Turbulence parameterization in Météo-France NWP models and challenges of high resolution modelling

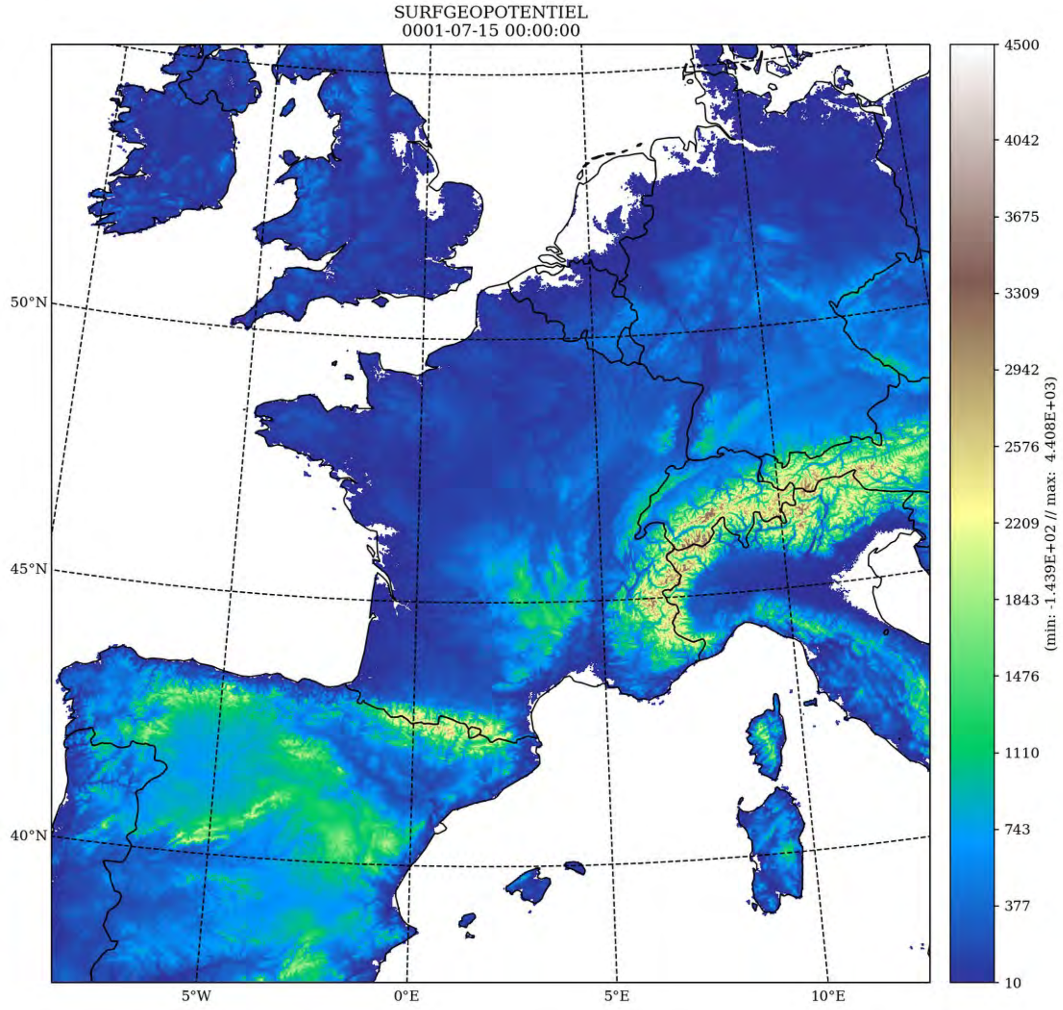
Léo Rogel (MF-CNRM)

December 5th, 2024

Météo-France AROME limited area model

Non-hydrostatic NWP model (Seity et al 2011)

- Compressible Euler equation system
- Semi-implicit, semi-lagrangian dynamics
- Large timestep (Dt=50s)
- Lateral BC forcing from ARPEGE/IFS global model
- Operational horizontal resolution 1.3km
  - Next configurations will target hectometer grid scales (750m,500m)



Operational AROME France domain

Contents

How do we parameterize local mixing fluxes for NWP ?

- Cuxart et al (2000) 1D turbulence scheme (used in operations at MF)
- New challenges at hectometric resolutions
- LES study of stratified layers at Upper Troposphere-Lower Stratosphere

https://tinyurl.com/mrxeu5r4

General features in AROME (NWP) driving closure design

- At operational resolutions, turbulence is assumed to be mostly subgrid
- for mesoscale forecasts, grid resolution is assumed :
  - sufficient on the vertical (dz~10-100m) for various BL regimes description
  - but relatively coarse on the horizontal (dx~1km → single-column physics)
- Scheme constrained in time and memory consumption → simplified approach
- It must allow very large time steps → implicit scheme

Turbulence closure : « K-gradient » formulation

- Turbulence entirely subgrid → RANS* formalism
- Fluctuations derived from the inviscid anelastic equation system
- Fluxes derived from the 2nd order turbulent moments (SOTMs) simplification (Sommeria 1976, **Redelsperger and Sommeria 1981**):

$$\overline{u_i' u_j'} = \frac{2}{3} e \delta_{ij} - K_u \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} - \frac{2}{3} \frac{\partial \overline{u_k}}{\partial x_k} \right)$$

$$\overline{u_i' \phi'} = -K_\phi \frac{\partial \overline{\phi}}{\partial x_i}$$

- Exchange coefficient is determined from 2 quantities:

$$K_\psi = C_\psi L \sqrt{e}$$

e : turbulent kinetic energy (TKE)
L : diagnostic mixing length scale

*Reynolds Averaged Navier Stokes

CBR parameterization : 1D TKE equation

- Cuxart et al. (2000) scheme implemented in Méso-NH and AROME
- 1D formulation with TKE equation :

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta \overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_{TT} L \sqrt{e}\frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} \underbrace{- C_{\epsilon}\frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

CBR parameterization : 1D TKE equation

- Cuxart et al. (2000) scheme implemented in Méso-NH and AROME
- 1D formulation with TKE equation :

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta \overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_{TT} L \sqrt{e} \frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} - \underbrace{C_{\epsilon}\frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

Some assumptions :

1D : horizontal homogeneity

K-gradient TKE transport
(TOMs + presso-correlations)

Local isotropic equilibrium

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

METEO FRANCE

CBR 1D parameterization : 1D turbulent fluxes

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta \overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_{TT} L \sqrt{e} \frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} - \underbrace{C_\epsilon \frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

CBR 1D parameterization : 1D turbulent fluxes

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta \overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_{TT} L \sqrt{e}\frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} - \underbrace{C_\epsilon \frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

K-gradient formulation for fluxes gives :

$$\overline{u'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{u}}{\partial z}$$

$$\overline{v'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{v}}{\partial z}$$

$$\overline{w'\theta'} = -\frac{2}{3}\frac{L}{C_s}e^{1/2}\frac{\partial \overline{\theta}}{\partial z}\phi_3$$

$$\overline{w'r_v'} = -\frac{2}{3}\frac{L}{C_h}e^{1/2}\frac{\partial \overline{r_v}}{\partial z}\phi_3$$

$$\overline{\theta' r_v'} = C_2 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}(\phi_3 + \psi_3)$$

$$\overline{\theta'^2} = C_1 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{\theta_v}}{\partial z}\phi_3$$

$$\overline{r_v'^2} = C_1 L^2 \frac{\partial \overline{r_v}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}\psi_3$$

Constants values following Cheng et al. (2002)

CBR 1D parameterization : 1D turbulent fluxes

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta\overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_{TT} L\sqrt{e}\frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} - \underbrace{C_\epsilon \frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

K-gradient formulation for fluxes gives :

$$\overline{u'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{u}}{\partial z}$$

$$\overline{v'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{v}}{\partial z}$$

$$\overline{w'\theta'} = -\frac{2}{3}\frac{L}{C_s}e^{1/2}\frac{\partial \overline{\theta}}{\partial z}\boxed{\phi_3}$$

$$\overline{w'r_v'} = -\frac{2}{3}\frac{L}{C_h}e^{1/2}\frac{\partial \overline{r_v}}{\partial z}\boxed{\phi_3}$$

$$\overline{\theta' r_v'} = C_2 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}\left(\boxed{\phi_3} + \boxed{\psi_3}\right)$$

$$\overline{\theta'^2} = C_1 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{\theta_v}}{\partial z}\boxed{\phi_3}$$

$$\overline{r_v'^2} = C_1 L^2 \frac{\partial \overline{r_v}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}\boxed{\psi_3}$$

Thermal stability functions
(Redelsperger and Sommeria 1981)

CBR 1D parameterization : 1D turbulent fluxes

$$\underbrace{\frac{De}{Dt}}_{\text{TKE variation}} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}_{\text{Dynamic production}} + \underbrace{\beta \overline{w'\theta'}}_{\text{Thermal production}} + \underbrace{\frac{\partial}{\partial z}\left(C_T L \sqrt{e}\frac{\partial e}{\partial z}\right)}_{\text{Turbulent diffusion}} - \underbrace{C_\epsilon \frac{e^{3/2}}{L}}_{\text{Dissipation}}$$

K-gradient formulation for fluxes gives :

$$\overline{u'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{u}}{\partial z}$$

$$\overline{v'w'} = -\frac{4}{15}\frac{L}{C_m}e^{1/2}\frac{\partial \overline{v}}{\partial z}$$

$$\overline{w'\theta'} = -\frac{2}{3}\frac{L}{C_s}e^{1/2}\frac{\partial \overline{\theta}}{\partial z}\phi_3$$

$$\overline{w'r_v'} = -\frac{2}{3}\frac{L}{C_h}e^{1/2}\frac{\partial \overline{r_v}}{\partial z}\phi_3$$

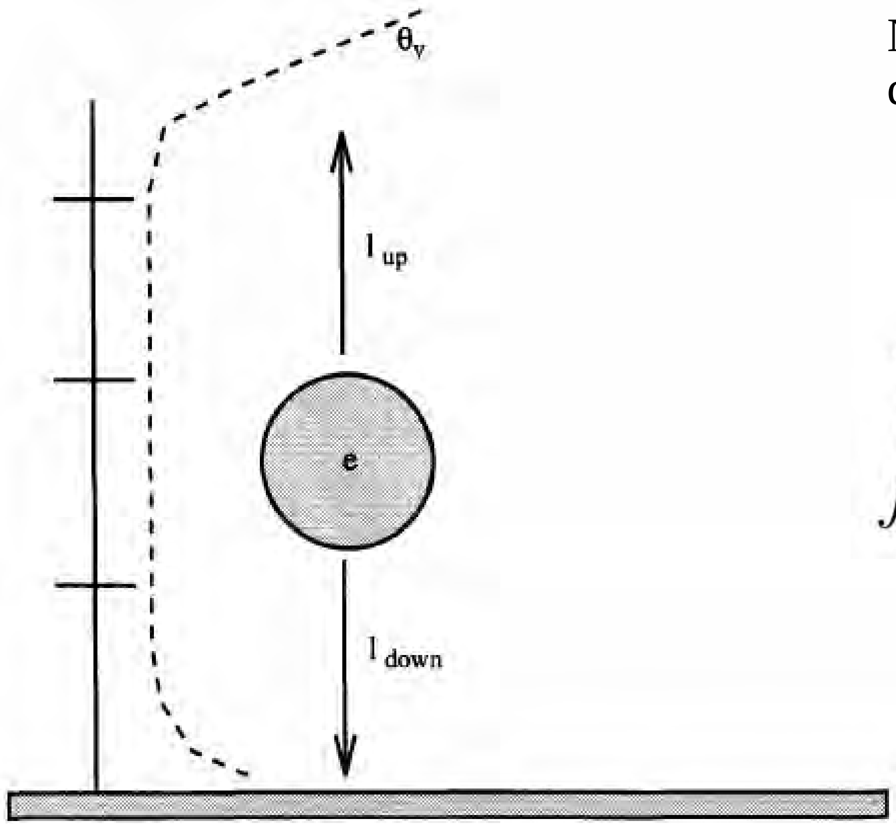
$$\overline{\theta' r_v'} = C_2 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}(\phi_3 + \psi_3)$$

$$\overline{\theta'^2} = C_1 L^2 \frac{\partial \overline{\theta}}{\partial z}\frac{\partial \overline{\theta_v}}{\partial z}\phi_3$$

$$\overline{r_v'^2} = C_1 L^2 \frac{\partial \overline{r_v}}{\partial z}\frac{\partial \overline{r_v}}{\partial z}\psi_3$$

One length to rule them all : the master length scale !!!

Mixing length : Bougeault-Lacarrere (1989) formulation



Non-local budget formulation for upward or downward travelling air parcel:

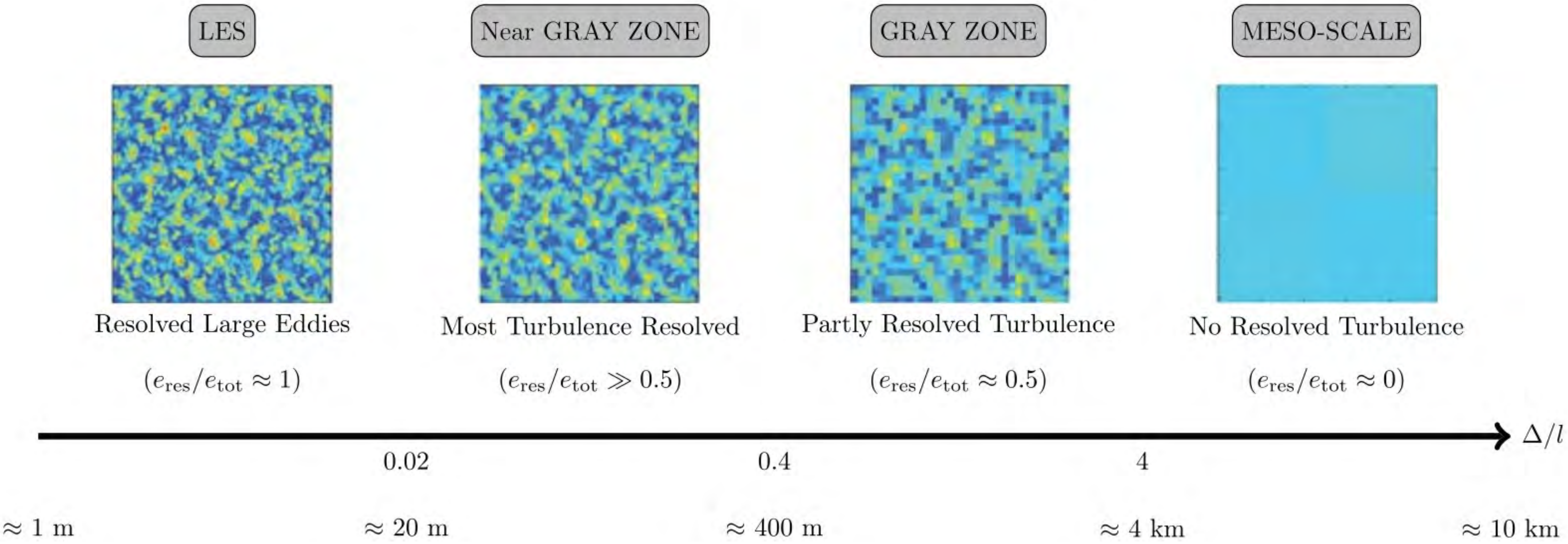
$$\int_{z}^{z+L_{up}} \frac{g}{\overline{\theta_v}} \left[\overline{\theta_v}(z') - \overline{\theta_v}(z) \right] dz' = \overline{e}$$

$$\int_{z-L_{down}}^{z} \frac{g}{\overline{\theta_v}} \left[\overline{\theta_v}(z) - \overline{\theta_v}(z') \right] dz' = \overline{e}$$

$$\frac{1}{(L_m)^{\alpha}} = \frac{1}{2} \left[\frac{1}{(L_{up})^{\alpha}} + \frac{1}{(L_{down})^{\alpha}} \right]$$

α computed as in Lemarié et al. (2021)

Parameterization challenges for future hectometric resolutions



Honnert et al (2020)

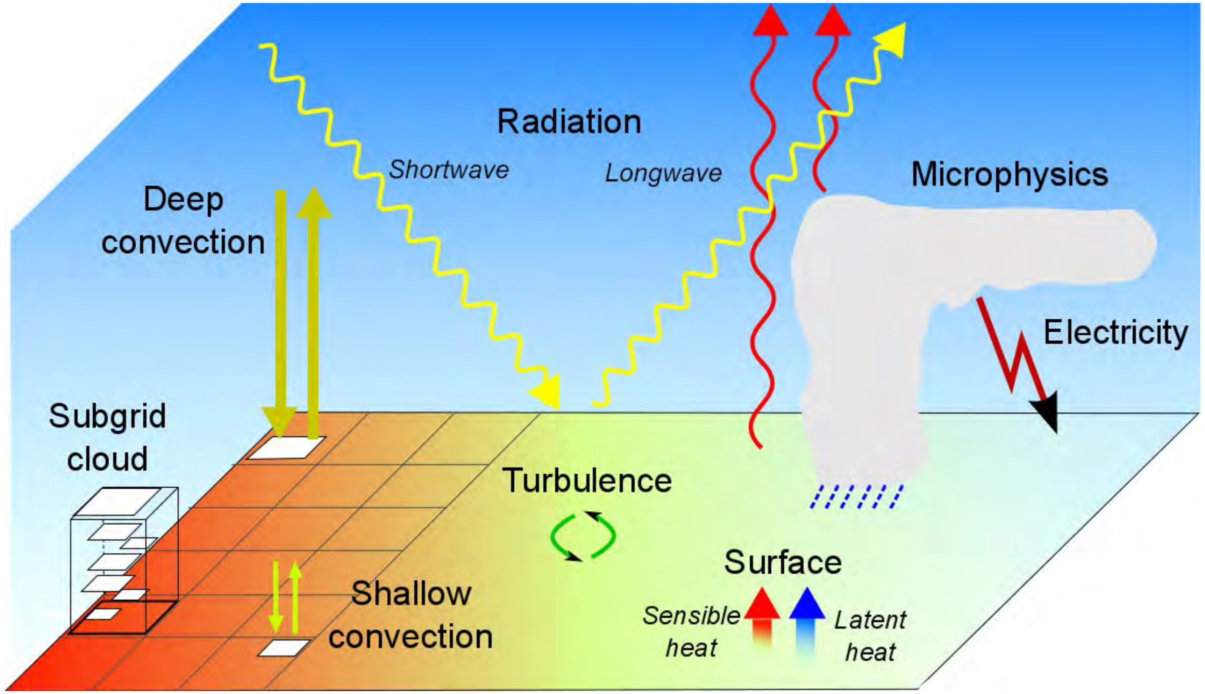
- Increase in resolution → Assumptions validity ?
  - Horizontal homogeneity (1D→3D) ?
  - Mixing length formulation ?
  - RANS formalism ?
  - Subgrid equilibrium ?

Need for dedicated process studies at high resolution to assess scheme deficiencies.

Méso-NH research model

- Research mesoscale model (Lac et al. 2018)
- Conjoint development between
  - Laboratoire d'Aérologie
  - CNRM
- Tool for process studies
- Sharing physics package with AROME (incl. Turb.)
- Also used to perform LES with 3D CBR scheme and

$$L^{\mathrm{DEAR}} = \min\left(0.76\frac{e^{1/2}}{N}, (\Delta x \Delta y \Delta z)^{1/3}\right)$$



Meso-NH physics parameterizations (Lac et al. 2018)

→ **Research model and LES approach complementary to NWP operational models**

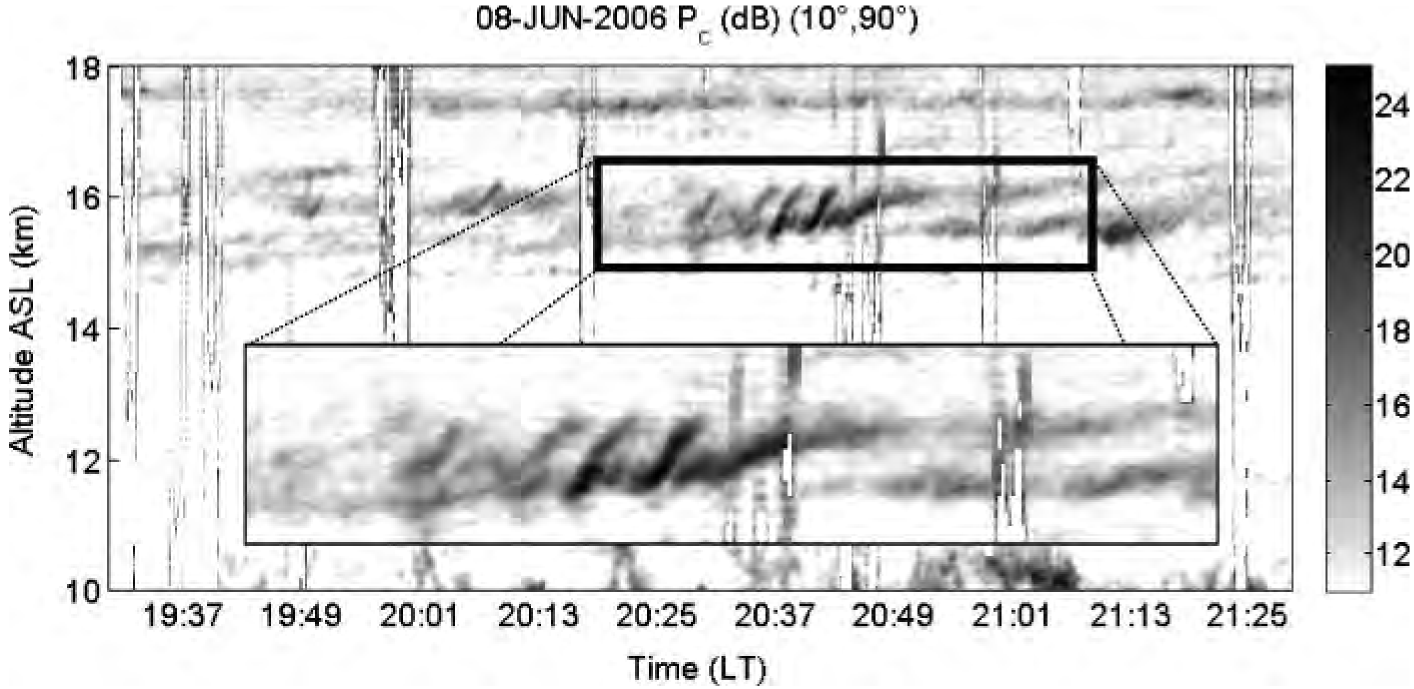
Evaluation of turbulence parameterization at upper levels from a LES reference simulation in Meso-NH

Léo Rogel,
Didier Ricard, Eric Bazile (MF-CNRM), Irina Sandu (ECMWF)

December 5th, 2024

Clear Air Turbulence (CAT)

Clear air radar echoes from Shigaraki S. T. radar (Fukao et al. 2011)

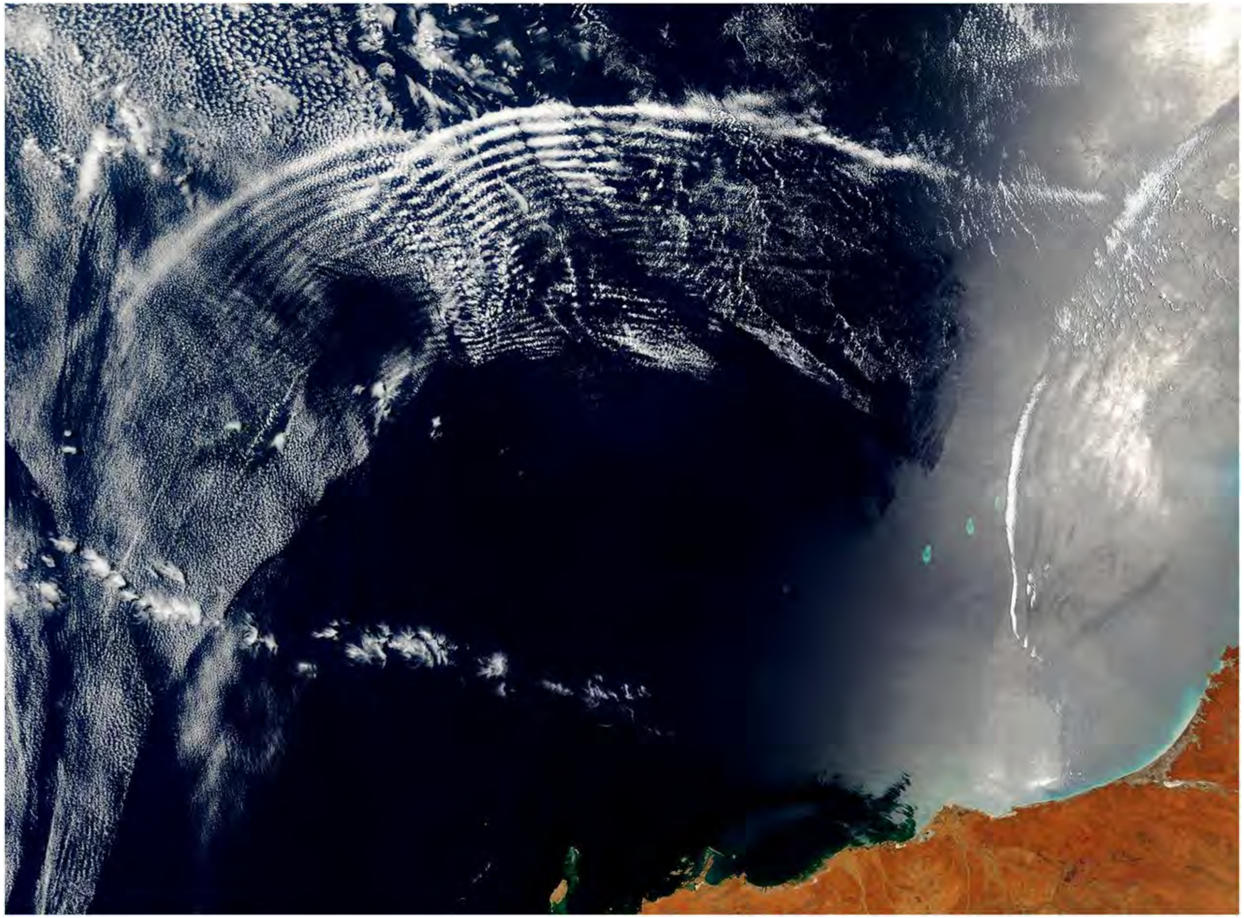


- High occurences in jet regions near the tropopause (UTLS region).
- Event linked to Kelvin-Helmholtz instabilities (Dutton and Panofsky, 1970)
- Turbulence forecasts important for aeronautic applications
  (reduction of injuries and cost)

K.H. billows (Wikipedia)

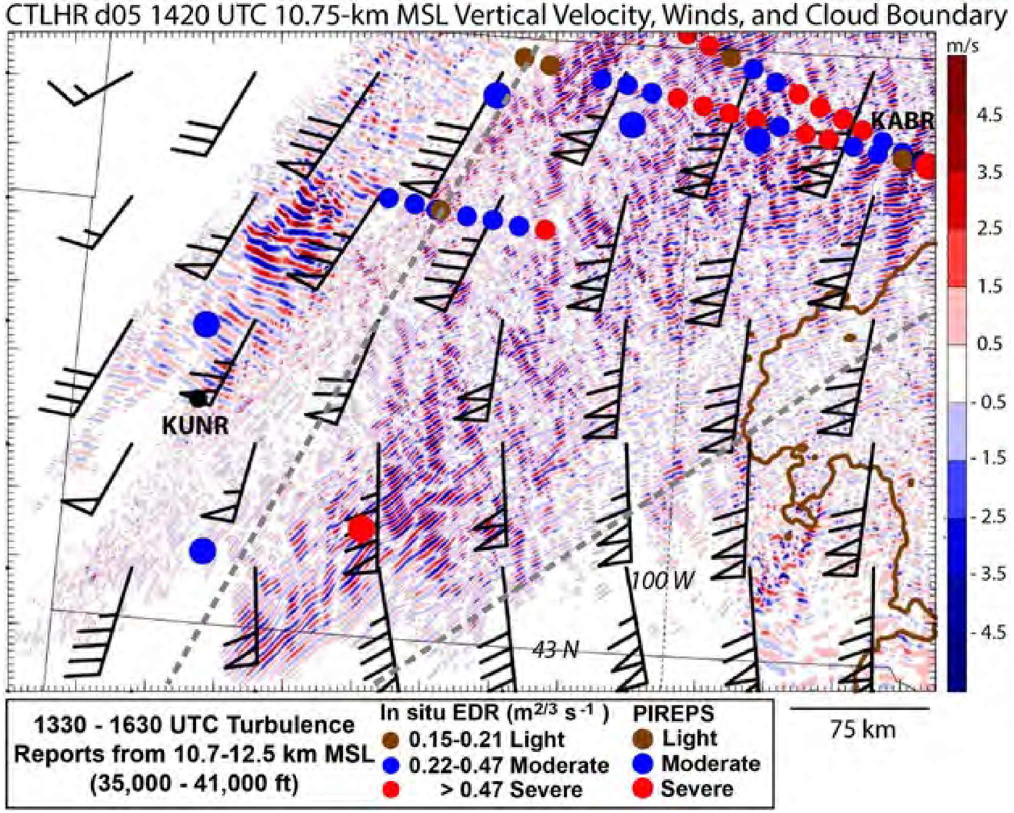
Primary synoptic and mesoscale forcing mechanisms

- Reduced dynamic stability regions in the vicinity of the jet (low Ri)
- Triggered by mesoscale phenomena, such as :
  - gravity waves (GWs)
  - convection
  - orographic waves.



From Mann (2019)

State of the art : hectometric simulations of CAT events



Example of a real case simulation at Δx = 370m. From Trier et al. (2020)

- Real cases of CAT now reproduced using hectometric simulations

- Need to resolve both the large scale flow containing the forcing mechanisms and « small scale » hydrodynamic instabilities

  - ► In practice this means simulating the flow on **large grids** or grid nesting

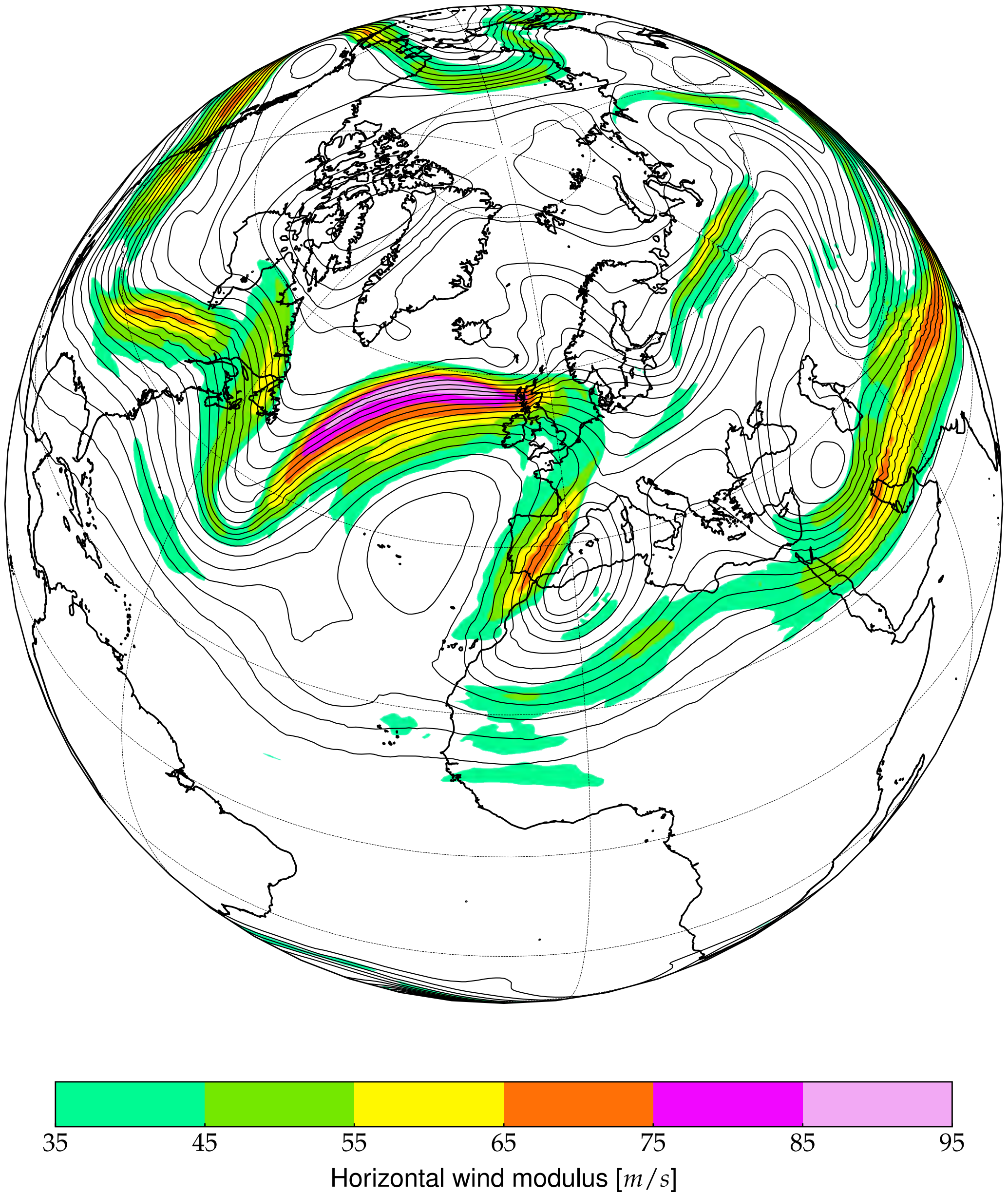
Problematic and outline

Can we use high resolution datasets from LES in the UTLS to evaluate the turbulence parameterization at coarser resolutions ?

- Case presentation
- LES overview
- Reference turbulence statistics from LES at Dx=130m

Upper level jet situation : January 27, 2018
Synoptic situation

27/01/2018, 300hPa ARPEGE wind and geopotential analysis 1200 UTC

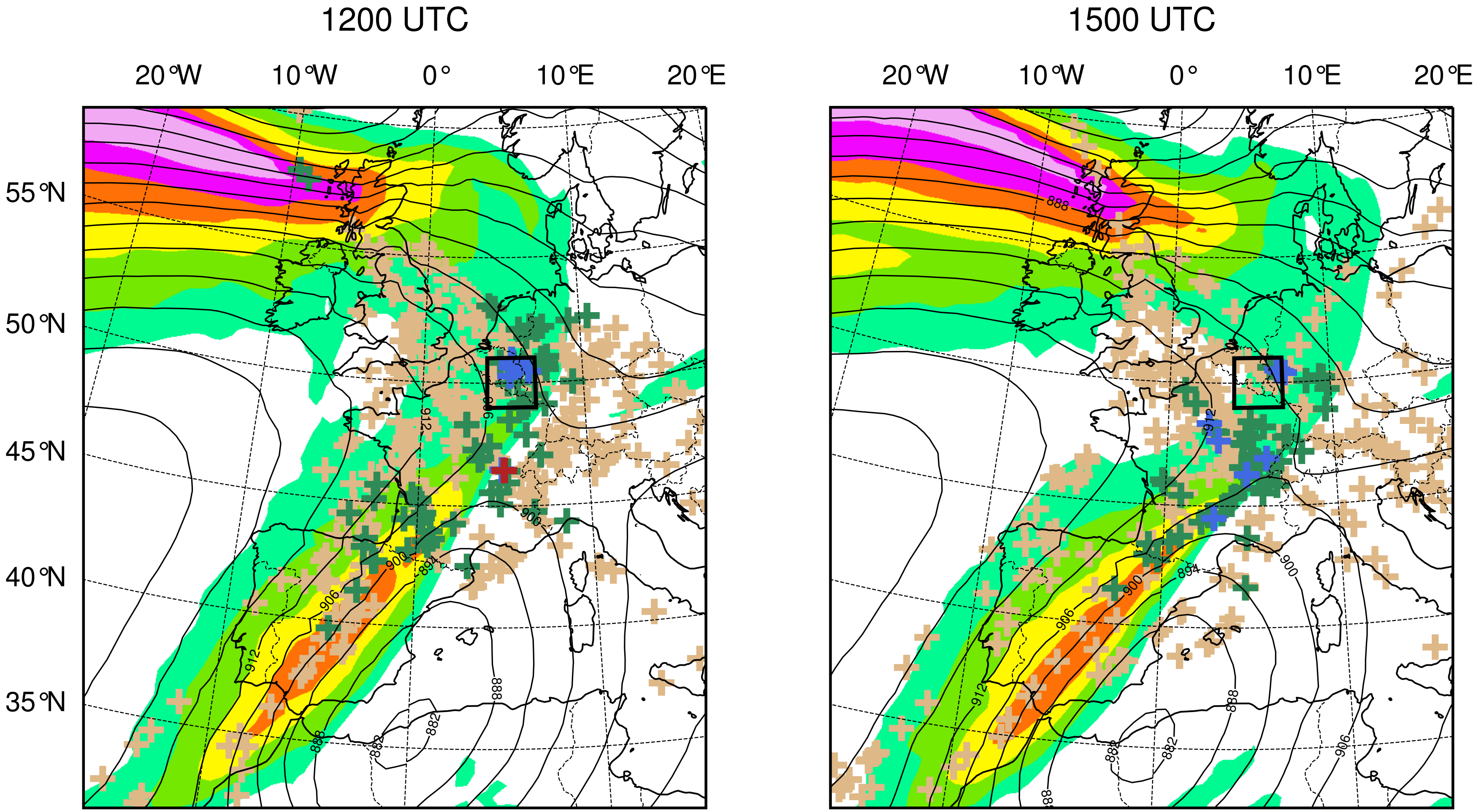


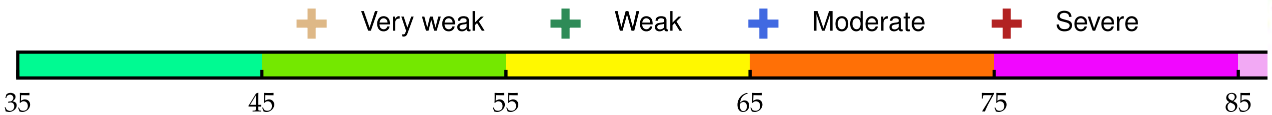
Winterly jet above Atlantic and Europe

Jet exit area favourable region
for CAT events (Knox 1997)

- Strong curvature of the flow
- Possible emission of GWs
(Plougonven and Zhang 2014)

Upper level jet situation : January 27, 2018
Observations

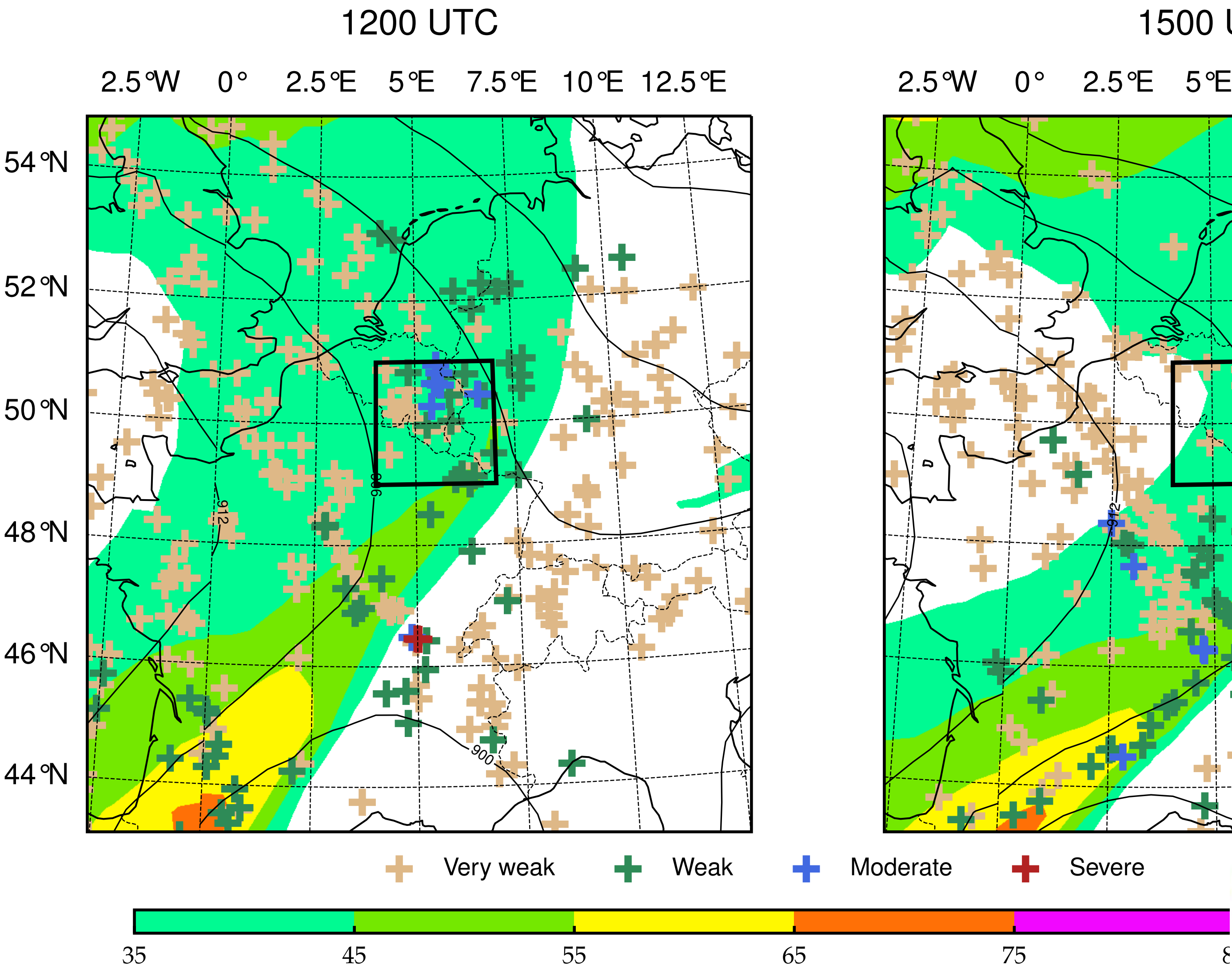




Very Weak	:	EDR $\leq$ 0.1
Weak	:	0.2 $\geq$ EDR $\geq$ 0.1
Moderate	:	0.3 $\geq$ EDR $\geq$ 0.2
Severe	:	EDR $\geq$ 0.3

Large number of MOD EDR reports

Upper level jet situation : January 27, 2018
Observations



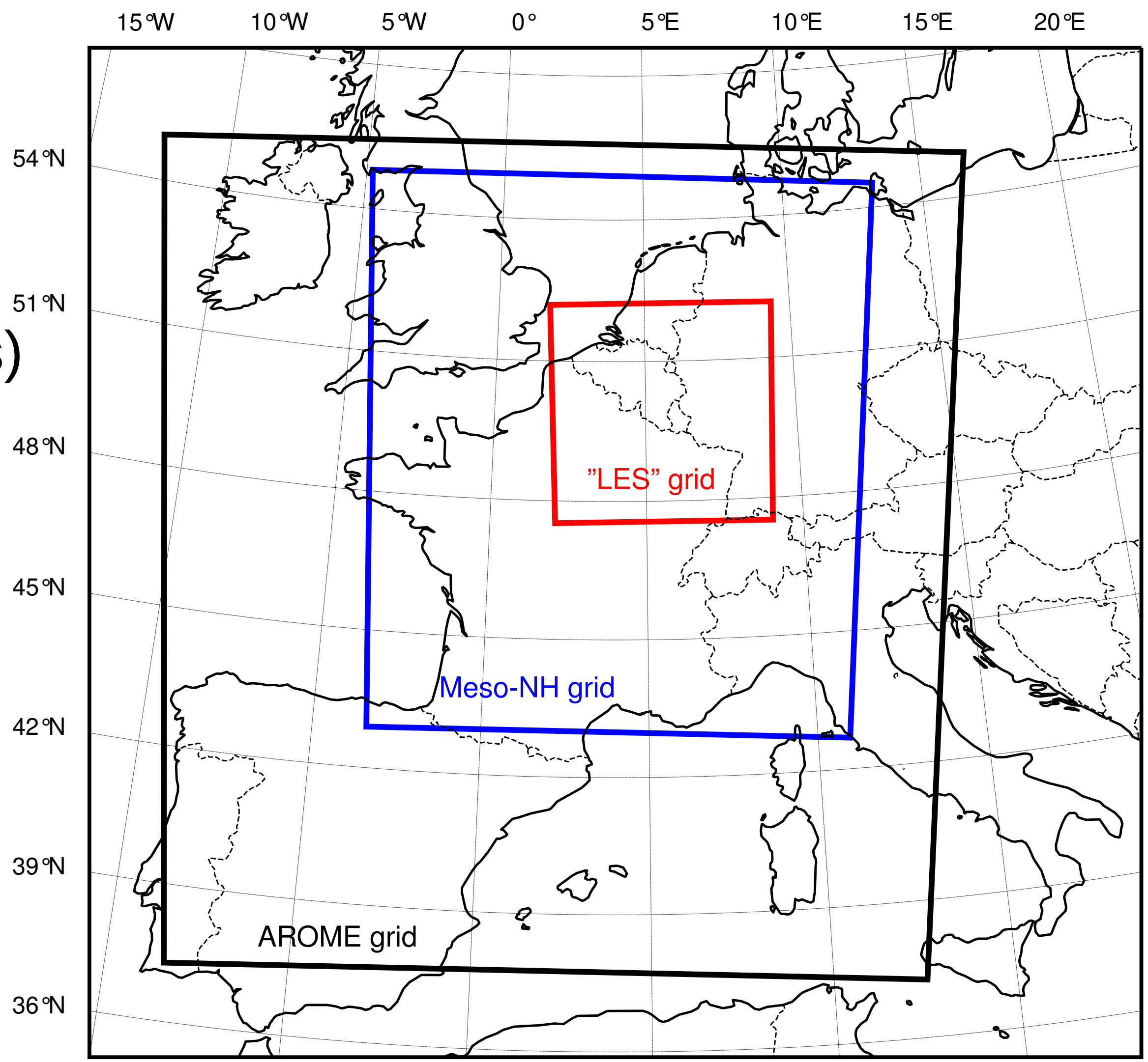
Very Weak	:	EDR $\leq$ 0.1
Weak	:	0.2 $\geq$ EDR $\geq$ 0.1
Moderate	:	0.3 $\geq$ EDR $\geq$ 0.2
Severe	:	EDR $\geq$ 0.3

Large number of MOD EDR reports

Focus on the Belgium region

LES simulation configuration

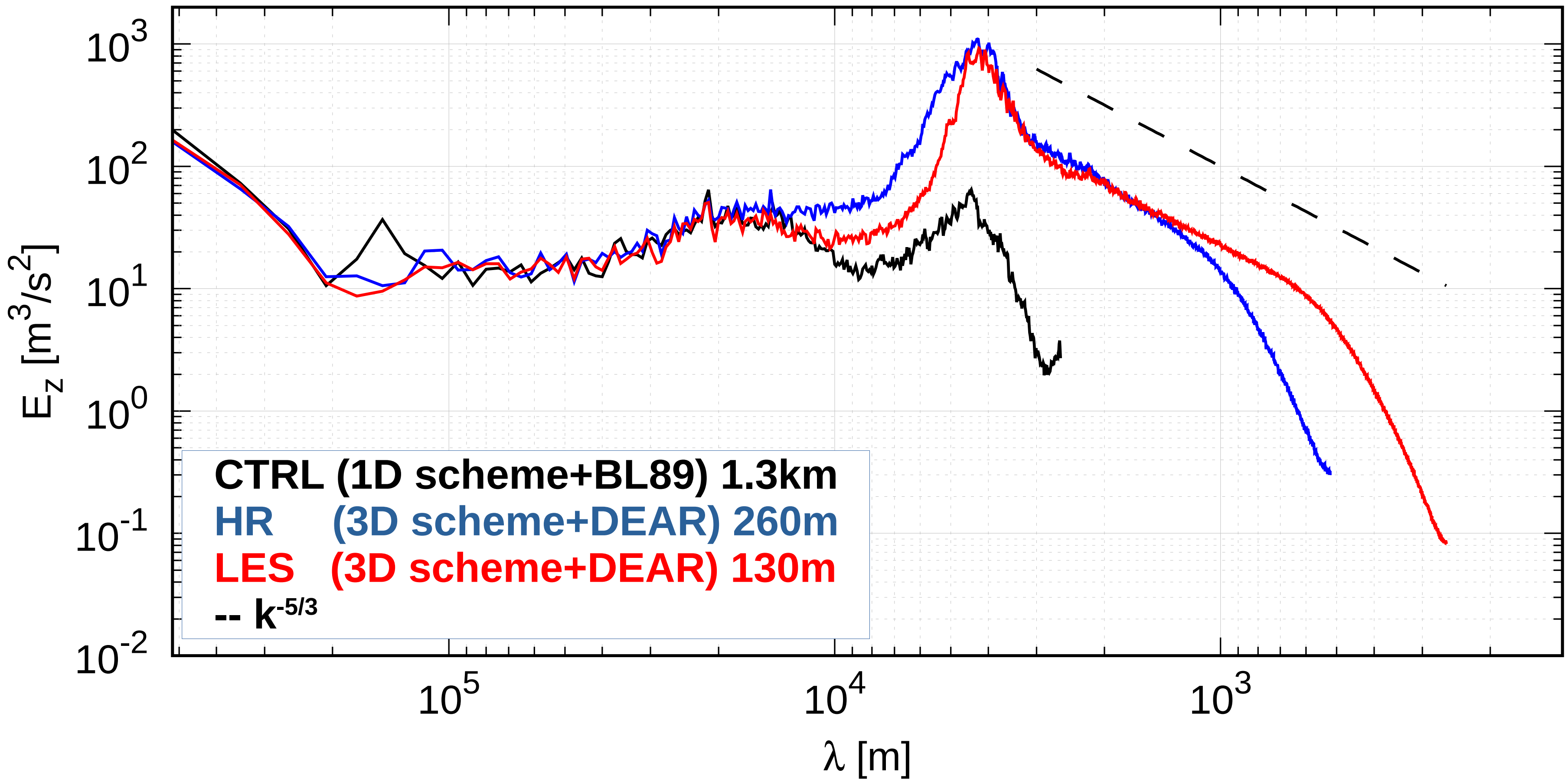
- Isotropic grid between 7-14km
- Dz=Dx=130m (127x4000x4000 pts)
- Simulation using Deardorff (1980)
- Dt = 1s
- Coupled to **Méso-NH (Dx=1.3km)**
  1D turbulence scheme
  BL89 length scale



animation

Wave-like **coherent structures** on vertical wind and TKE

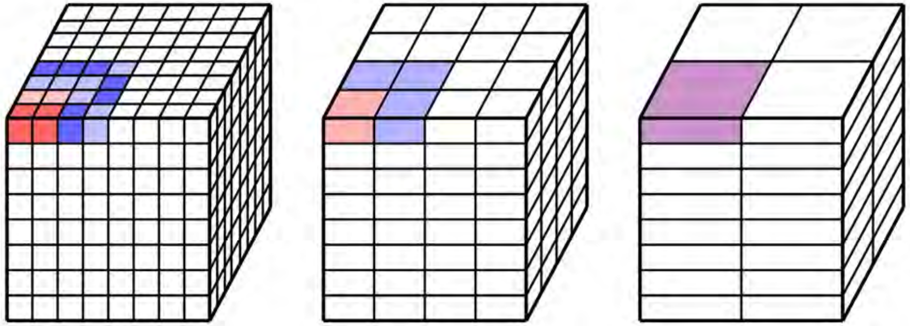
Vertical kinetic energy spectra, 200hPa, 1330 UTC



- Energy peak signature at 4.5km, coherent with shearing instability mode.
- Larger extension of spectral inertial region and narrower peak at Dx=130m

« Coarse graining » filter, w-wind and TKE 200hPa, 1330 UTC

Filter : successive horizontal box averaging (Honnert et al., 2011).

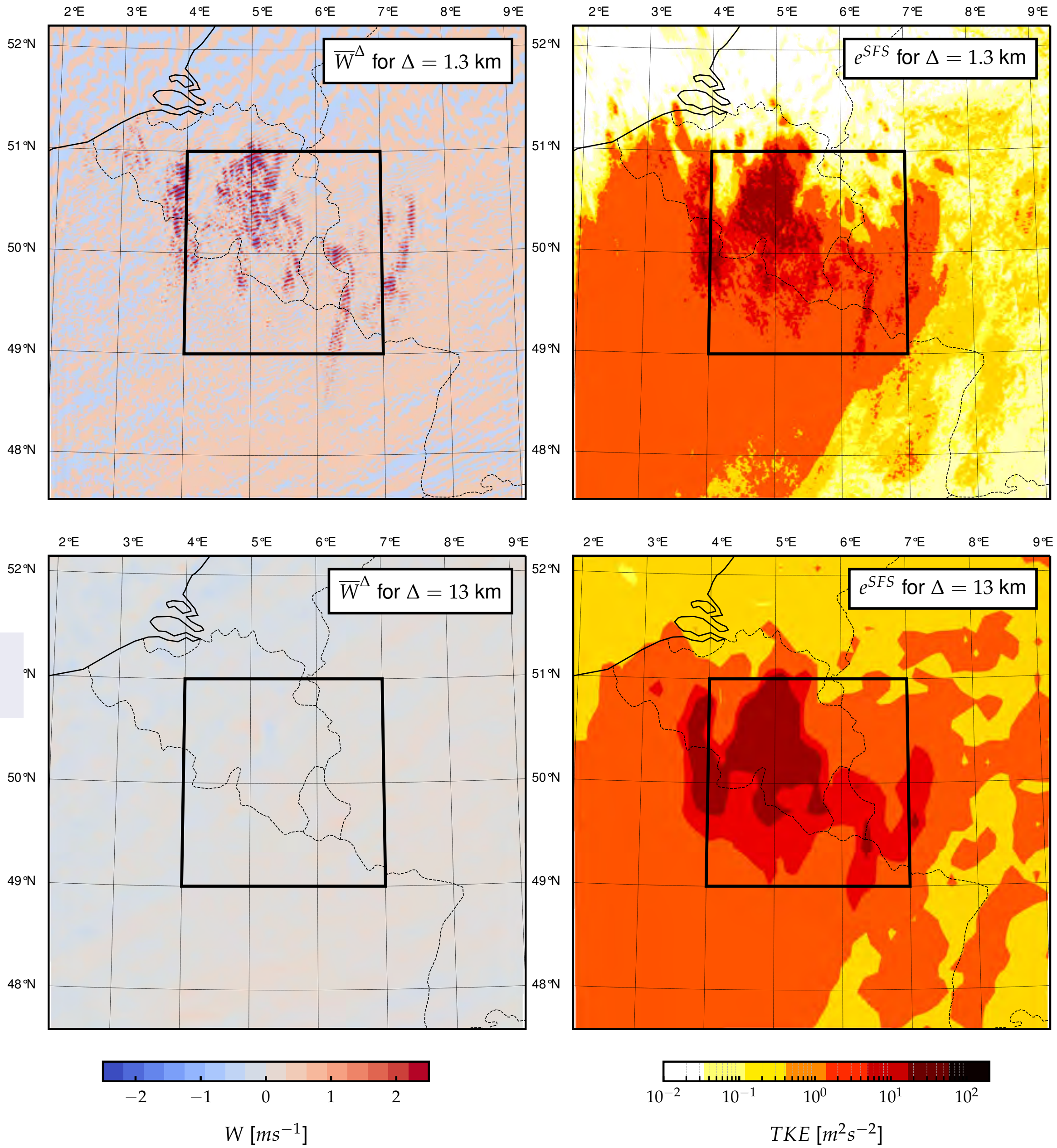


LES | Intermediate scales | Mesoscale (1D)

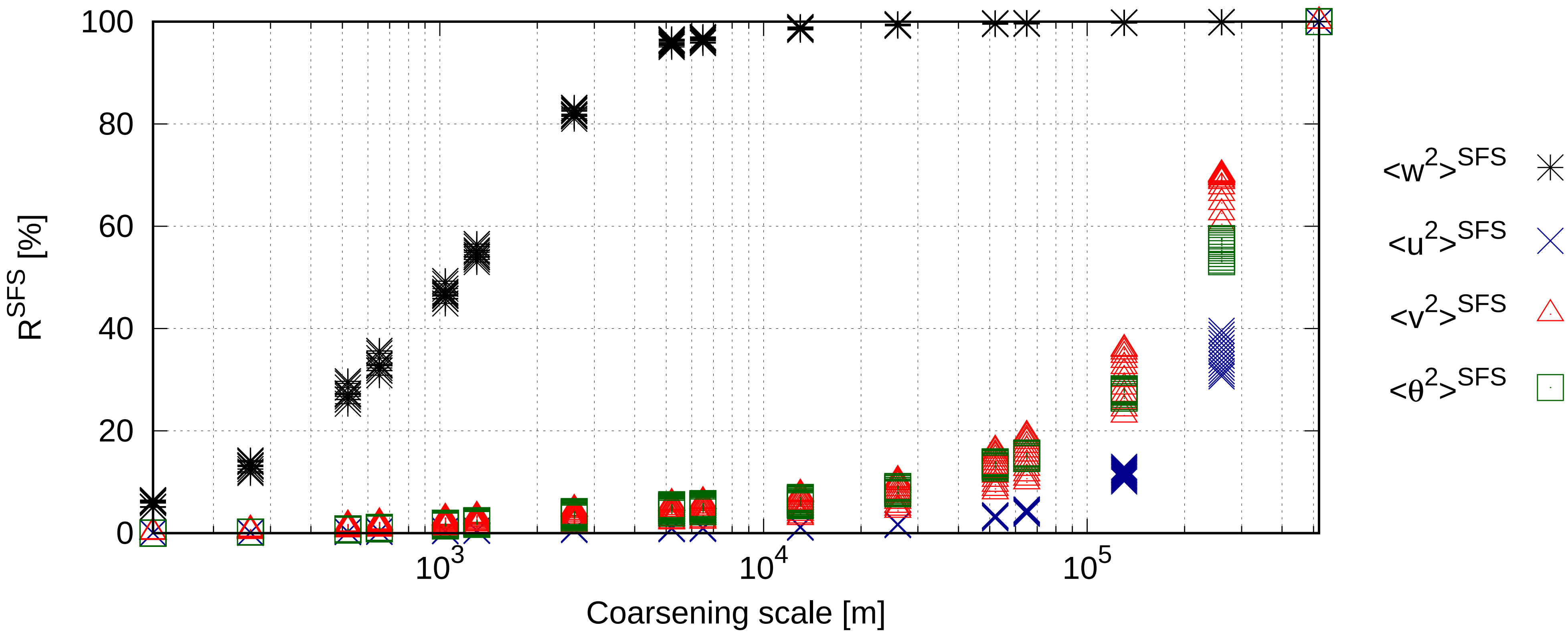
$$\overline{u_i' u_i'}^{SFS} = \overline{u_i' u_i'}^{\Delta} + \overline{(u_i - \overline{u_i}^{\Delta})(u_i - \overline{u_i}^{\Delta})}^{\Delta}$$

$$e^{SFS} = \frac{1}{2}\left(\overline{u'^2}^{SFS} + \overline{v'^2}^{SFS} + \overline{w'^2}^{SFS}\right)$$

Filter used to diagnose turbulent fluxes and TKE from LES data



Subgrid variability from LES
Averaged ratio between 7-13km (1300-1500 UTC)

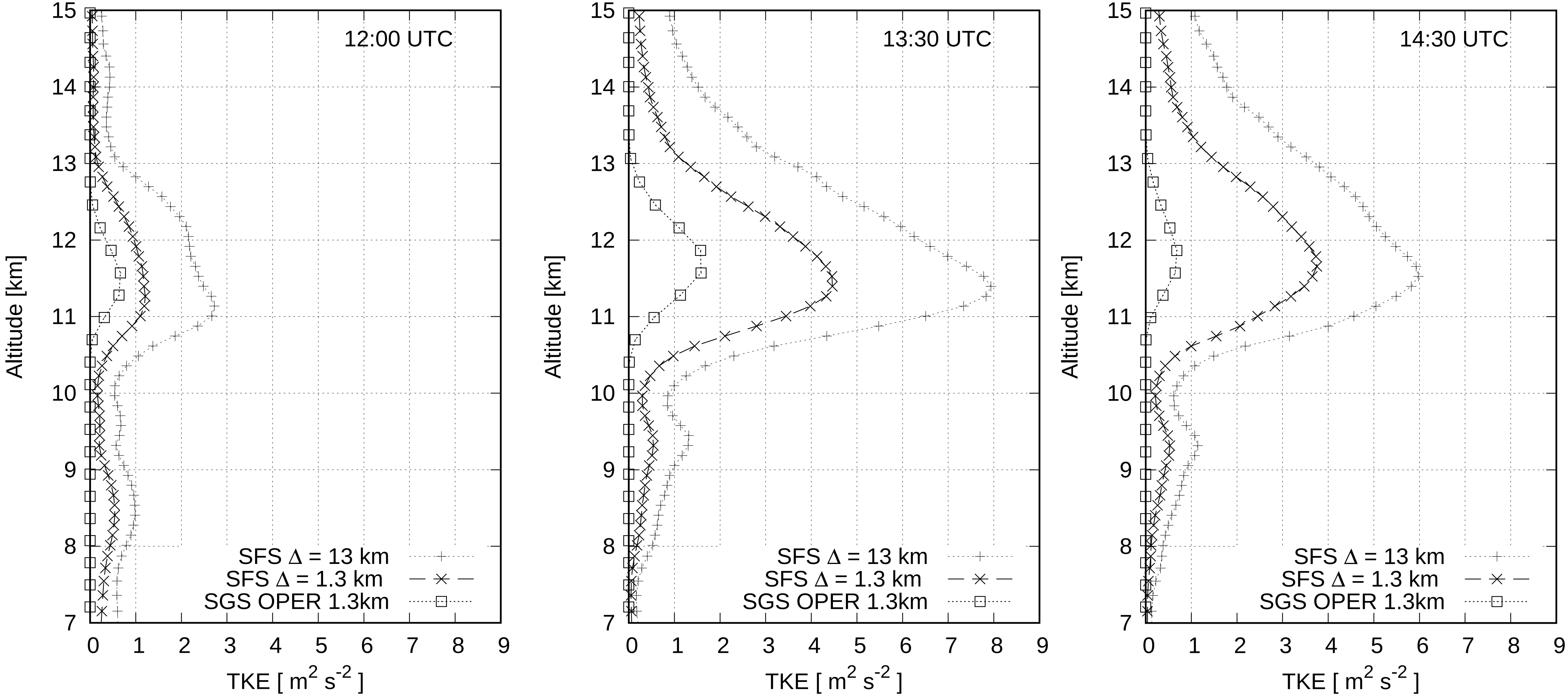


$$R^{SFS} = \frac{< \text{"Sub-filter" variance} >}{< \text{Total variance} >}$$

$R^{SFS} < 20$ % → simulation at Dx=130m is taken as reference.

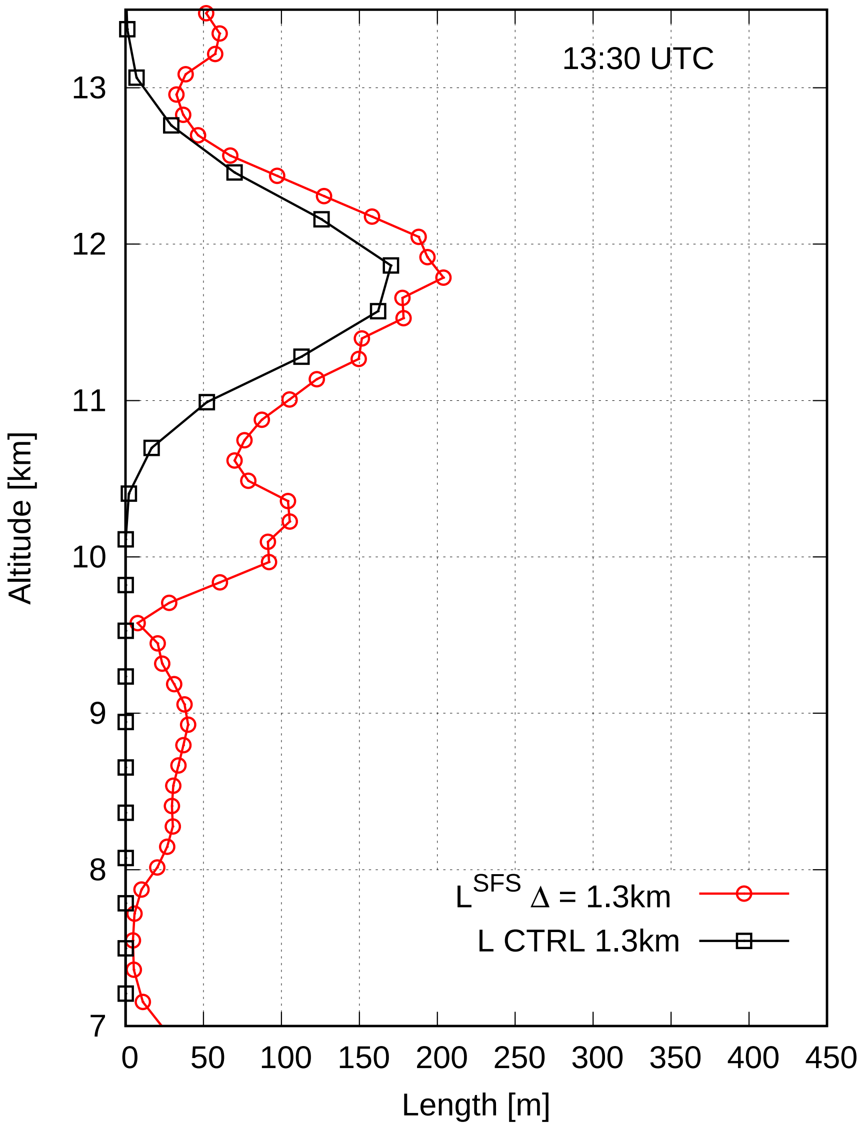
Reference TKE evolution : LES vs CTRL (Δx=1.3km)

$$e^{SFS} = \frac{1}{2}\left(\overline{u'^2}^{SFS} + \overline{v'^2}^{SFS} + \overline{w'^2}^{SFS}\right)$$



Underestimation of parameterized TKE and mixing during the event

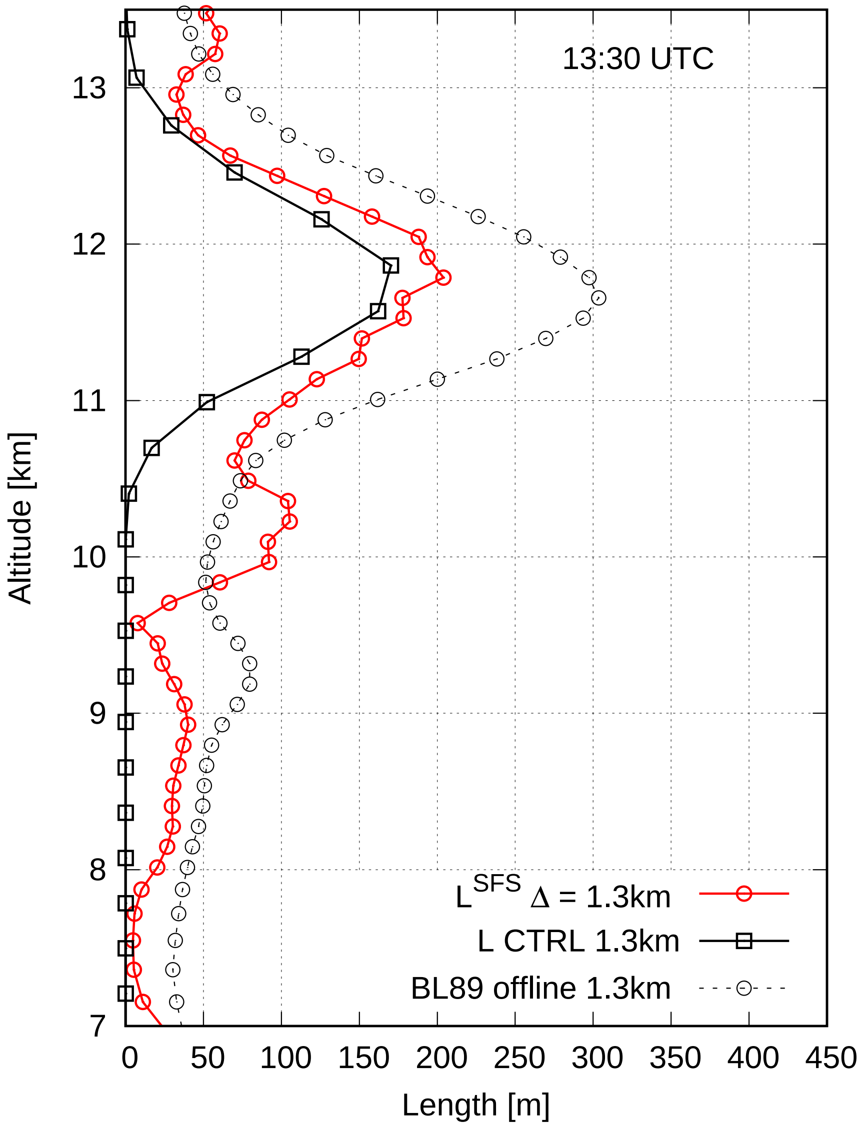
Reference vs parameterized mixing lengths



$$L^{SFS} = \frac{1}{C_m}\left(\frac{\left(\overline{u'w'}^{SFS}\right)^2 + \left(\overline{v'w'}^{SFS}\right)^2}{e^{SFS}S^2}\right)^{1/2}$$

Diagnosed reference length scale seems to validate parameterized values (BL89)

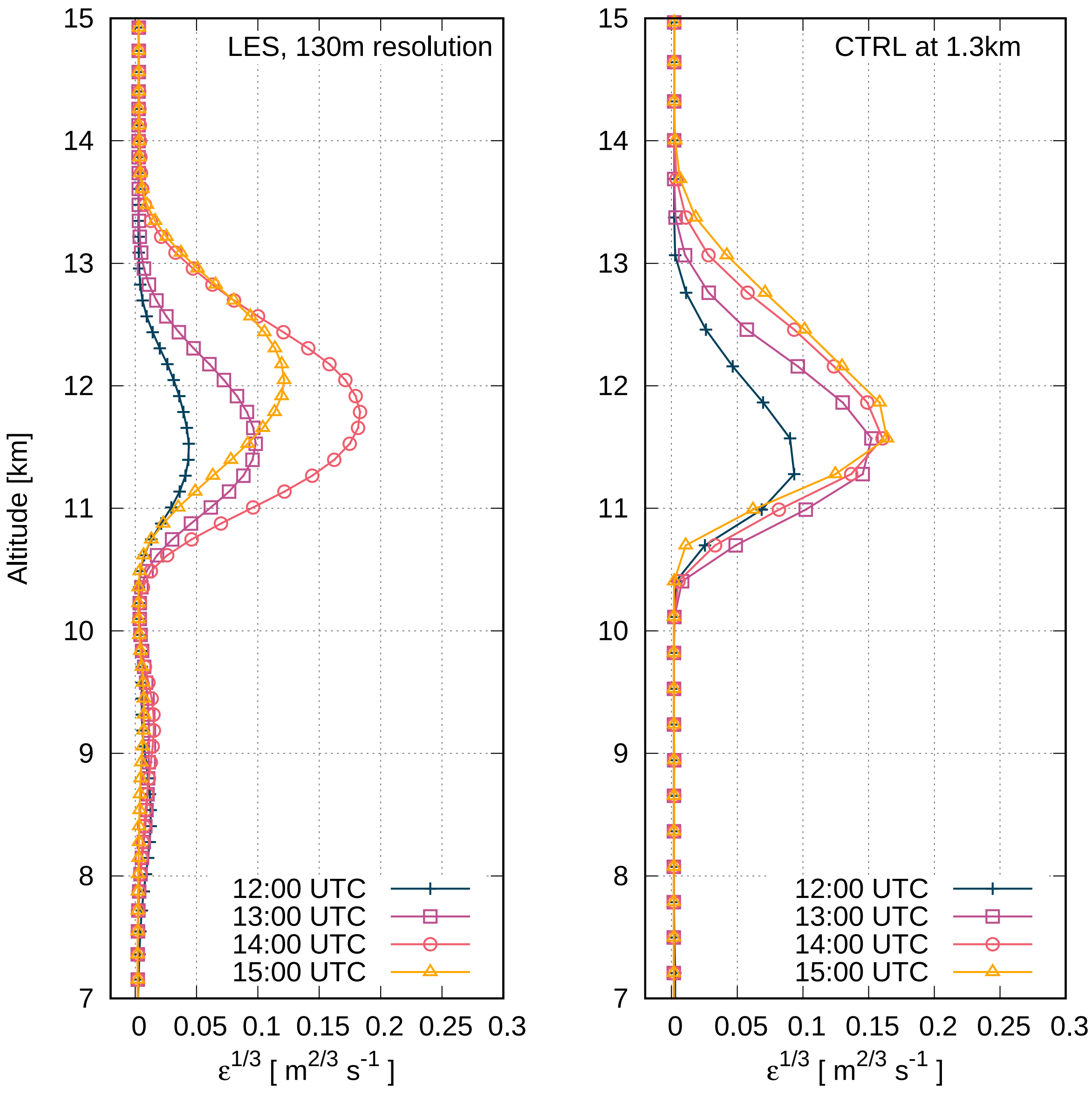
Reference vs parameterized mixing lengths



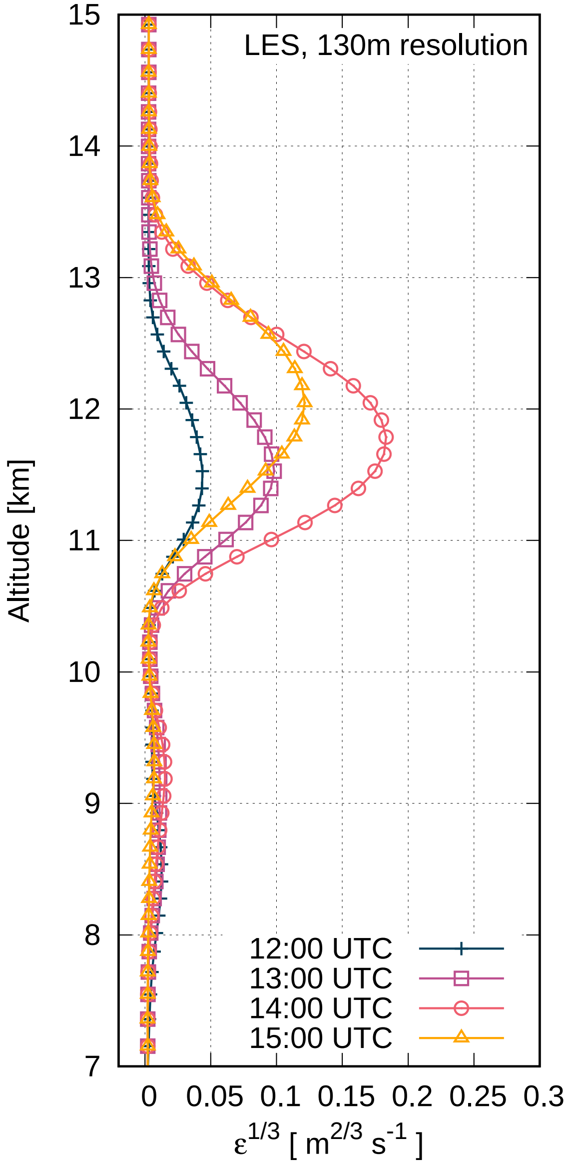
$$L^{SFS} = \frac{1}{C_m}\left(\frac{\left(\overline{u'w'}^{SFS}\right)^2 + \left(\overline{v'w'}^{SFS}\right)^2}{e^{SFS}S^2}\right)^{1/2}$$

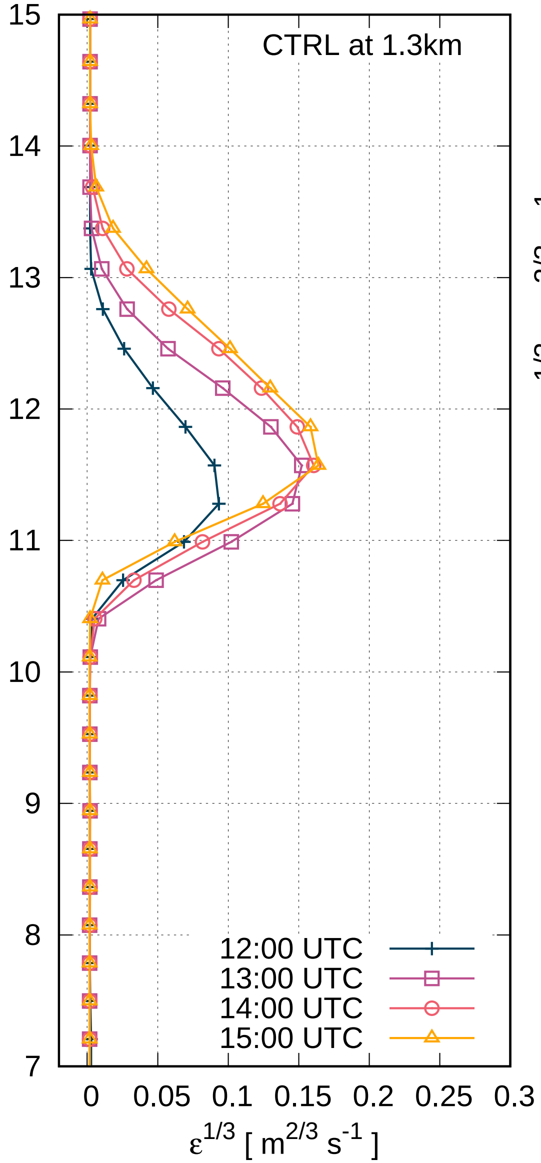
Diagnostic of the offline BL89 from reference TKE suggests **overestimation of the mixing length**

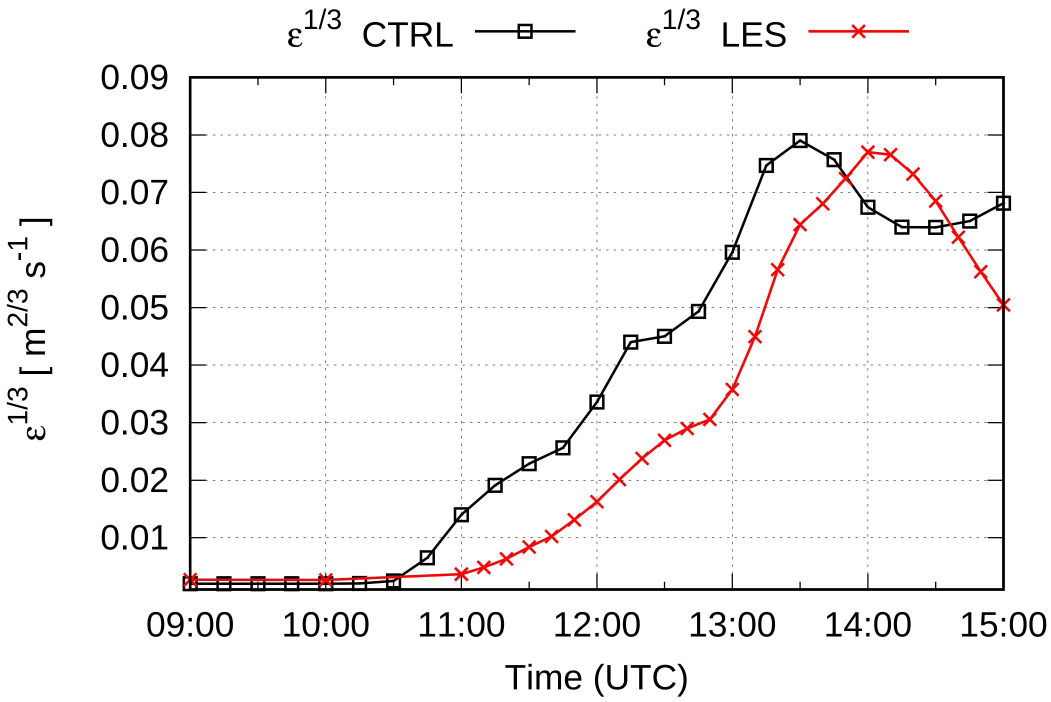
Evaluation of parameterized EDR : LES vs CTRL



Evaluation of parameterized EDR : LES vs CTRL

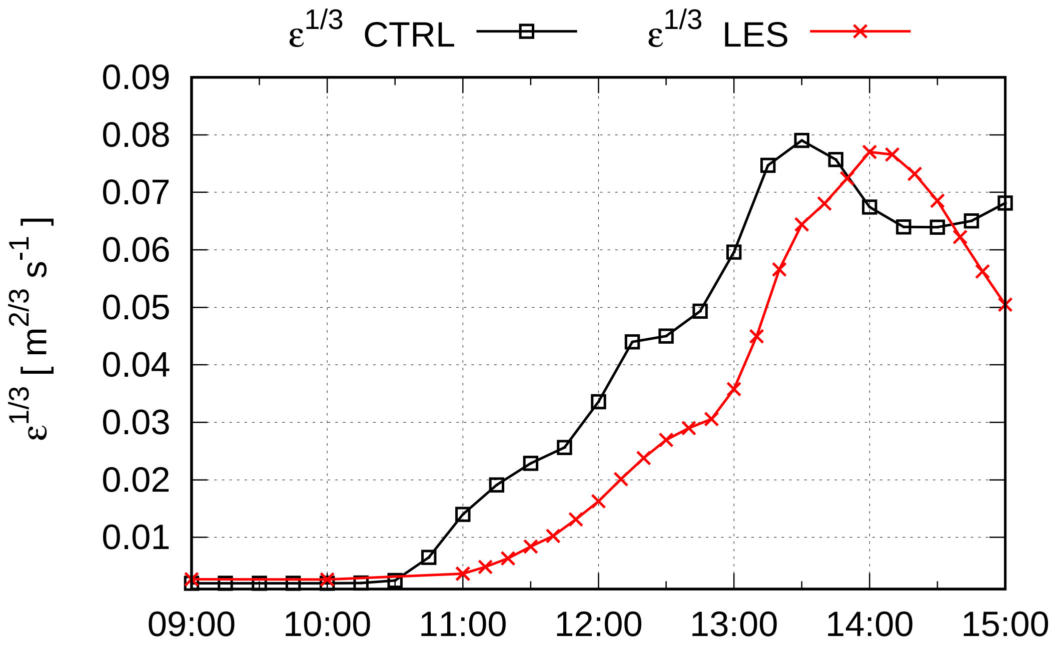


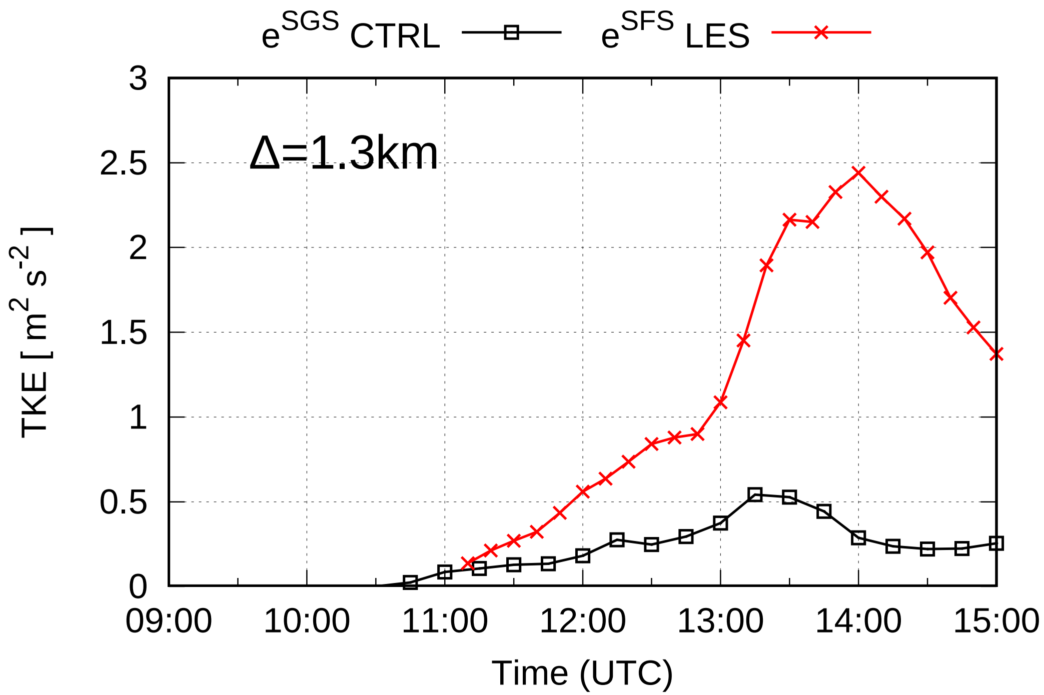




LES dissipation seems 8 times smaller than CTRL in the growth phase

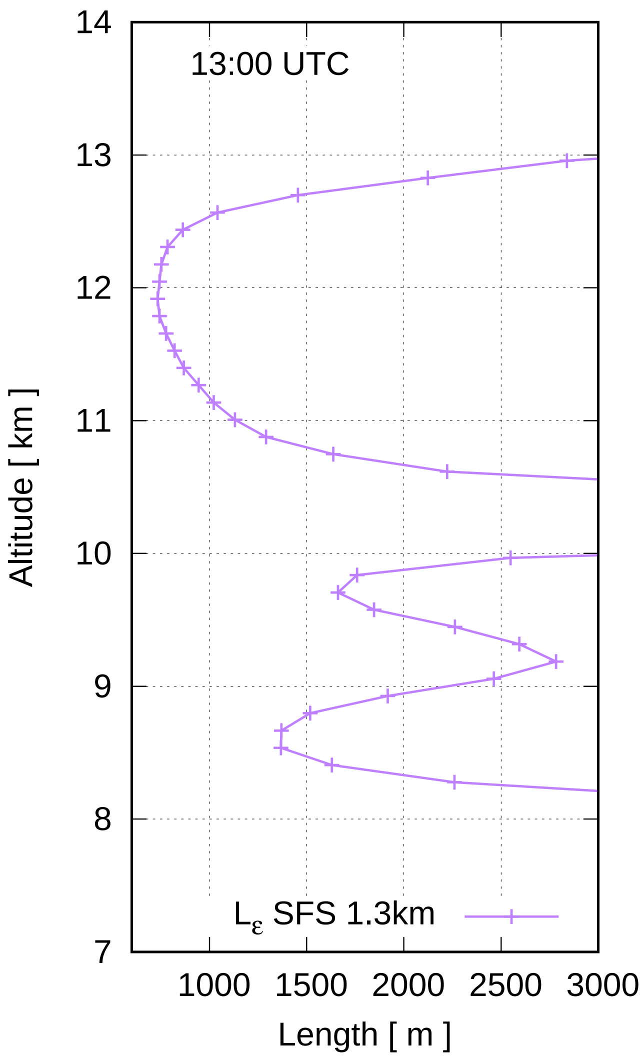
Reference vs parameterized dissipation

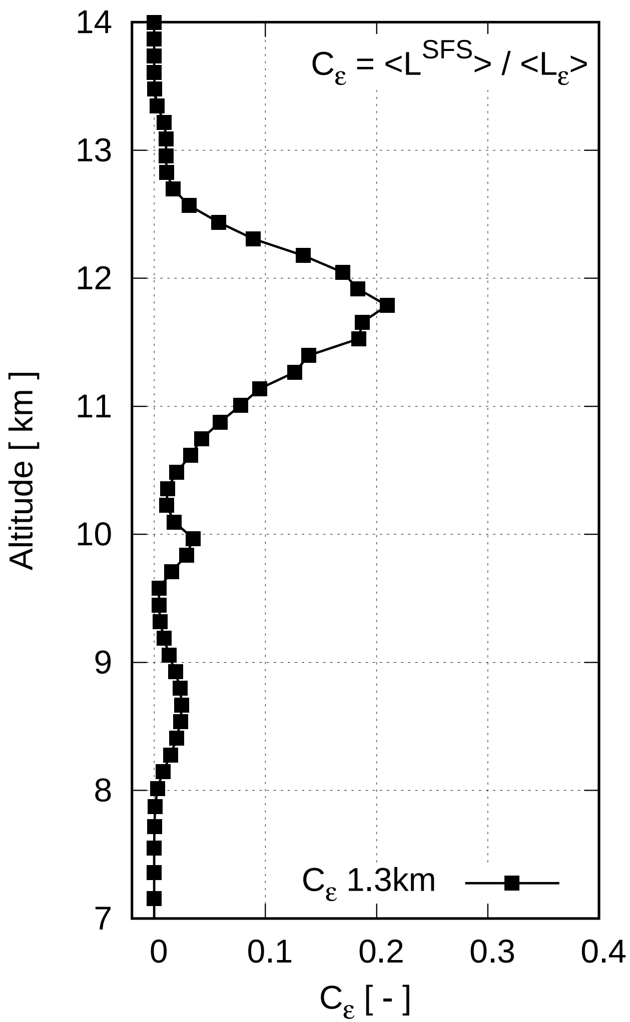




LES Dissipation seems 8 times smaller than CTRL in the growth phase

Reference dissipation length from LES data





$$L_\epsilon = \frac{\left(e^{\mathrm{SFS}}\right)^{3/2}}{\epsilon} \qquad C_\epsilon = \frac{L^{\mathrm{SFS}}}{L_\epsilon}$$

On average in the 11-12 km mixed layer :

- L_ε ~ 900m
- C_ε ~ 0.15 (0.84 in CBR)

Conclusion

- Turbulence parameterized with pronostic TKE equation and diagnostic mixing length formulation
- Spatial resolution increases in NWP model lead to new challenges for turbulence parameterisation in NWP, especially regarding their assumptions validity
- Scheme deficiencies should be identified using process studies with high resolution datasets

To illustrate this, we used a LES of a CAT event at tropopause levels

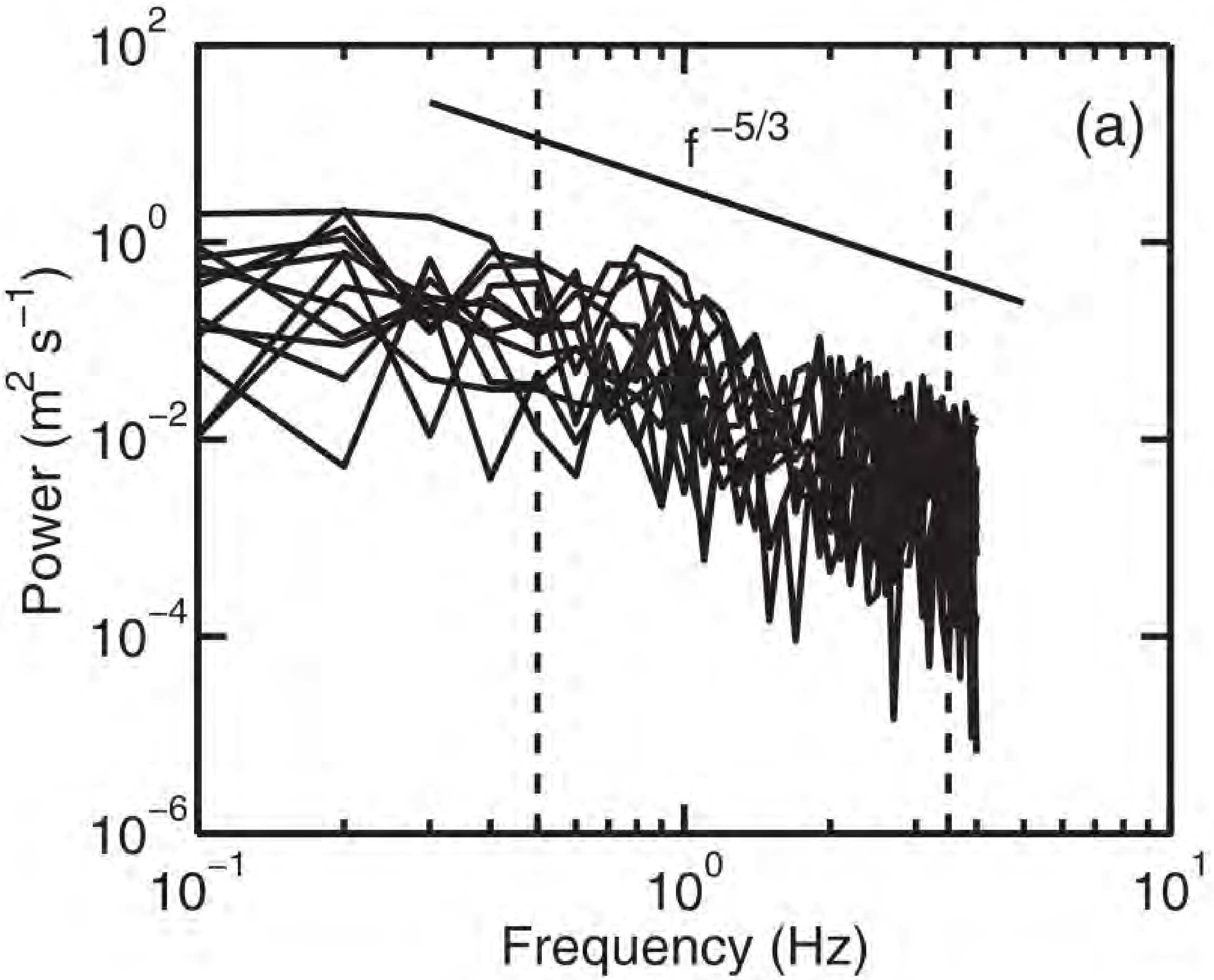
- The CAT event is in the grey zone of turbulence at kilometer resolutions (in Méso-NH. AROME ?)
- Underestimation of TKE and mixing at tropopause levels
- Dissipation of TKE seems overestimated
- This suggests revisiting dissipation parameterization (but more analysis needed)

Thank you !

In-situ observations

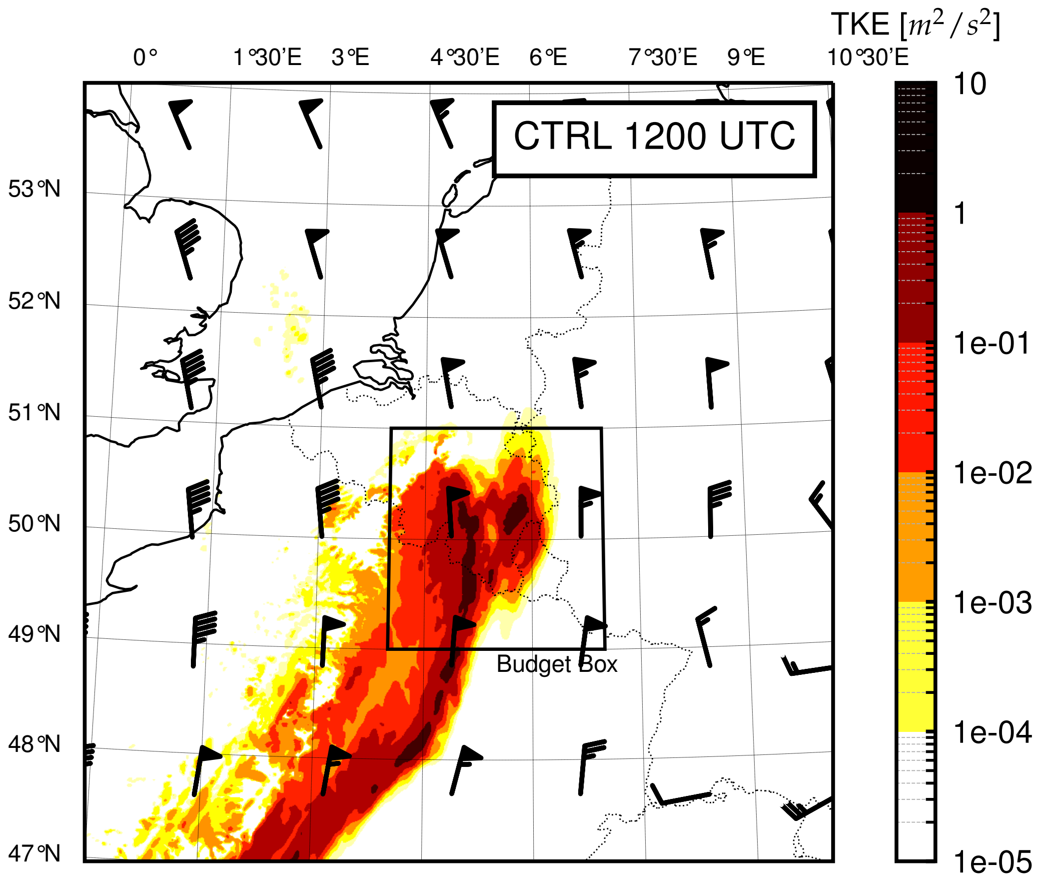
- Observations by commercial aircraft predominant in volume
- Generalization of automated observations, replacing pilot reports (PIREPS)
- Based on vertical acceleration timeseries
- Observation cast in EDR metric (ICAO standard)

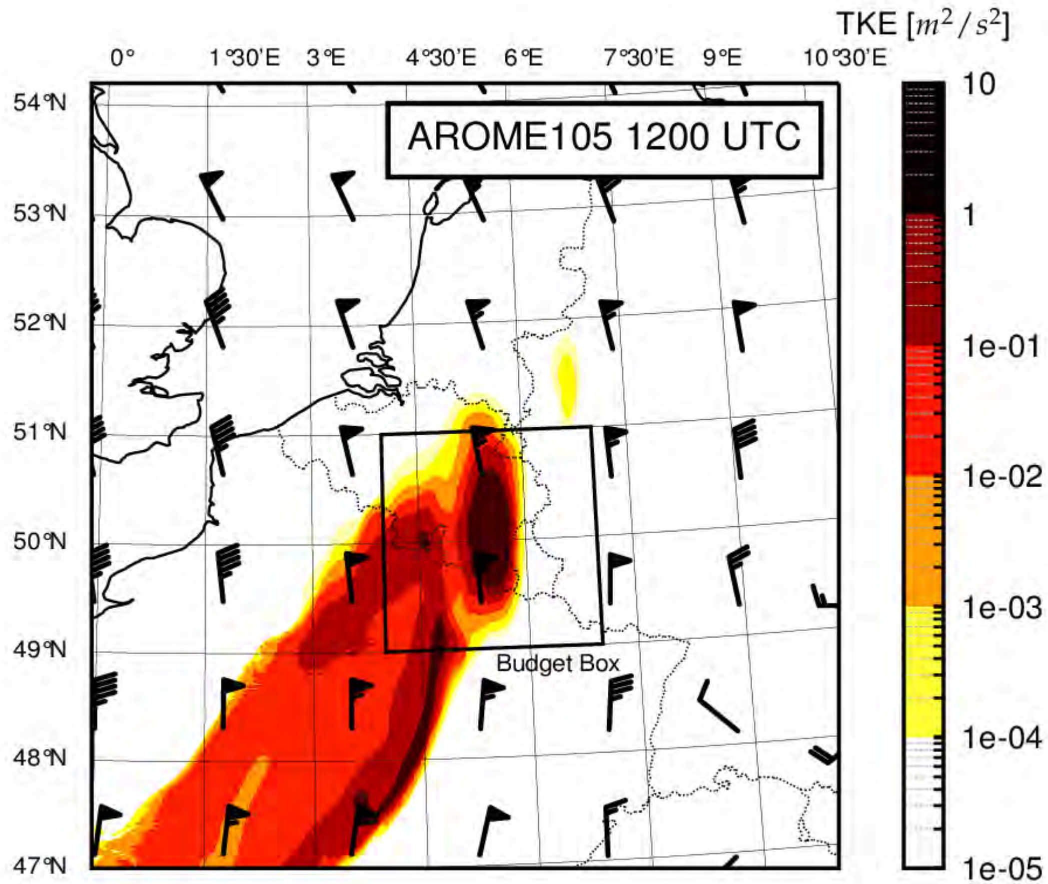
$$\mathrm{EDR} = \varepsilon_w^{1/3}$$



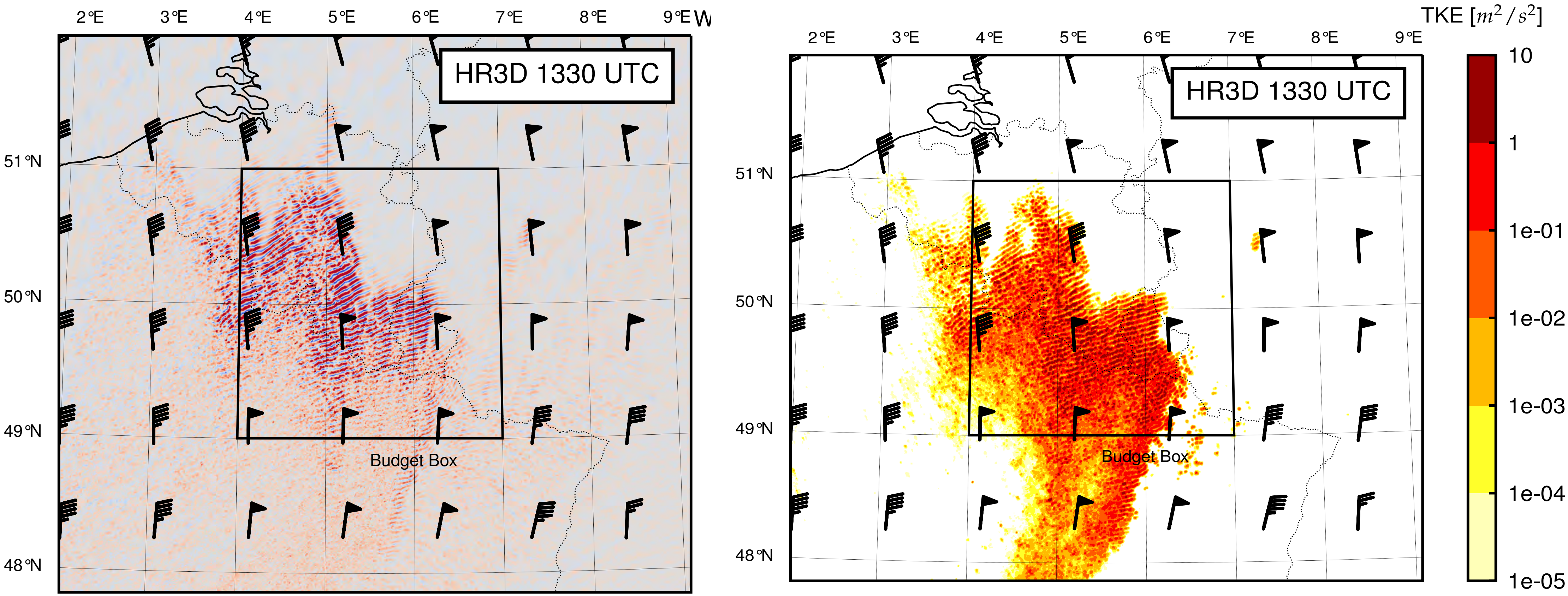
From Sharman et al. (2014)

TKE at 225 hPa (~12km), 1230 UTC, Δx=1.3km



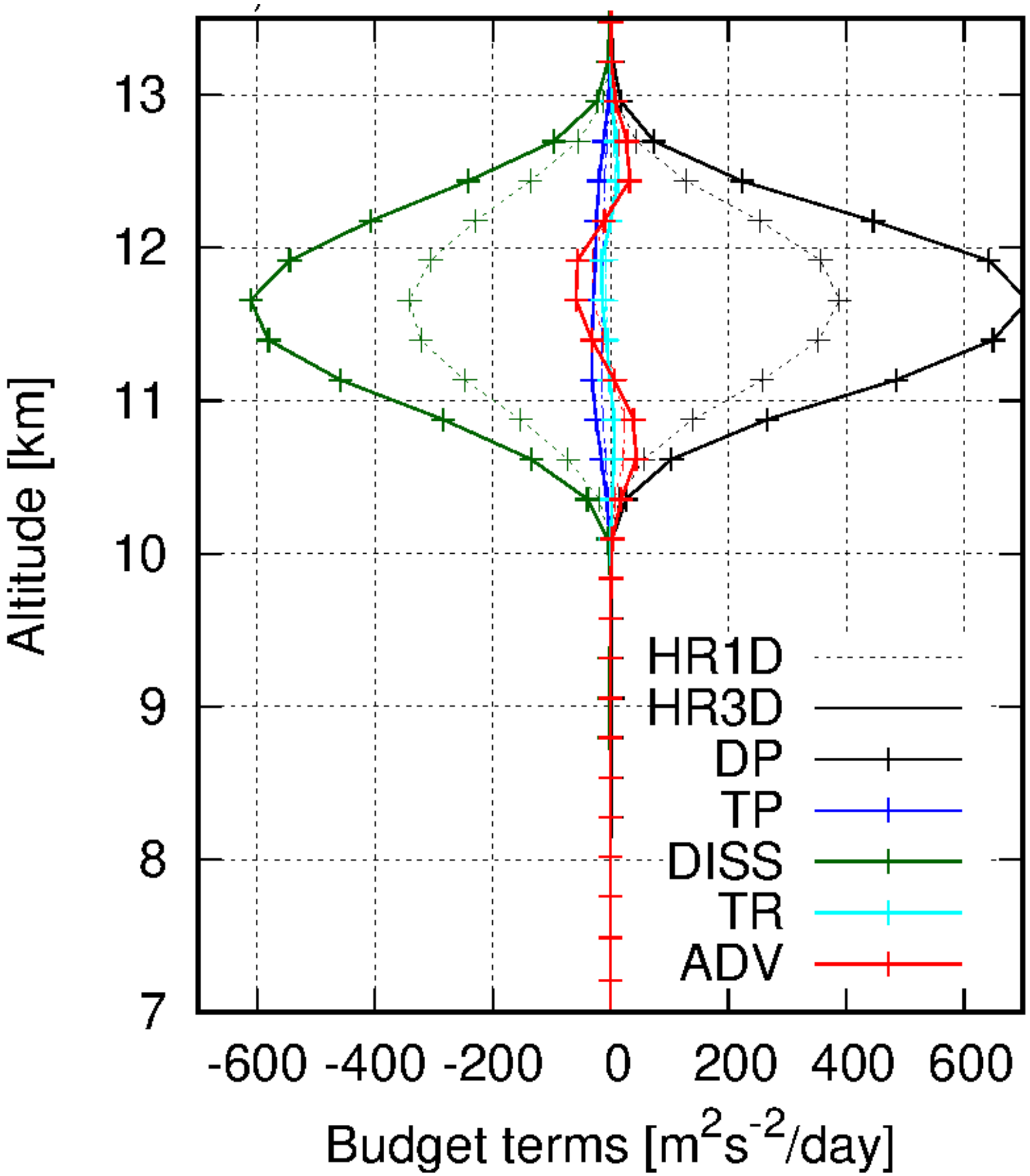


Wind and TKE at 225 hPa (~12km), 1330 UTC, Δx=260m



Wave-like **coherent structures** on vertical wind and TKE

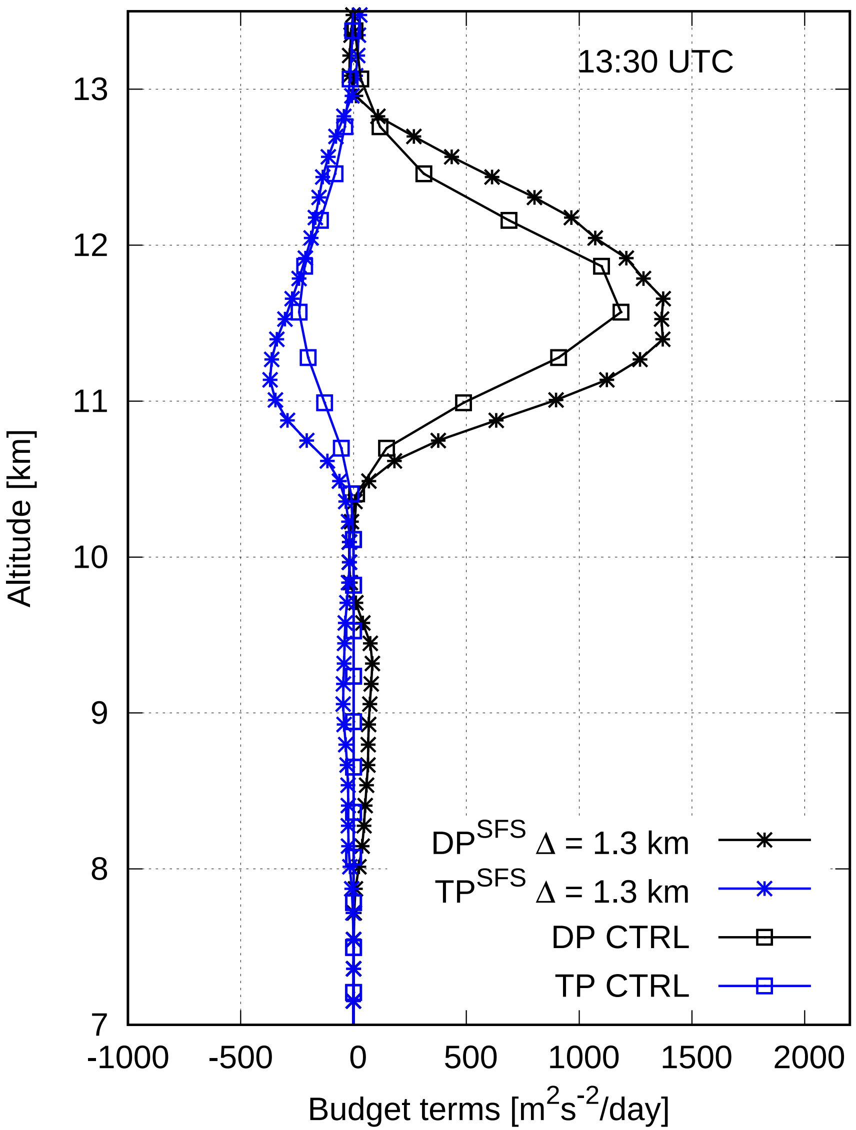
Budget of TKE at 200 hPa (1300 UTC) with Dx=260m



- Strong impact of 3D turbulence on **DP** and **DISS** terms

- Also nearly doubles subgrid TKE values

Reference vs parameterized budget terms



Instantaneous average profiles of **DP**^{SFS} and **TP**^{SFS}

$$\mathrm{DP}^{\mathrm{SFS}} = -\overline{u_i' u_j'}^{\mathrm{SFS}} \frac{\partial \overline{U_i}^{\Delta}}{\partial x_j}$$

$$\mathrm{TP}^{\mathrm{SFS}} = -\beta \overline{w'\theta'}^{\mathrm{SFS}}$$

Both fluxes slightly underestimated in CTRL

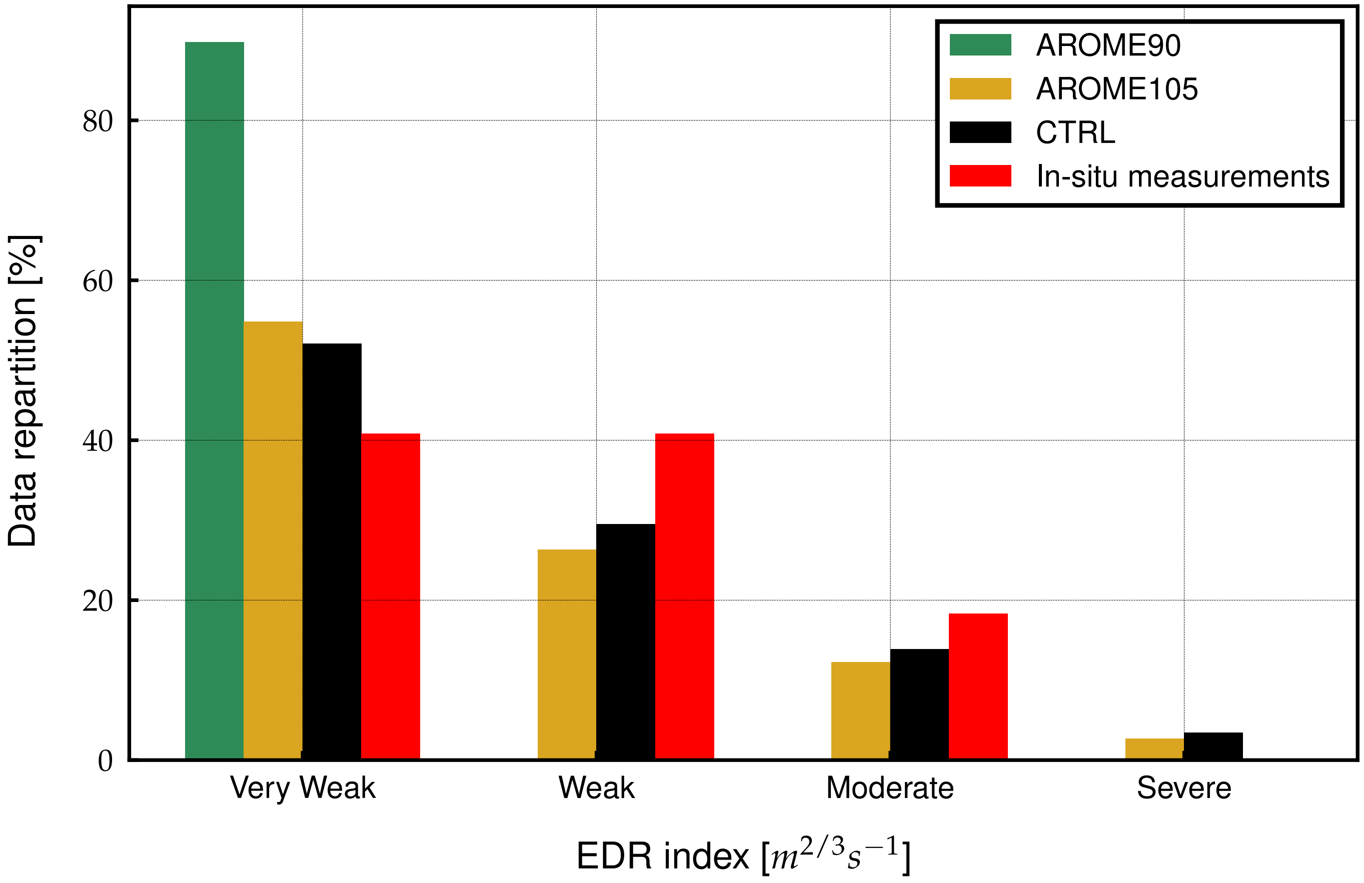
In conjunction with lower TKE

Kilometre scale simulations from observation

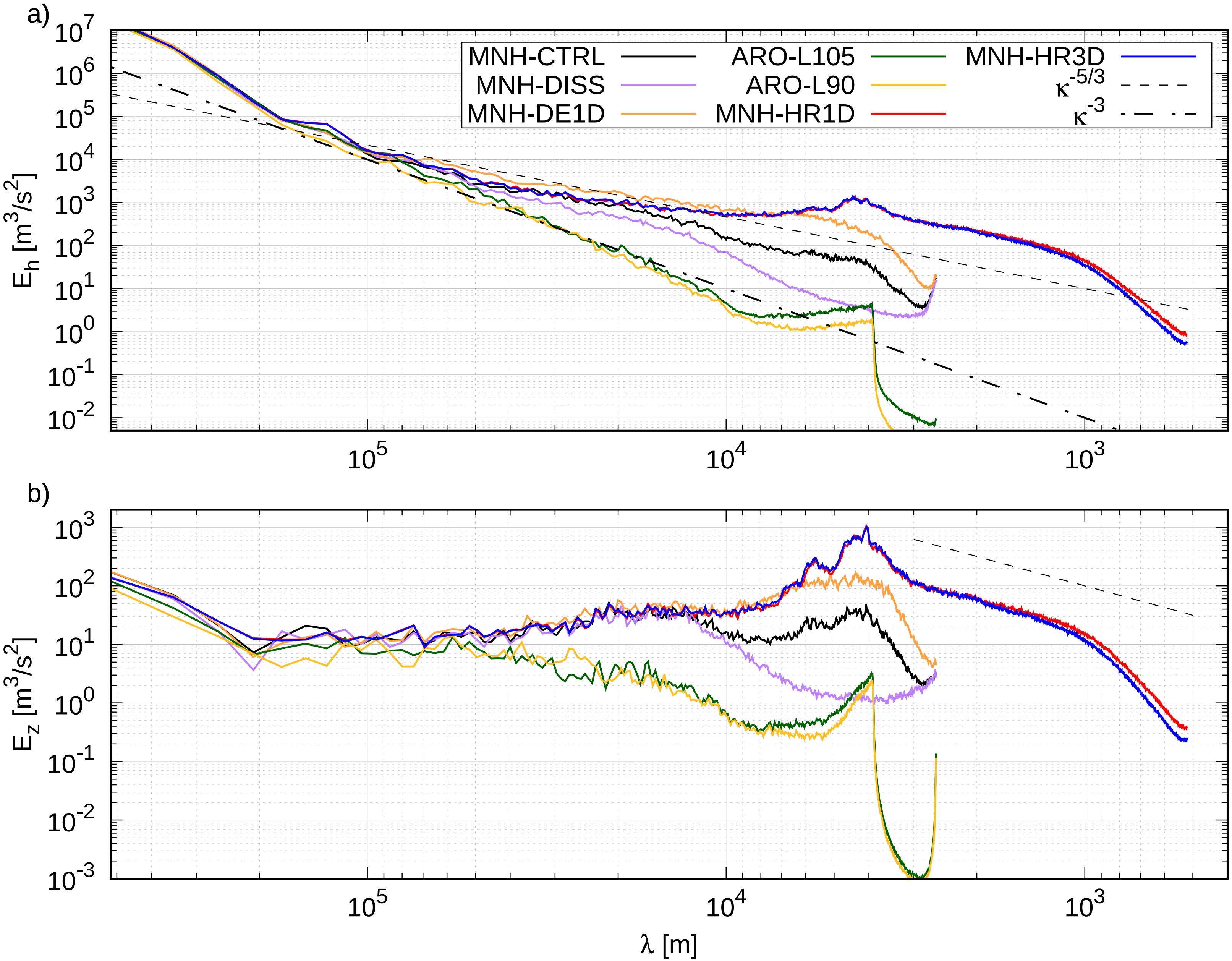
AROME90 :
90 operational levels

AROME105 :
105 levels, higher vertical resolution in tropopause

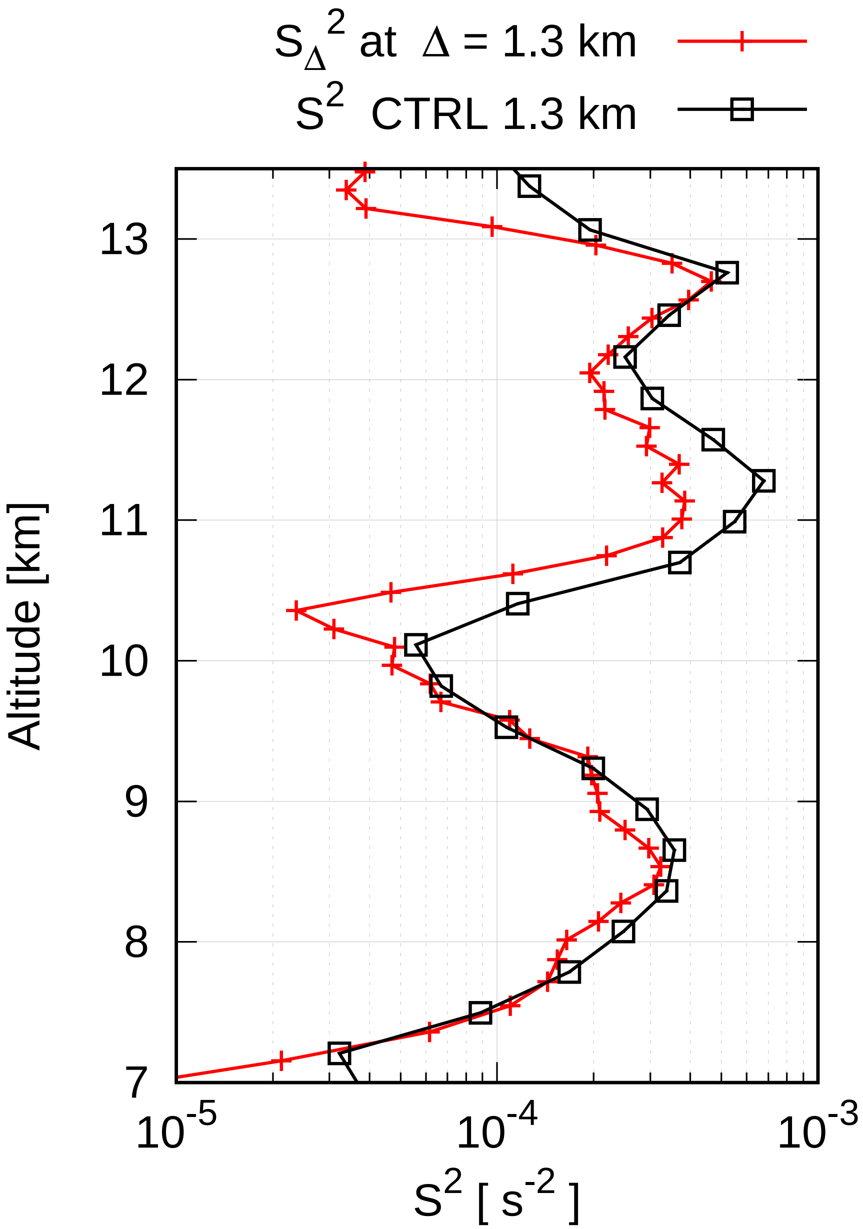
CTRL :
Méso-NH, 105 levels



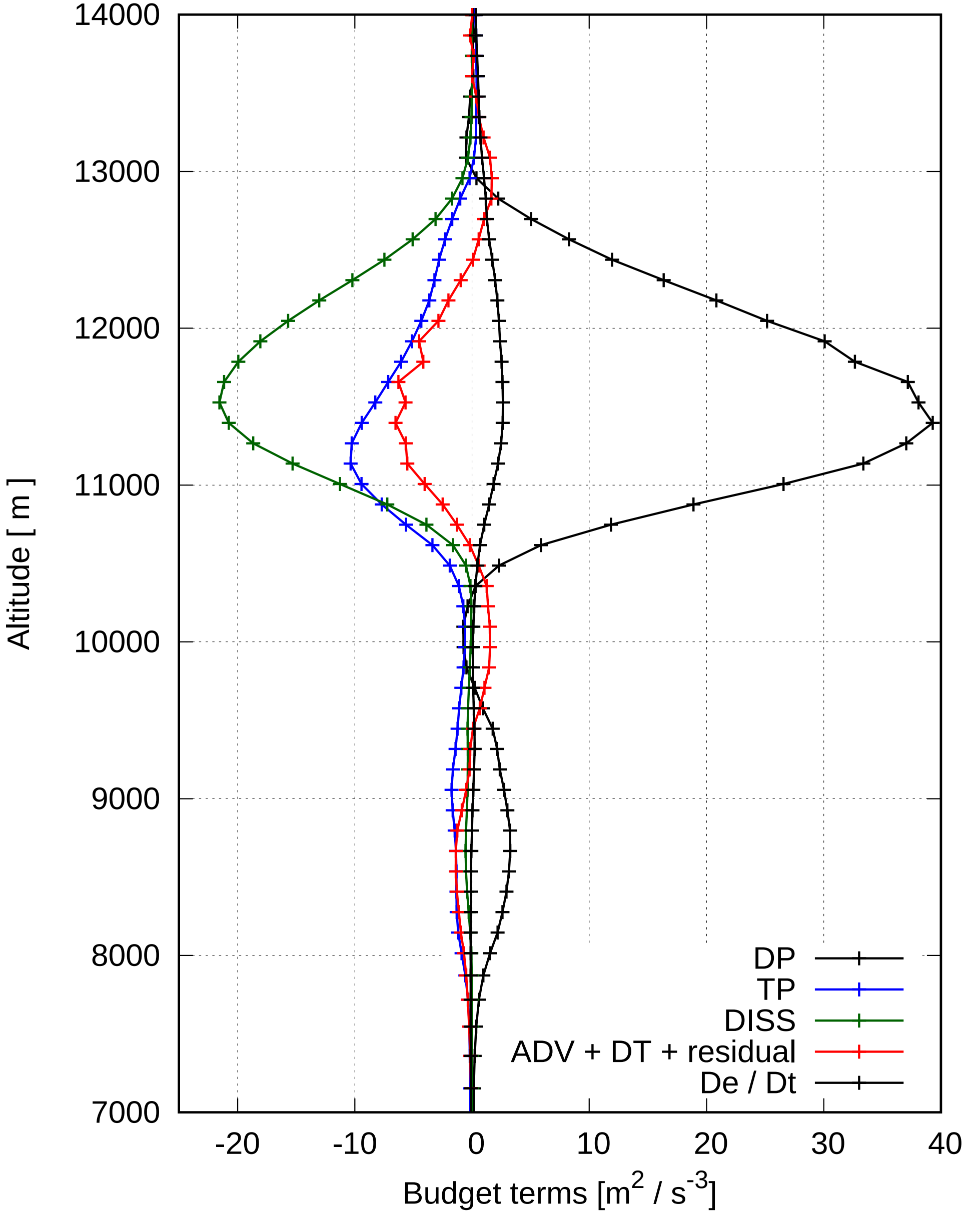
Kinetic energy spectra on LES grid (1300 UTC)



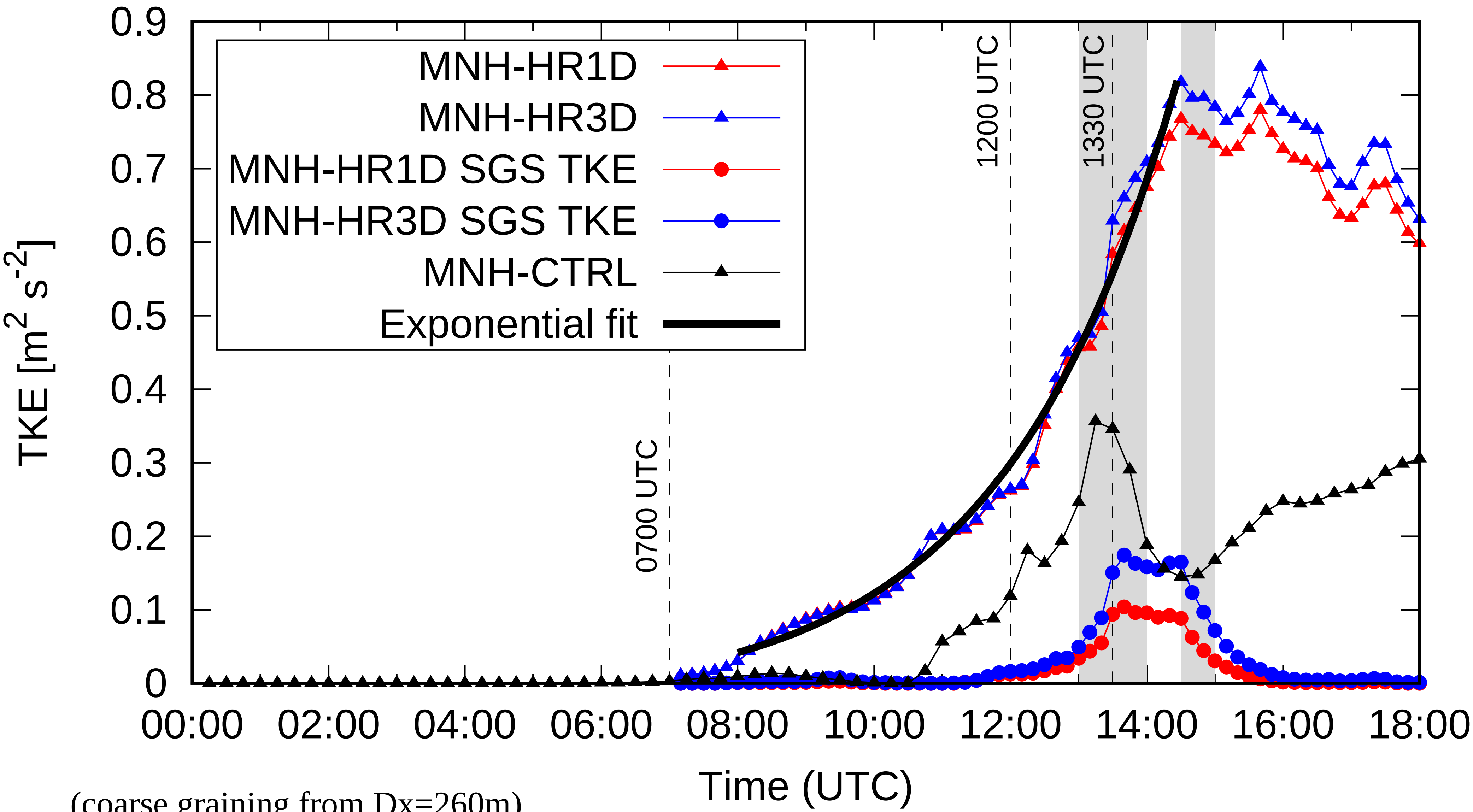
Backup : stability profiles



Budget of reference LES terms

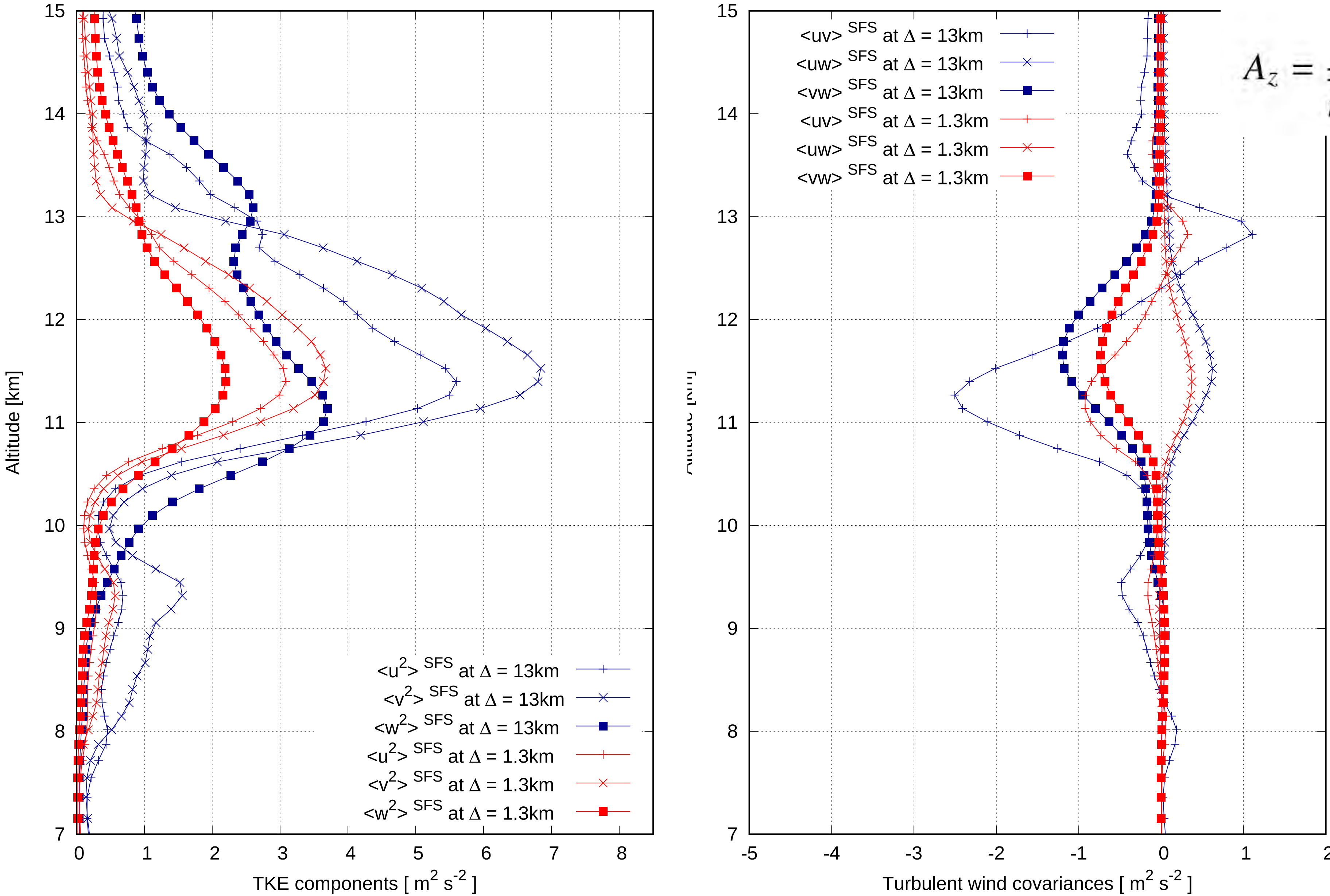


Subfilter (at 1.3km) TKE evolution (8-14km average)



(coarse graining from Dx=260m)

Subfilter covariances (1330 UTC)



$$A_z = \frac{\overline{w^2}}{\overline{u^2} + \overline{v^2} + \overline{w^2}}$$

Az = 0.24

Az = 0.22