On the use of a TKE equation to compute subgrid fluxes in the 'Grey Zone'

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&

CONSTRAIN case collaborators

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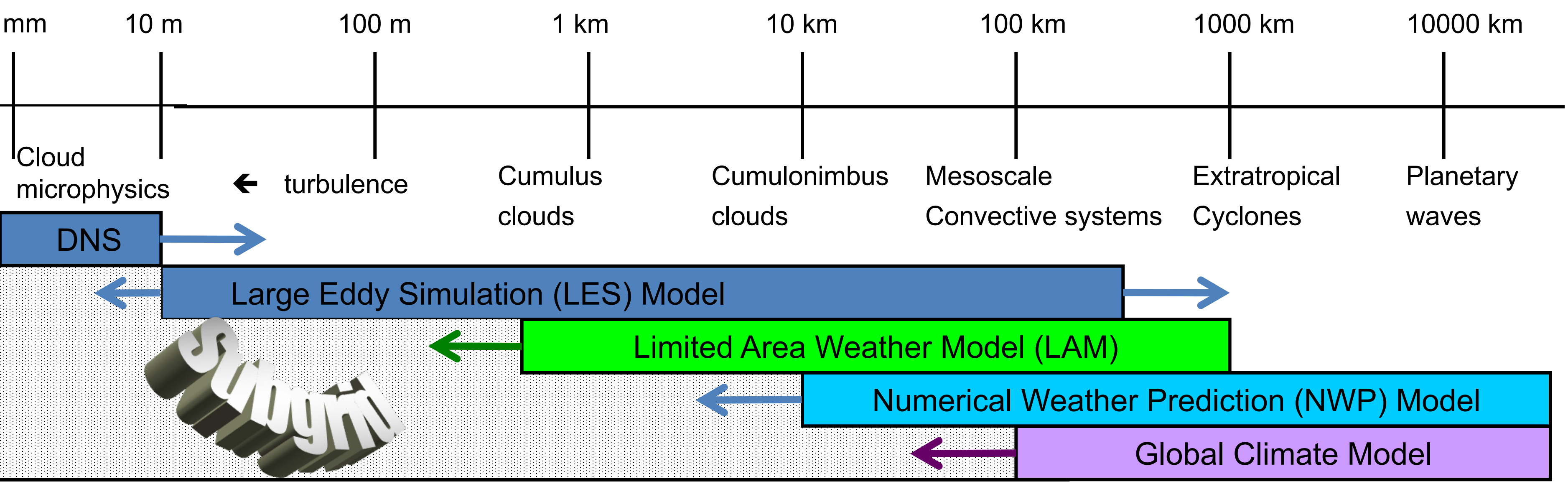
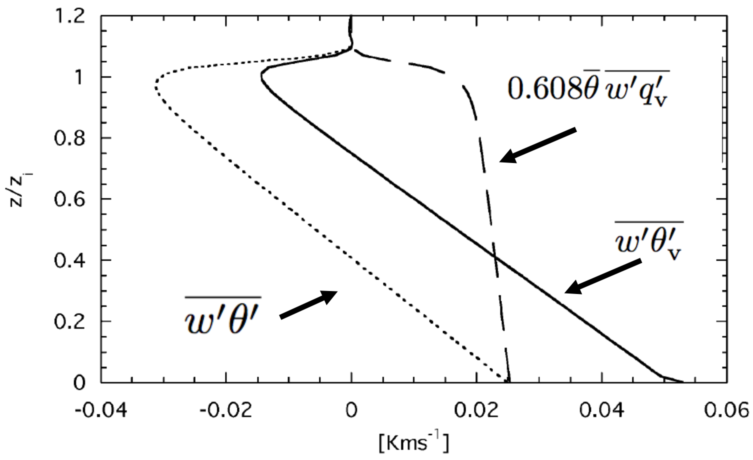
TU Delft

Current developments



- when does turbulence cause the growth of mesocale fluctuations?
- how does LES behave if Δx becomes very large ("LAM" or "NWP" limit)?
- is the Grey Zone case dependent?
  examples for the stable, convective and cloud-topped boundary layer

A Convective Boundary Layer driven by a surface temperature and humidity flux



$$\overline{w'\theta_v'} \approx \overline{w'\theta'} + 0.608\overline{\theta}\,\overline{w'q_v'}$$

de Roode et al. (JAS, 2004)

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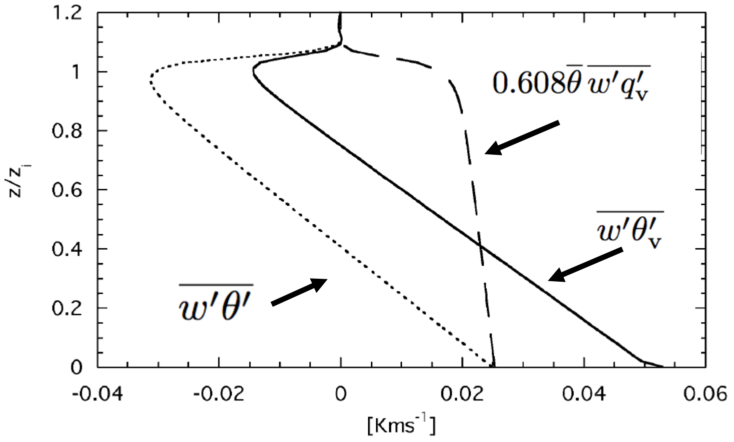

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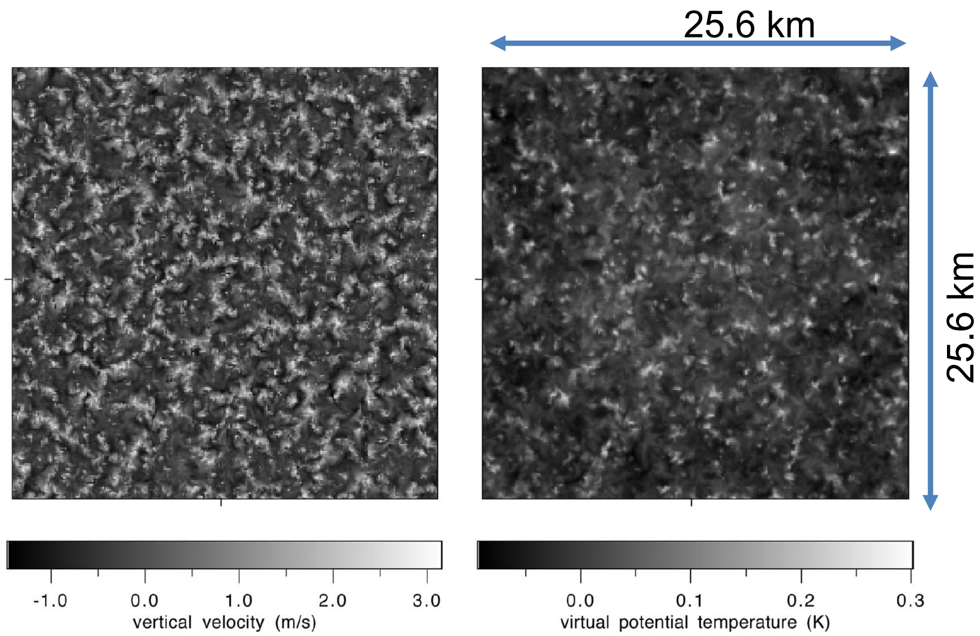

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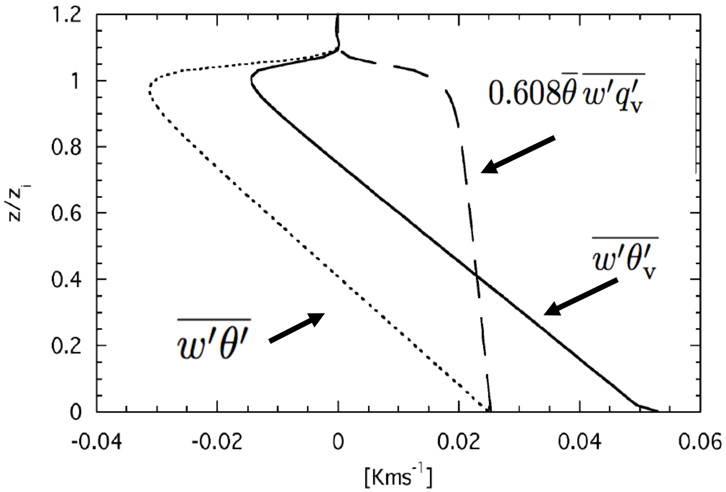

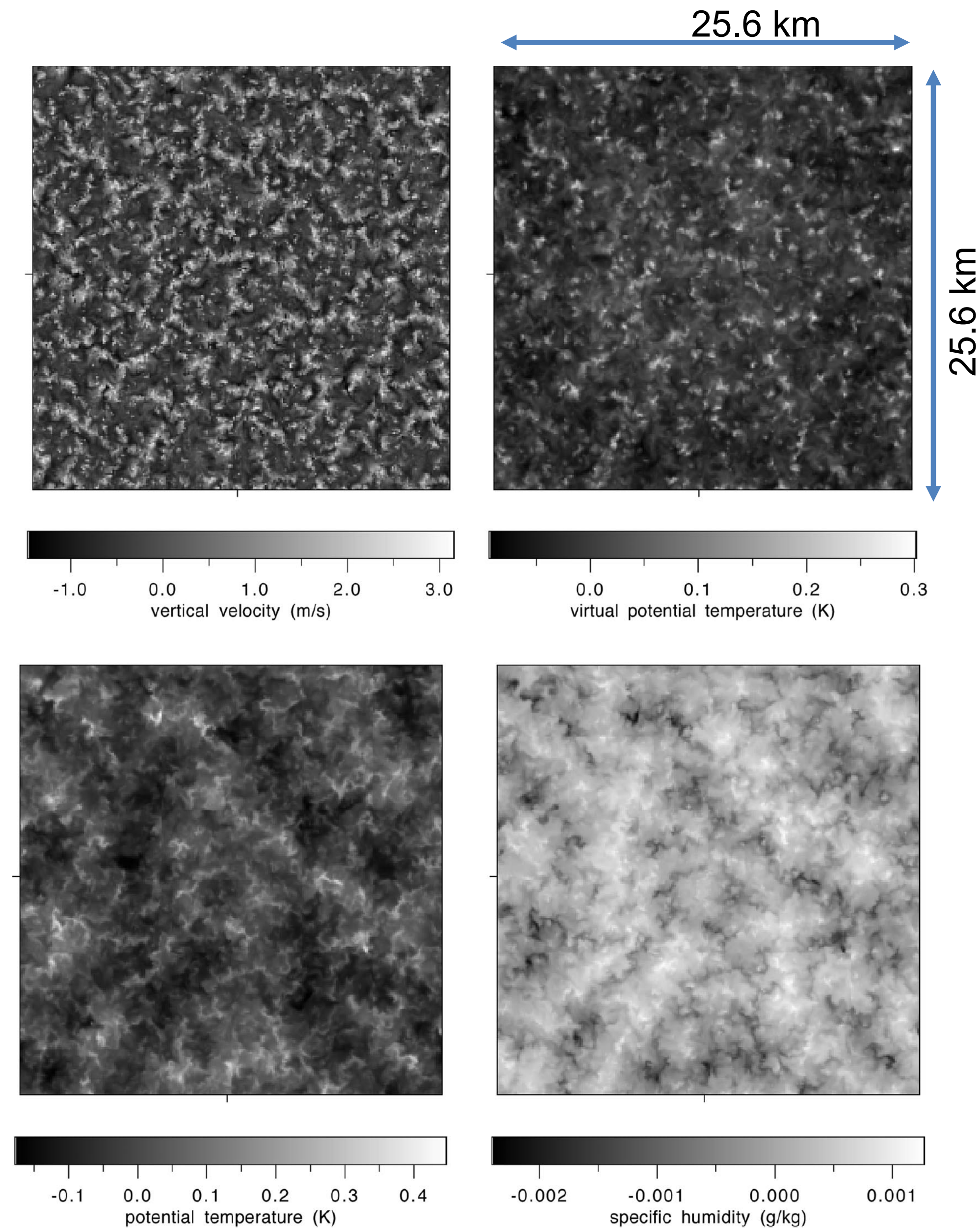

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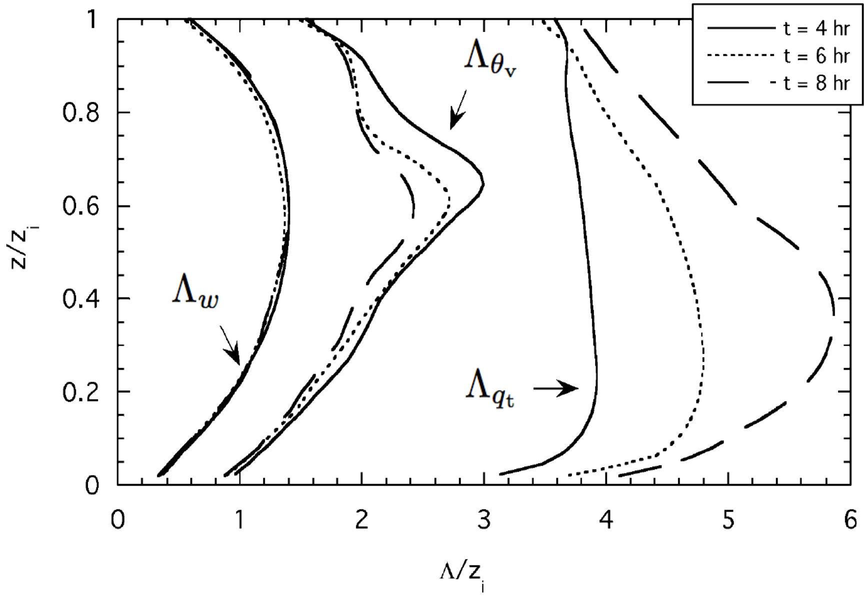
typical length scales

boundary layer size z_i: w, θ_v

mesoscales > z_i: θ, q_v

de Roode et al. (JAS, 2004)

Length scale (Λ, from spectra) evolution in time



Variance production terms

dynamics

$$\frac{\partial \overline{w'w'}}{\partial t} = \beta \overline{w'\theta_v'}$$

$$\frac{\partial \overline{\theta_v'\theta_v'}}{\partial t} = -2\overline{w'\theta_v'}\frac{\partial \overline{\theta_v}}{\partial z}$$

arbitrary scalar

$$\frac{\partial \overline{\chi'\chi'}}{\partial t} = -2\overline{w'\chi'}\frac{\partial \overline{\chi}}{\partial z}$$

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arbitrary scalar

$$\frac{\partial \overline{\chi'\chi'}}{\partial t} = -2\overline{w'\chi'}\frac{\partial \overline{\chi}}{\partial z}$$

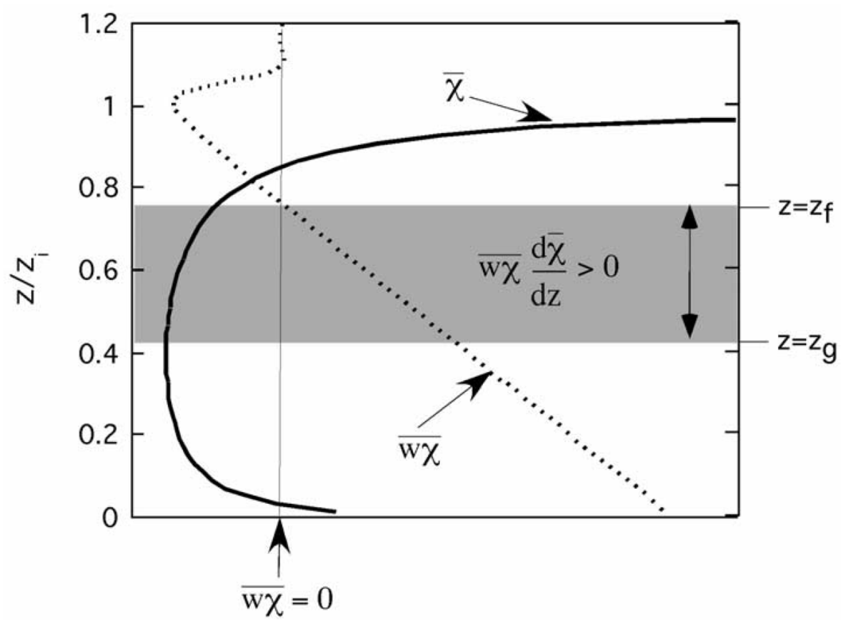
if flux is down the mean gradient

$$\overline{w'\chi'} = -K_h \frac{\partial \overline{\chi}}{\partial z}$$

then variance will be produced

$$\frac{\partial \overline{\chi'\chi'}}{\partial t} = +2K_h \left(\frac{\partial \overline{\chi}}{\partial z}\right)^2 > 0$$

Countergradient regime

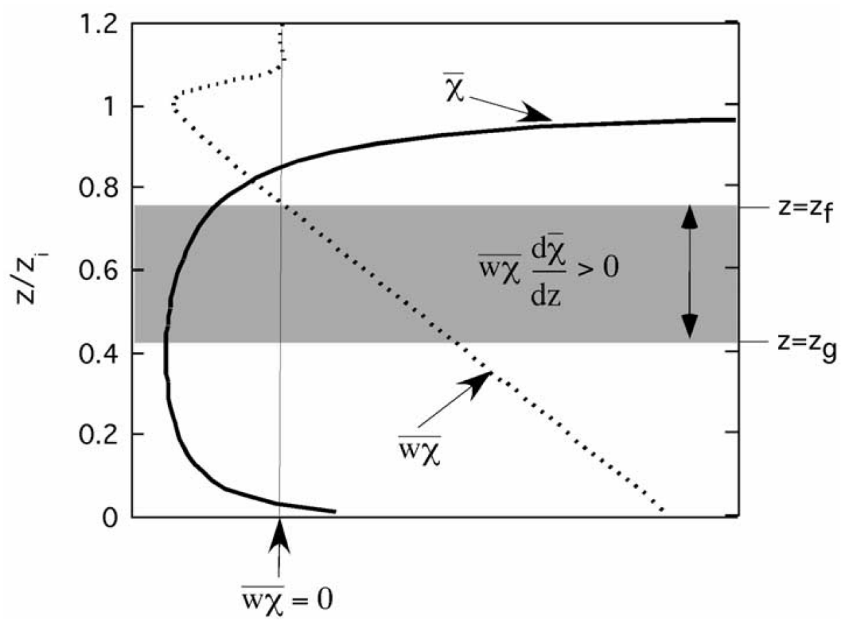


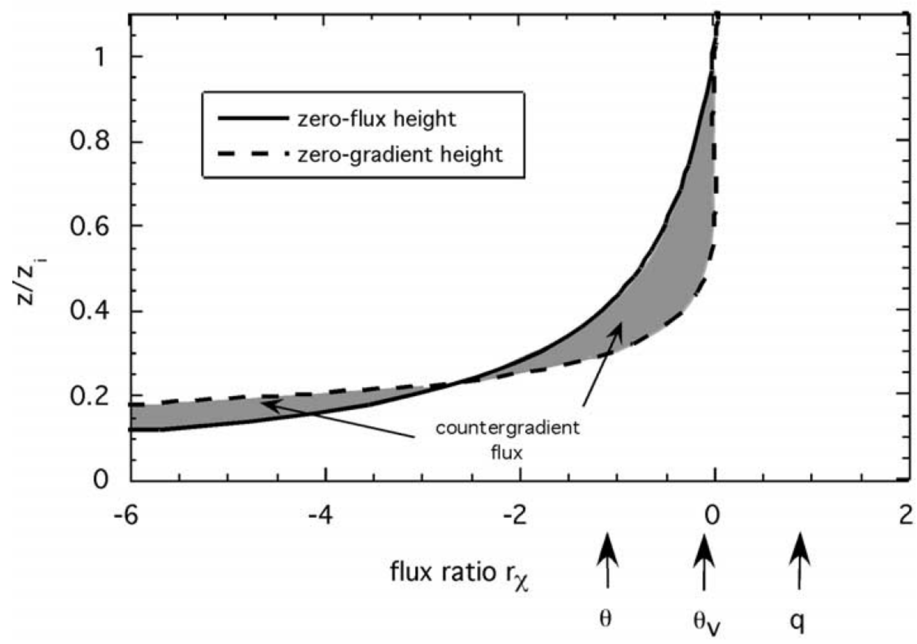
height where flux changes sign

height where mean vertical gradient changes sign

de Roode et al., 2004, BLM: ... countergradient ...

Countergradient regime as a function of the flux ratio flux ratio = top/bottom flux)

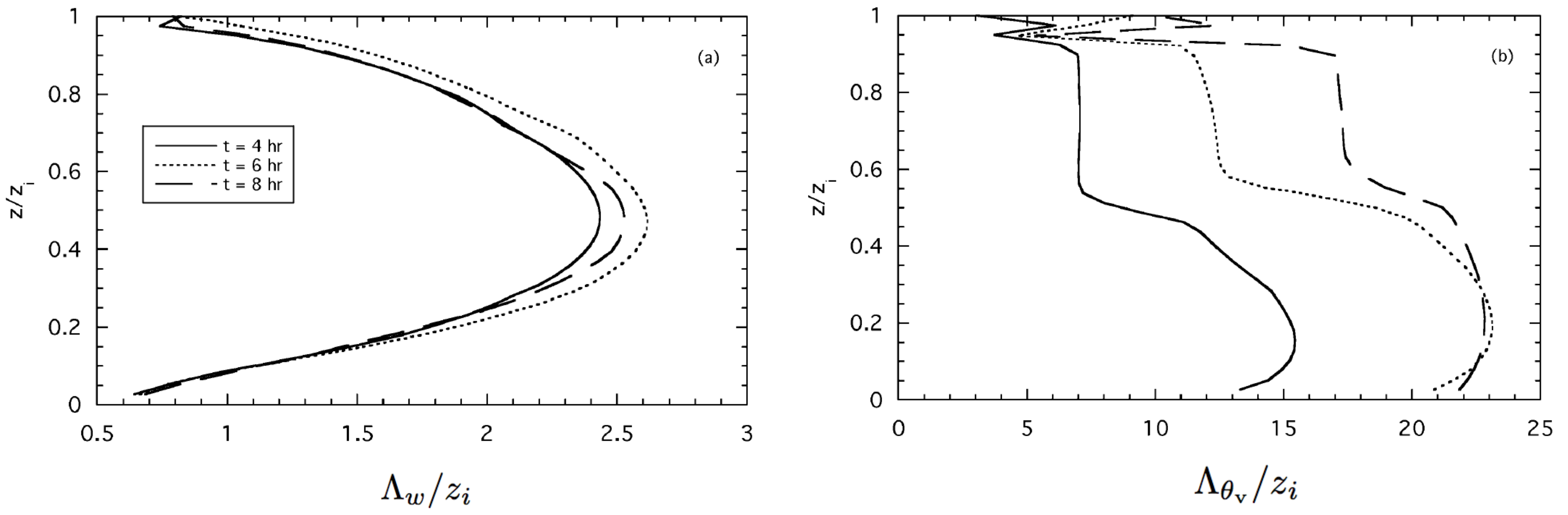




in the interior of the convective boundary layer the countergradient flux destroys θ_v variance

de Roode et al., 2004, BLM: ... countergradient ...

Stratocumulus

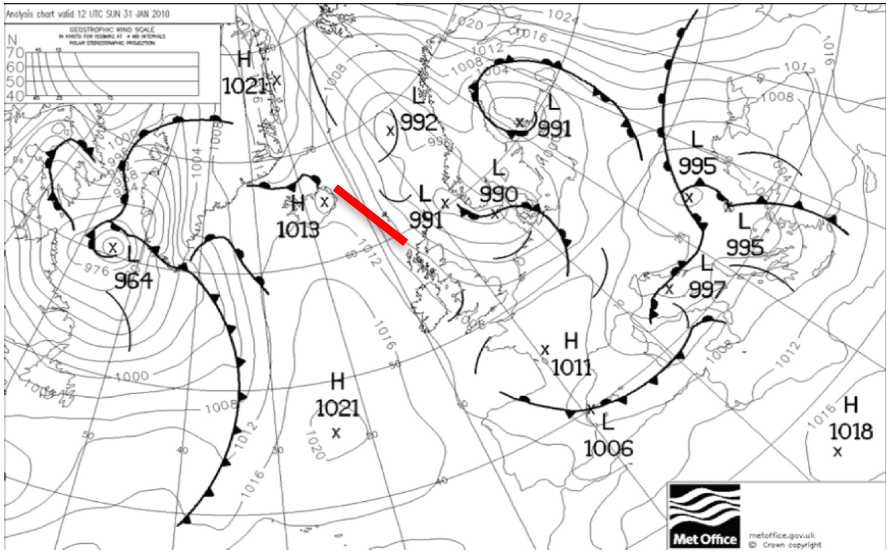


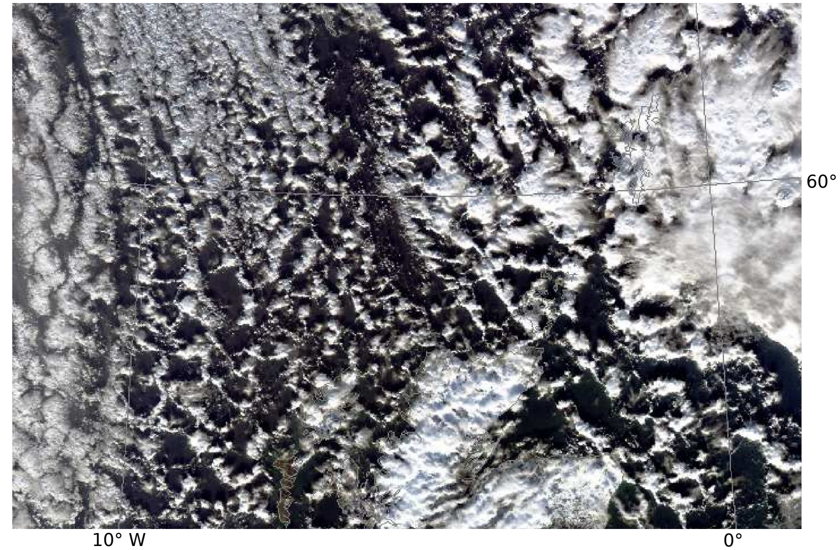
$$\theta'_v = A_w\theta'_l + B_w q'_t \approx B_w q'_t$$

$$\frac{\partial \overline{q'_t q'_t}}{\partial t} = -2\overline{w' q'_t}\frac{\partial \overline{q_t}}{\partial z}$$

> 0 throughout the cloud layer

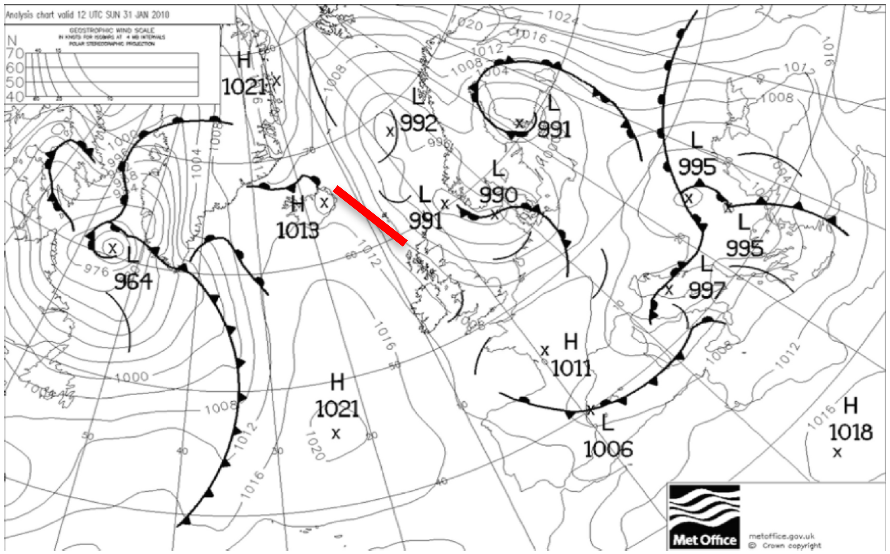
CONSTRAIN Cold Air Outbreak (Field et al. 2017)

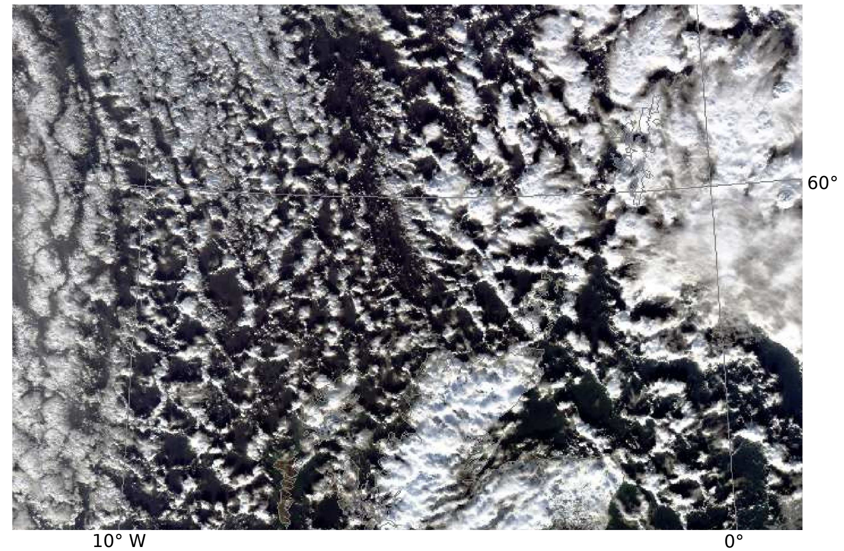




January 31, 2010 12:53 UTC

CONSTRAIN Cold Air Outbreak (Field et al. 2017)



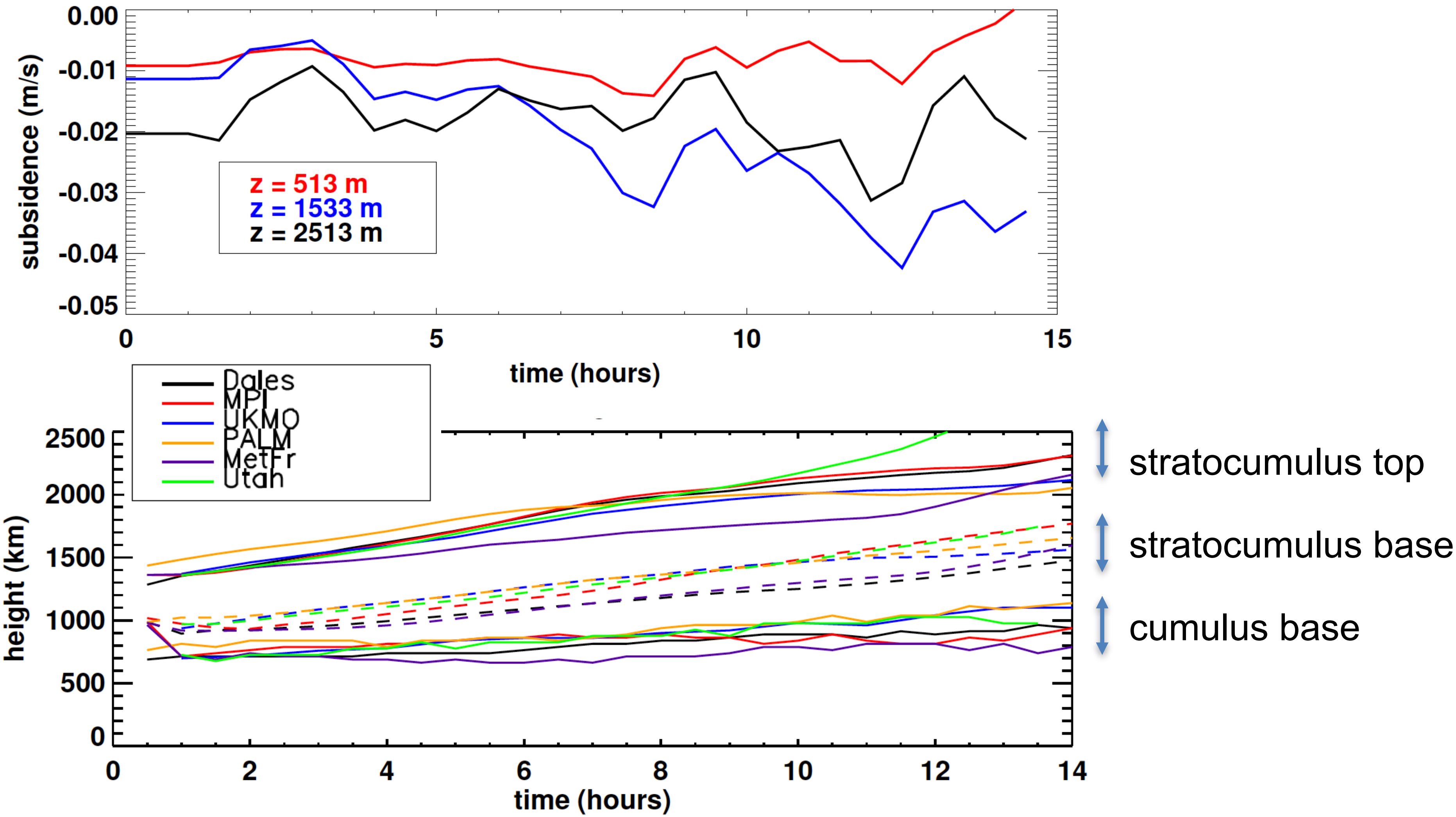


January 31, 2010 12:53 UTC

Lagrangian Large-Eddy Simulations (6 participating groups)
Horizontal domain 100x100 km^2
Horizontal grid size 200 m
Interactive radiation, SST increases with time, with and without ice microphysics
Δz=25 m up to 3 km, stretched grid above

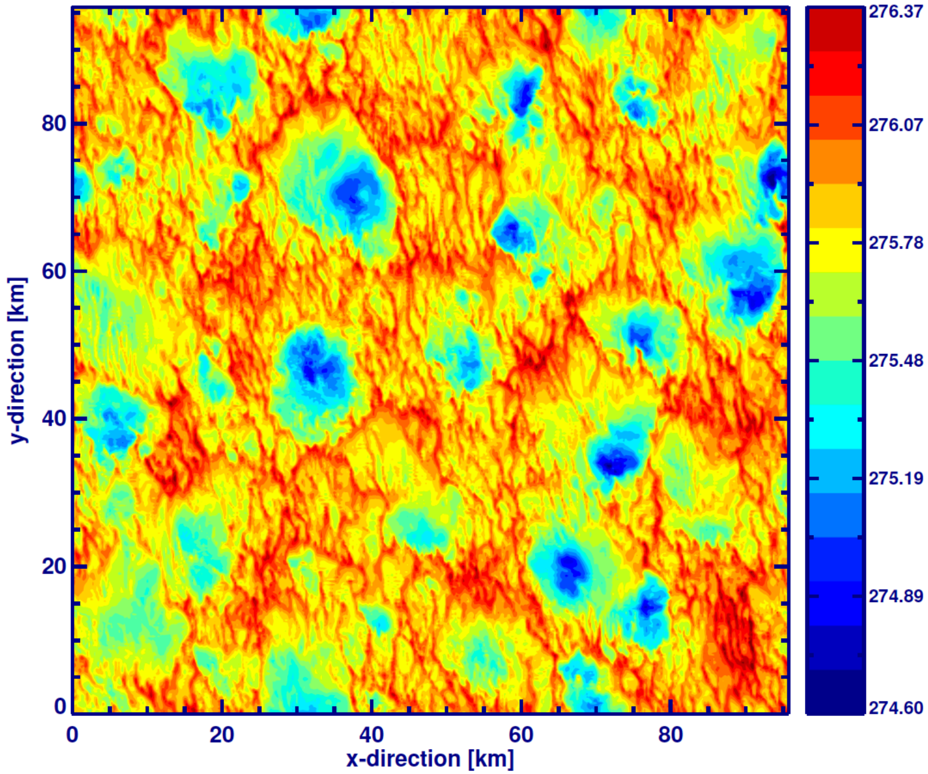
Requested additional LES runs:
Varying cloud droplet concentration number
Coarsening horizontal grid size "NWP mode" (0.2, 0.4, 0.8, 1.6, 3.2 km)

CONSTRAIN Cold Air Outbreak

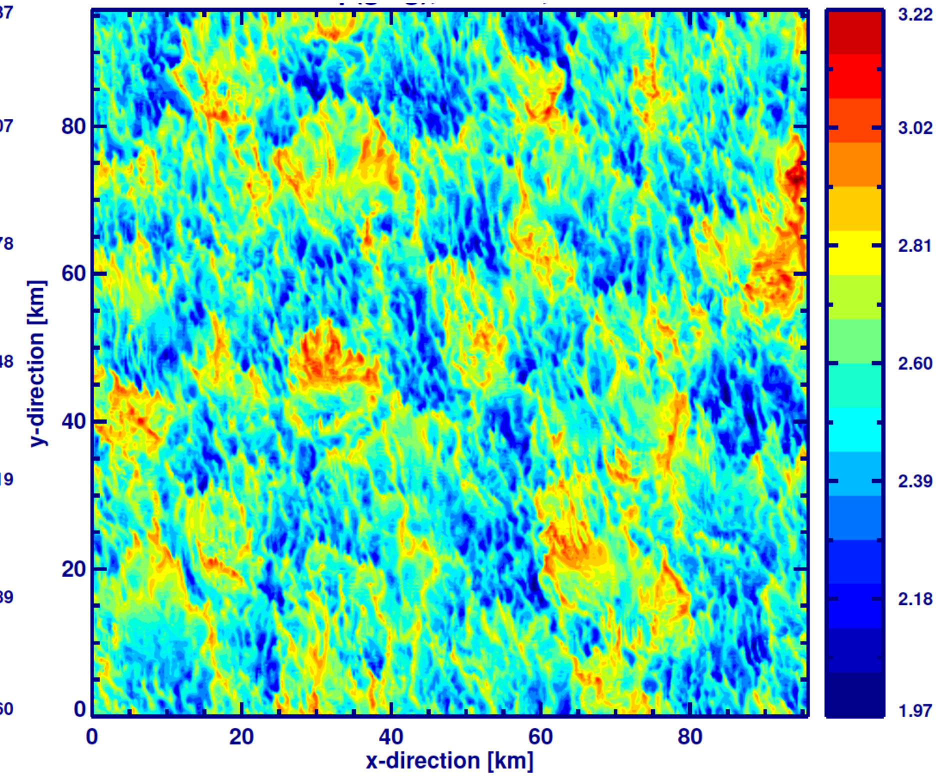


Cold pool formation (example from the UCLA-LES model)
t = 12 h, z = 100 m

potential temperature θ (K)



specific humidity q_v (g/kg)



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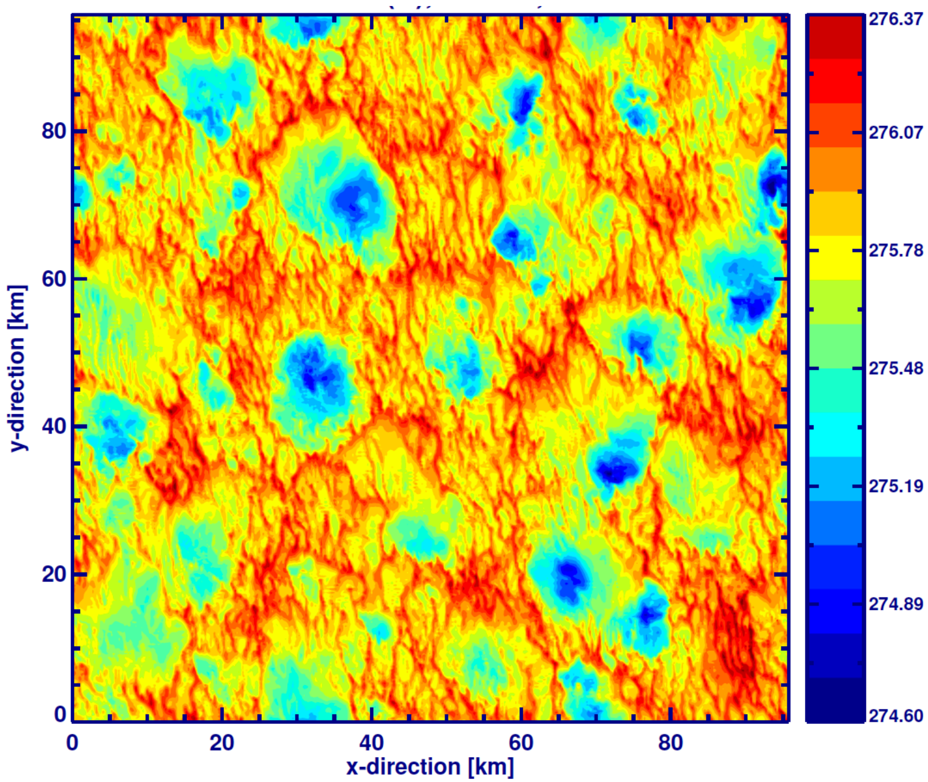
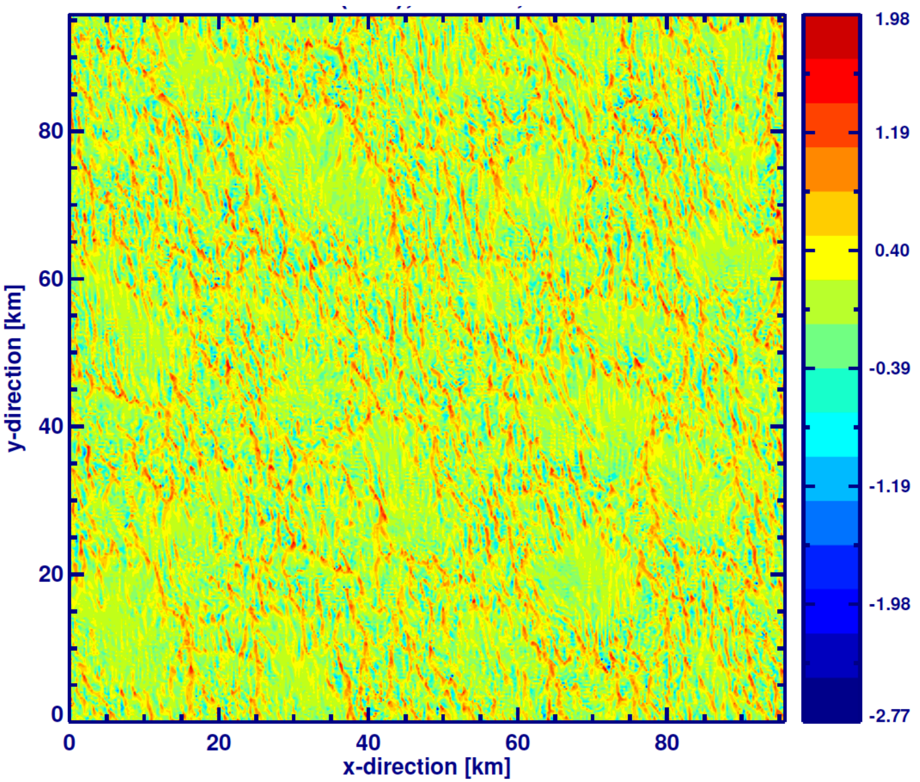
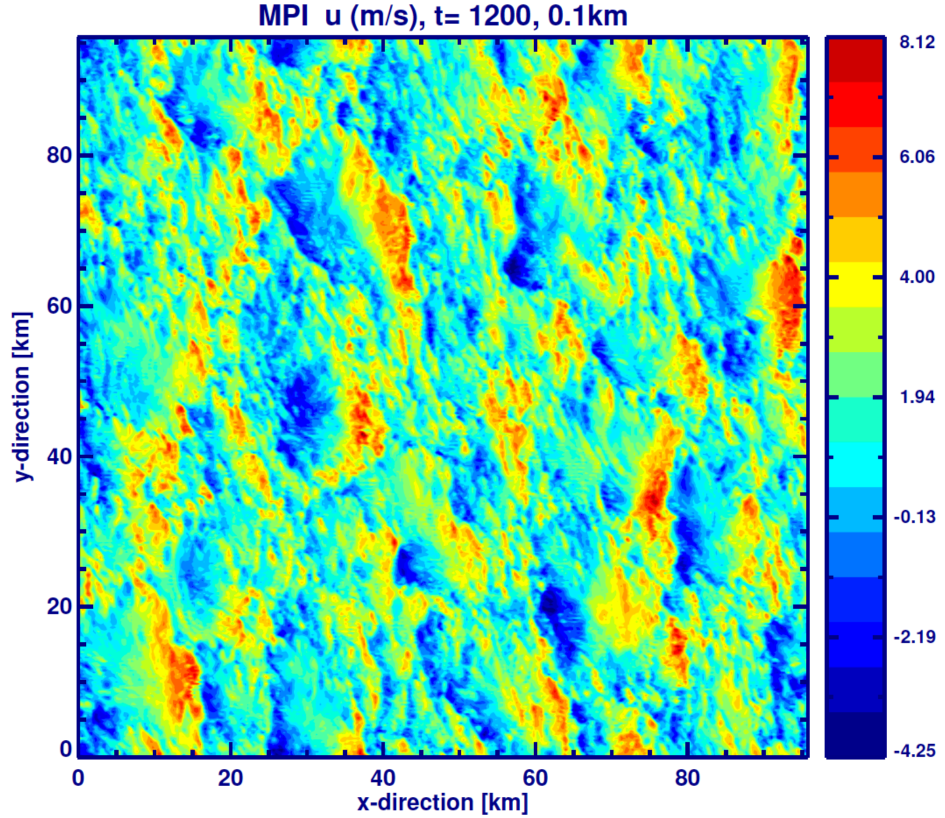


vertical velocity w (m/s)



Horizontal wind velocity (note u ranges between -4 and 8 m/s)



Equally large variations are found in the other LES model fields

Turbulent/convective flux in traditional NWP

$$\overline{w'\phi'}_{total} = \overline{w'\phi'}_{resolved} + \overline{w'\phi'}_{subgrid}$$

zero for sufficiently large Δx

Turbulent/convective flux in very high resolution NWP

$$\overline{w'\phi'}_{total} = \overline{w'\phi'}_{resolved} + \overline{w'\phi'}_{subgrid}$$

becomes non-zero for sufficiently fine Δx

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should reduce accordingly

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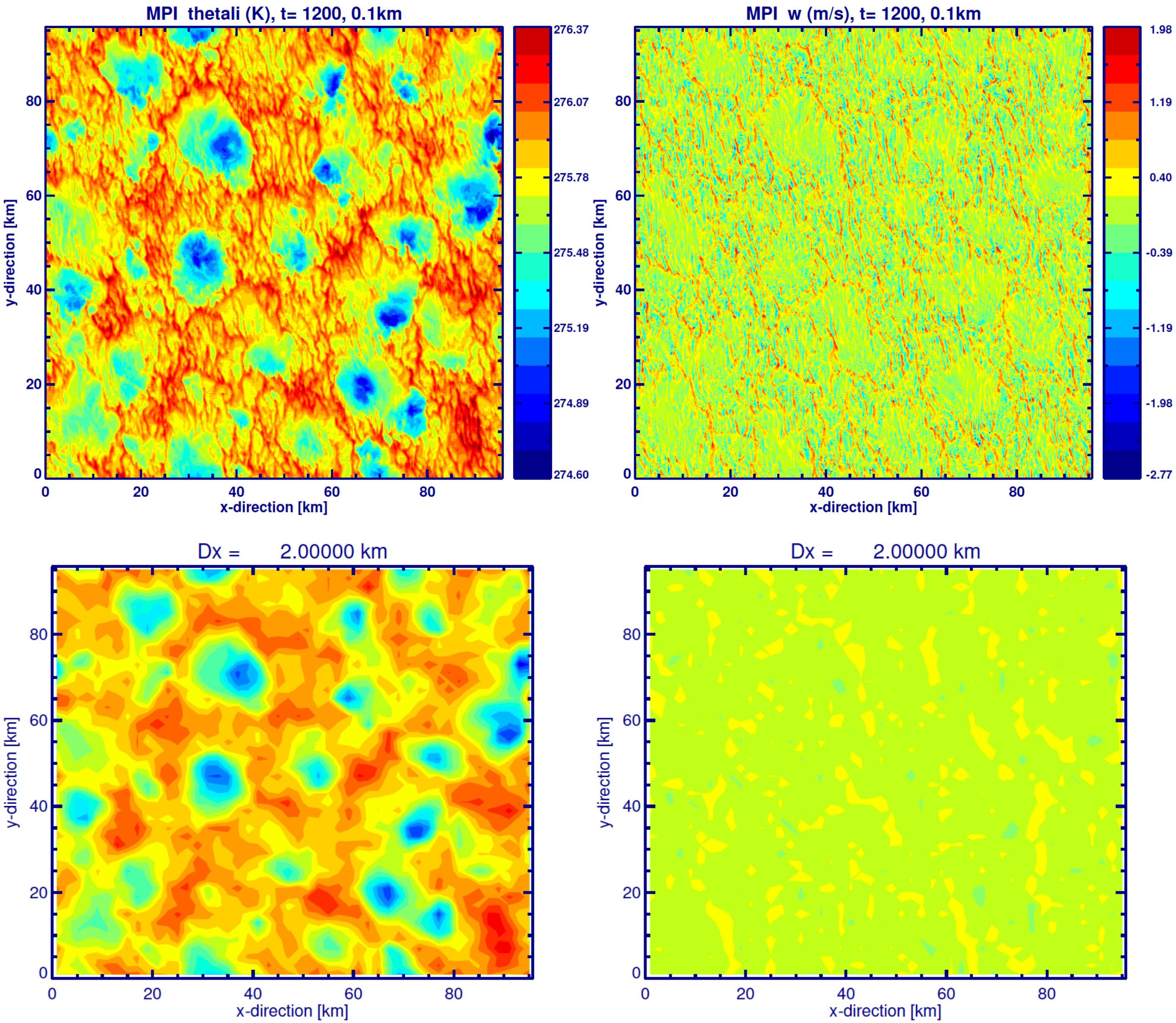
$$\overline{w'\phi'}_{total} = \overline{w'\phi'}_{resolved} + \overline{w'\phi'}_{subgrid}$$

becomes non-zero for sufficiently fine Δx

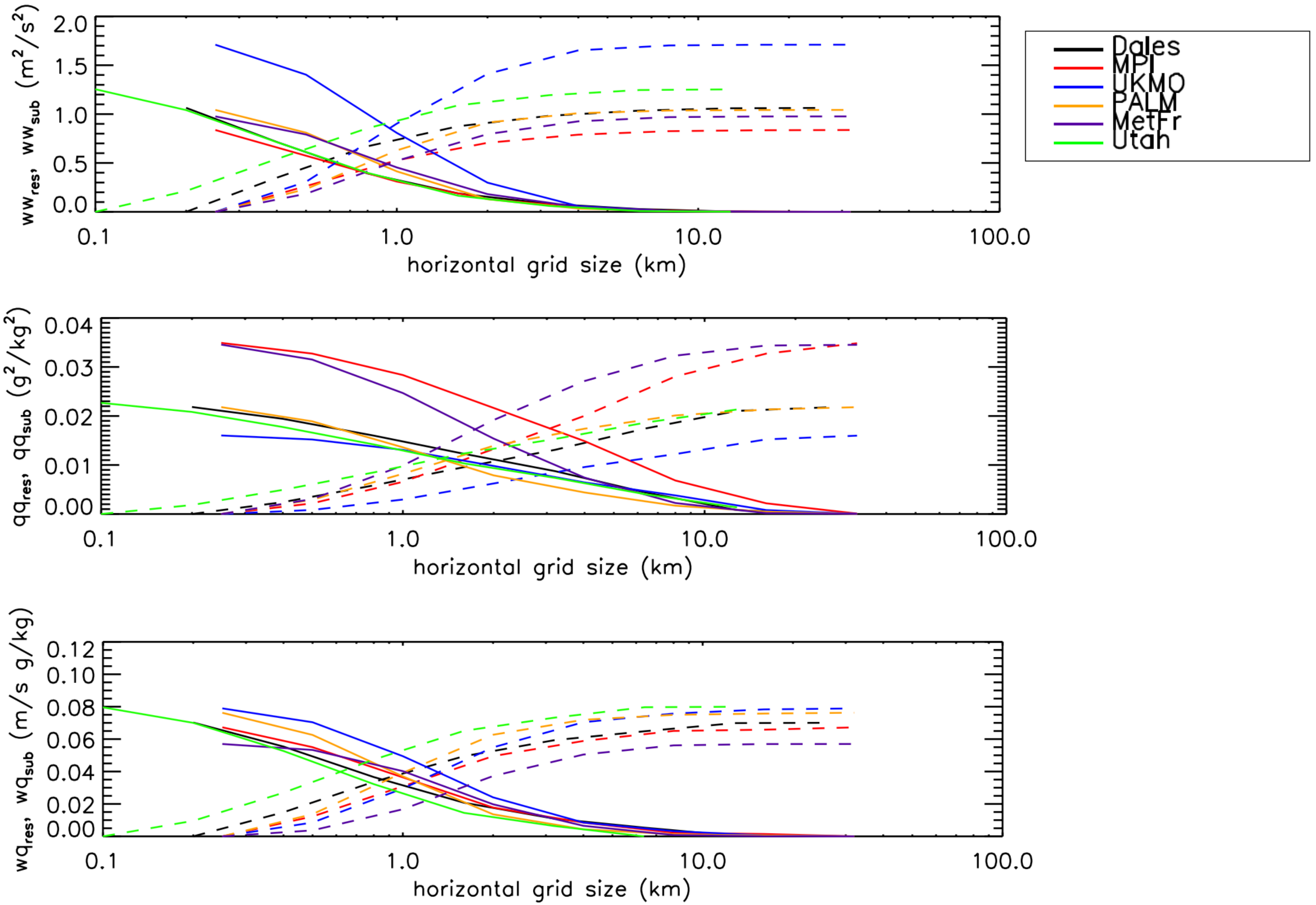
should reduce accordingly

Diagnose resolved and subgrid flux from LES fields as a function of the horizontal grid size Δx that the NWP would use

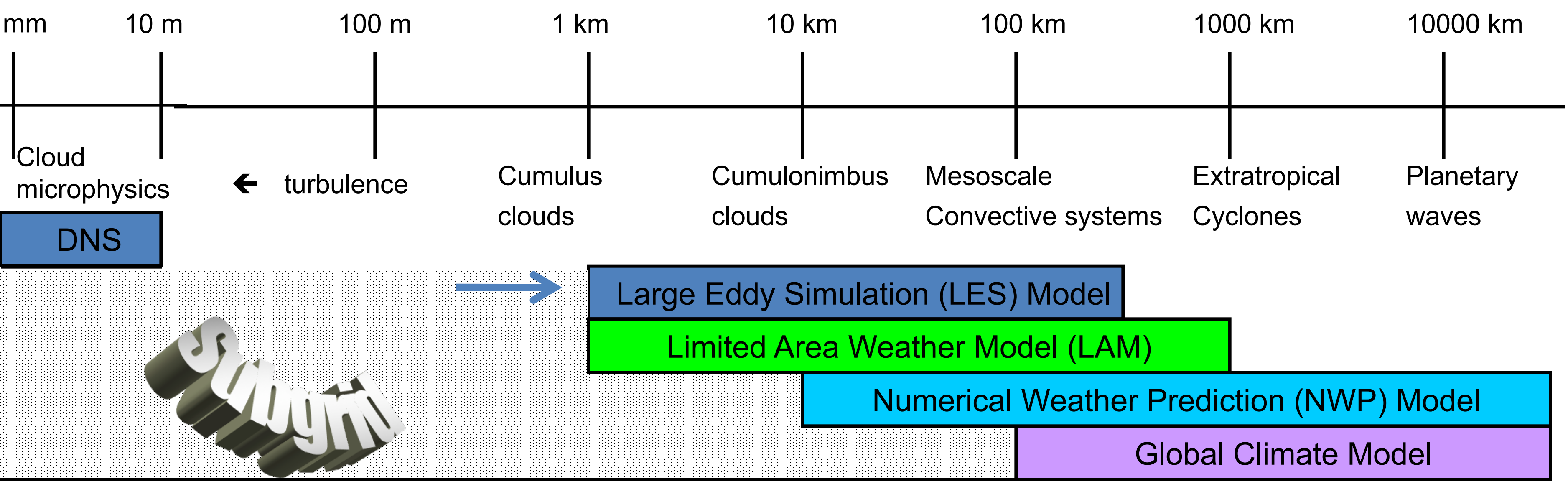
Coarse graining the fields: example



Coarse graining the fields
Resolved (res) and subgrid (sub) fluxes



Run LES in a "LAM" or "NWP' mode



NWP:
TKE all eddies

$$\frac{\partial E}{\partial t} = -\left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) + \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \frac{\partial}{\partial z}\left(\overline{w'E} + \overline{w'p'}/\overline{\rho}\right) - \varepsilon$$

LES:
TKE subgrid eddies

$$\frac{\partial e}{\partial t} + u_j\frac{\partial e}{\partial x_j} = \frac{g}{\theta_0}\widetilde{w''\theta_v''} - \widetilde{u_i''u_j''}\frac{\partial u_i}{\partial x_j} - \frac{\partial \widetilde{u_j''e}}{\partial x_j} - \frac{1}{\rho_0}\frac{\partial \widetilde{u_j''p''}}{\partial x_j} - \varepsilon$$

TKE closure for subgrid fluxes (example of HARMONIE)

$$\frac{\partial E}{\partial t} = -\left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) + \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \frac{\partial}{\partial z}\left(\overline{w'E} + \overline{w'p'}/\overline{\rho}\right) - \varepsilon$$

$$\overline{w'\psi'} = -K_\psi \frac{\partial \overline{\psi}}{\partial z}$$

downgradient flux

$$K_\psi = l_\psi \sqrt{E}$$

$$\frac{1}{l_{m,h}} = \frac{1}{c_n \kappa z} + \frac{1}{l_s}$$

length scale depends on **size of the eddies**

Baas et al., BLM, 2007

TKE (e) closure for subgrid fluxes (~) in an LES model

$$\frac{\partial e}{\partial t} + u_j \frac{\partial e}{\partial x_j} = \frac{g}{\theta_0}\widetilde{w''\theta_v''} - \widetilde{u_i''u_j''}\frac{\partial u_i}{\partial x_j} - \frac{\partial \widetilde{u_j''e}}{\partial x_j} - \frac{1}{\rho_0}\frac{\partial \widetilde{u_j''p''}}{\partial x_j} - \varepsilon$$

$$\widetilde{u_j''\varphi''} = -K_{\mathrm{h}}\frac{\partial \varphi}{\partial x_j}.$$

downgradient flux

$$K_{\mathrm{m,h}} = c_{\mathrm{m,h}}\lambda e^{1/2}$$

$$\lambda = l_\Delta \equiv (\Delta x \Delta y \Delta z)^{1/3}$$

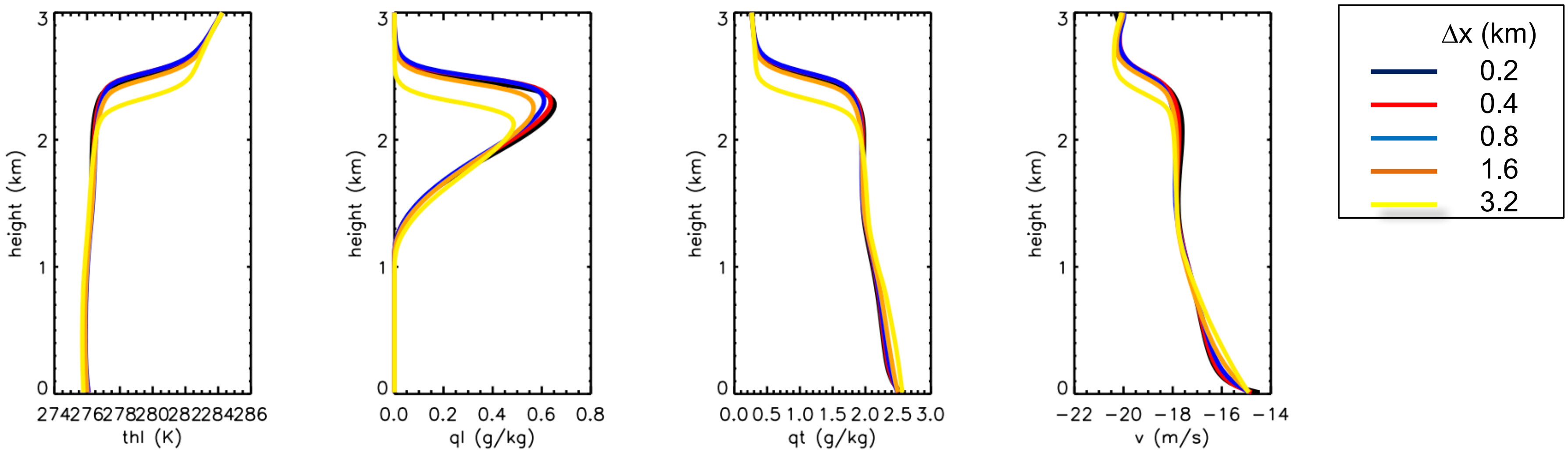
length scale depends on **grid size**

Analytical solution for LES subgrid TKE (steady-state, zero turbulent transport)

$$K_{\mathrm{m},\Delta} = c_s^2 \left[1 - \frac{Ri_{\mathrm{g}}}{Ri_{\mathrm{C},\Delta}}\right]^{1/2} l_\Delta^2 S,$$

Eddy mixing depends on grid size $l_\Delta \equiv (\Delta x \Delta y \Delta z)^{1/3}$

DALES results for Δx = 0.2, 0.4, 0.8, 1.6 and 3.2 km
Note: Stratocumulus clouds are dominating



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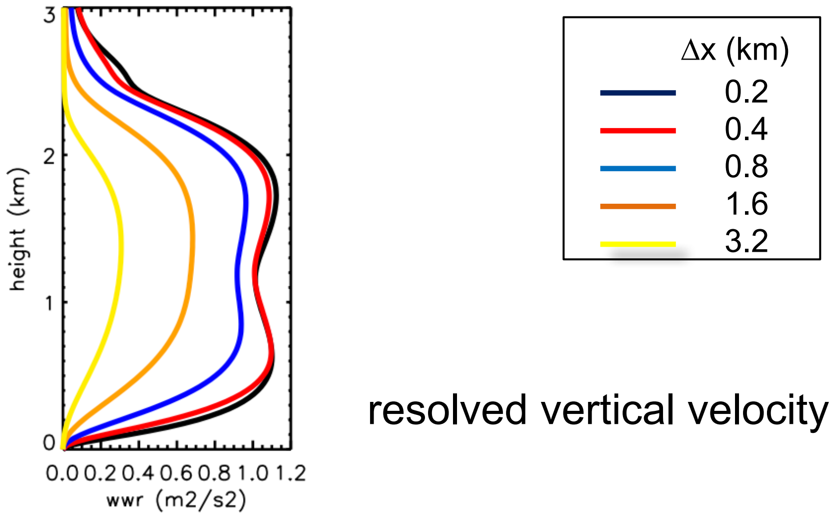

resolved vertical velocity variance

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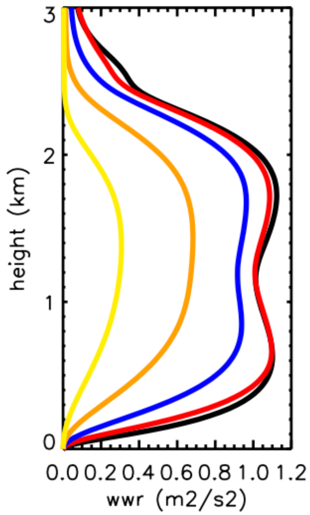

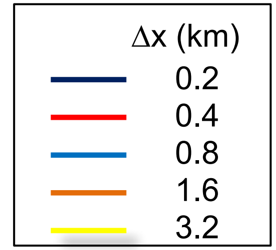

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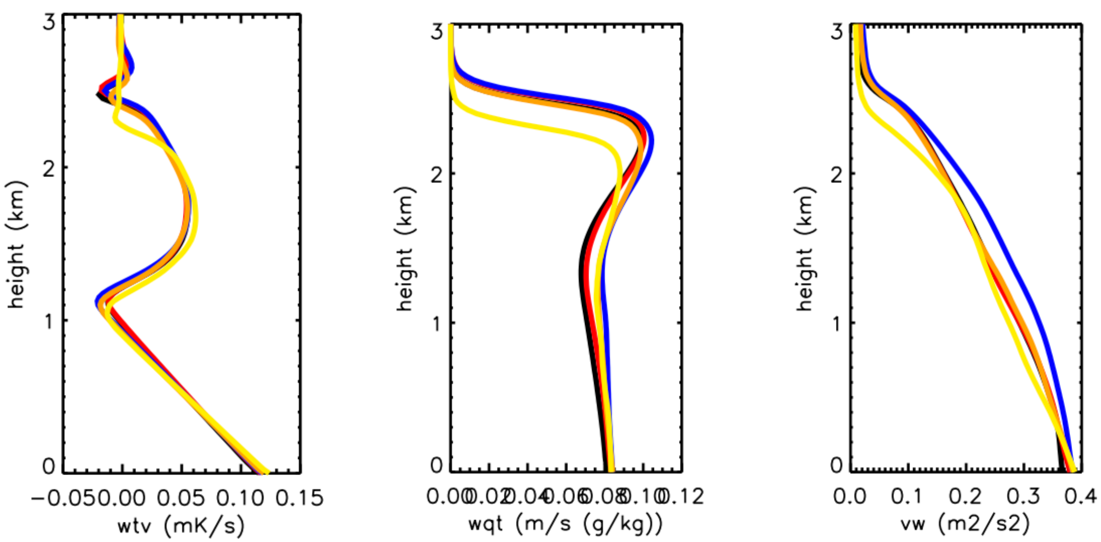
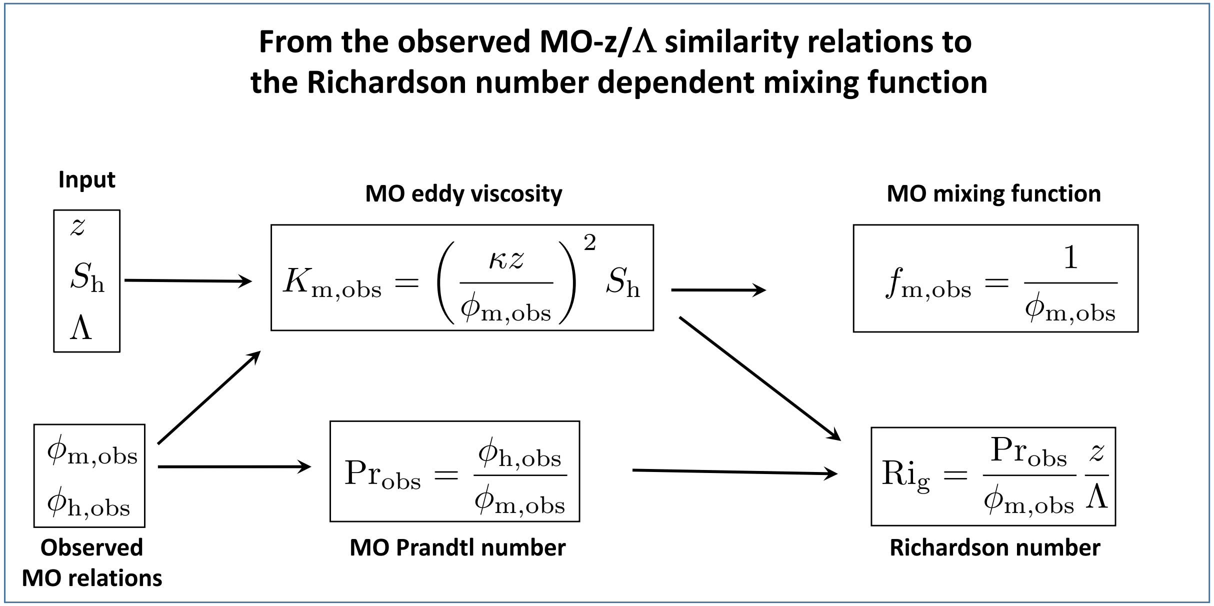


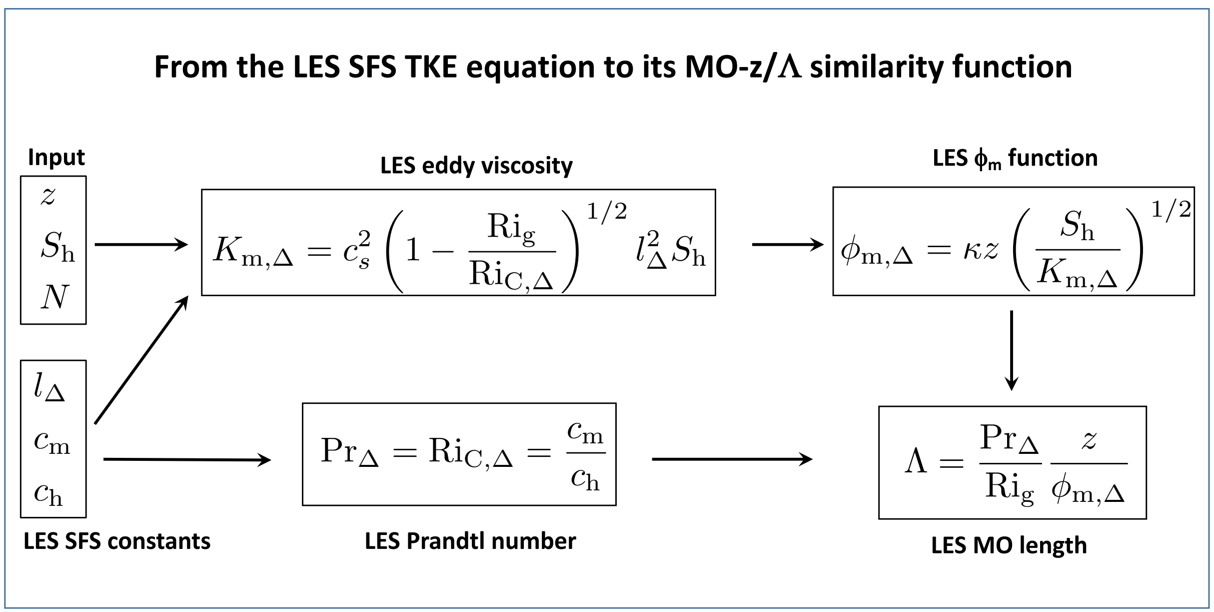
total fluxes (resolved + subgrid)

Analytical solution LES subgrid TKE model in terms of the mixing function f_m for a stable stratification

$$K_m = f_m^2 (\kappa z)^2 \left| \frac{\partial U}{\partial z} \right|$$

$$f_{\mathrm{m},\Delta} = c_{\mathrm{s}} \left(1 - \frac{Ri_{\mathrm{g}}}{Ri_{\mathrm{C},\Delta}} \right)^{1/4} \frac{l_\Delta}{\kappa z}.$$



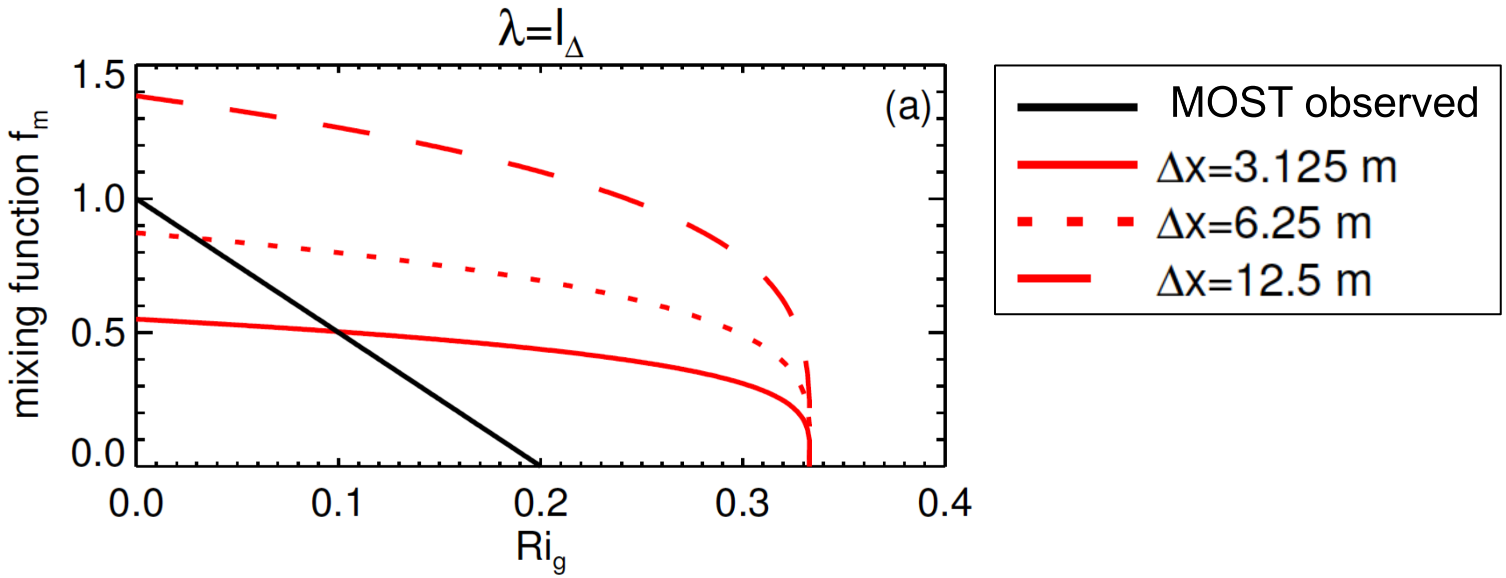


De Roode et al., JAS, 2017

Analytical solution LES subgrid TKE model in terms of the mixing function f_m for a stable stratification

$$K_m = f_m^2 (\kappa z)^2 \left| \frac{\partial U}{\partial z} \right|$$

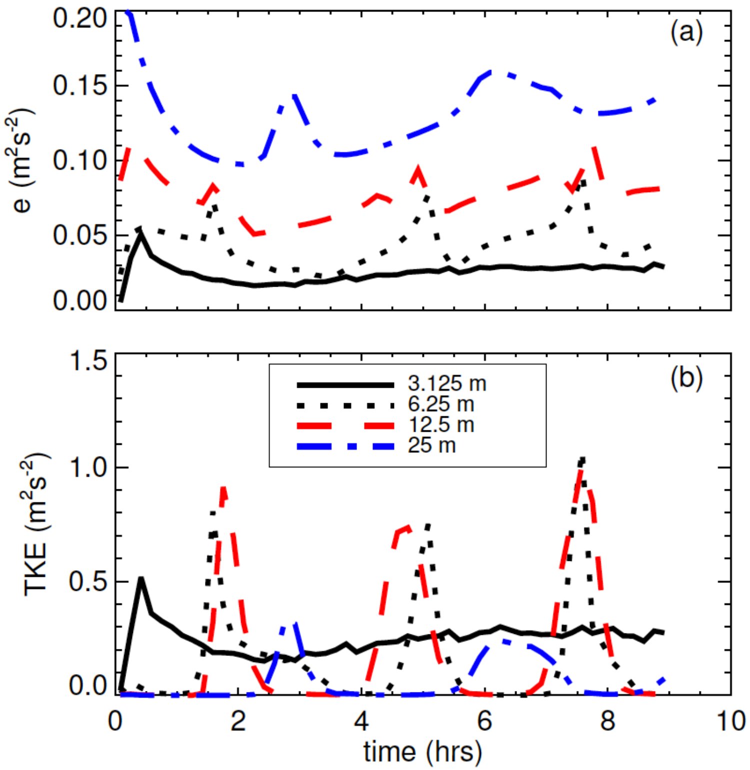
$$f_{m,\Delta} = c_s \left(1 - \frac{Ri_g}{Ri_{C,\Delta}}\right)^{1/4} \frac{l_\Delta}{\kappa z}.$$

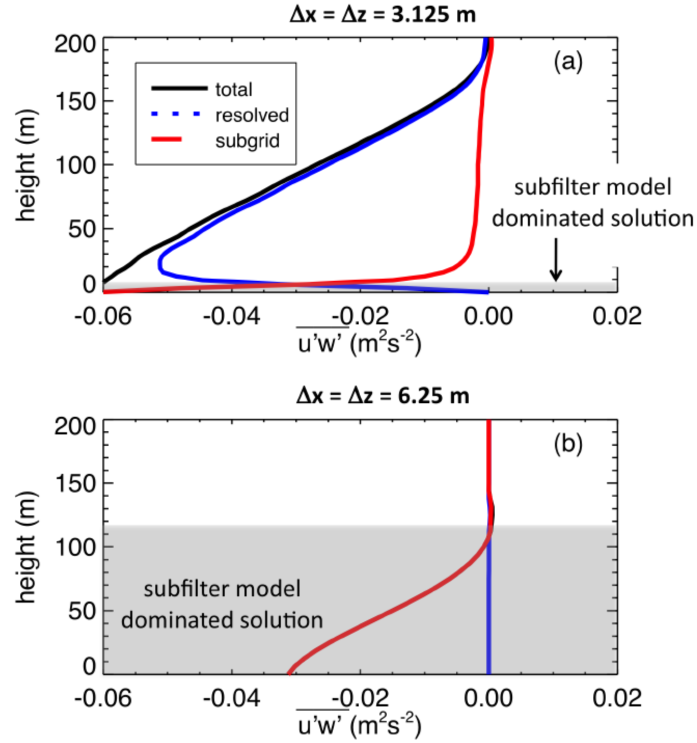


Larger $\Delta x/\Delta z$ leads to excessive mixing

Consequences of excessive mixing: resolved motions disappear and solution is controlled by subgrid TKE model

effect of changing Δx





Conclusions

CBL

* Mesoscale fluctuations in buoyancy very small ("countergradient regime")
* Mesoscale growth if scalar flux is down its mean gradient

Stratocumulus

* Positive feedback $q_t \rightarrow \theta_v \rightarrow w$

Performance subgrid TKE equation for large Δx

* Good for stratocumulus (because large eddies)
* Danger of excessive mixing, e.g. in the stable boundary layer (small eddies)

Outlook

* The dependency of horizontal turbulent fluxes on Δx

$$\frac{\partial \overline{\chi}}{\partial t} = -\frac{\partial \overline{u'\chi'}}{\partial x} - \frac{\partial \overline{w'\chi'}}{\partial z} + \ldots$$