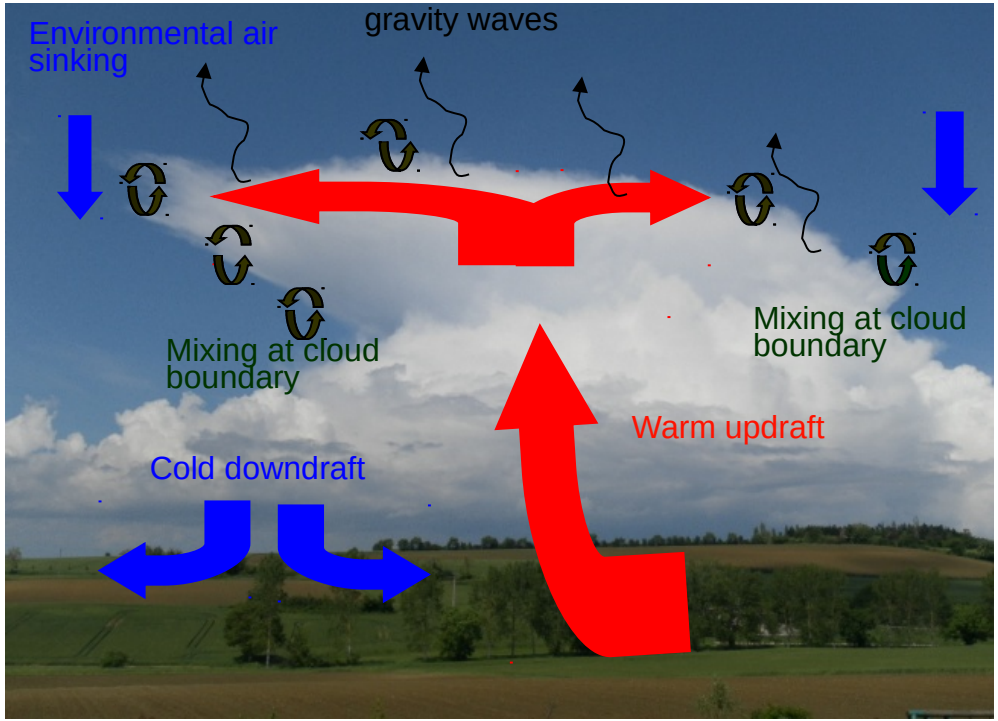
Turbulence: extensively studied in the atmospheric boundary layer

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(1km)



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)

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

Dynamical production

Thermal production

Dissipation

Meso-NH
mesoscale non-hydrostatic model

Lac et al 2018 GMD

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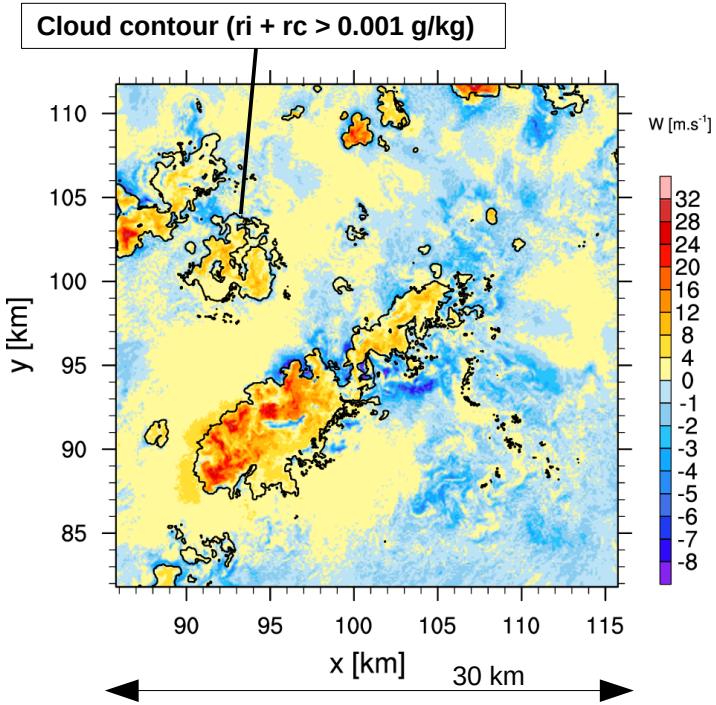
Dynamical production — Thermal production — Dissipation

Initial conditions:

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



LES: Δx = Δy = Δz = 50 m

Verrelle, Ricard, Lac 2017 MWR

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

LES of deep convective clouds

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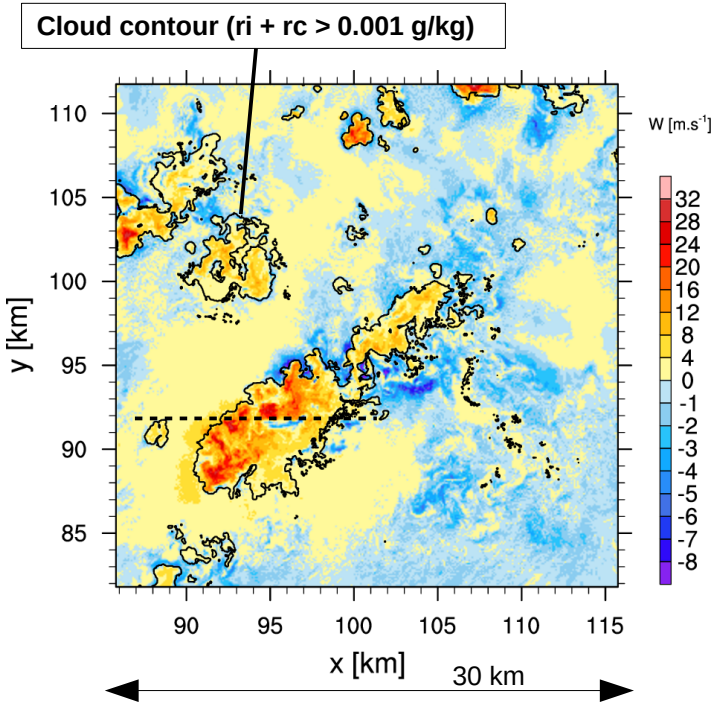

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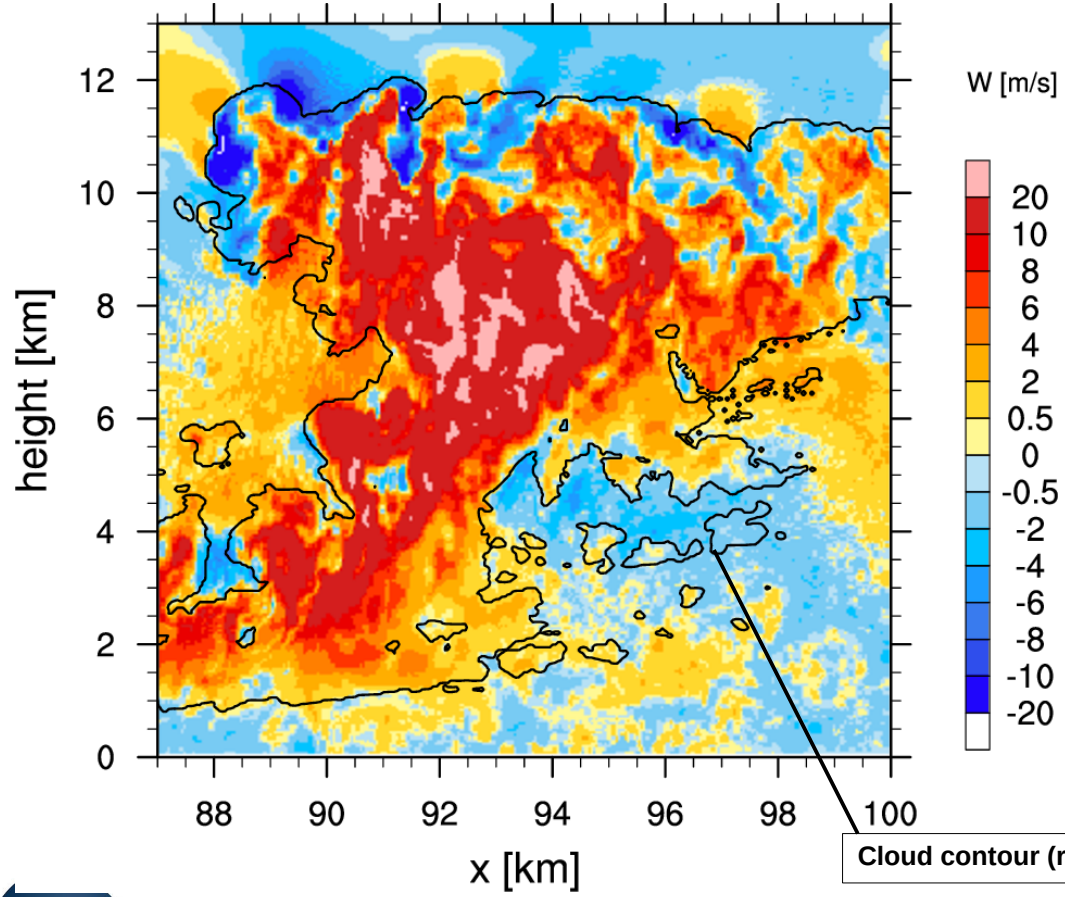
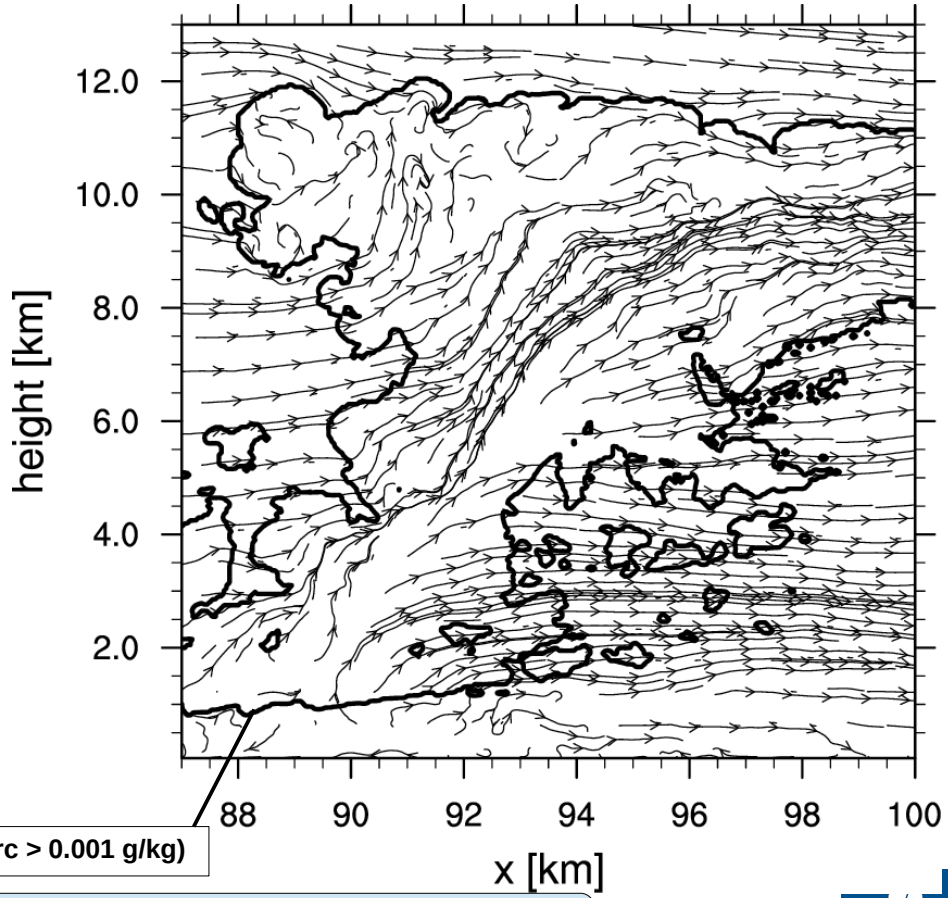
LES of deep convective clouds dx

Vertical cross sections of vertical velocity (m/s) t=175 min



Streamlines t = 175 min

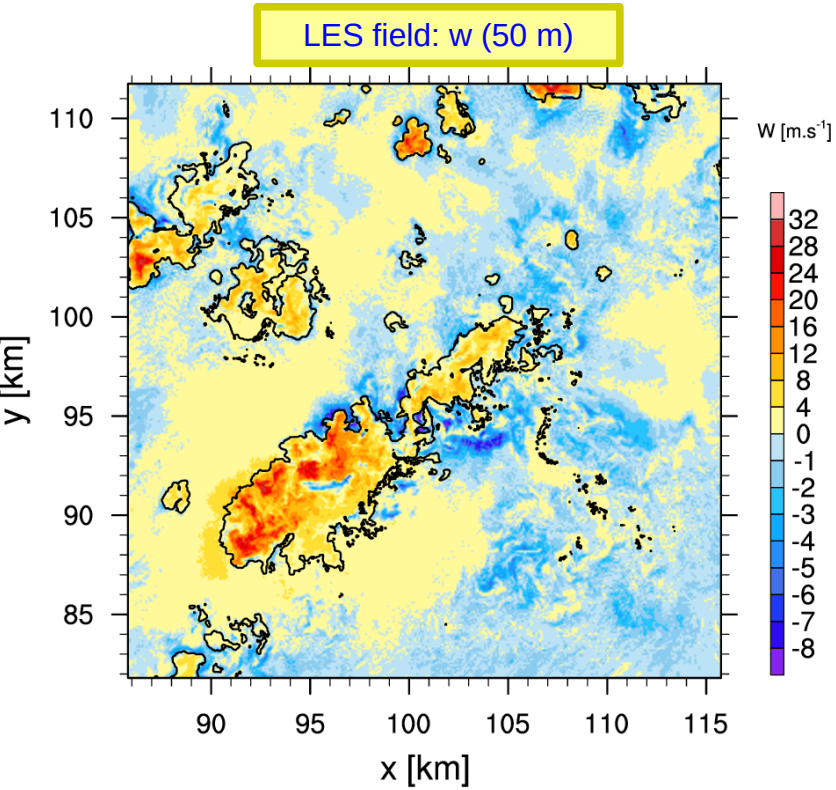


Cloud contour (ri + rc > 0.001 g/kg)

→ well developed cumulonimbus with a strong updraft and many eddies

Characterization of turbulence inside convective clouds

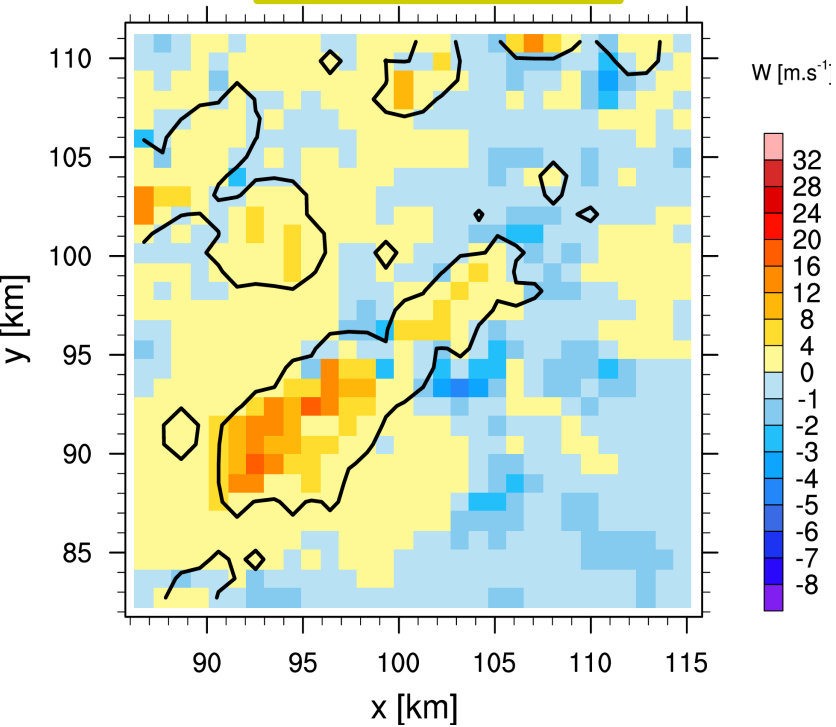
- LES: reference simulation (50-m grid spacing)



Characterization of turbulence inside convective clouds

- LES: reference simulation (50-m grid spacing)
- Computation of reference fields at coarser resolutions **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 …)*

Filtered field: $\overline{w}^{\Delta x=1km}$



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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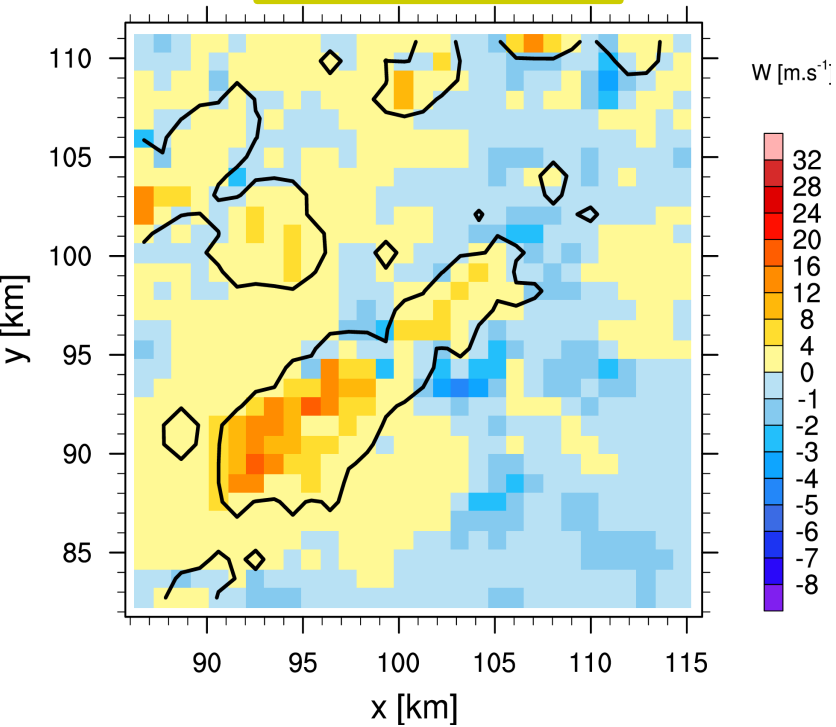

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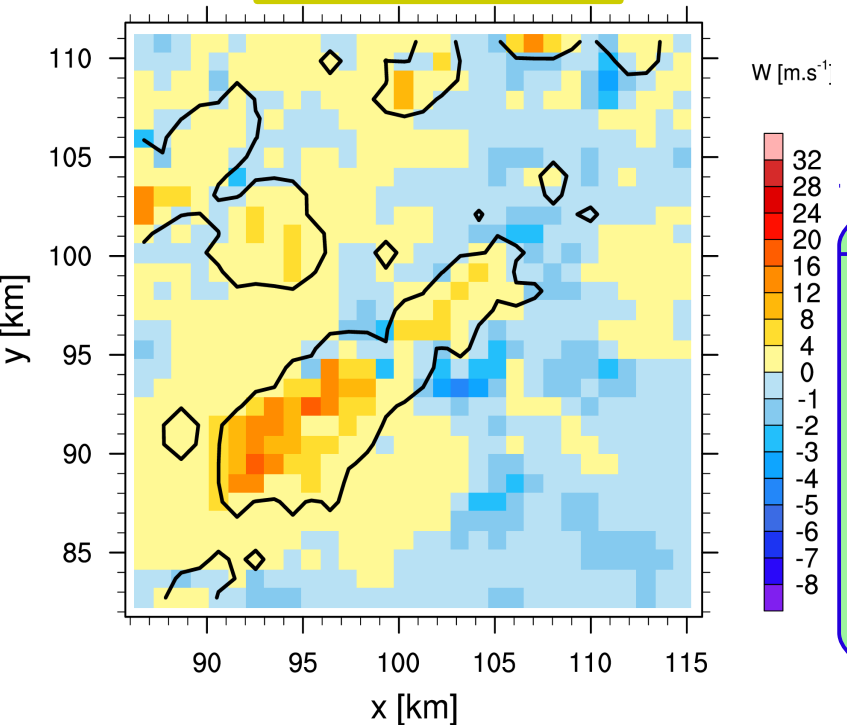

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Computation of subgrid terms at Δx:

Turbulent fluxes:

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

Variances:

$$\overline{u'^2}^{\Delta_x}, \overline{v'^2}^{\Delta_x}, \overline{w'^2}^{\Delta_x}, \overline{r_{np}'^2}^{\Delta_x}, \overline{\theta_l'^2}^{\Delta_x}, \ldots$$

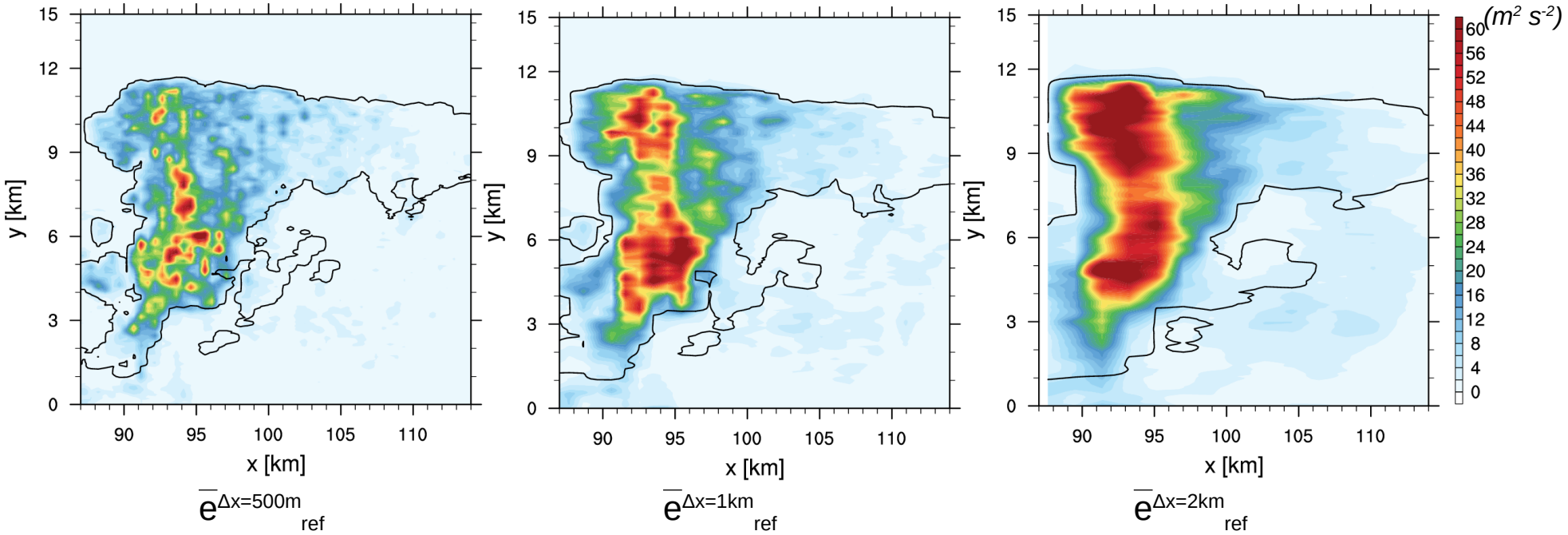
Subgrid TKE:

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

METEO FRANCE

Characterization of turbulence inside convective clouds

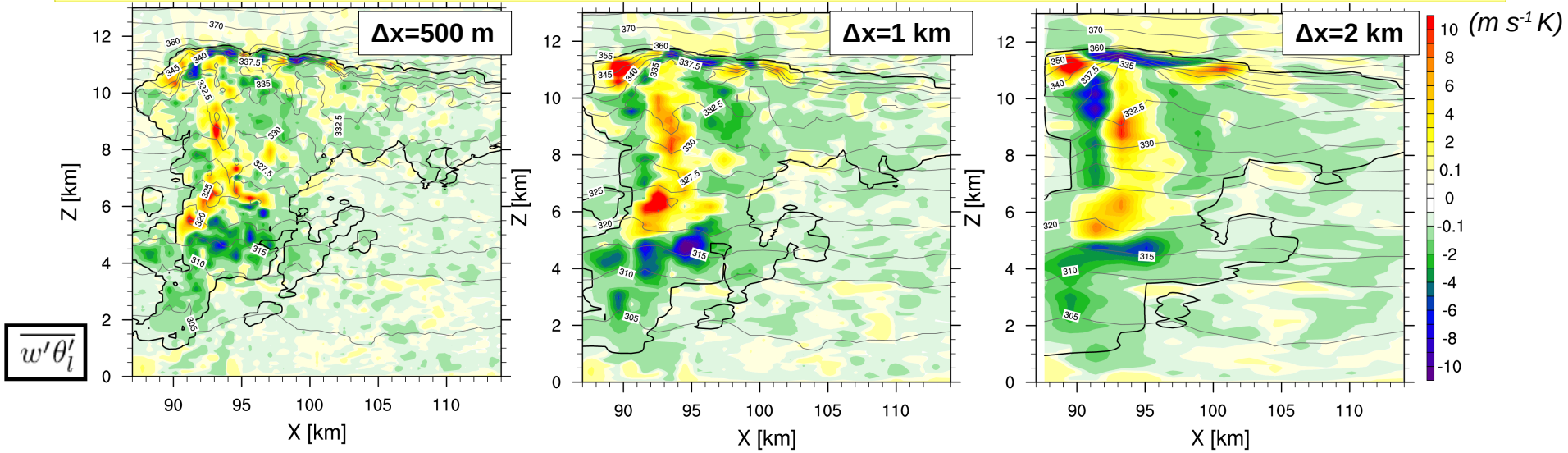
Vertical cross sections: subgrid TKE (m²/s²) computed from the LES at different Δx (500 m, 1 km and 2 km) at t=175 min



→ 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 Δx (500 m, 1 km and 2 km) at t=175 min



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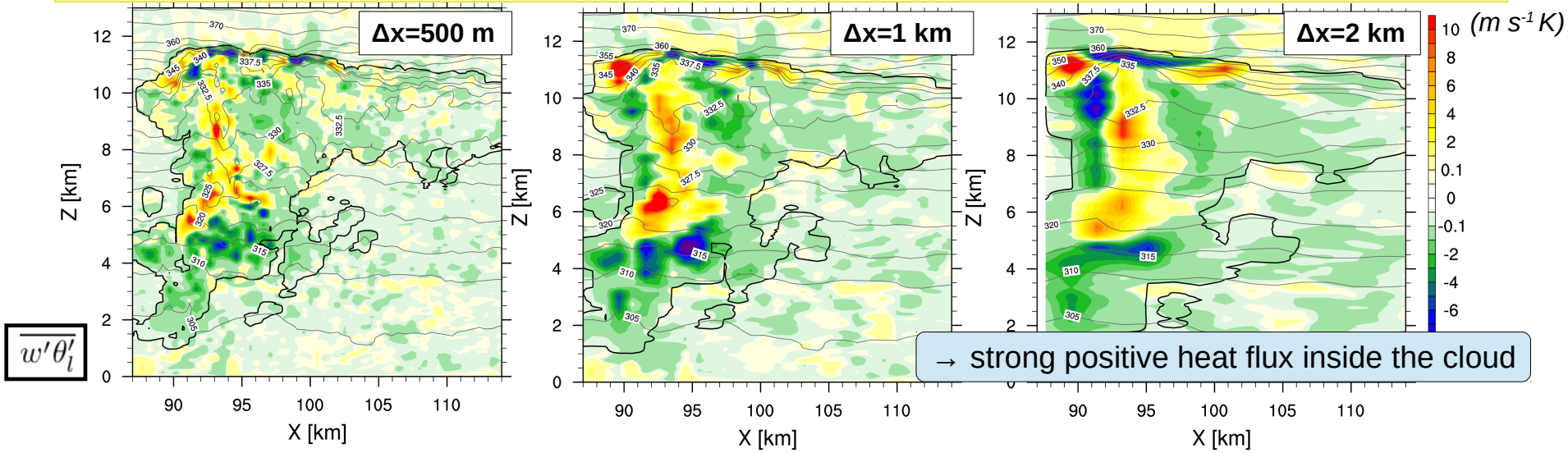

→ strong positive heat flux inside the cloud

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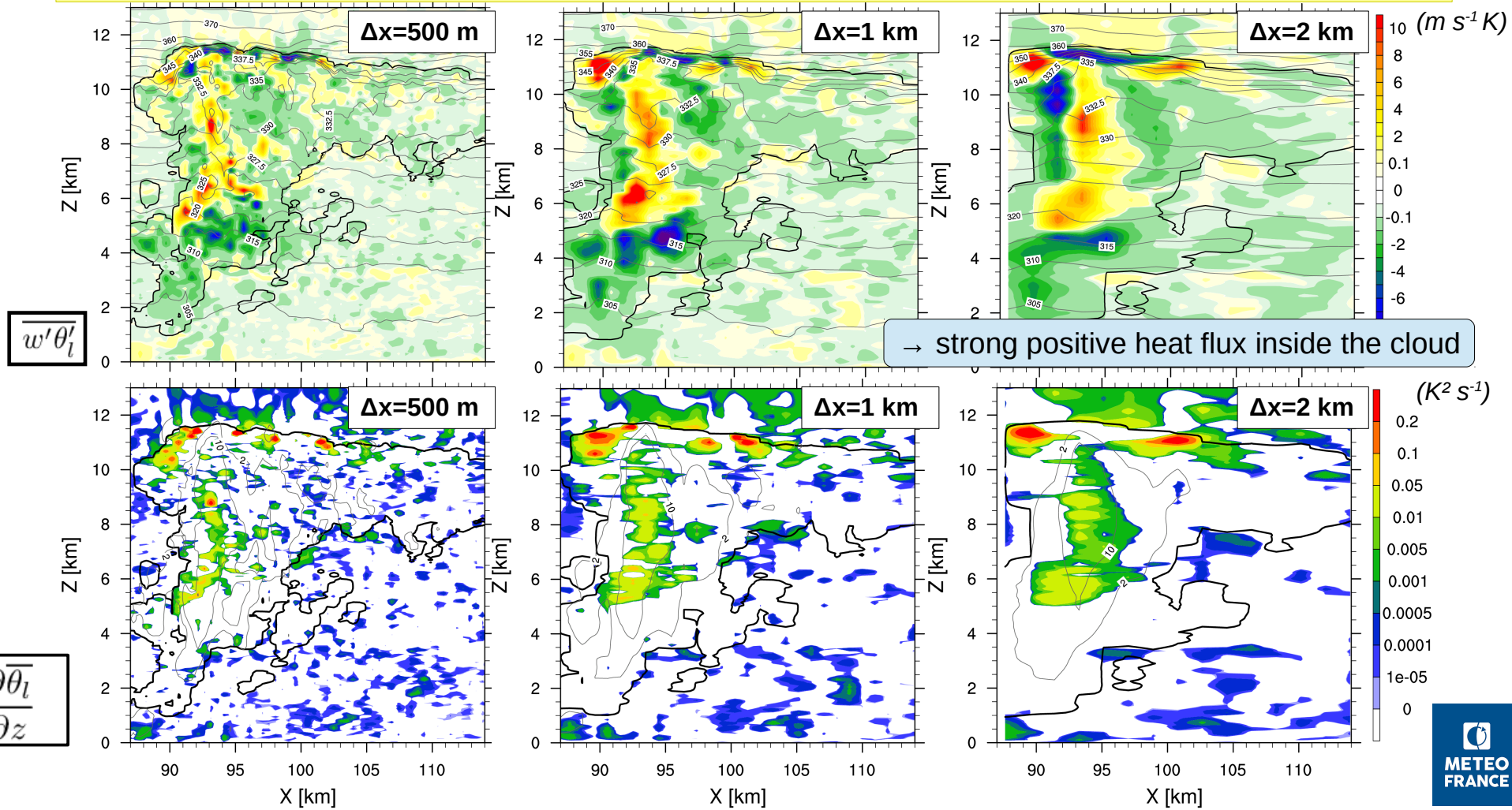

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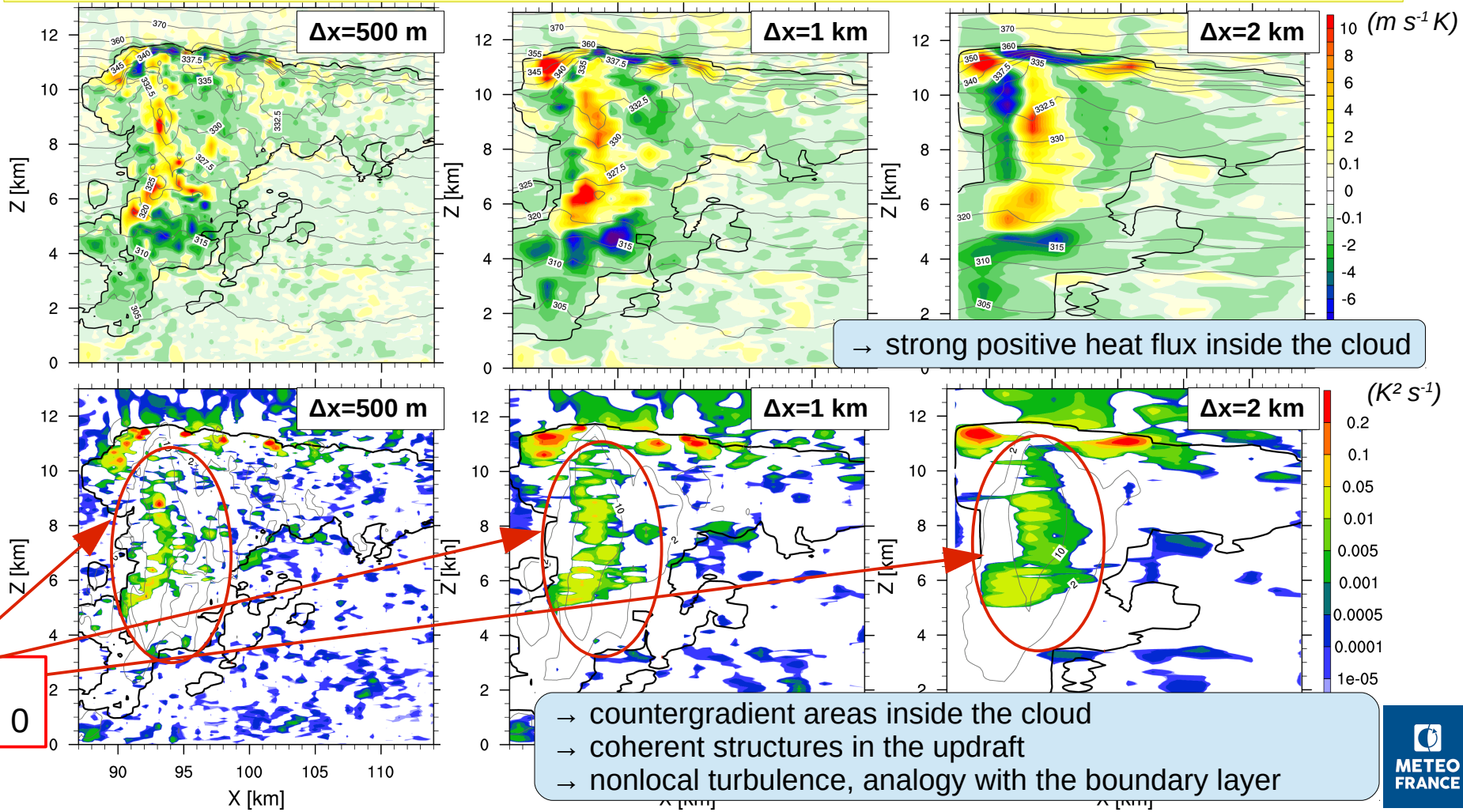

→ strong positive heat flux inside the cloud

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

→ 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 Δx → $\overline{w'\theta_l'}$

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Kgrad

Cuxart et al, 2000
CBR scheme

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

L mixing length of *Bougeault-Lacarrere 1989*

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

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Hgrad

Moeng et al, 2010

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

based on product of horizontal gradients: $\overline{w'\theta_l'} = C\left(\frac{\partial\overline{w}}{\partial x}\frac{\partial\overline{\theta_l}}{\partial x} + \frac{\partial\overline{w}}{\partial y}\frac{\partial\overline{\theta_l}}{\partial y}\right)$

related to a mass flux *(Moeng, 2014)*

Evaluation of turbulence parameterizations

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

Kgrad

Cuxart et al, 2000
CBR scheme

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

L mixing length of *Bougeault-Lacarrere 1989*

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

Hgrad

Moeng et al, 2010

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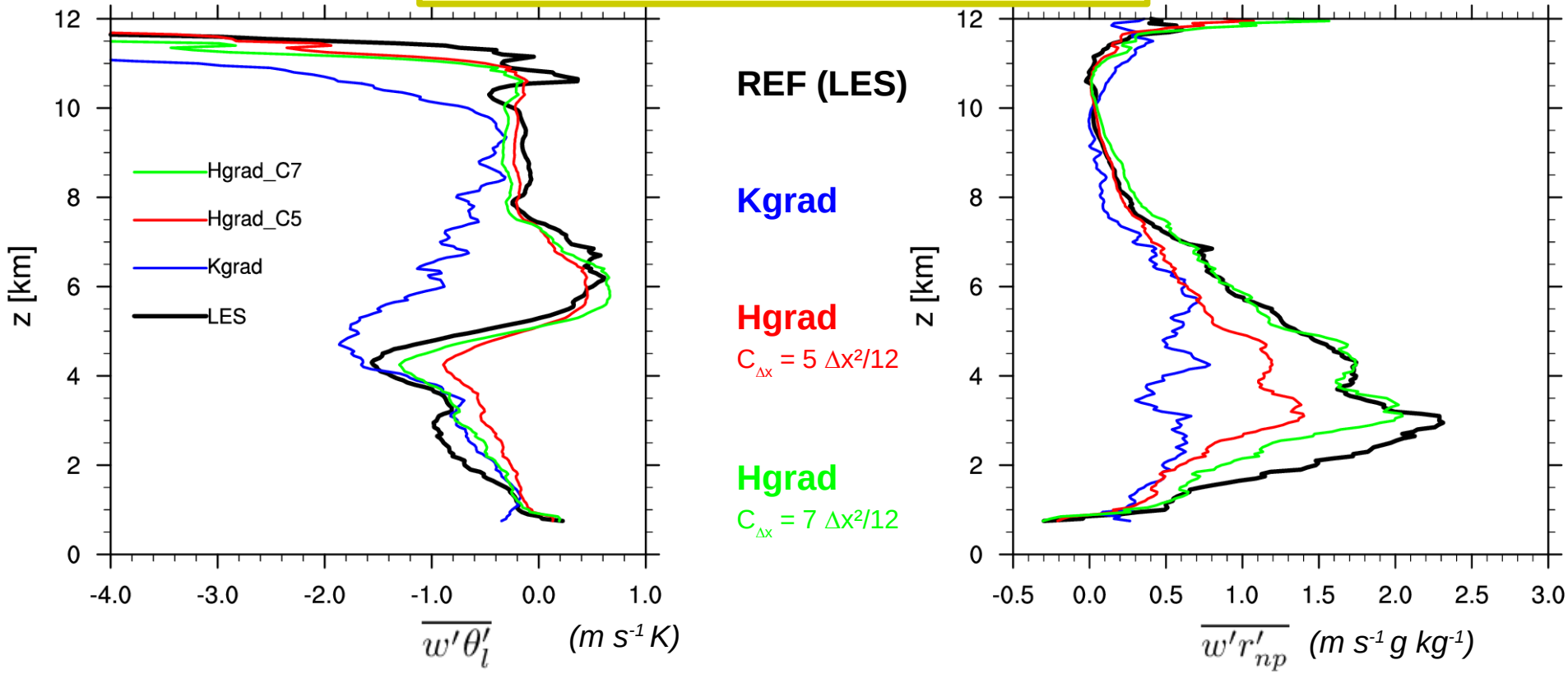
related to a flux mass *(Moeng, 2014)*

Evaluation of turbulence parameterizations

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

Mean vertical profiles inside convective clouds at t=175 min

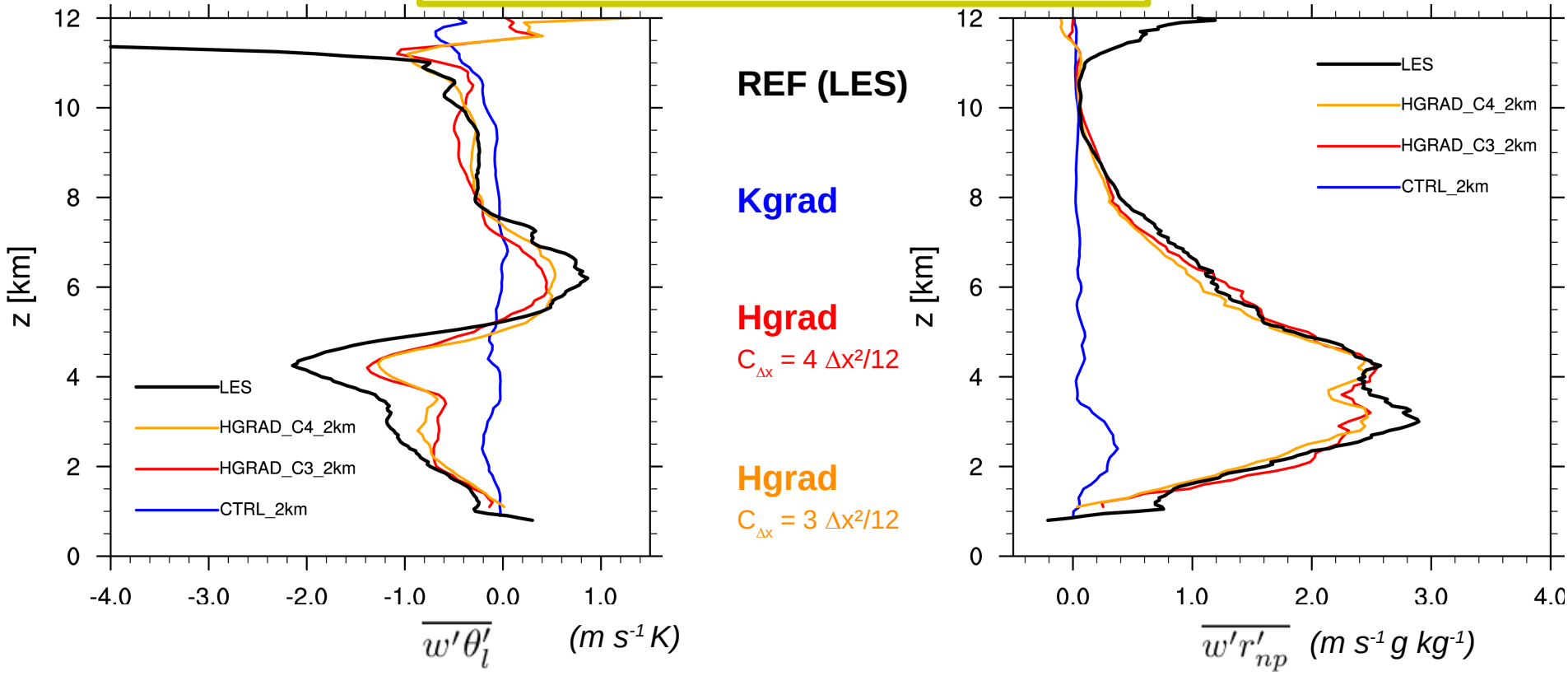


→ **Kgrad** underestimates these two fluxes compared to **REF**
→ **Hgrad** increases these two fluxes and represents the positive heat flux in mid-troposphere

Evaluation of turbulence parameterizations

Online evaluation: simulations with Δx = 2 km

Mean vertical profiles inside convective clouds at t=175 min



→ better representation of these two fluxes with **Hgrad** approach compared to the **Kgrad** approach

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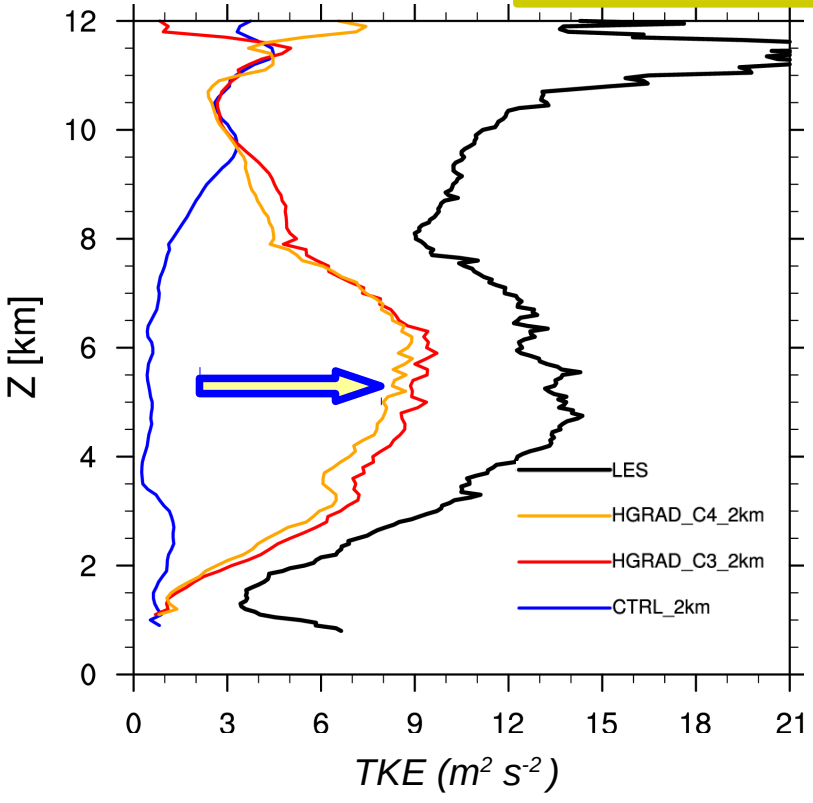
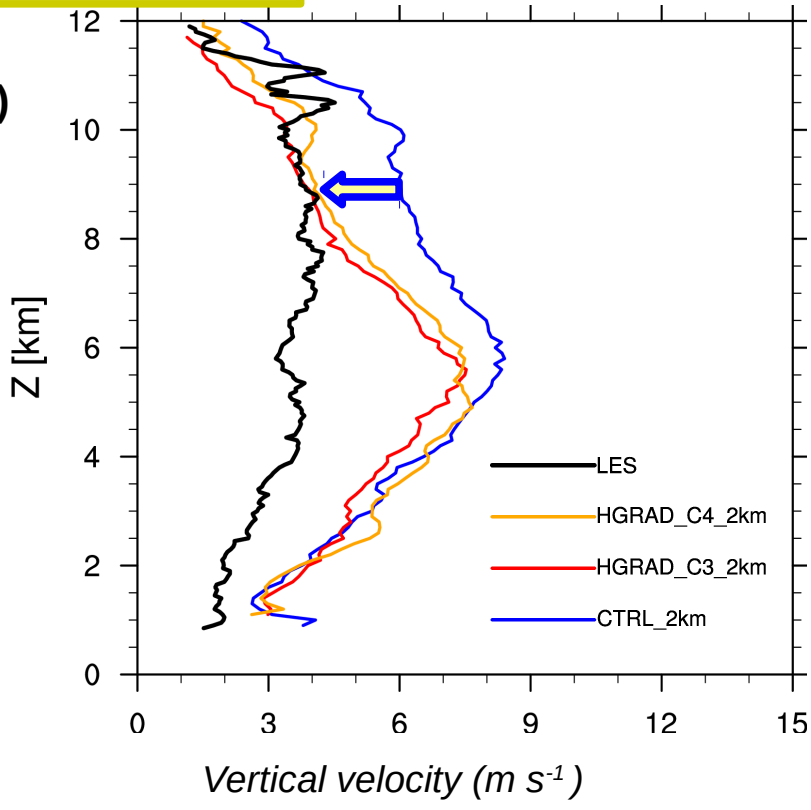


REF (LES)

Kgrad

Hgrad
$C_{\Delta x} = 4\ \Delta x^2/12$

Hgrad
$C_{\Delta x} = 3\ \Delta x^2/12$



→ more subgrid TKE and less intense vertical velocity with **Hgrad** compared to **Kgrad**
→ better balance between resolved and subgrid parts

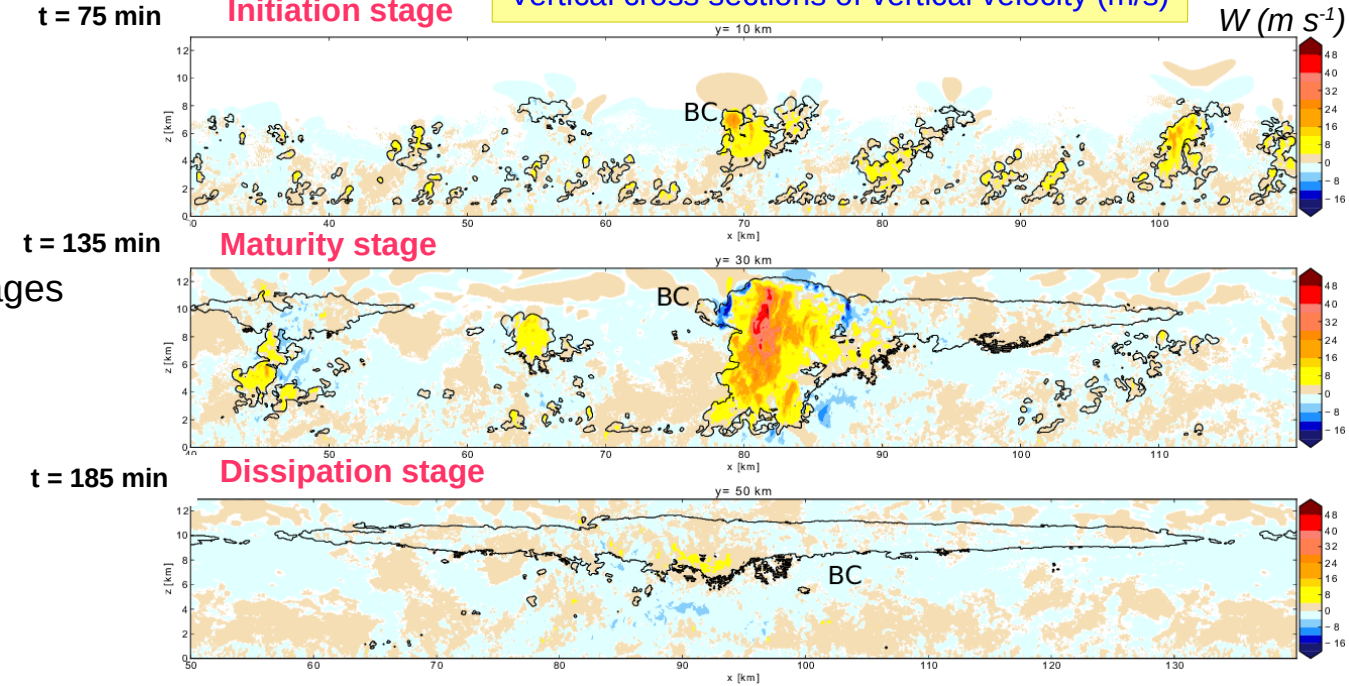
LES of deep convective clouds

- 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

Vertical cross sections of vertical velocity (m/s)



- 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

SMAG

Smagorinsky,1963

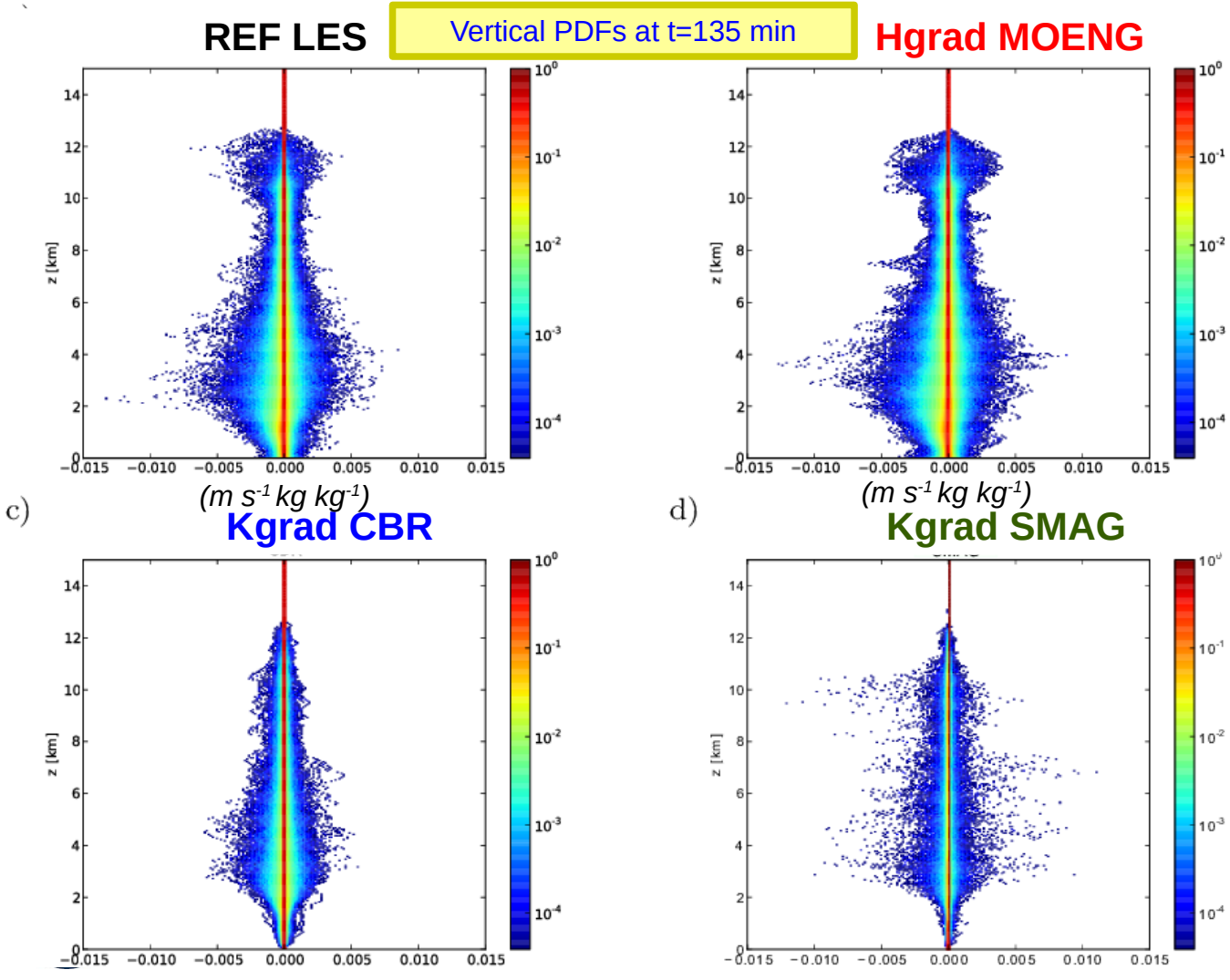
$$\overline{u_i' r_{np}'}^{\Delta x} = -\frac{(c_s L)^2}{Pr}\overline{D}\sqrt{max(0, 1 - \frac{Ri}{Pr})}\frac{\partial \overline{r_{np}}^{\Delta x}}{\partial x_i}$$

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

Ri Richardson number
Pr Prandtl number
D deformation tensor

Evaluation of turbulence parameterization

Vertical PDFs at t=135 min



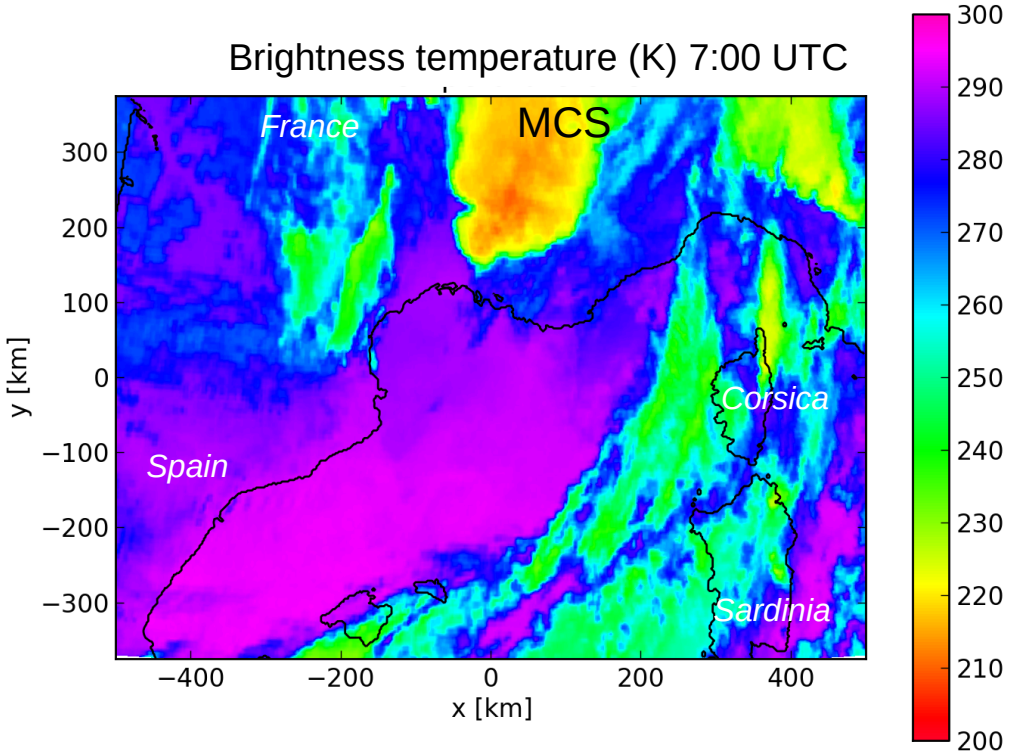
Off-line evaluation $\overline{u'r'_{np}}$ *(m s^{-1} kg kg^{-1})*
Δx = 1 km

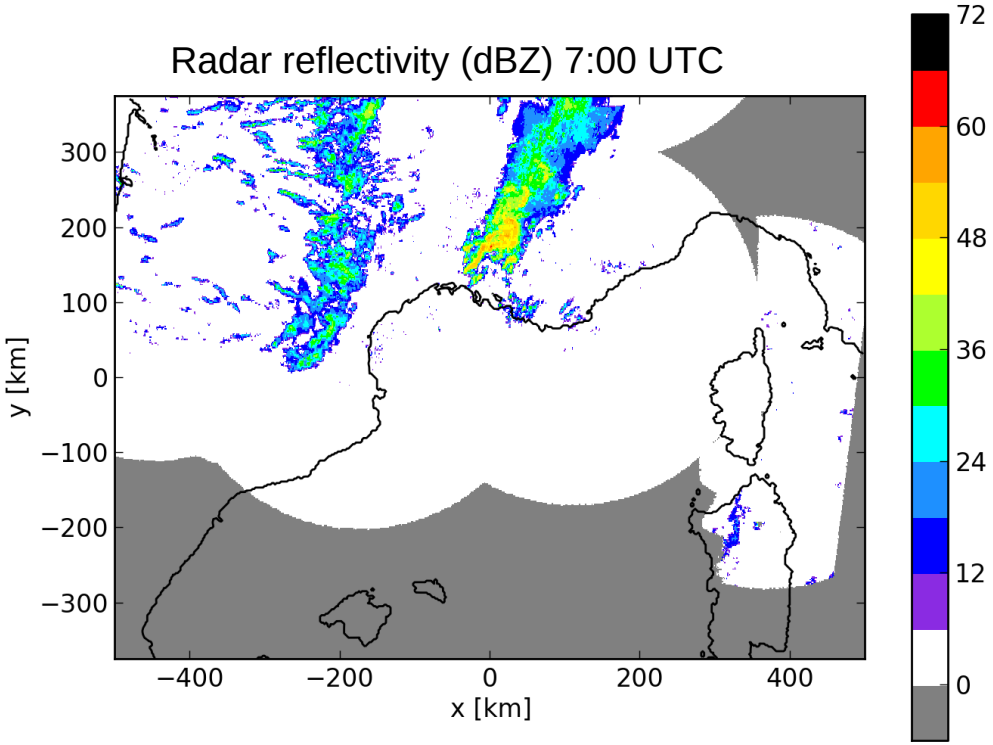
Thermodynamical fluxes:
Better distribution with **Hgrad**

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

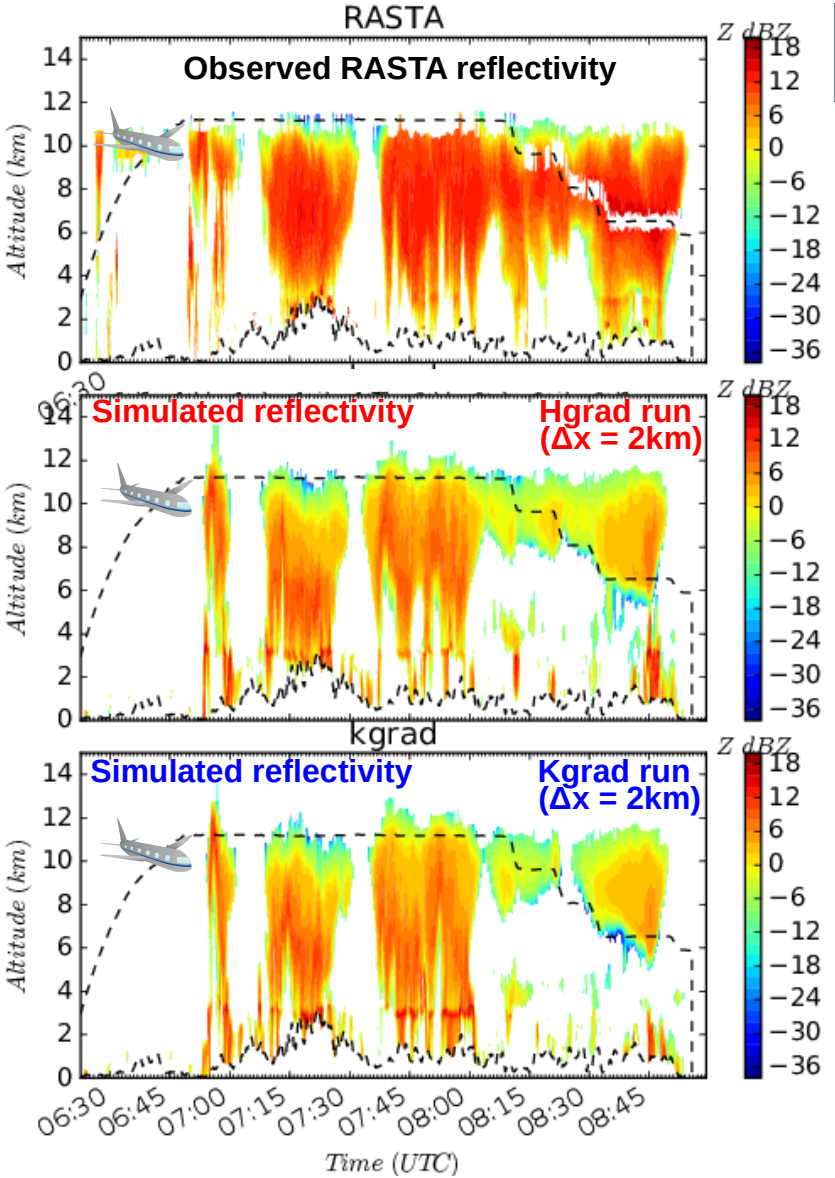




Impact on convective systems

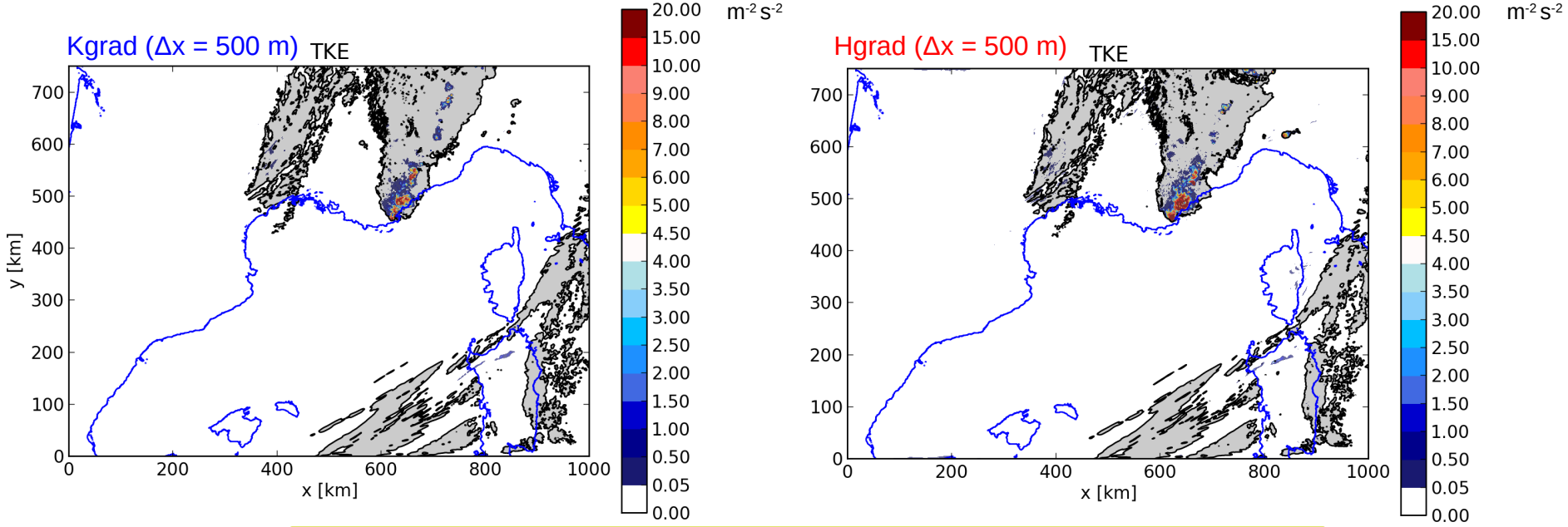
Vertical cross section of radar reflectivity (dBZ) along the Falcon-20 trajectory during the morning (24 September 2012)

(Delanoë et al, 2013)



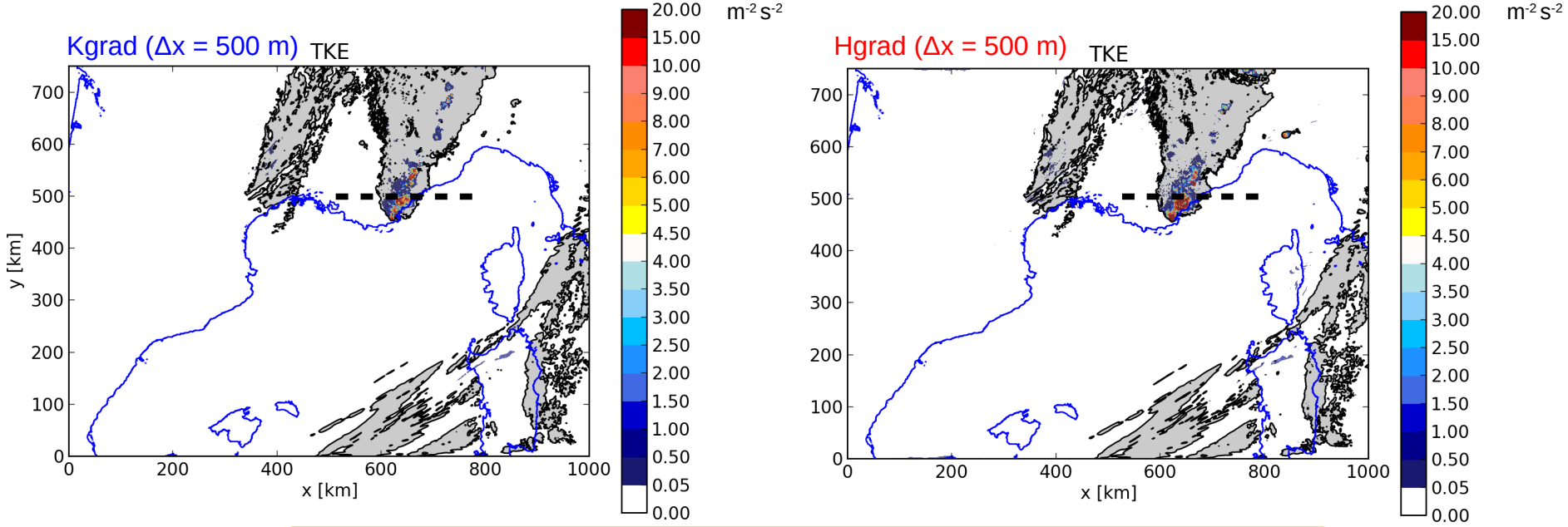
→ Good vertical extension of convective systems
→ Underestimation of reflectivity
→ Higher reflectivity in the upper part of the clouds with the Hgrad run

Turbulence inside convective systems



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

Turbulence inside convective systems



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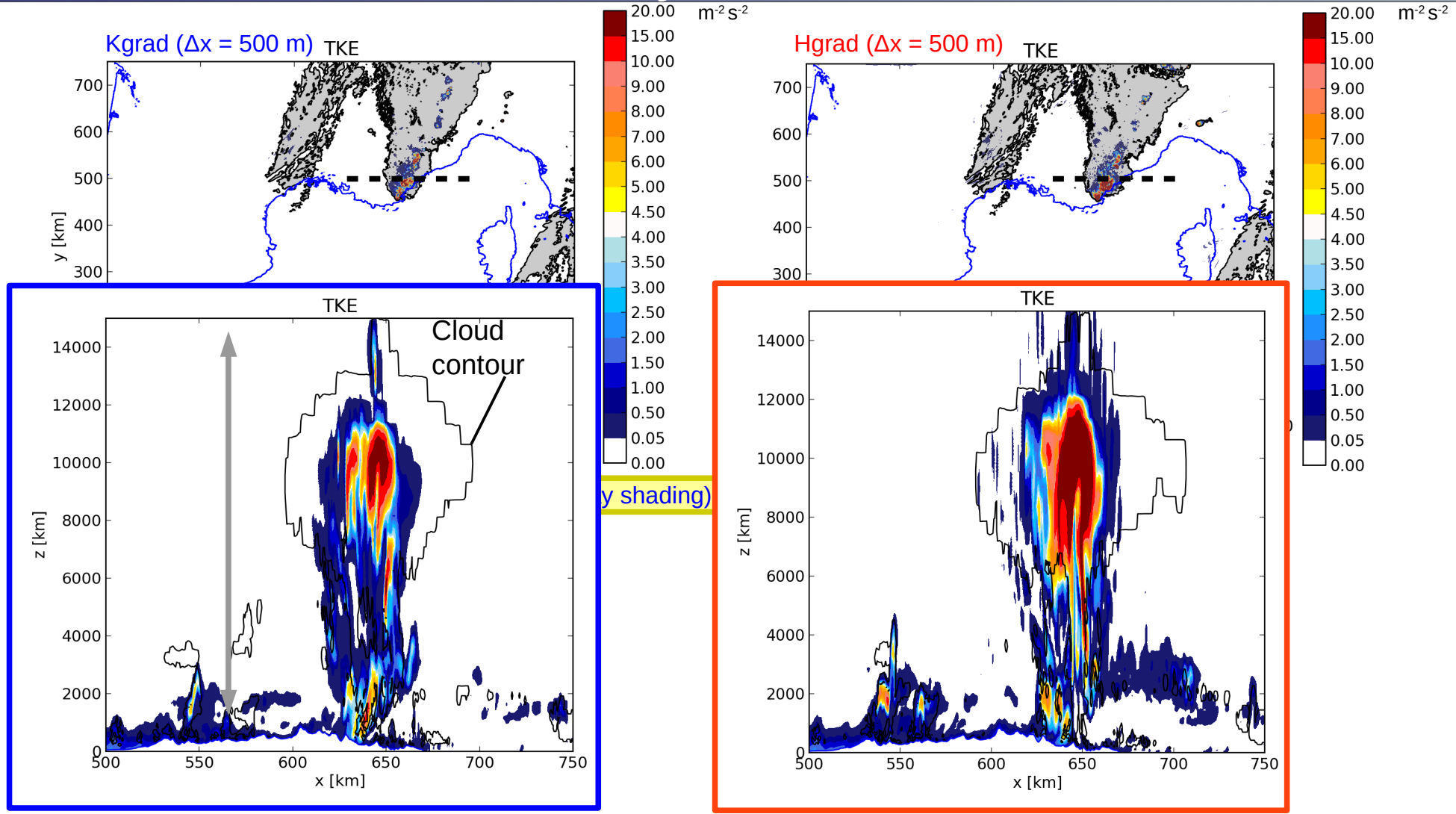
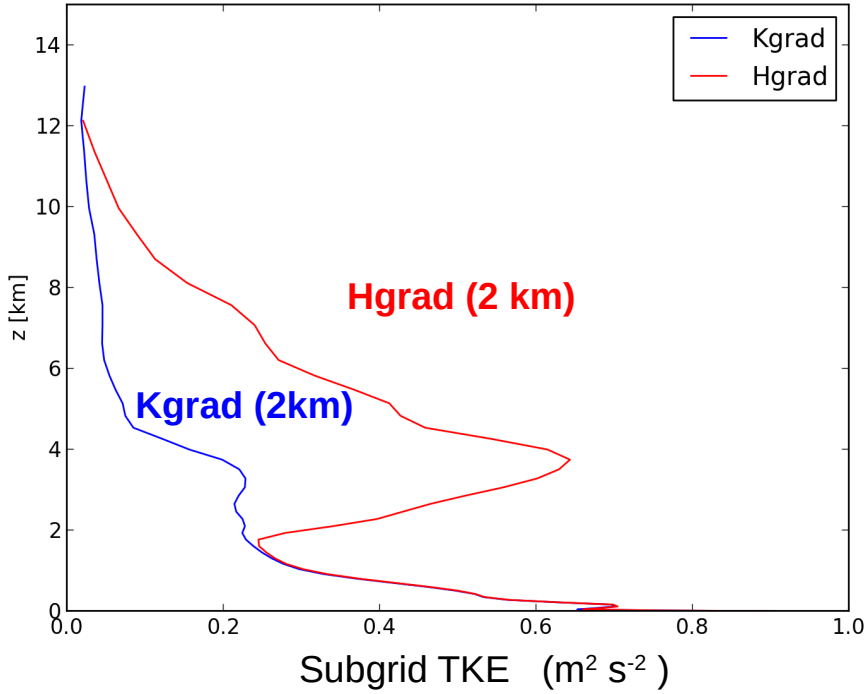
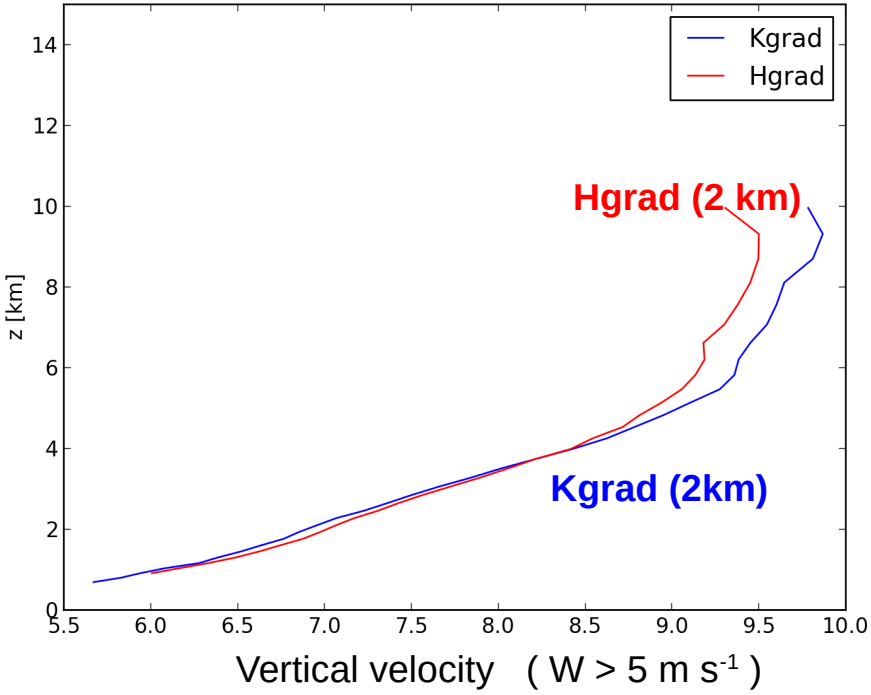


Turbulence and vertical velocity inside convective systems

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

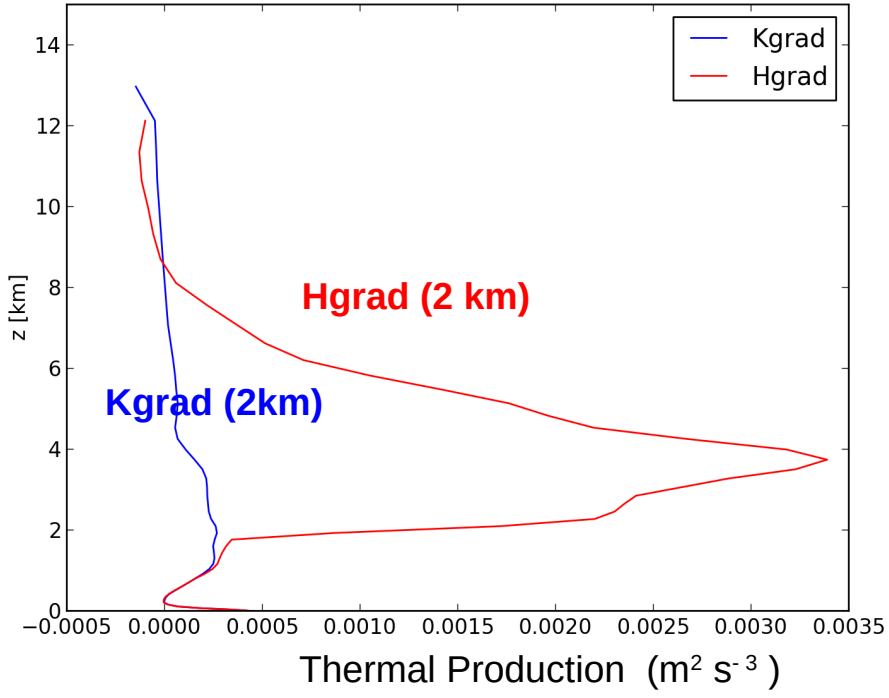


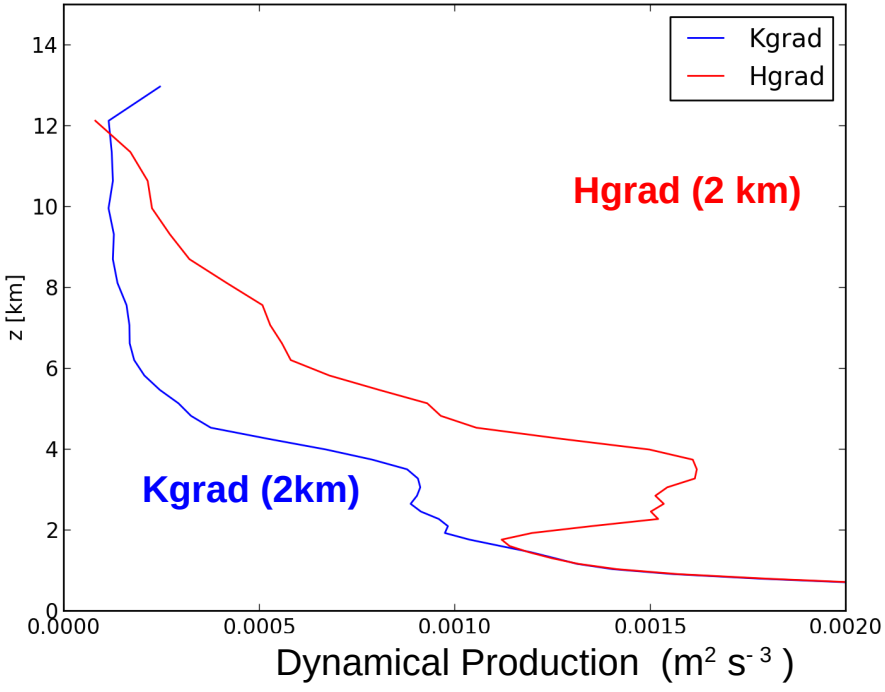


→ more subgrid TKE with the **Hgrad run** compared to the **Kgrad run**
→ less intense vertical velocity in updraft cores (W > 5 m/s)
→ better balance between resolved and subgrid parts

Turbulence production inside convective systems

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

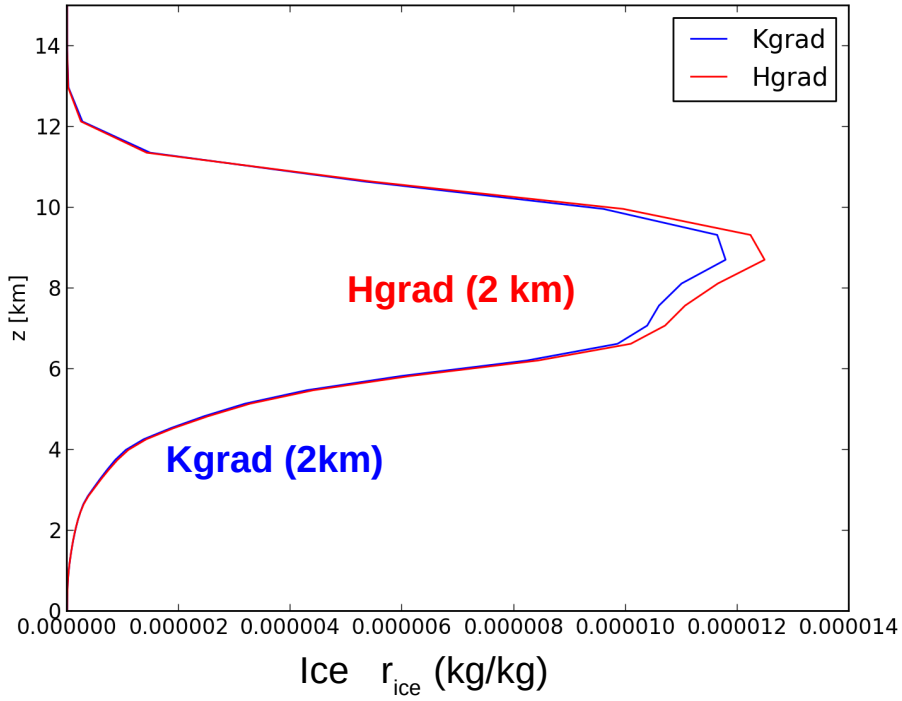


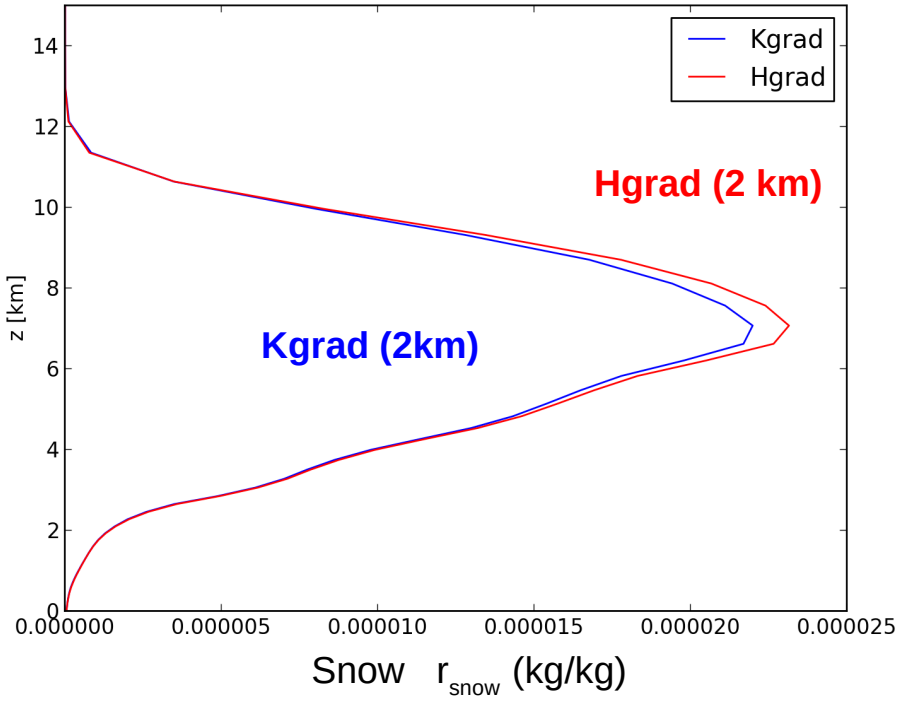


→ more subgrid Thermal Production with the **Hgrad run** compared to the **Kgrad run**
→ this explains the larger TKE with the **Hgrad run**, this induces more dynamical production (from TKE)

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

    Verrelle, A., D. Ricard, and C. Lac, 2015: Sensitivity of high-resolution idealized simulations of thunderstorms to horizontal resolution and turbulence parametrization. Quart. J. Roy. Meteor. Soc., 141, 433–448.
  - 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, A., D. Ricard, and C. Lac, 2017: Evaluation and Improvement of Turbulence Parameterization inside Deep Convective Clouds at Kilometer-Scale Resolution. Mon. Wea. Rev., 145, 3947–3967
  - generalization: better vertical and horizontal turbulent fluxes of heat and moisture, slightly better dynamical covariances but better dynamical variances with CBR scheme

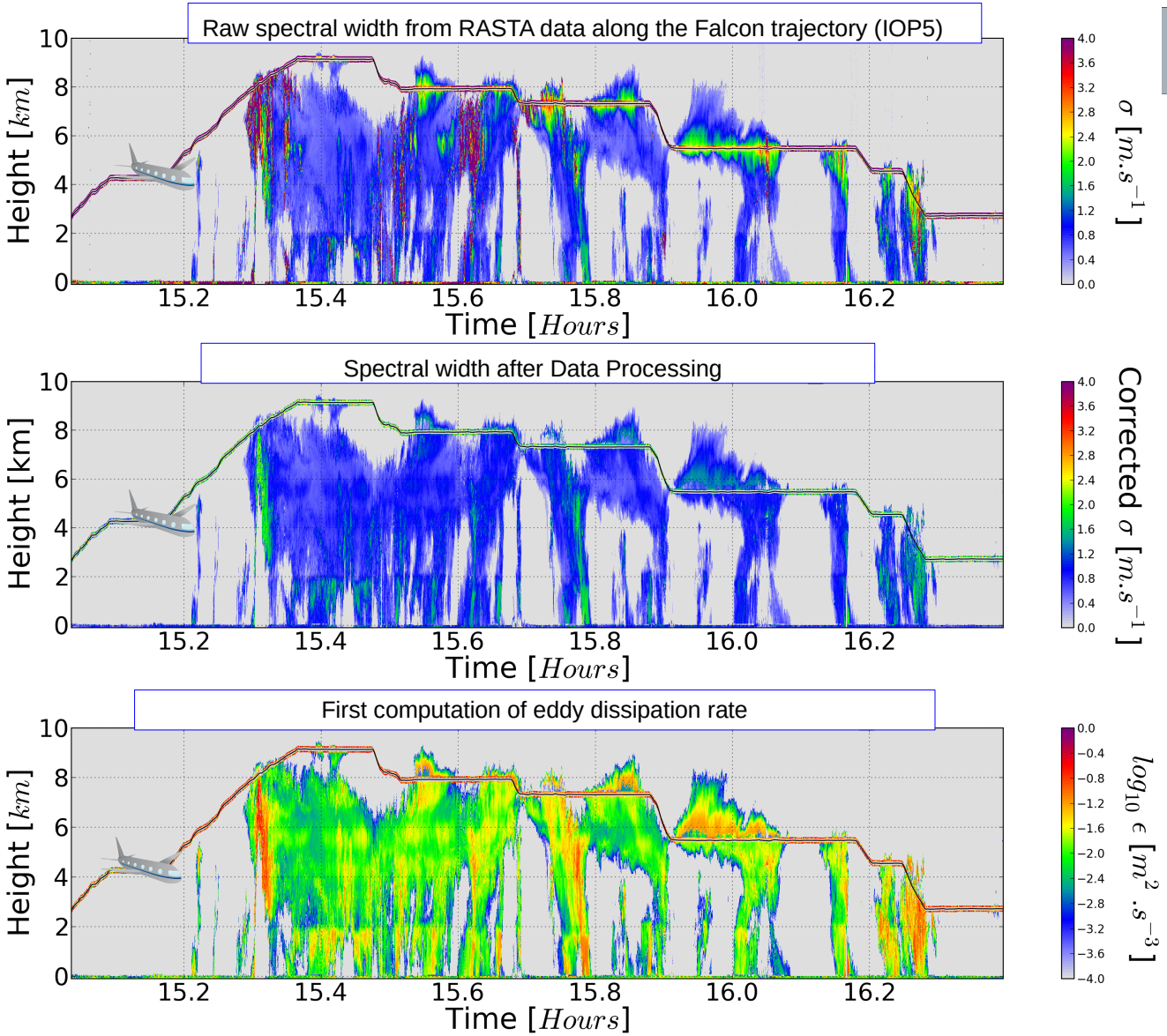
    Strauss, C, D. Ricard, C. Lac, A. Verrelle, 2019: Evaluation of turbulence parameterizations in convective clouds and their environment based on a large-eddy simulation. Quart. J. Roy. Meteor. Soc., accepted.
- Online evaluation of a new turbulence scheme on real cases of deep convection (IOP6 and IOP16)

  → 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)

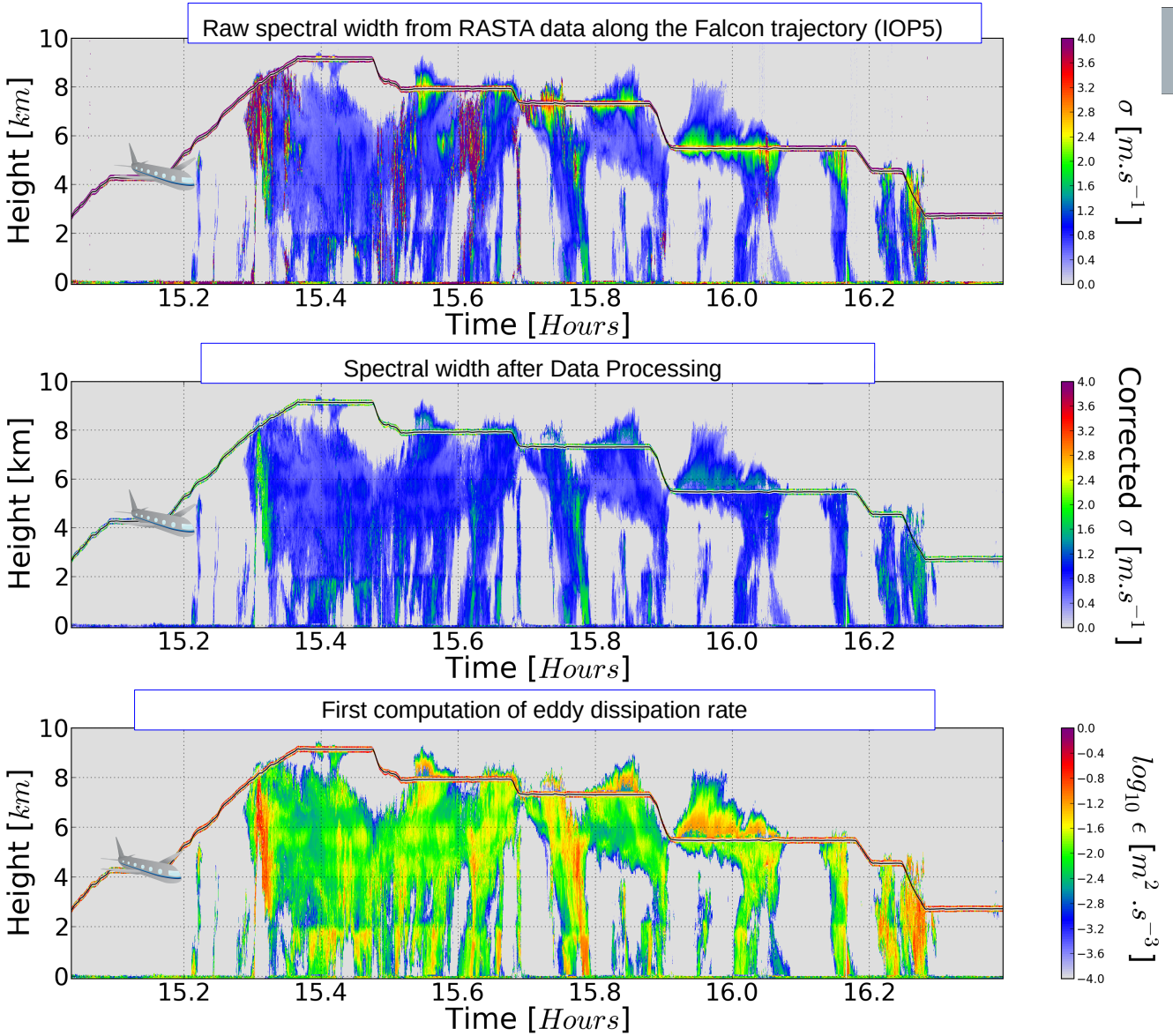


Conclusion

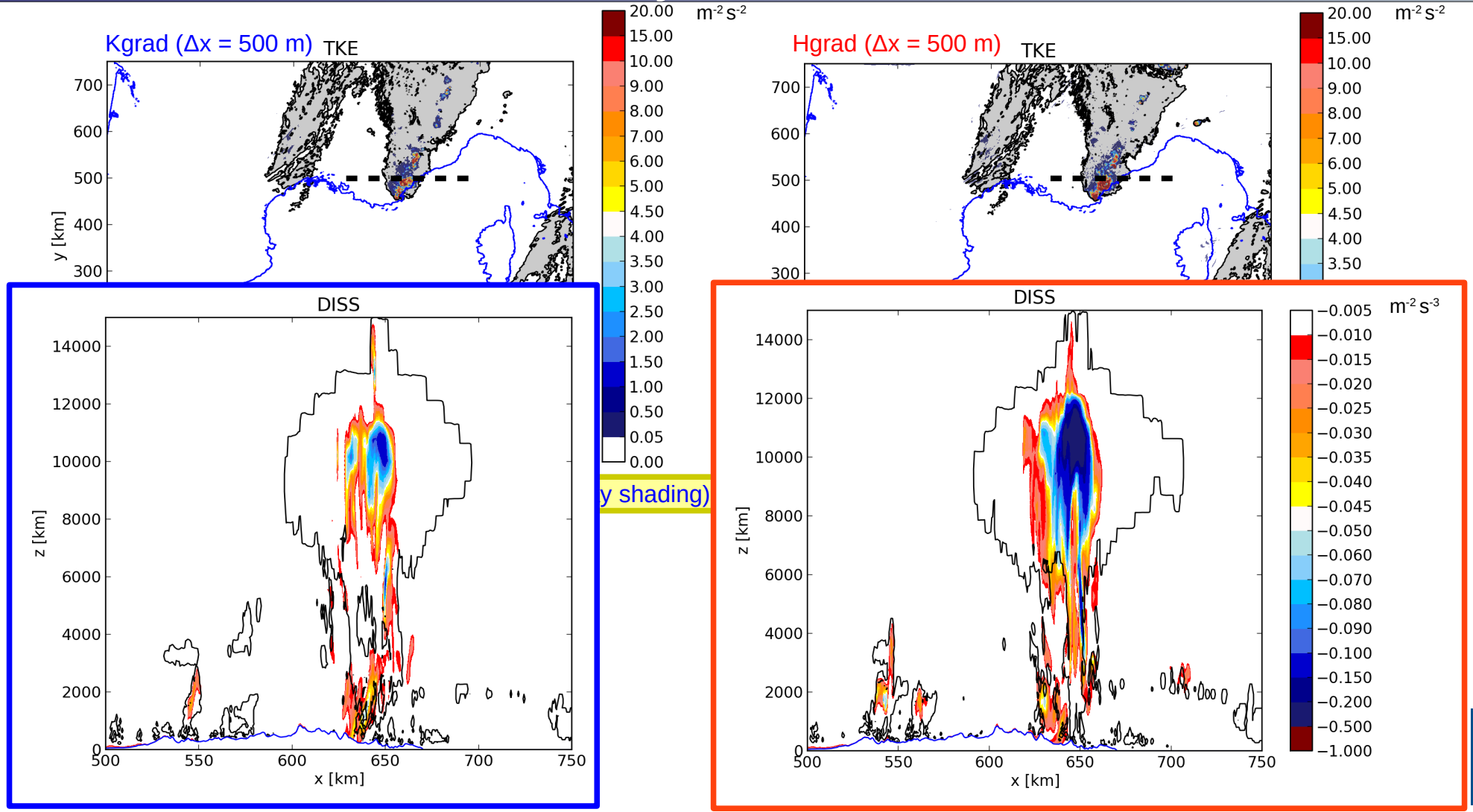
EDR estimates from RASTA data for IOP5 (EXAEDRE field campaign) 10 October 2018: convection over the Gulf of Genoa

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

Thank you for your attention

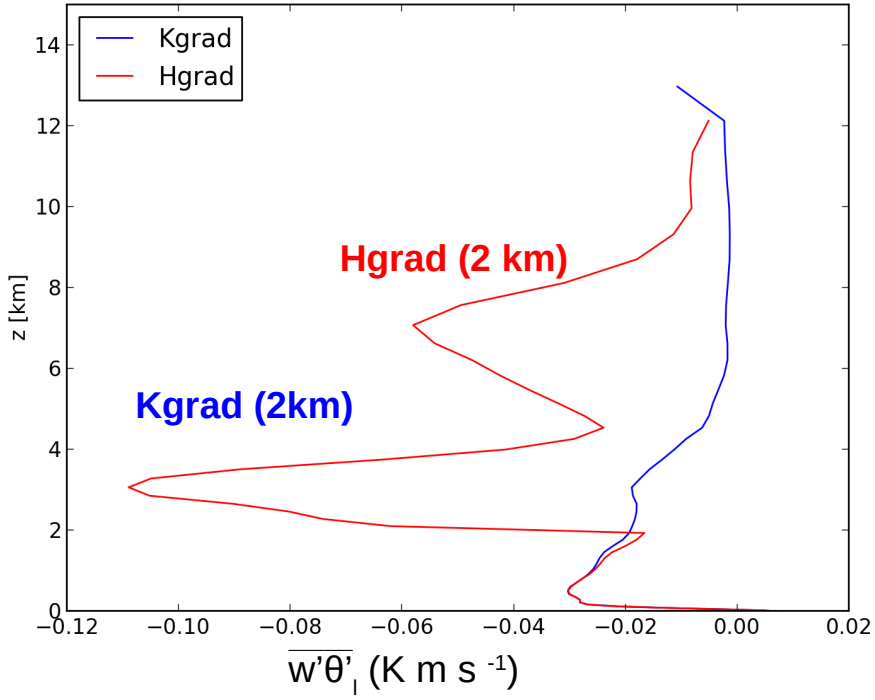


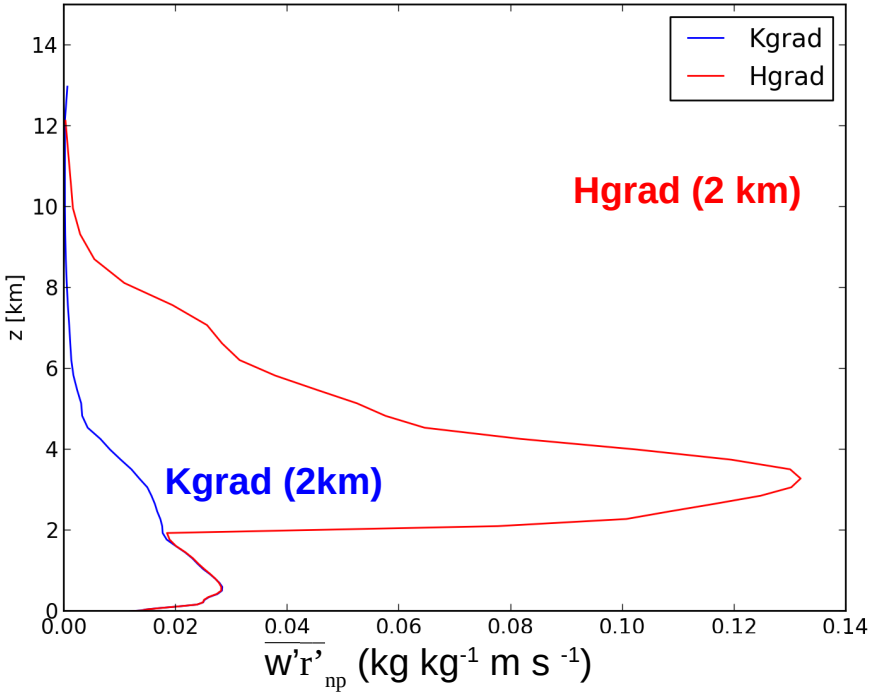
Turbulence inside convective systems



Turbulent fluxes inside convective systems

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

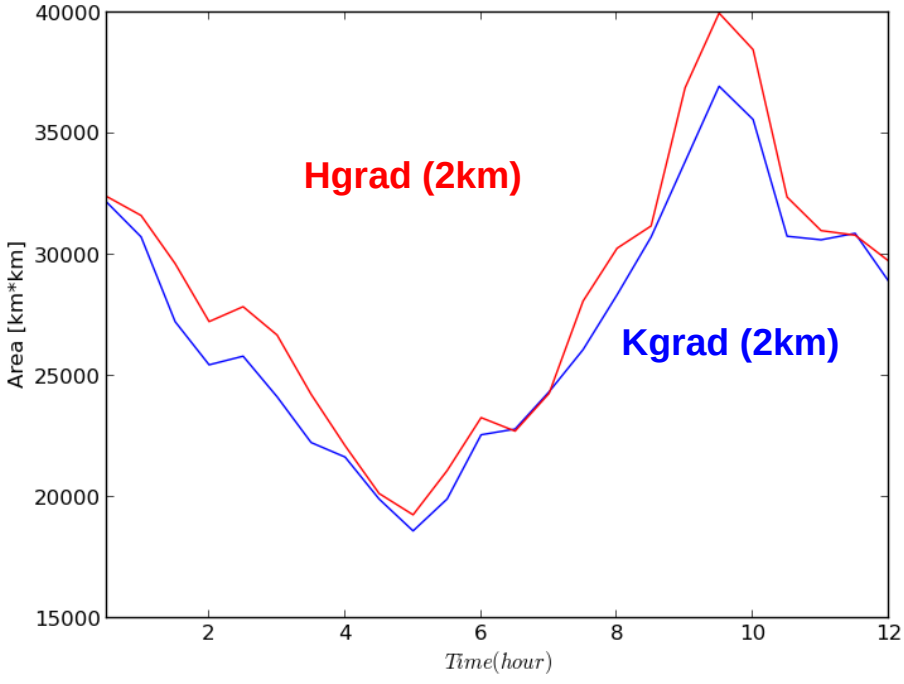




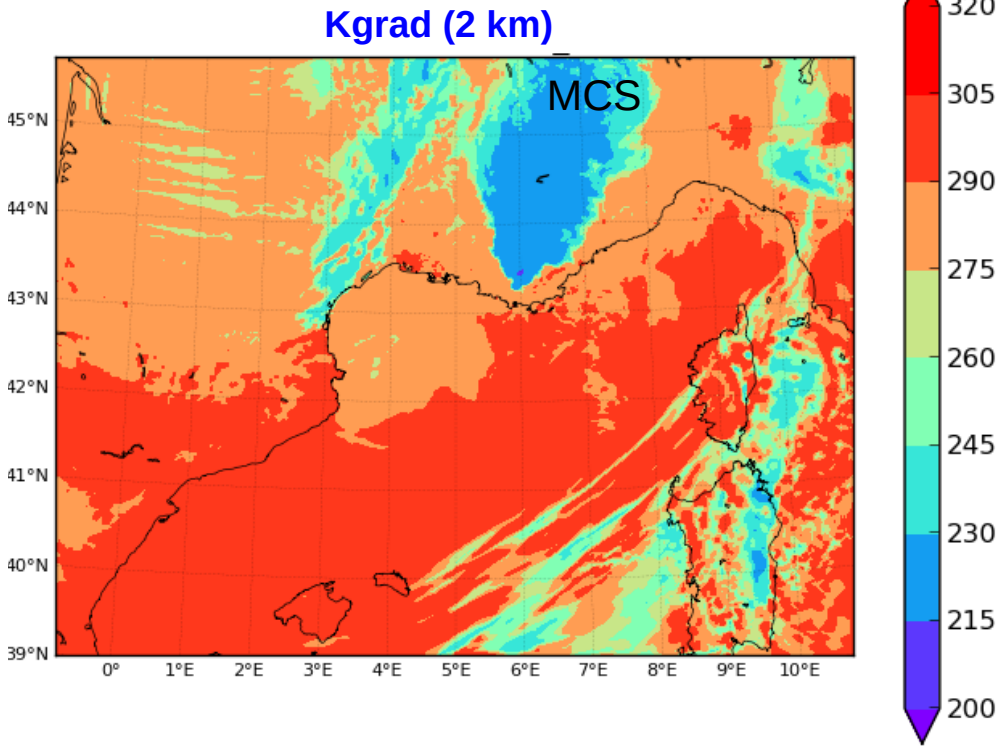
→ more intense subgrid turbulent fluxes the **Hgrad run** compared to the **Kgrad run**

Time evolution of high cloud cover (Tb < 230 K)

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



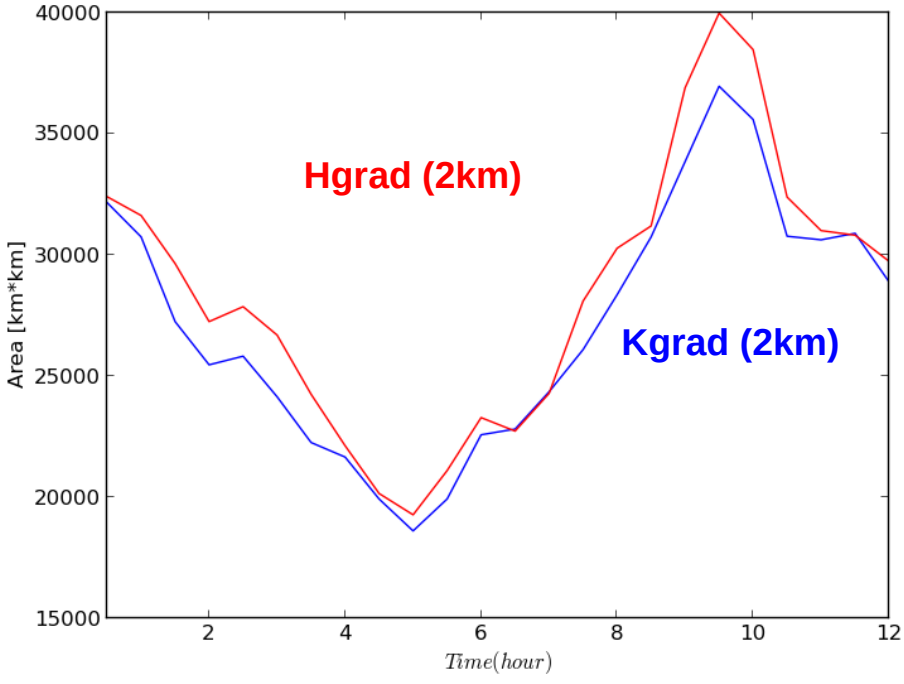
Brightness temperature (K) 9:00 UTC



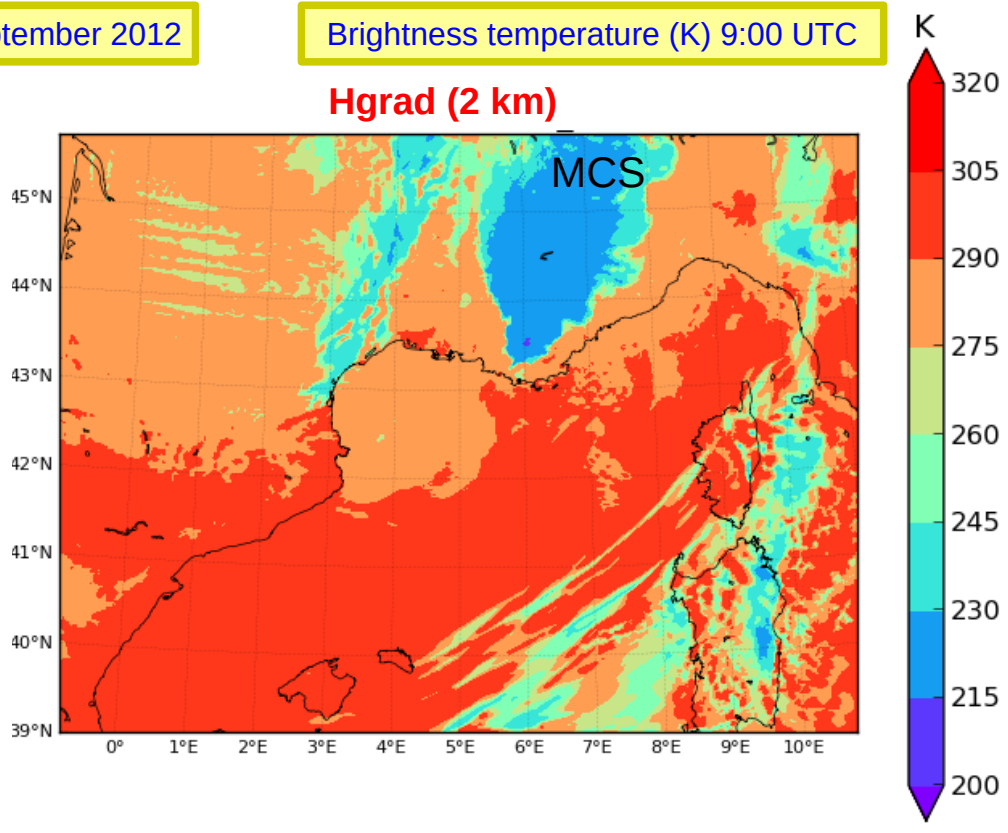
→ more anvils with **Hgrad run** compared to the **Kgrad run**

Time evolution of high cloud cover (Tb < 230 K)

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



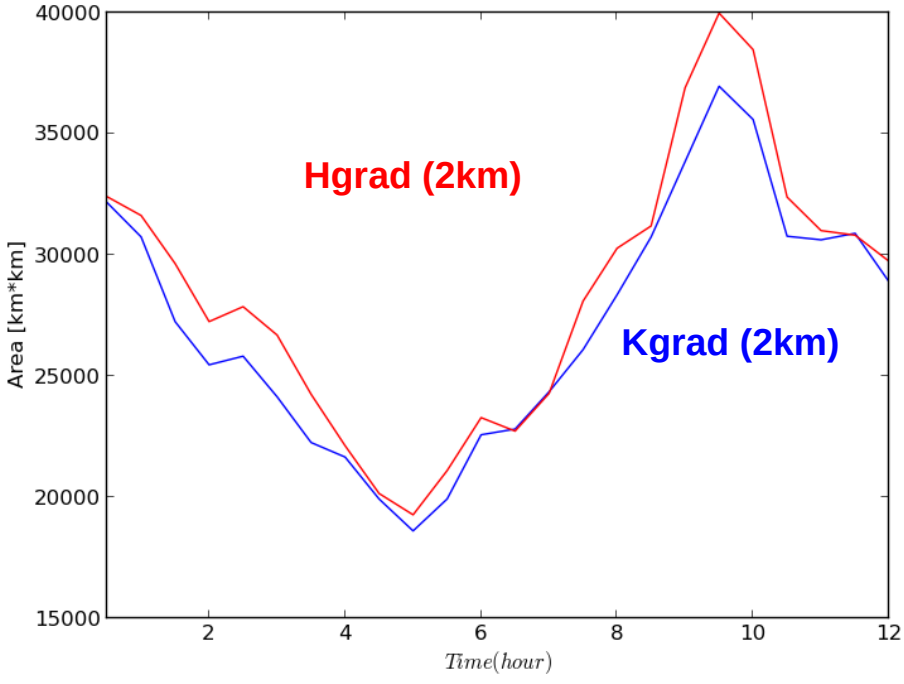
Brightness temperature (K) 9:00 UTC



→ more anvils with **Hgrad run** compared to the **Kgrad run**

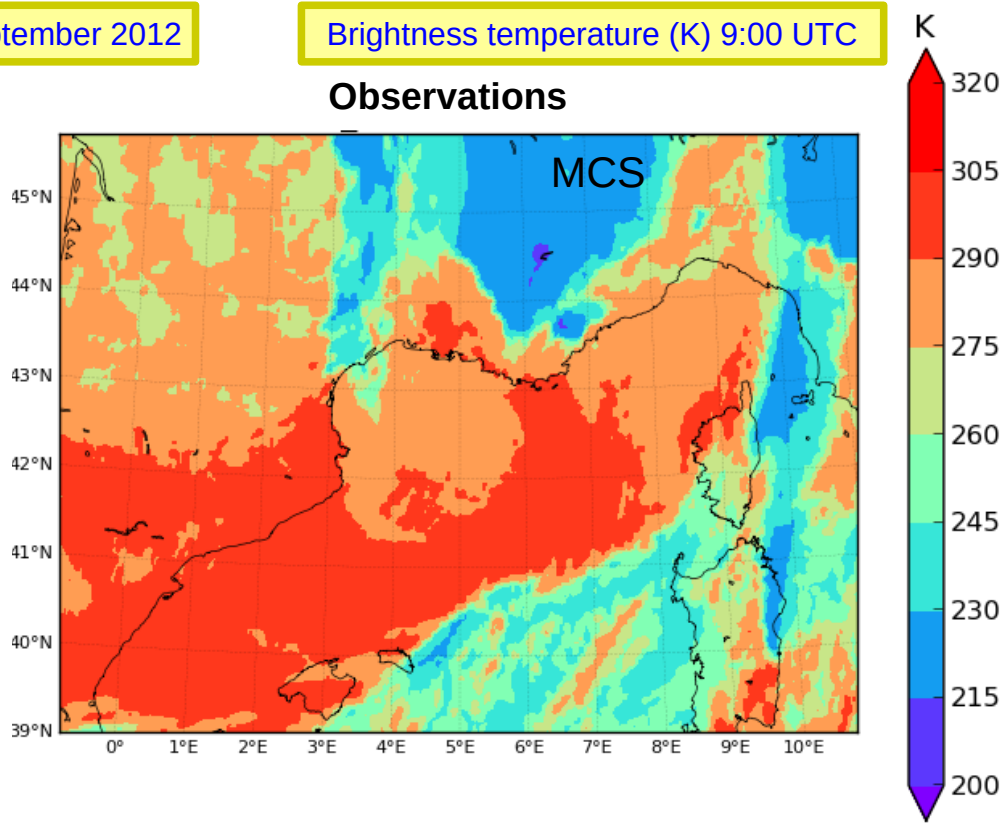
Time evolution of high cloud cover (Tb < 230 K)

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



Brightness temperature (K) 9:00 UTC

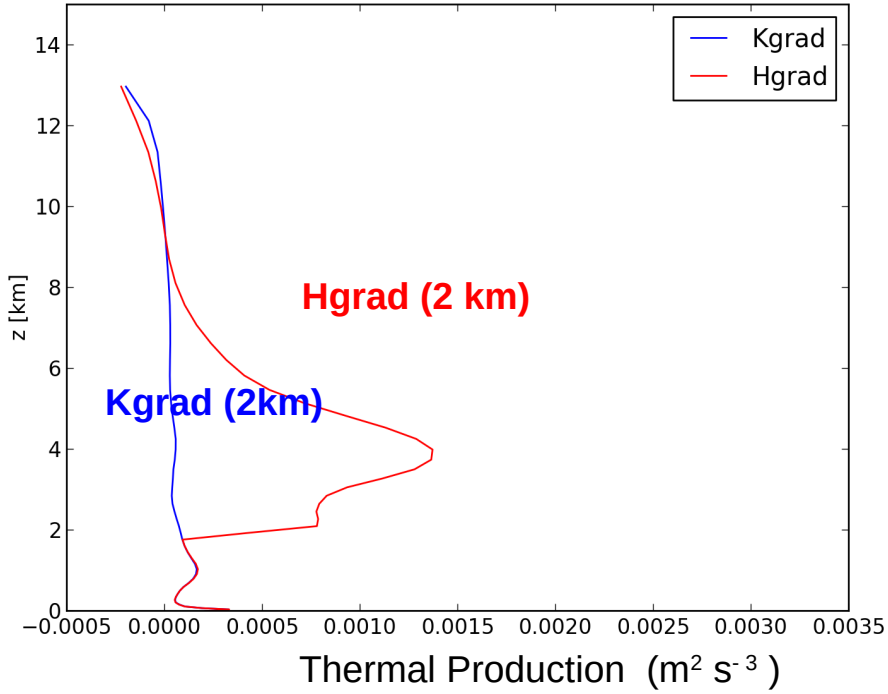
Observations

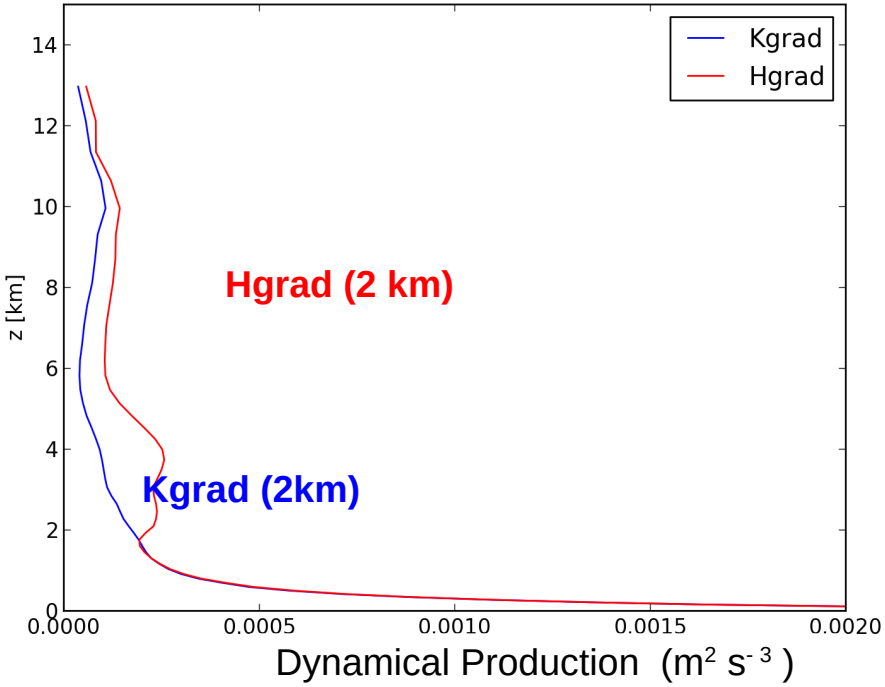


→ more anvils with **Hgrad run** compared to the **Kgrad run**
→ more differences at 2 km resolution
→ underestimation in comparison with observations

Turbulence production inside convective systems IOP16

Mean vertical profiles inside convective clouds between between 00UTC 26 October and 00 UTC 27 October 2012

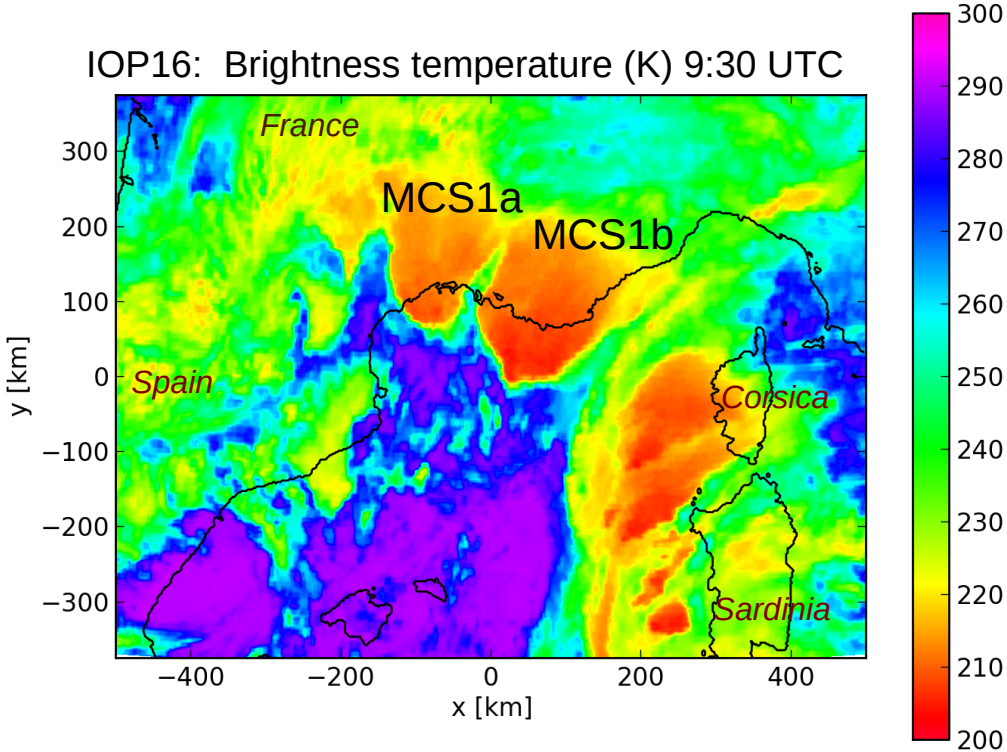


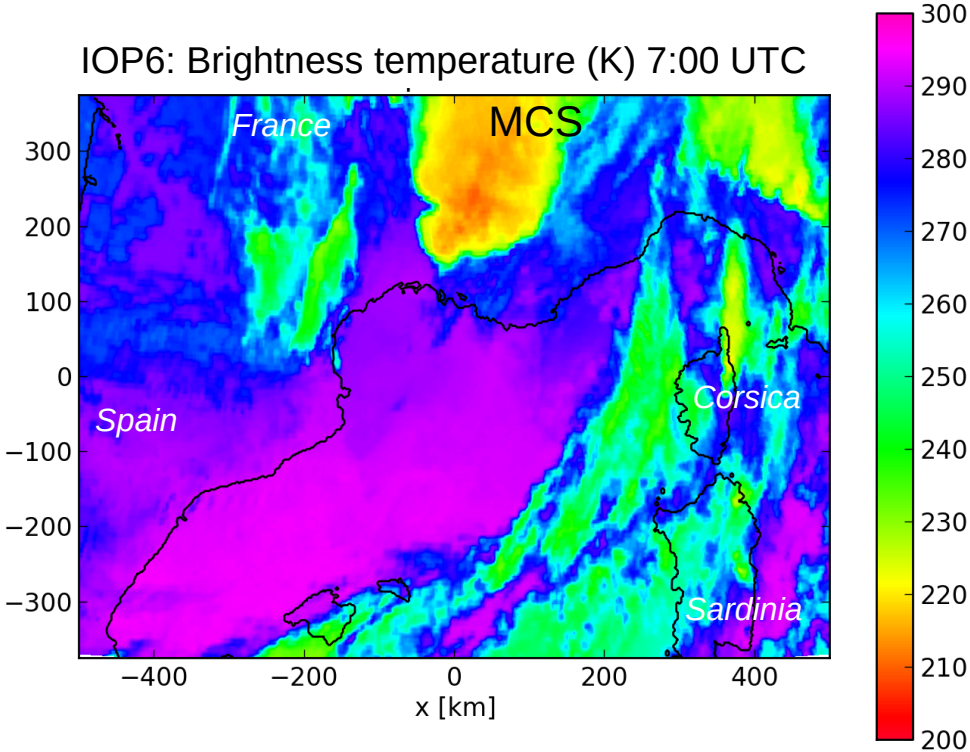


→ more subgrid Thermal Production with the **Hgrad run** compared to the **Kgrad run**
→ this explains the larger TKE with the **Hgrad run**, this induces more dynamical production (from TKE)
→ For IOP6, there is a larger contribution of dynamical production than for IOP16 (strong wind shear)

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**

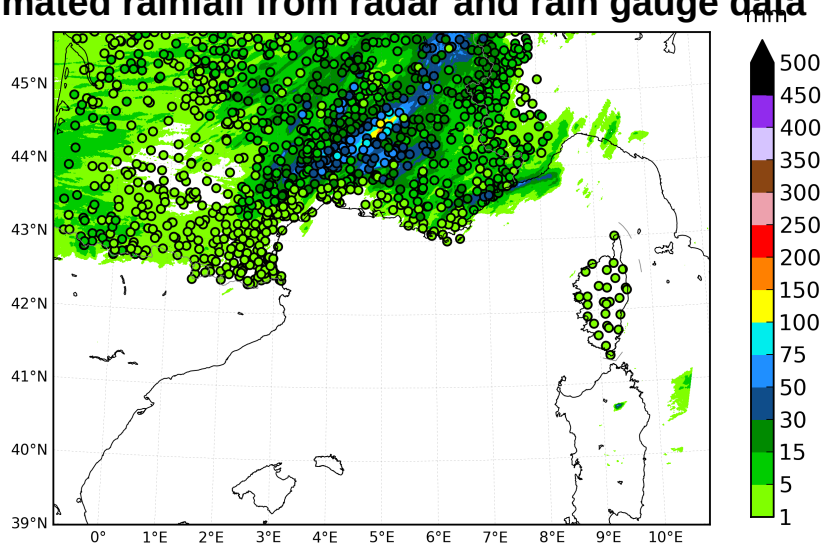




12-h accumulated precipitation

→ Large rainfall accumulation over the orography (00 → 12 UTC)

Estimated rainfall from radar and rain gauge data



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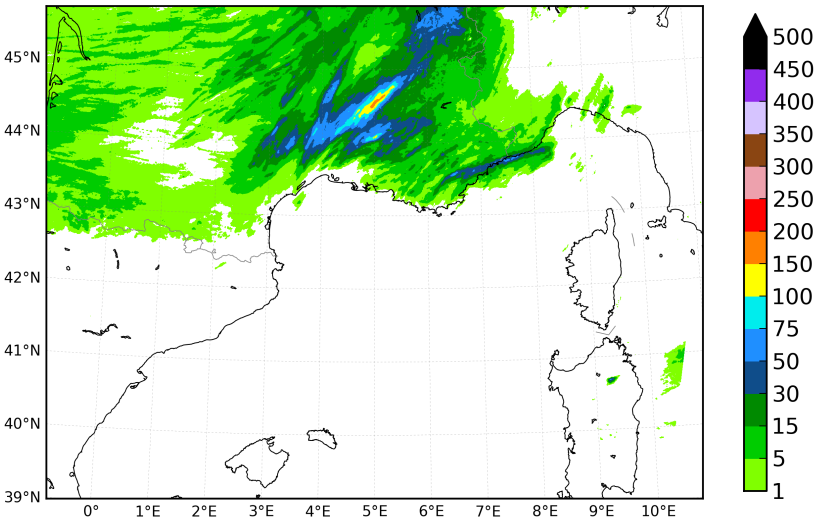
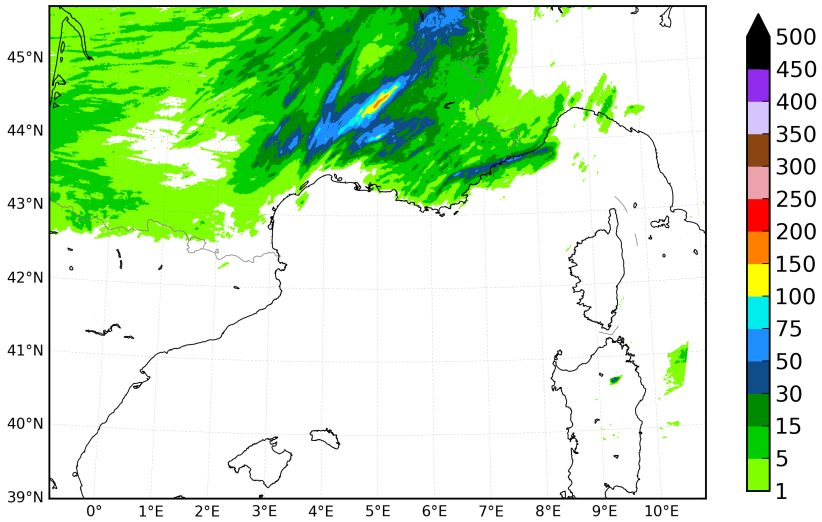


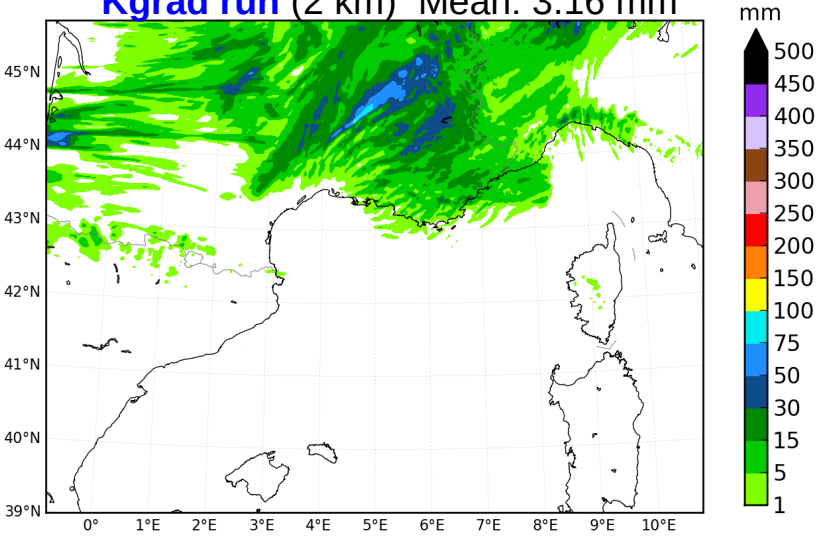
12-h accumulated precipitation

→ 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**

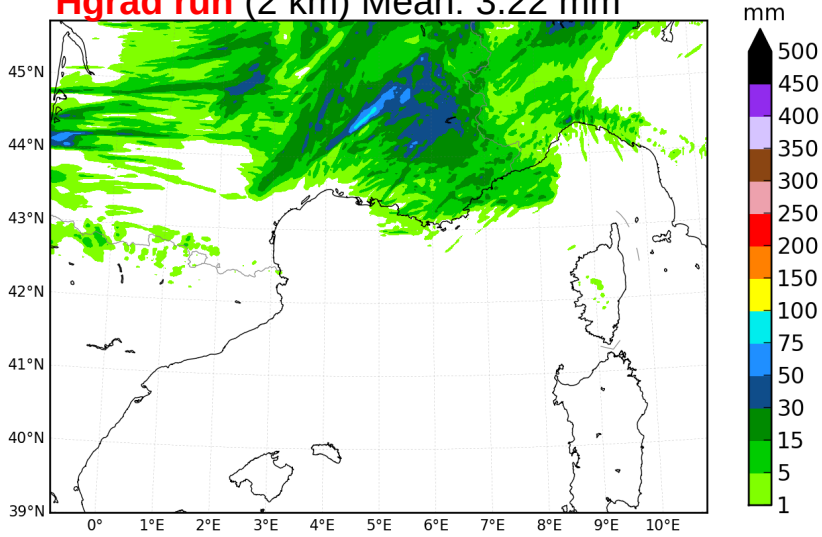
Estimated rainfall from radar and rain gauge data



Kgrad run (2 km) Mean: 3.16 mm



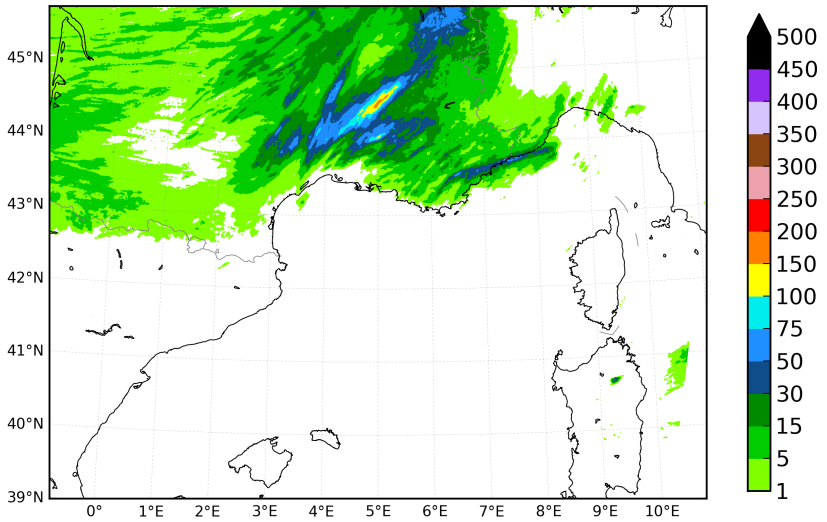
Hgrad run (2 km) Mean: 3.22 mm



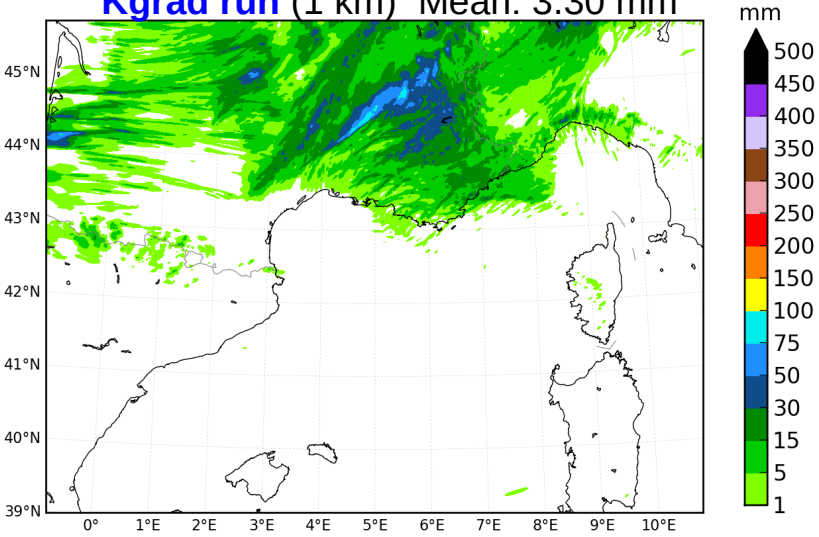
12-h accumulated precipitation

→ 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

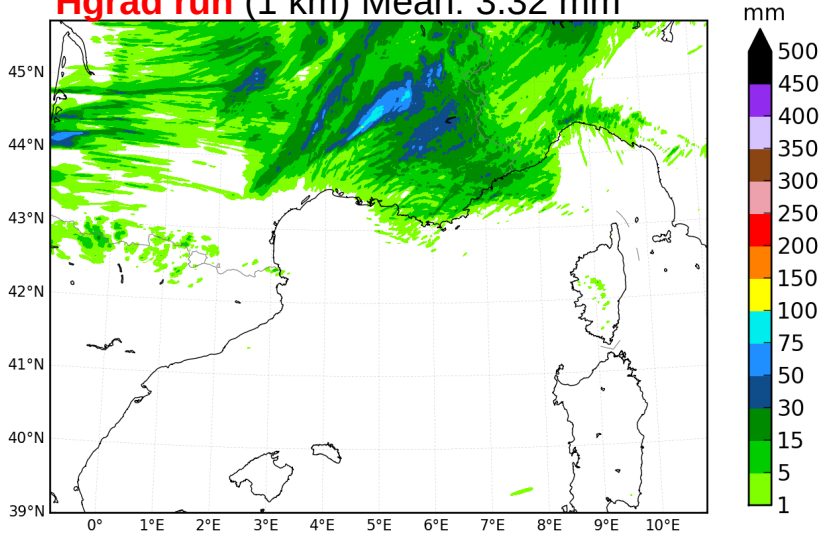
Estimated rainfall from radar and rain gauge data



Kgrad run (1 km) Mean: 3.30 mm



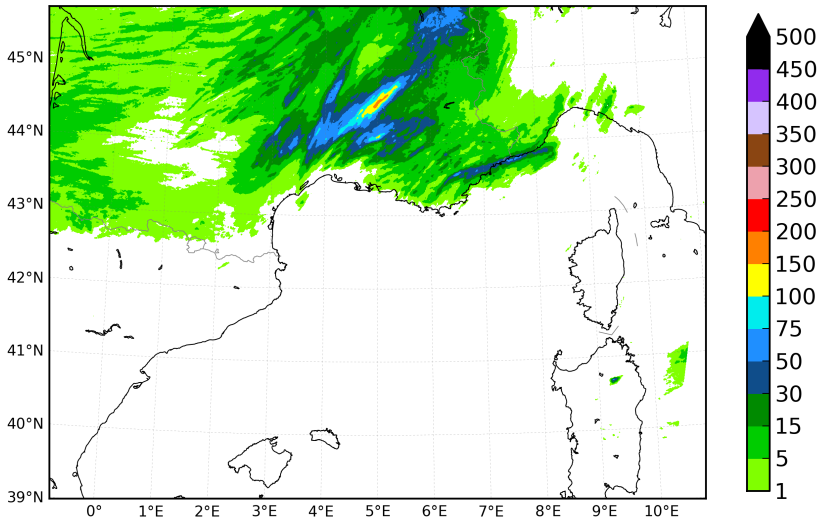
Hgrad run (1 km) Mean: 3.32 mm



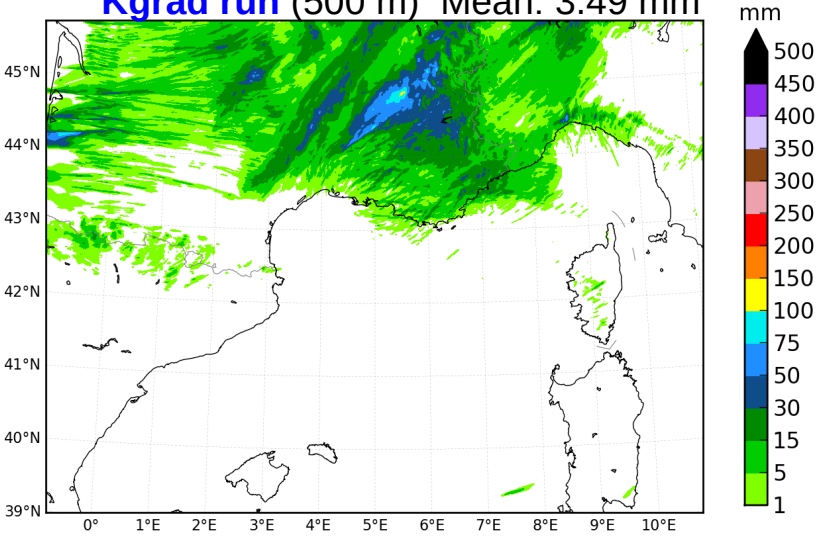
12-h accumulated precipitation

→ 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

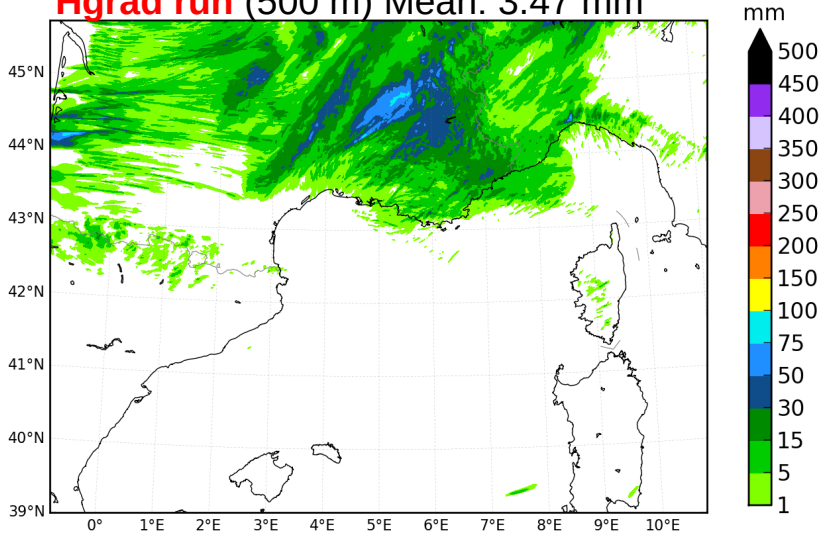
Estimated rainfall from radar and rain gauge data



Kgrad run (500 m) Mean: 3.49 mm

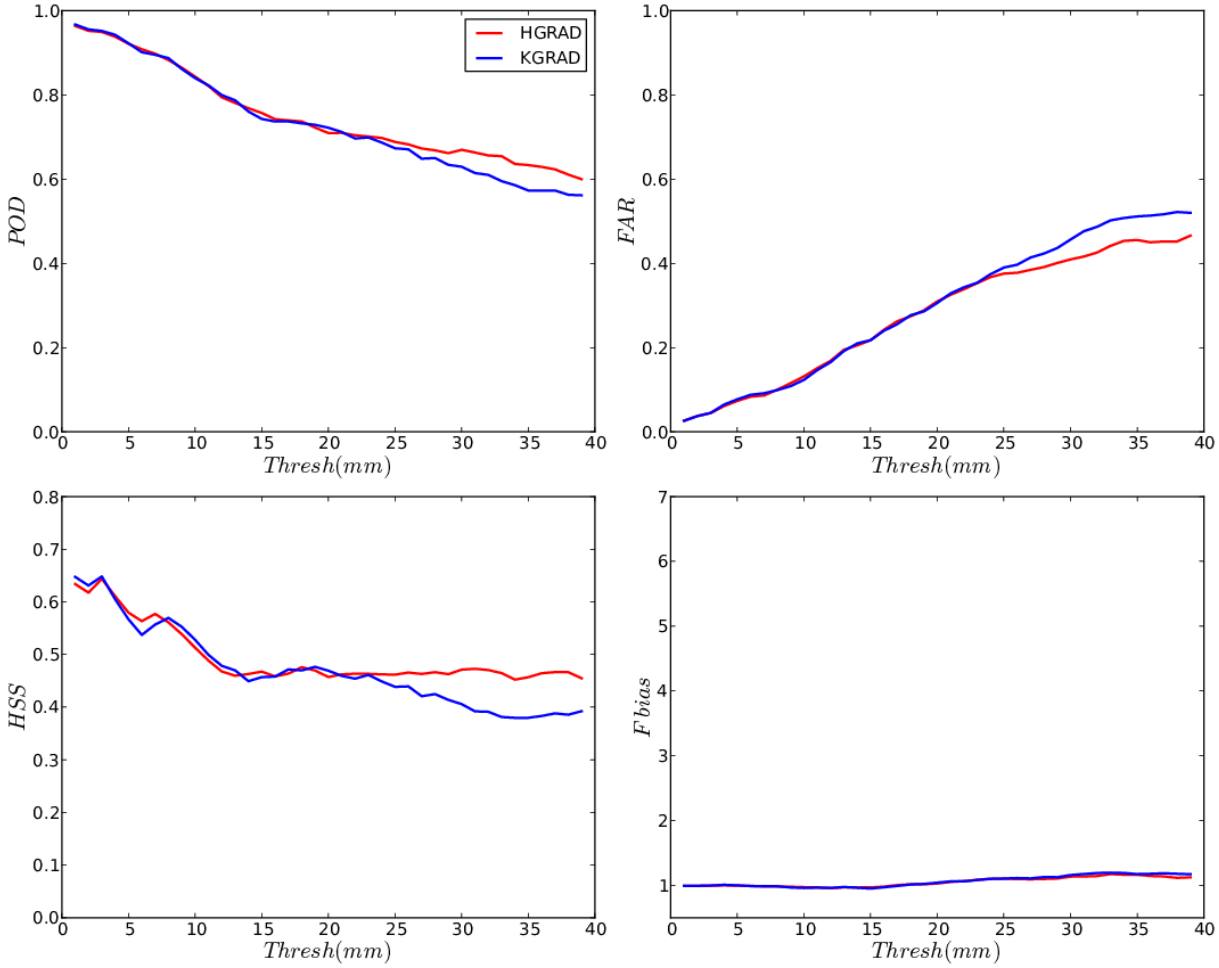


Hgrad run (500 m) Mean: 3.47 mm



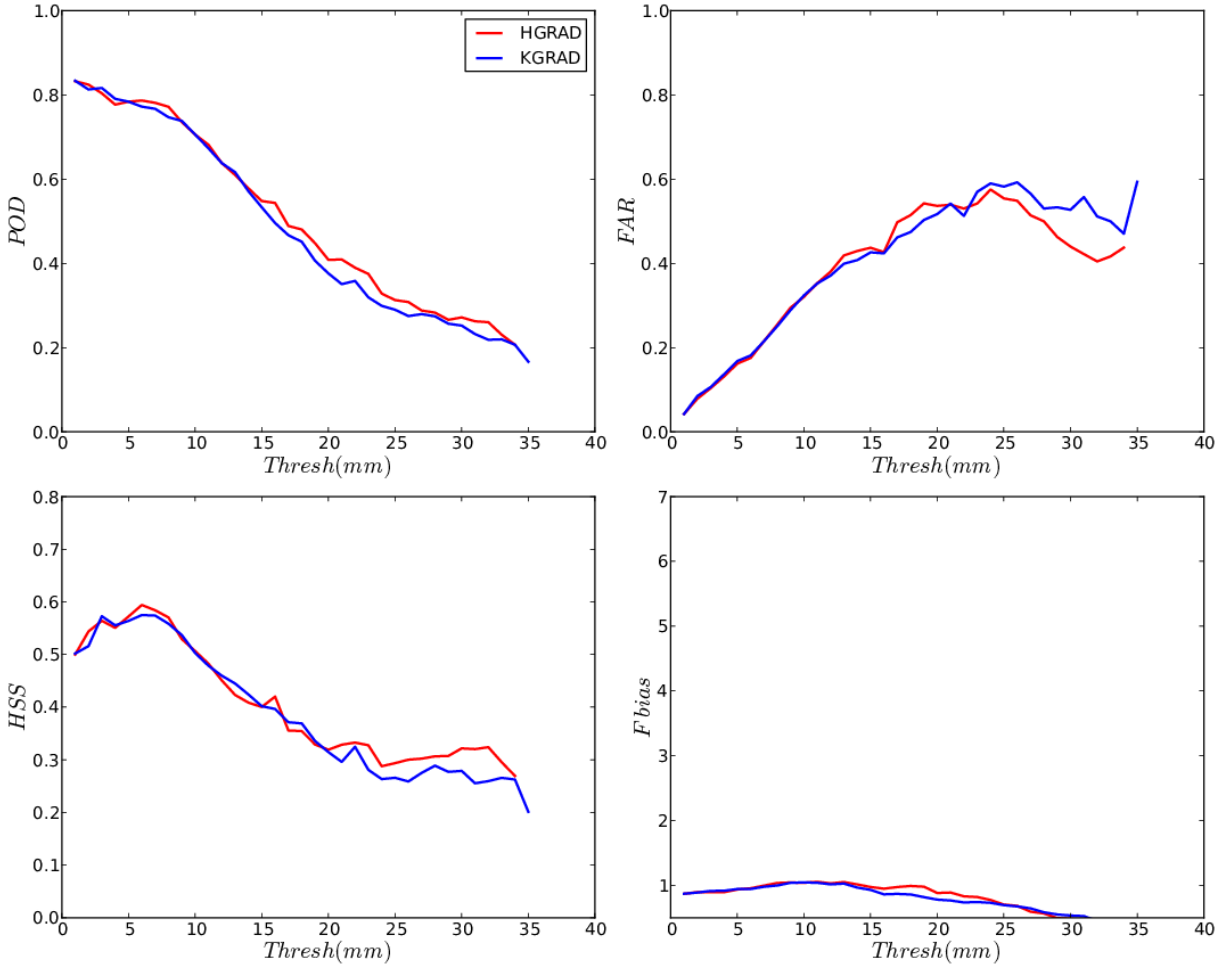
24-h accumulated precipitation (IOP16)

Objectives scores



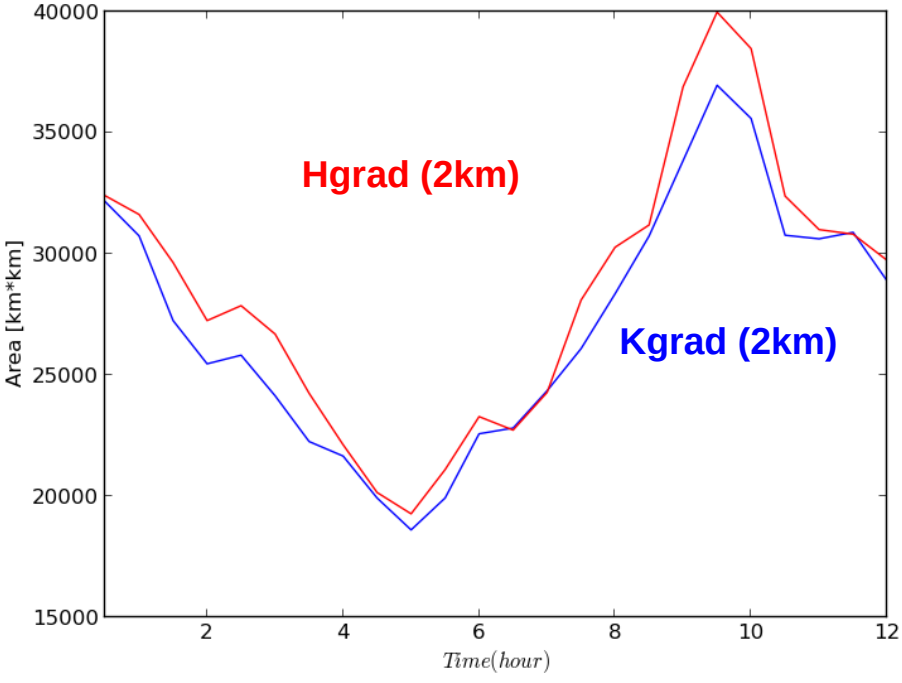
12-h accumulated precipitation (IOP6)

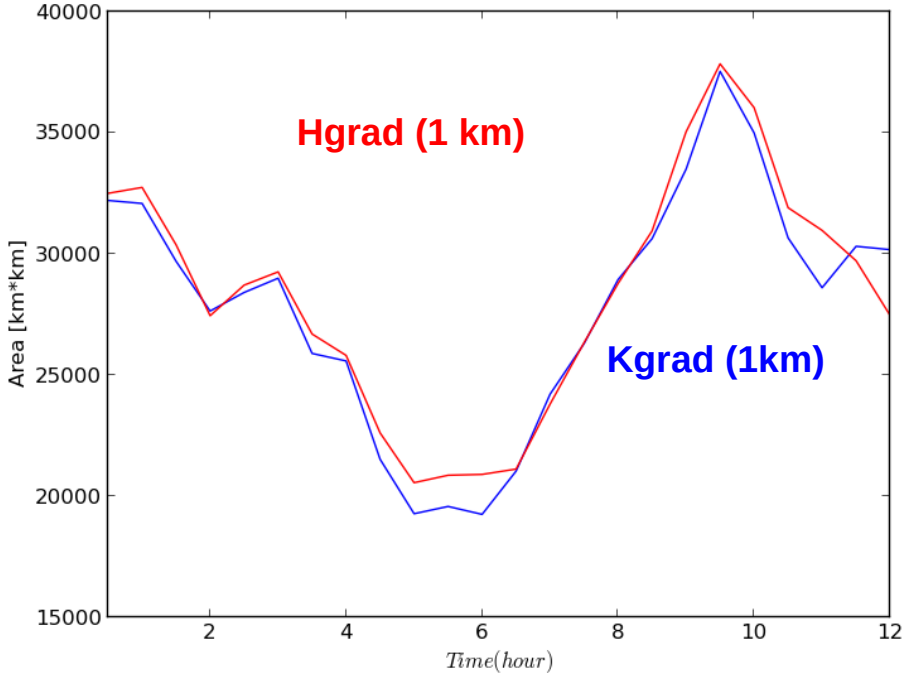
Objectives scores



Time evolution of high cloud cover (Tb < 230 K)

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

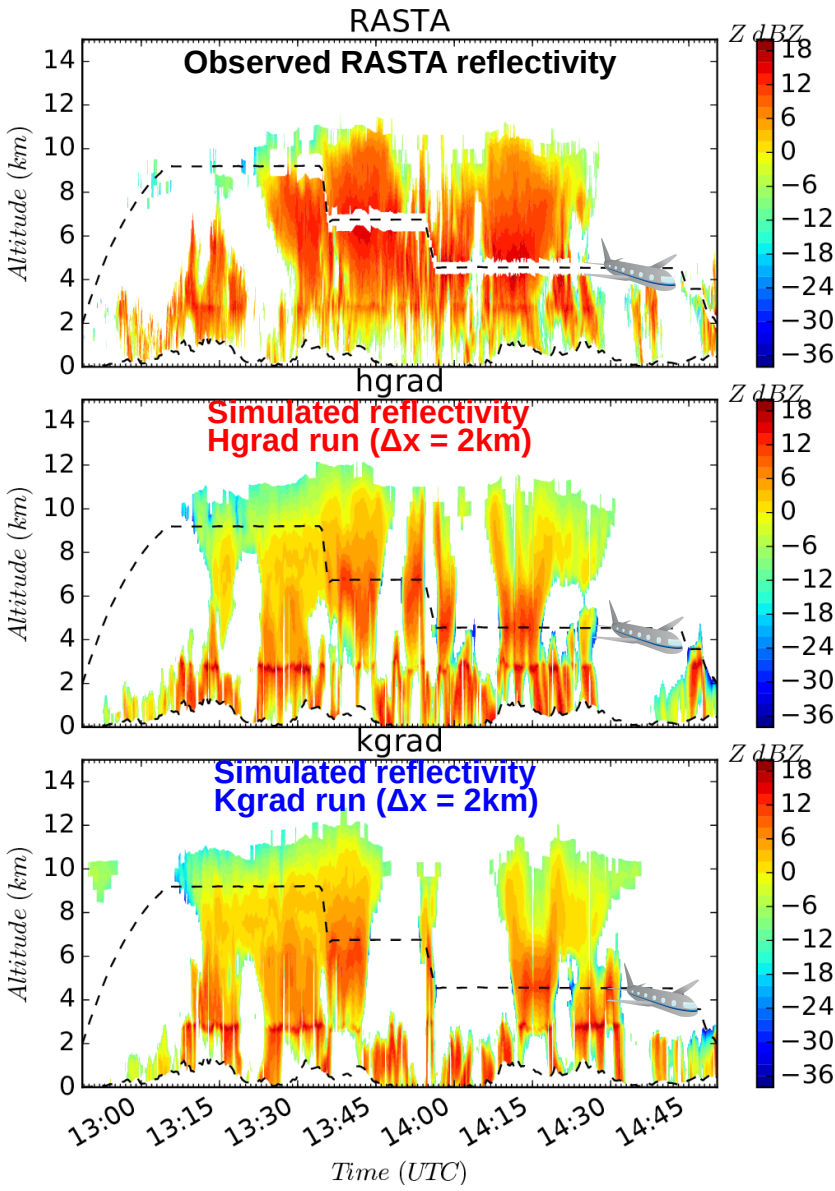




→ more anvils with **Hgrad run** compared to the **Kgrad run**
→ more differences at 2 km resolution
→ underestimation in comparison with observations

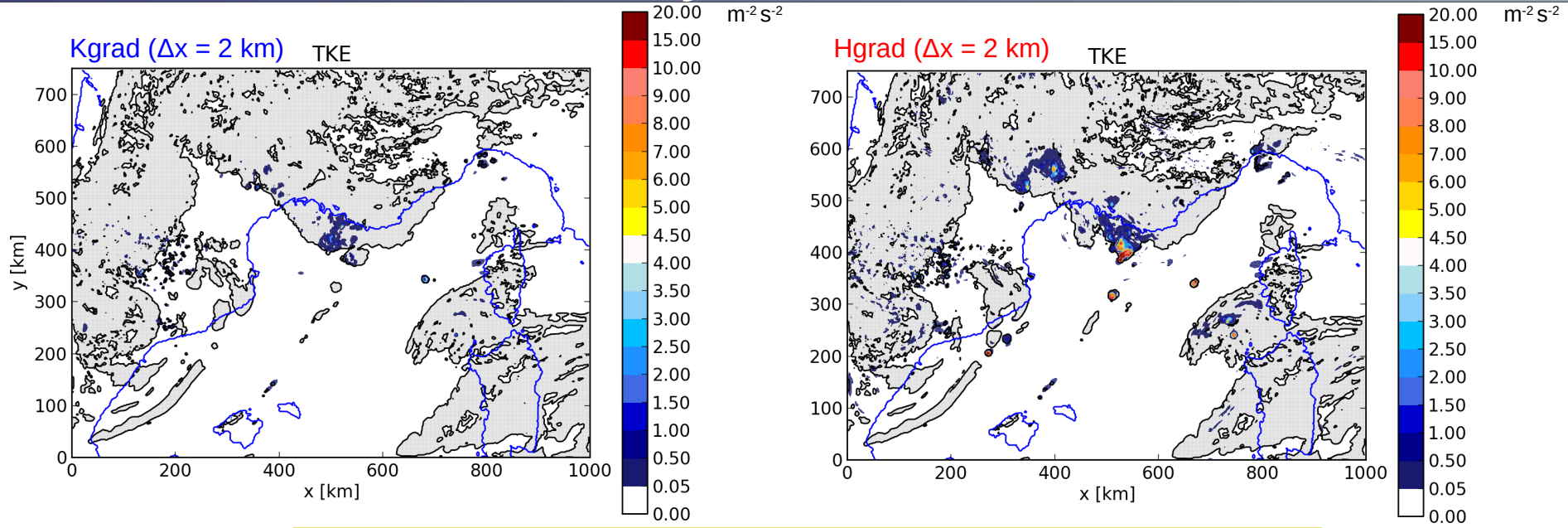
Impact on convective systems

Vertical cross section of radar reflectivity (dBZ) along the Falcon-20 trajectory (26 0ctober 2012)



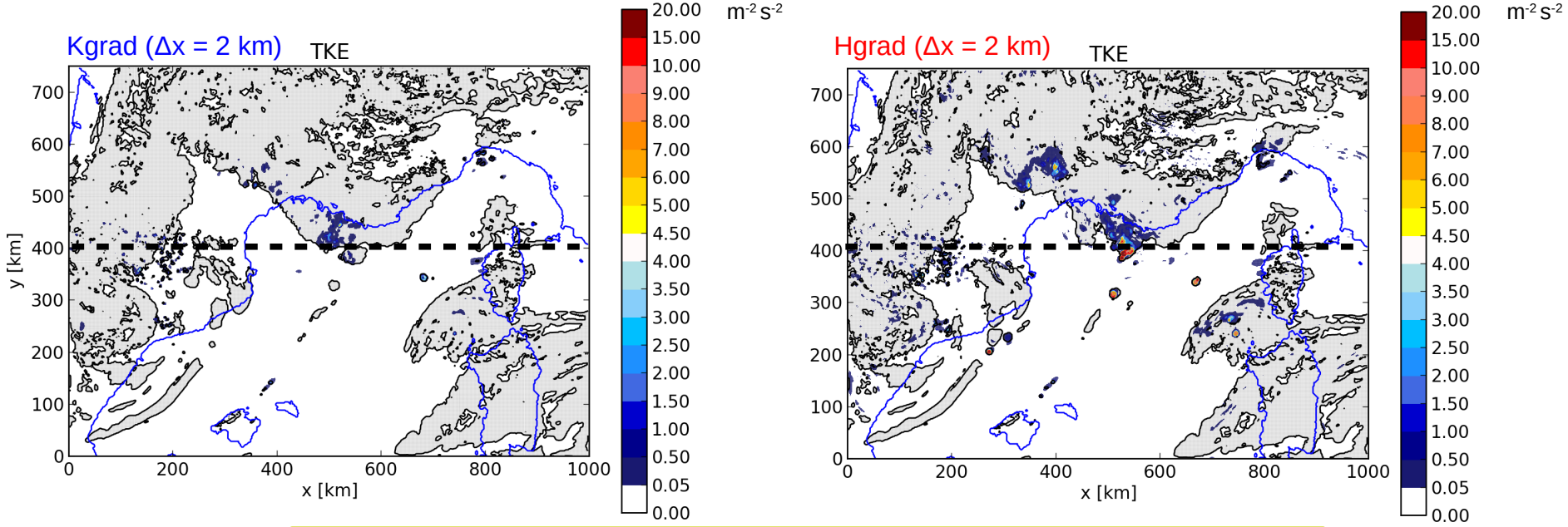
→ Good vertical extension of convective systems
→ Underestimation of reflectivity
→ Higher reflectivity in the upper part of the clouds with the Hgrad run

Turbulence inside convective systems



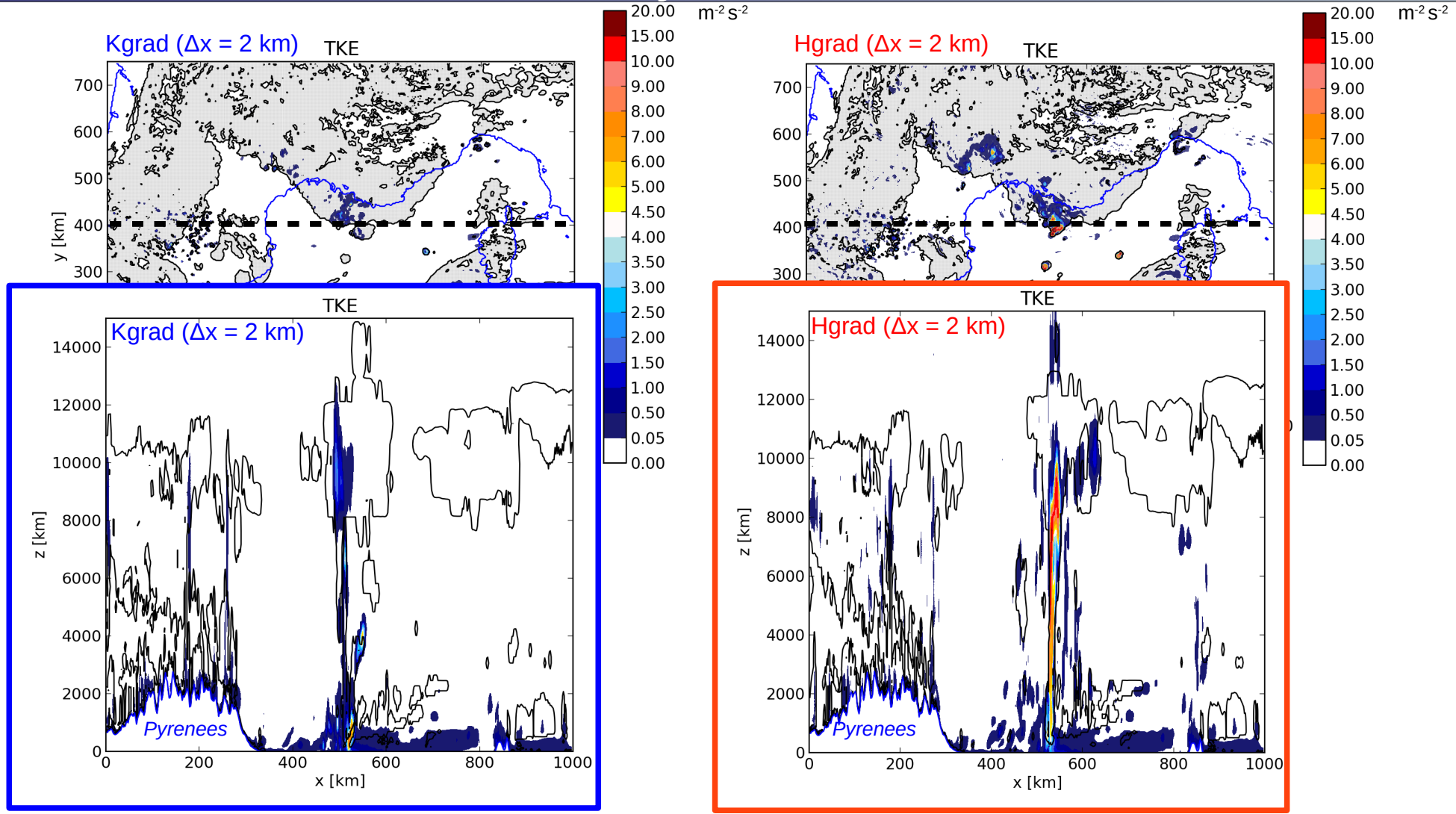
Subgrid TKE and cloud (gray shading) at 8000 m AGL - 11 UTC (26 october 2012)

Turbulence inside convective systems

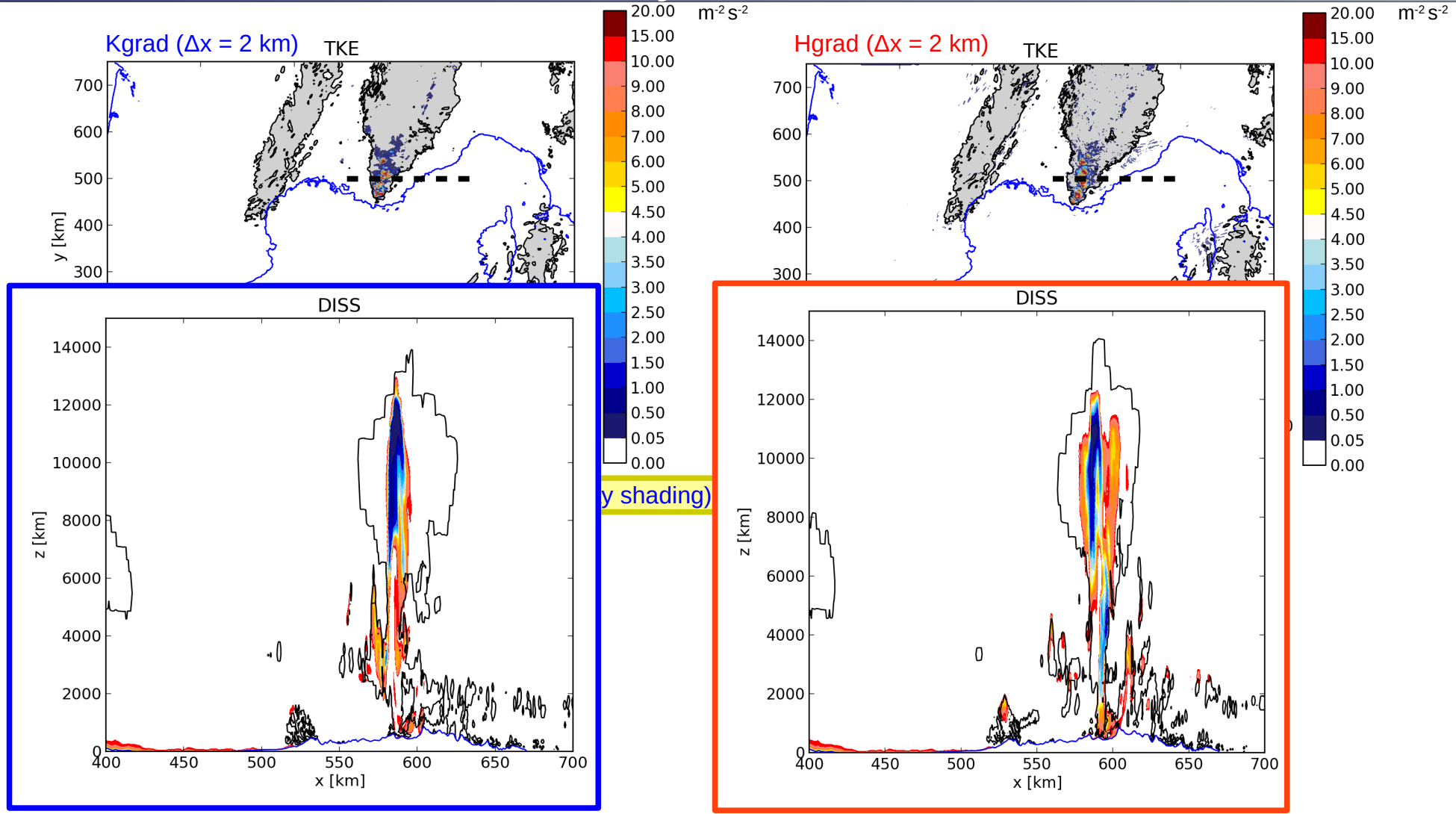


Subgrid TKE and cloud (gray shading) at 8000 m AGL - 11 UTC (26 october 2012)

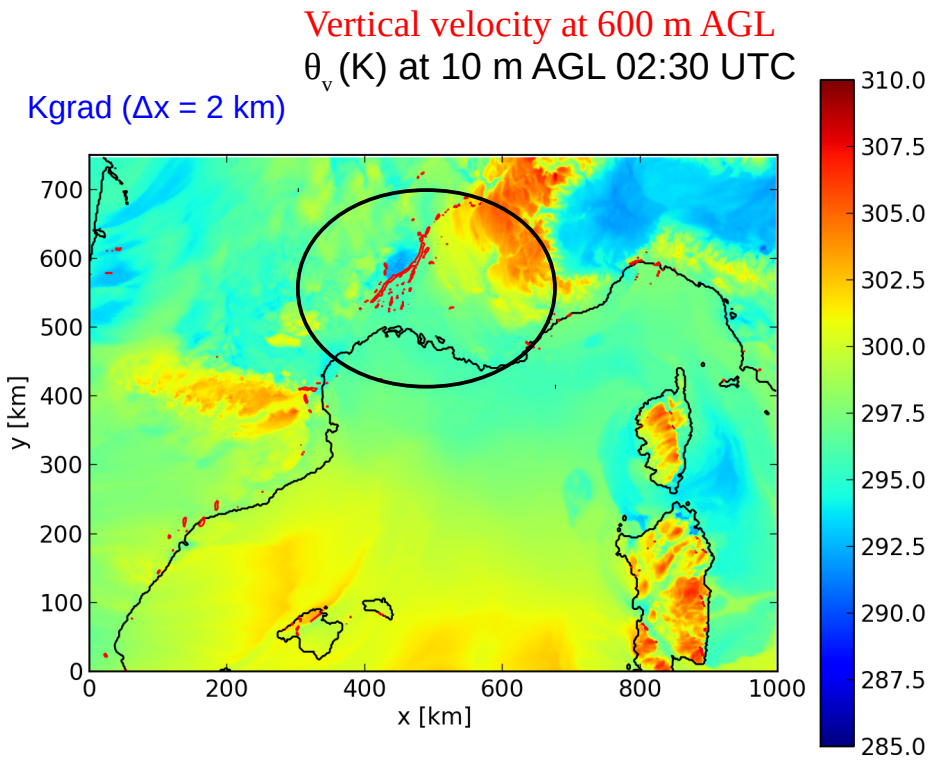
Turbulence inside convective systems

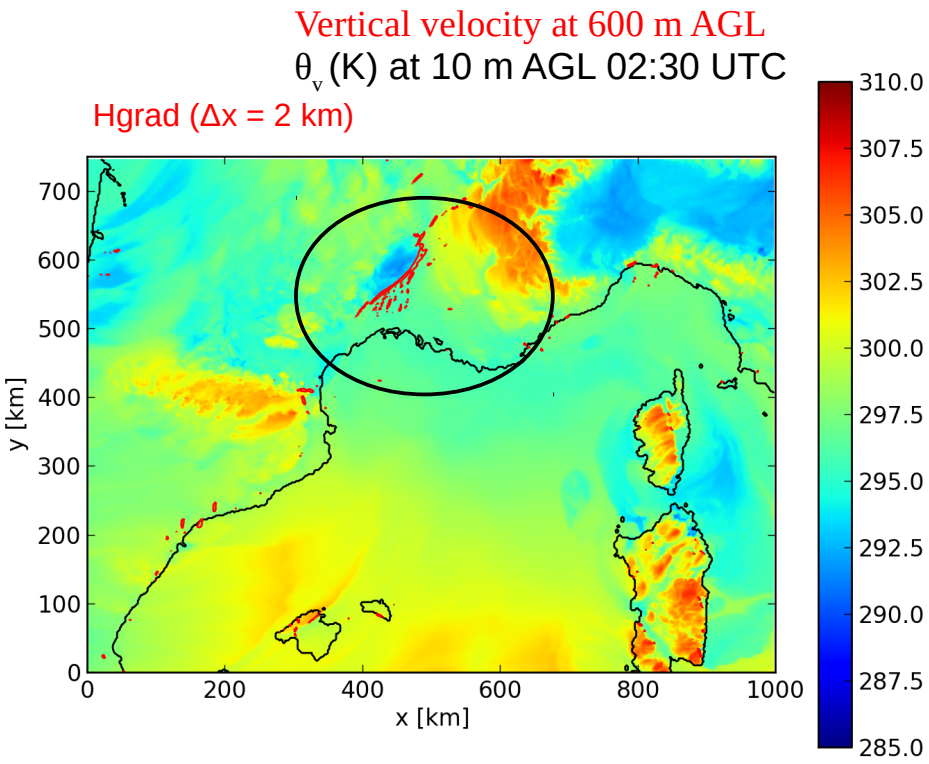


Turbulence inside convective systems



Cold pools under convective systems IOP6





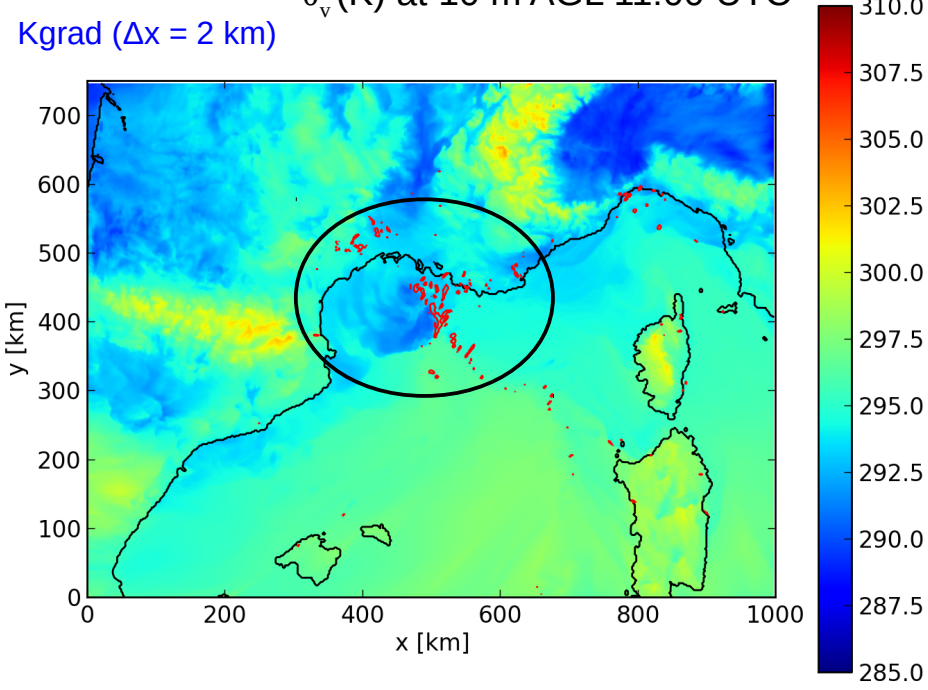
→ differences in cold pool extension
→ differences in lifting of the low-level inflow

Cold pools under convective systems IOP16

Vertical velocity at 600 m AGL

θ_v (K) at 10 m AGL 11:00 UTC

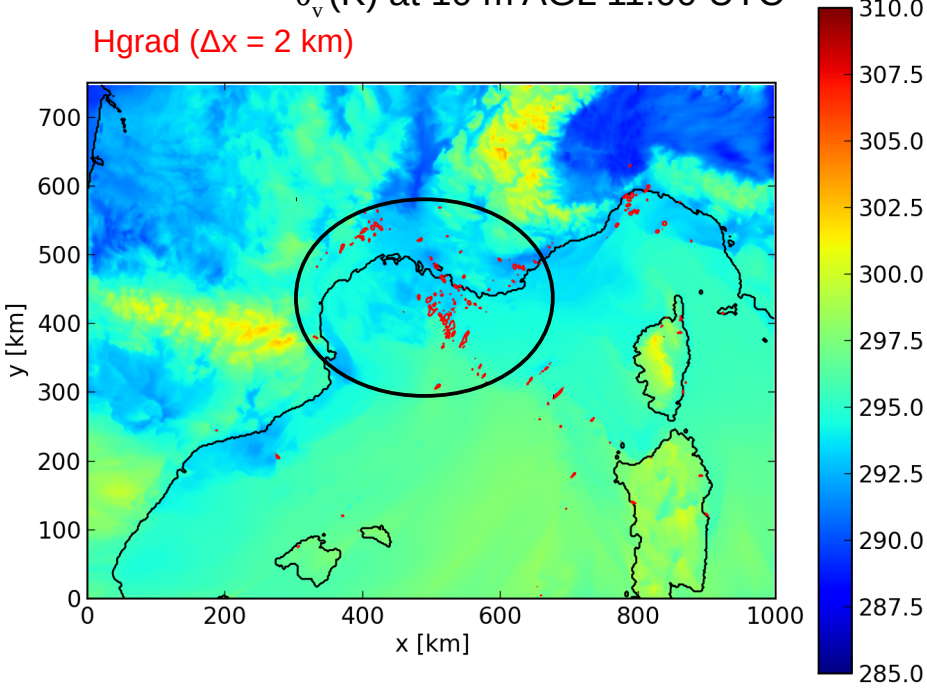
Kgrad (Δx = 2 km)



Vertical velocity at 600 m AGL

θ_v (K) at 10 m AGL 11:00 UTC

Hgrad (Δx = 2 km)

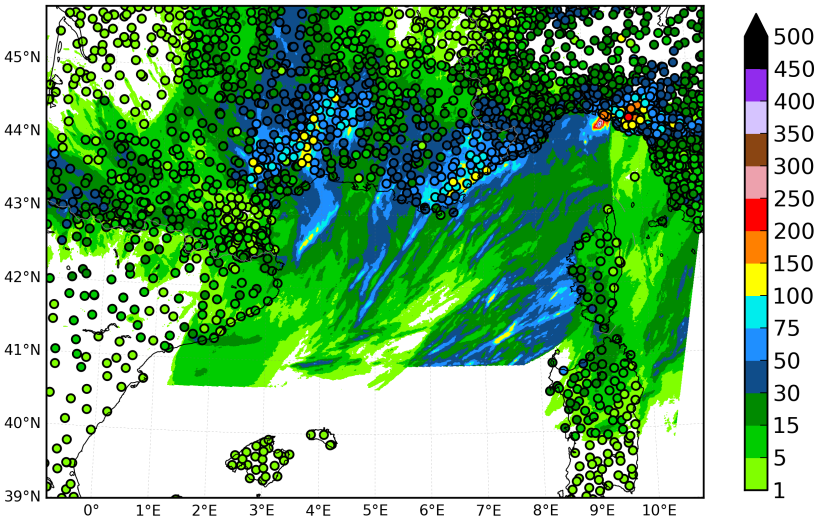


→ differences in cold pool extension
→ differences in lifting of the low-level inflow

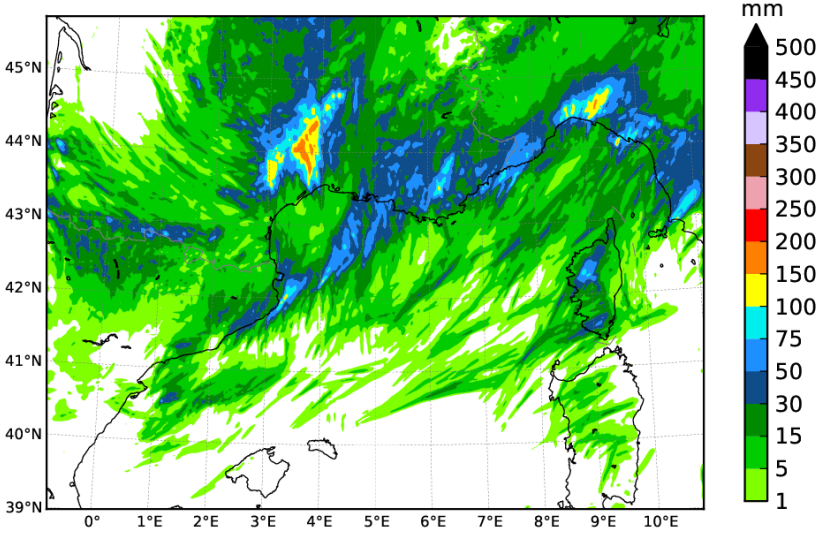
24-h accumulated precipitation

→ 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**

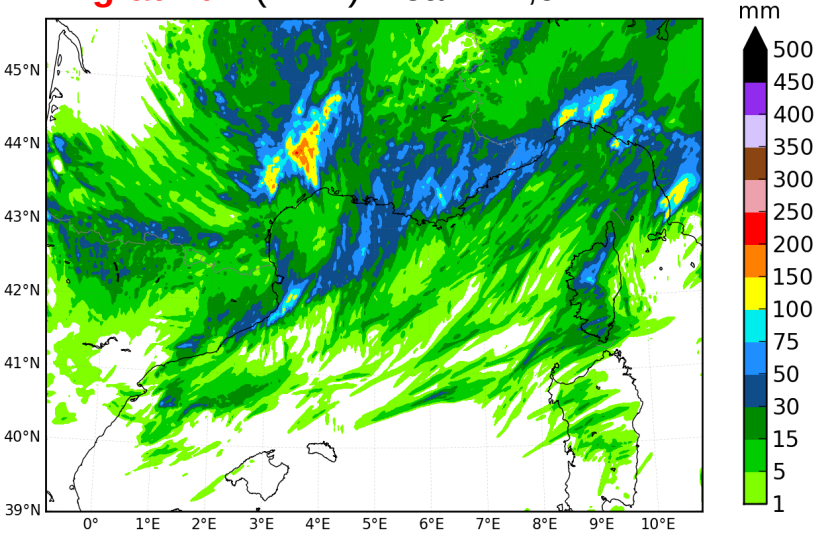
Estimated rainfall from radar and rain gauge data



Kgrad run (2 km) Mean: 12.62 mm

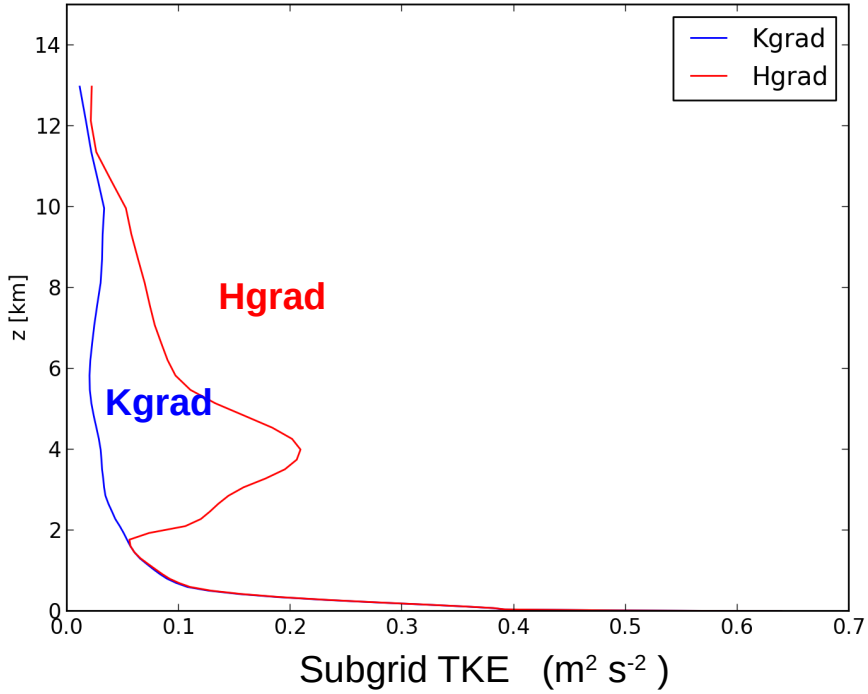


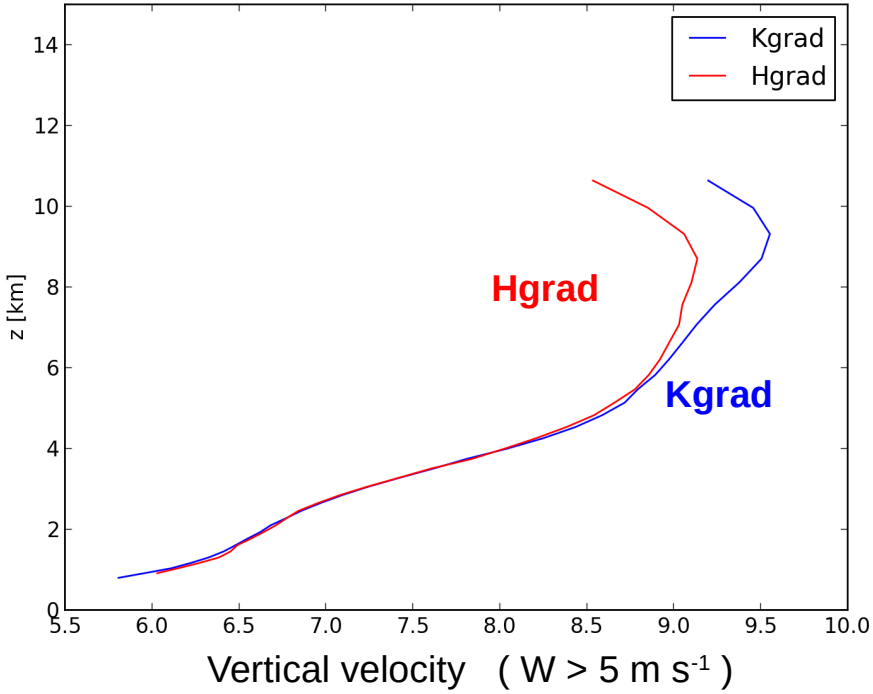
Hgrad run (2 km) Mean: 12,9 mm



Turbulence and vertical velocity inside convective systems IOP16

Mean vertical profiles inside convective clouds between 00UTC 26 October and 00 UTC 27 October 2012

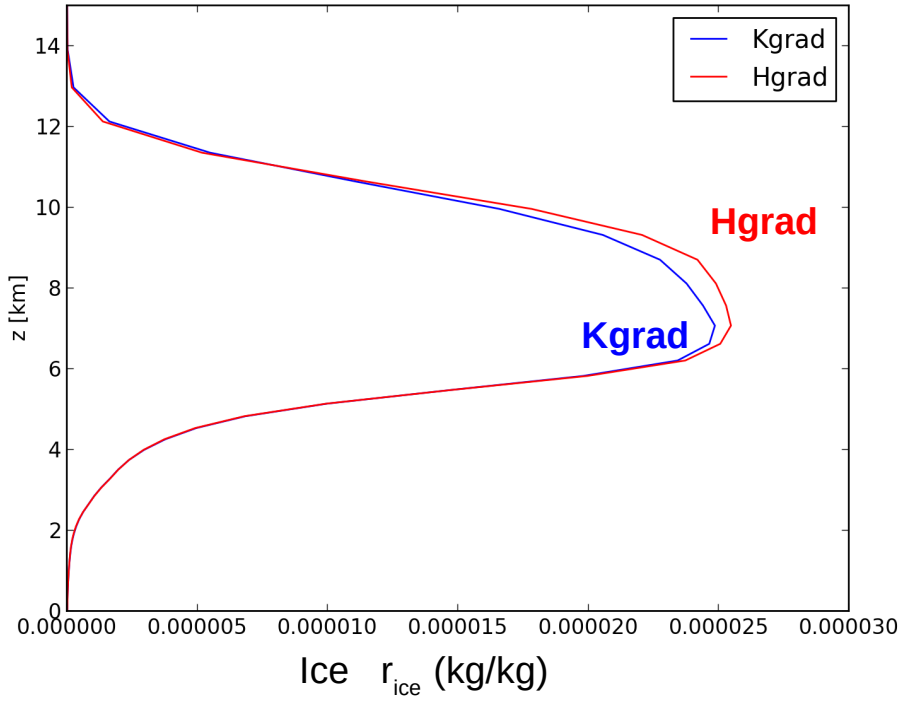


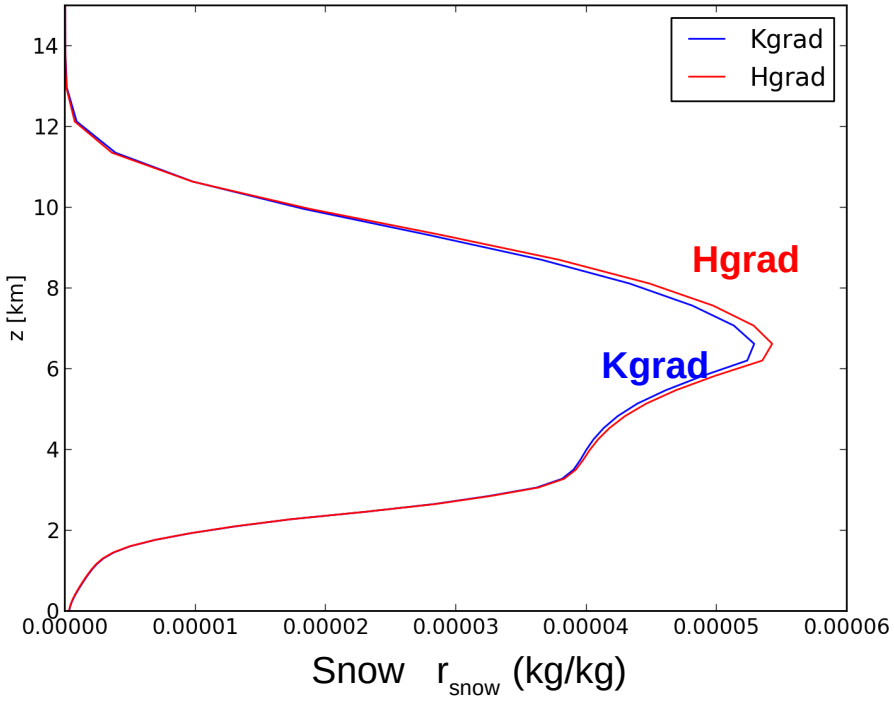


→ more subgrid TKE with the **Hgrad run** compared to the **Kgrad run**
→ less intense vertical velocity in updraft cores (W > 5 m/s)
→ better balance between resolved and subgrid parts

Hydrometeor mixing ratio IOP16

Mean vertical profiles between 00UTC 26 October and 00 UTC 27 October 2012

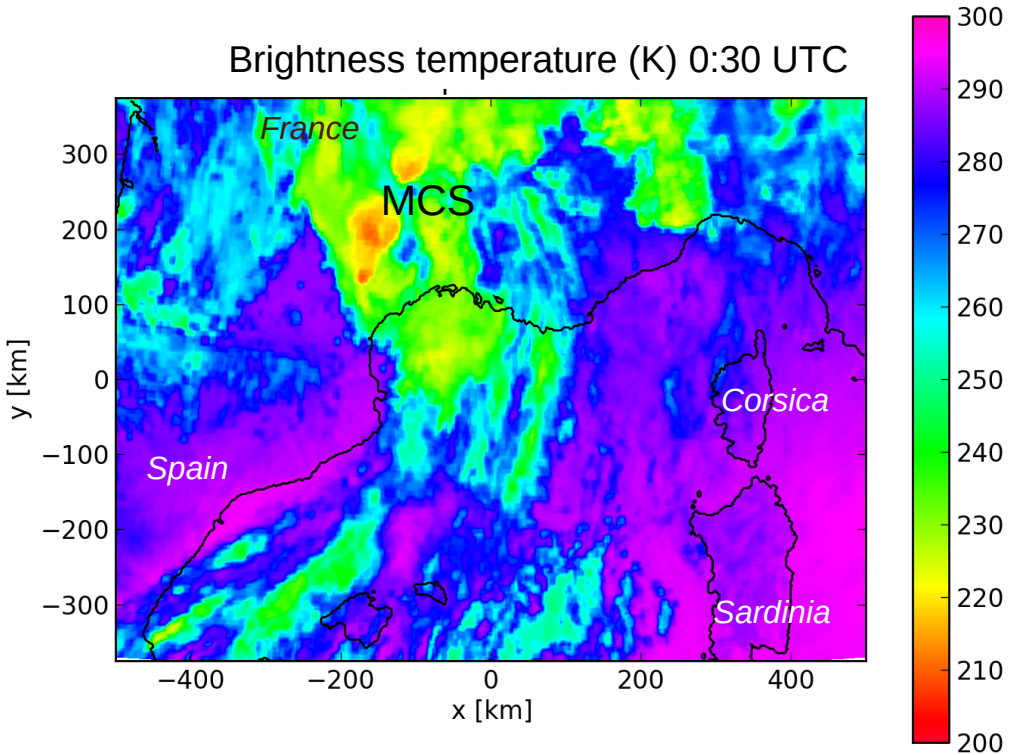


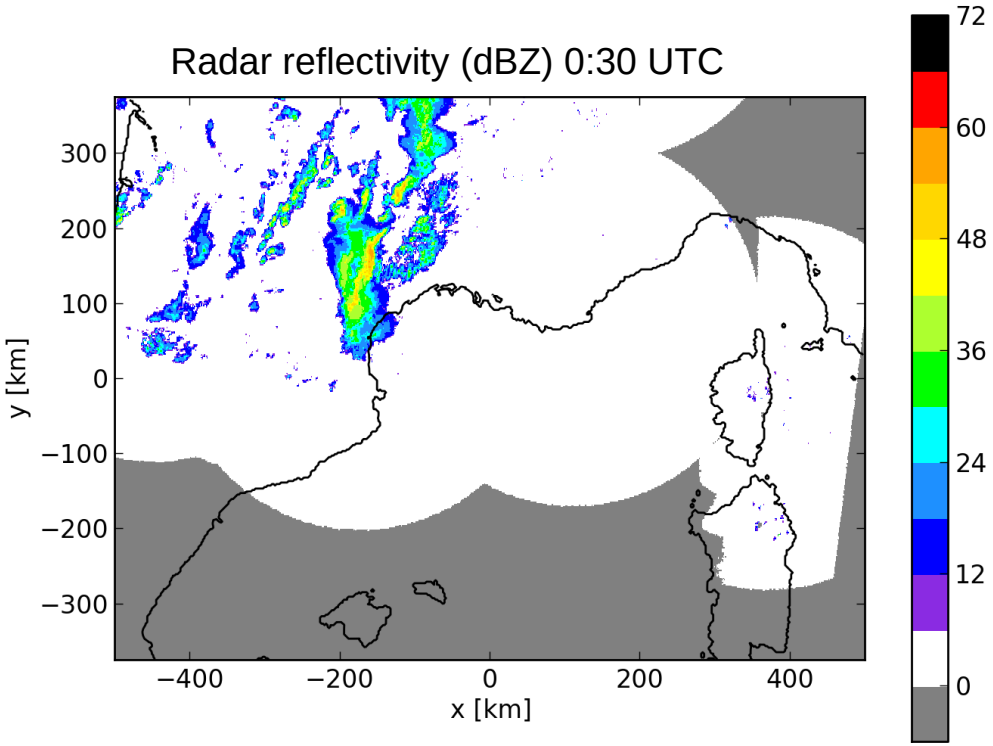


→ more ice, snow, and graupel with the **Hgrad run** compared to the **Kgrad run**

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**





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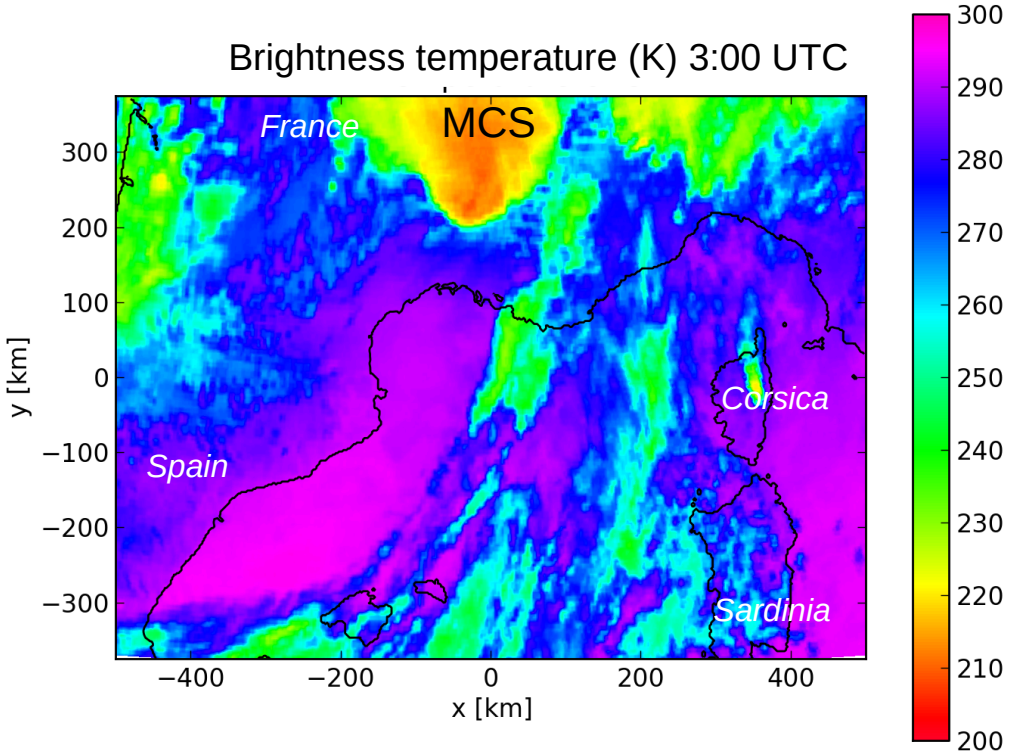

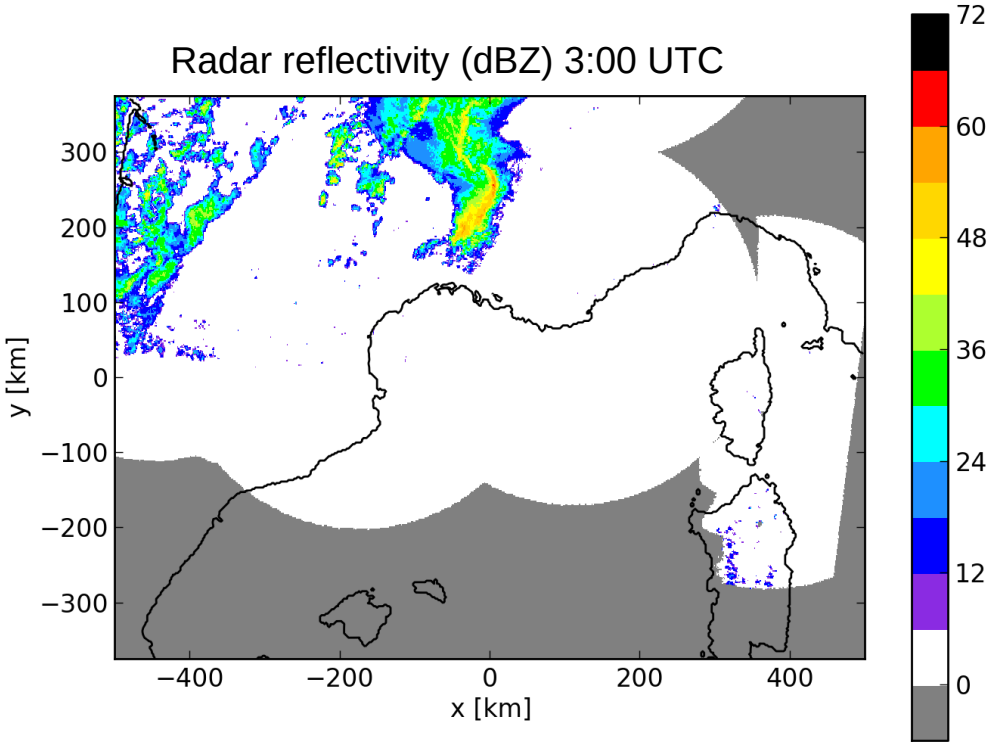

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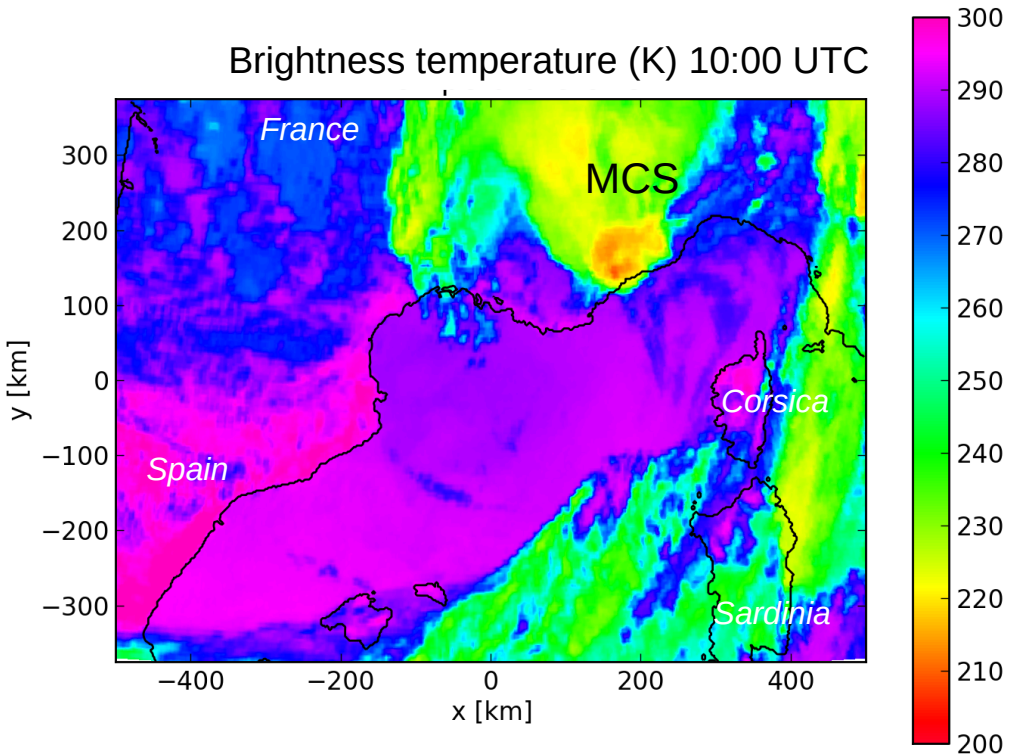
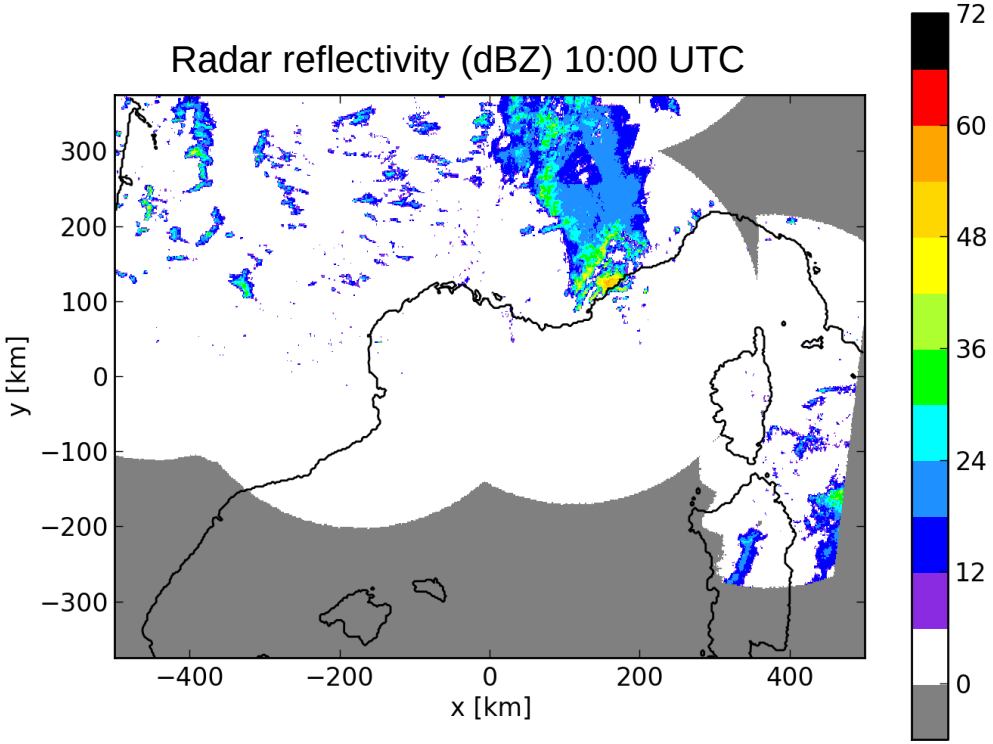
  - new scheme applied above 2000 m (with c=3) → **Hgrad runs**
  - comparison with the current scheme → **Kgrad runs**
  - convection triggers over the Massif Central during the night
  - a convective line develops, fastly moving eastward during the night and the morning





Turbulence parameterization

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)

$$\frac{\partial e}{\partial t} = -\frac{1}{\rho_{dref}}\frac{\partial(\rho_{dref} e \overline{u_i})}{\partial x_j} \boxed{-\overline{u_i' u_j'}\frac{\partial \overline{u_i}}{\partial x_j}} + \boxed{\frac{g}{\theta_{vref}}\overline{u_3'\theta_v'}} + \frac{1}{\rho_{dref}}\frac{\partial}{\partial x_j}(C_T \rho_{dref} L e^{1/2}\frac{\partial e}{\partial x_j}) \boxed{- C_\epsilon \frac{e^{3/2}}{L}}$$

Dynamical production — Thermal production — Dissipation

- Thermodynamical fluxes (thermal production) based on:

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

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

$K = A\,L\,e^{1/2}$

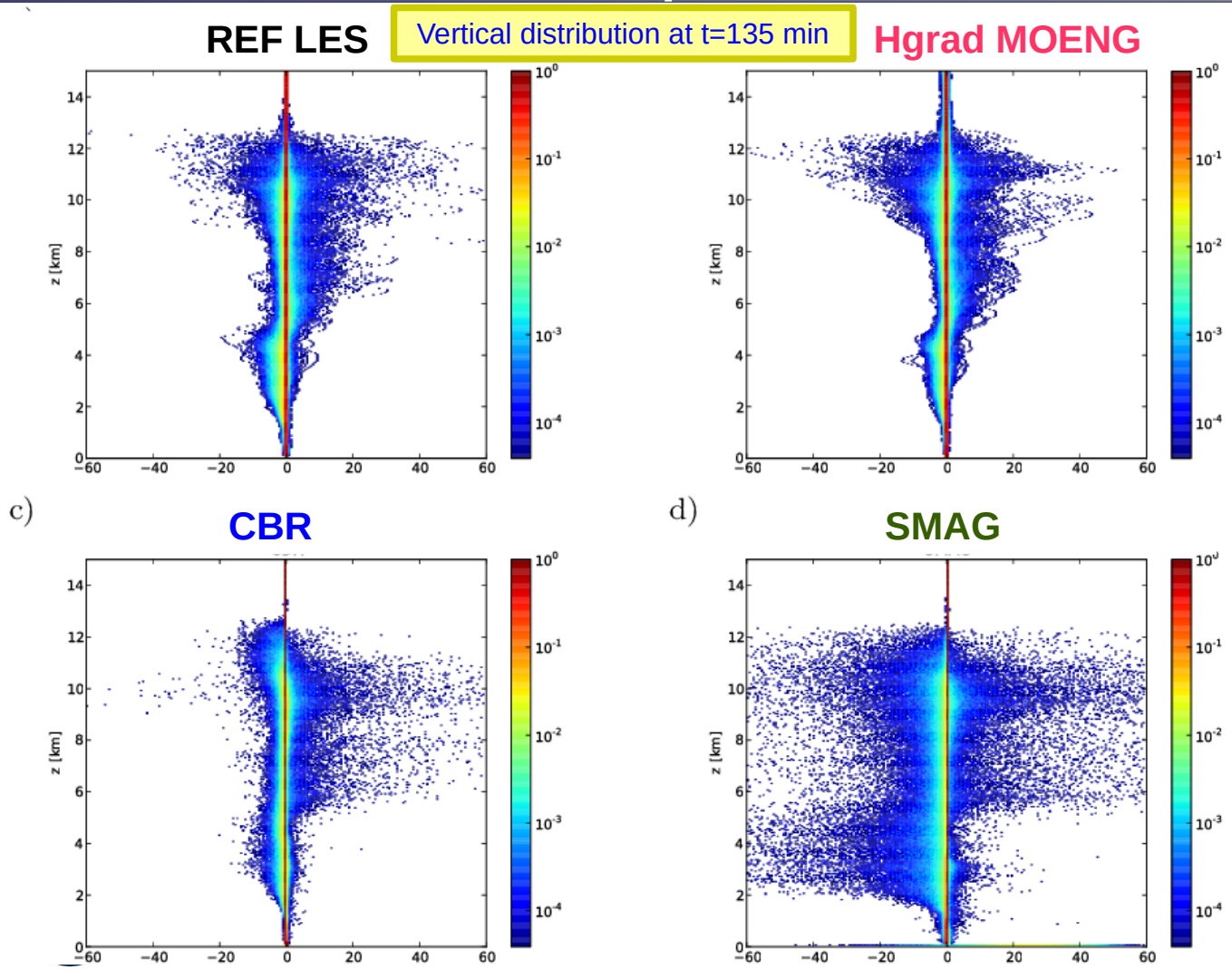
H-gradient formulation *(Moeng, 2014)*

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

$C = c\,\Delta x^2/12$
$c=3$

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

Evaluation of turbulence parameterization

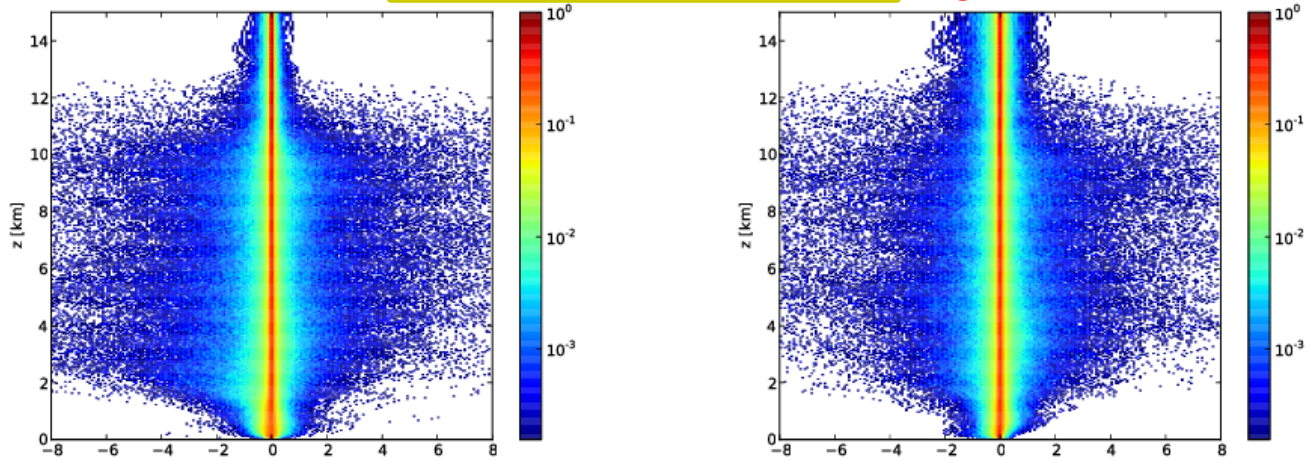


Off-line evaluation $\overline{w'\theta_l'}$ *(m s^{-1} kg kg^{-1})*

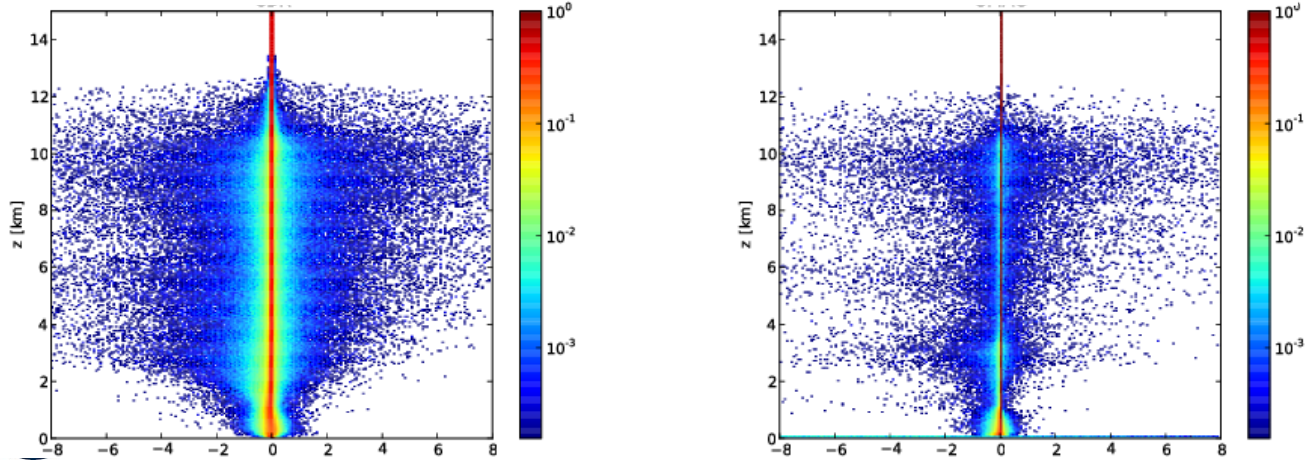
Thermodynamical fluxes:
Better distribution with Hgrad

Evaluation of turbulence parameterization

REF LES | Vertical distribution at t=135 min | **Hgrad MOENG**



c) **CBR**



d) **SMAG**

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

Thermodynamical fluxes:
Better distribution with **Hgrad**

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

METEO FRANCE