Towards a better simulation of the stably stratified boundary layer

Matthias Raschendorfer, DWD, Offenbach

The problem with the stable boundary layer (SBL):

- **Almost no production term in a classical TKE equation**

$$D_t\left(\bar{\rho}\,TKE\right) \approx -\overline{\rho u'' w''} \cdot \partial_z \hat{u} + \frac{g}{\bar{\theta}_v}\overline{\rho \theta_v'' w''} - \varepsilon$$

vertical shear by the mean flow	buoyancy	dissipation
almost zero for low wind conditions	negative for downward heat flux	always a sink

→ almost no vertical mixing even though it isusually present in nature

→ complete decoupling of the surface

→ almost no dissolution of fog and inversion layer clouds

→ singularities in turbulence model

→ model solution is strongly dependent on numerical details

→ considerable problems with numerical stability

The classical solution:

- **Introduction of artificial background mixing**
  - minimal value of TKE
  - restriction of thermal stability
  - **minimal value for turbulent diffusion coefficients (tkm[m,h]min)**

    (m → momentum; h → scalars (heat))

- **Problems with these measures**
  - not physically based (except some additional **laminar** diffusion)
  - often too much mixing in the lower nocturnal BL
  - either too fast or too slowly dissolution of inversion layer clouds
  - either too strong or too weak nocturnal temperature decrease at the surface
  - danger of smoothing out vertical jet structure (e.g. of the low level jet)

- **Alternatives**
  - Adopted numerical schemes
    - inherent **vertical smoothing** without explicit minimal diffusion coefficients
    - prognostic variance equations guaranteeing **positive definiteness** without explicit limits

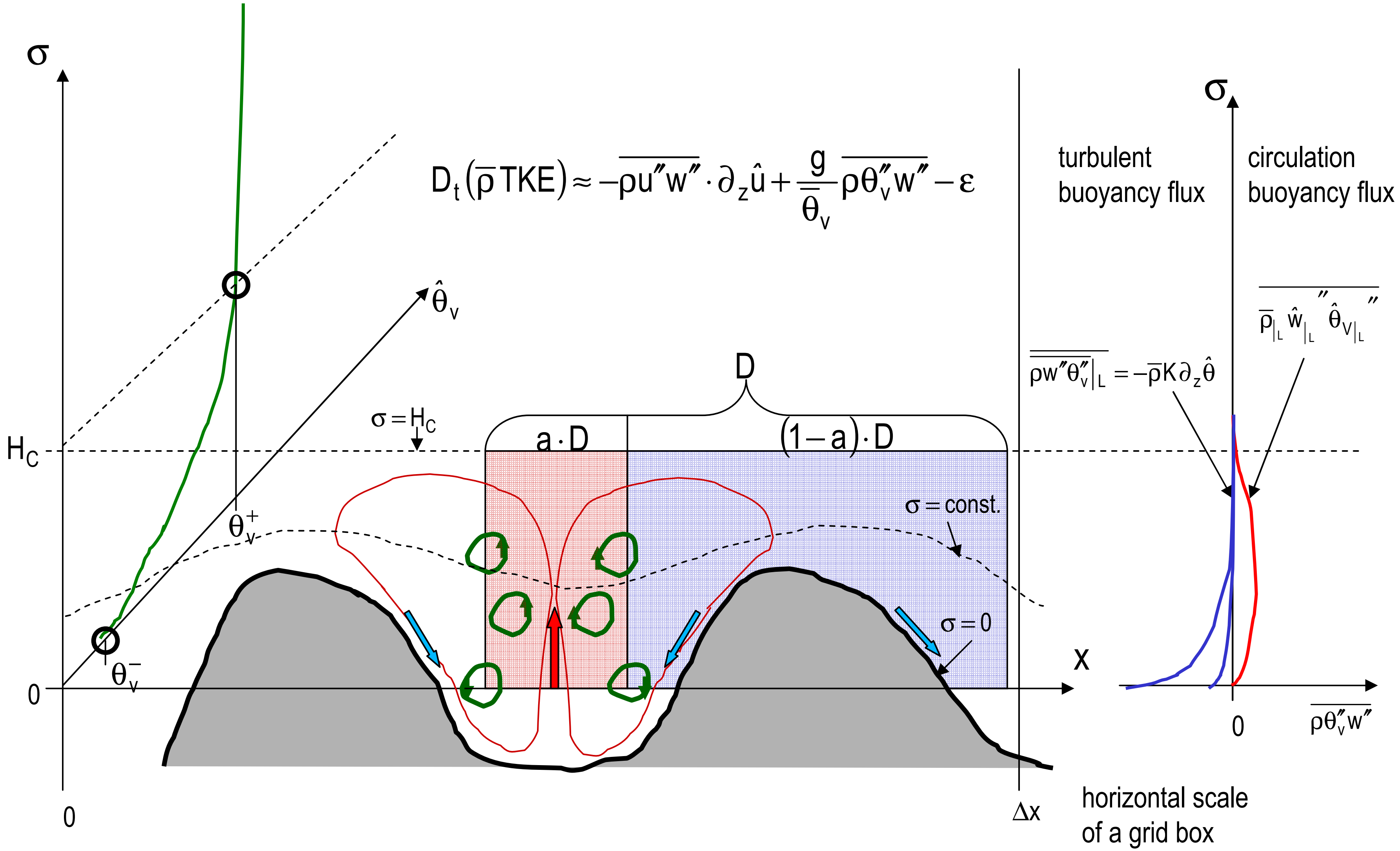
The new physical solution:

- **Physical reason for the problems with a classical scheme**
  - Classical turbulence closure will only be valid, if all sub-grid structures are in accordance with turbulence closure assumptions
  - Usually other sub-grid processes are present and in the near surface SBL they are even dominant
  - ➢ **The presence of non-turbulent sub-grid scale structures needs to be considered**

- **Generalization of the closure scheme by scale separation**
  - Separation of turbulence by a sub-filter only smoothing “turbulence” provides variance equations for turbulence automatically containing **shear production terms by non-turbulent sub-gird processes** (**scale transfer terms**)
  - ➢ The non-turbulent structures **can’t** be described by turbulence closure, rather we necessarily need **separate schemes** for them with **specific closure assumptions**, in particular **specific length scales**.
  - ➢ The additional production terms **can’t** be introduced **only** by treating all scalar variances by **prognostic** equations that simply introduce **additional transport** of them (UTCS-extension) but no additional sources for TKE.
  - ➢ **Turbulent fluxes** remain in **flux gradient form**, those by **non-turbulent flow structures do not**.

- **Already (partly) implemented TKE-production by scale transfer from kinetic energy of …**
  - **wakes generated** by surface inhomogeneity (from SSO-blocking scheme) — **still operational**
  - **thermal circulation** by surface inhomogeneity (due to differential heating/cooling) — only crude approximation
  - **horizontal eddies** generated by horizontal shear (e.g. at frontal zones) — not yet verified
  - **Convection circulation** (buoyant production from convection scheme) — not yet verified

Effect of the density flow driven circulation term for stabile stratification:



$$D_t(\bar{\rho}\,TKE) \approx -\overline{\rho u''w''}\cdot\partial_z\hat{u} + \frac{g}{\bar{\theta}_v}\overline{\rho\theta_v''w''} - \varepsilon$$

$$\overline{\rho w''\theta_v''|_L} = -\bar{\rho}K\partial_z\hat{\theta}$$

$$\overline{\bar{\rho}|_L\,\hat{w}|_L''\,\hat{\theta}_V|_L''}$$

$$\overline{\rho\theta_v''w''}$$

- Even for **vanishing mean wind** and **negative turbulent buoyancy** there remains a **positive definite source term**

→ TKE will **not** vanish → Solution even for **strong stability**

Separated semi parameterized TKE equation (neglecting molecular transport):

$|_L$: with respect to a **separation scale** L

buoyant part of $-\overline{\mathbf{v}''\cdot\nabla p|_L}$

expressed by **turbulent flux gradient** solution

mean (horizontal) **shear** production of circulations,

buoyant and **wake** part of $-\hat{\mathbf{v}}|_L''\cdot\overline{(\bar\nabla\,\bar p)}|_L$

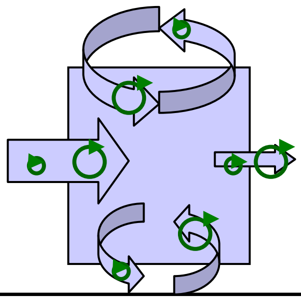
to be parameterized by a **non turbulent** approach

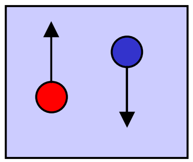
$-\mu\sum_{i=1}^{3}\overline{|\nabla v_i|^2}$

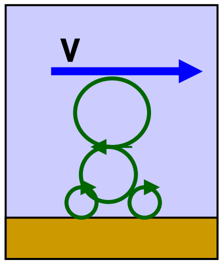
according Kolmogorov

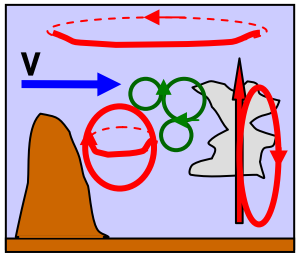
$$\partial_t\left(\frac{1}{2}\bar\rho\cdot\overline{q|_L{}^2}\right)=\frac{1}{2}\hat\nabla\cdot\left(\bar\rho\,\overline{q^2|_L}\,\hat{\tilde{\mathbf{v}}}+\sum_{i=1}^{3}\overline{\left(\rho v_i''^2\tilde{\mathbf{v}}''\right)|_L}\right)+\frac{g}{\hat\theta_v}\overline{\rho\theta_v''w''}|_L+\left[-\sum_{i=1}^{3}\overline{\overline{\rho v_i''\tilde{\mathbf{v}}''}|_L}\cdot\hat\nabla\hat v_i\right]+\left[-\sum_{i=1}^{3}\overline{\overline{\rho v_i''\tilde{\mathbf{v}}''}|_L{}'\cdot\left(\hat\nabla\hat v_i\right)|_L{}'}\right]+\left[-\bar\rho\,\frac{\overline{q|_L}^{3}}{\alpha^{MM}\ell}\right]$$

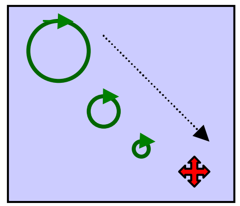
time tendency	transport (advection + diffusion)	buoyancy production	shear production by the mean flow	shear production by sub grid scale circulations	eddy-dissipation rate (**EDR**)
		labil: >0 neutral: $=0$ stabil: <0	≥ 0	≥ 0	<0







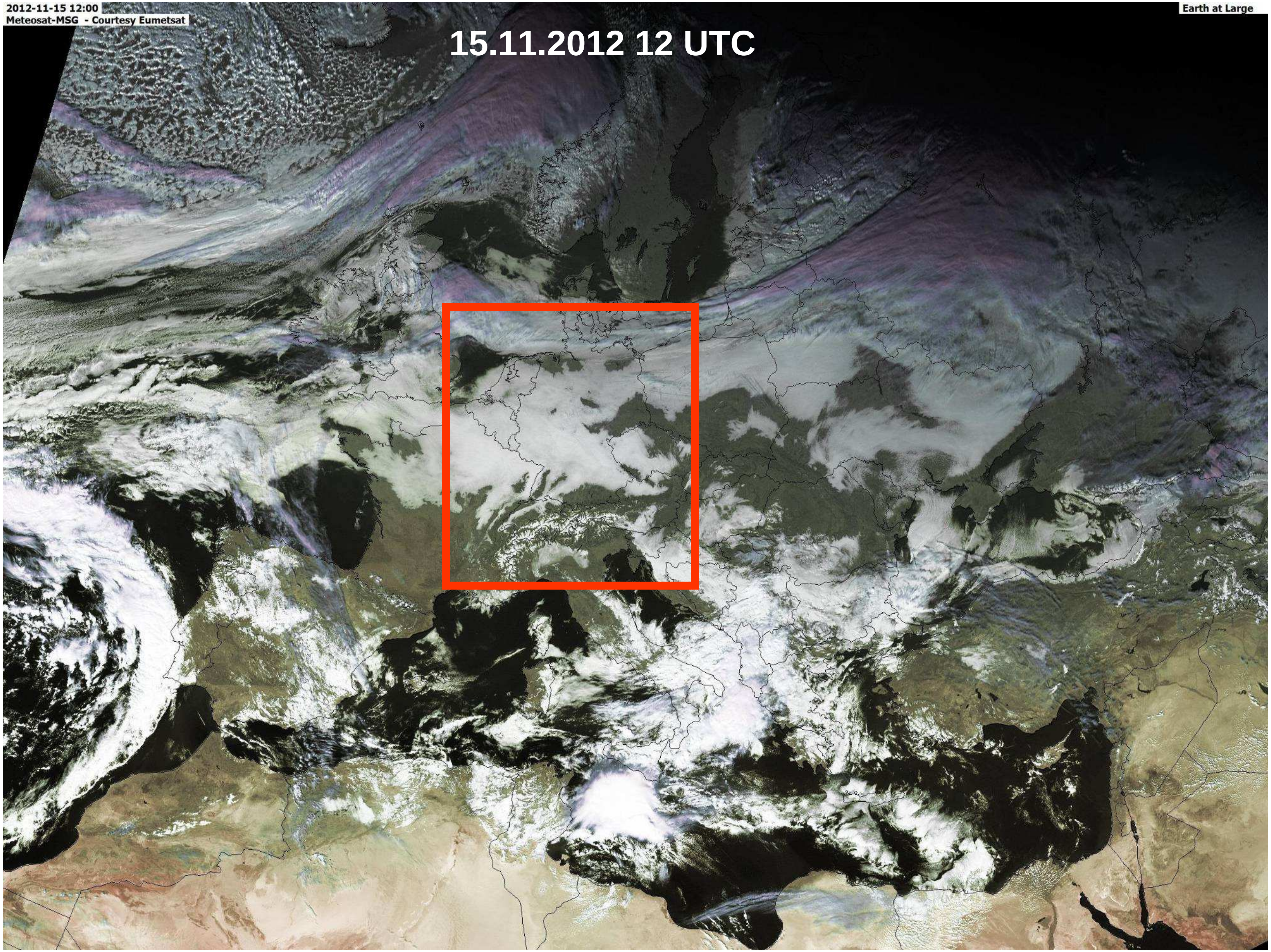




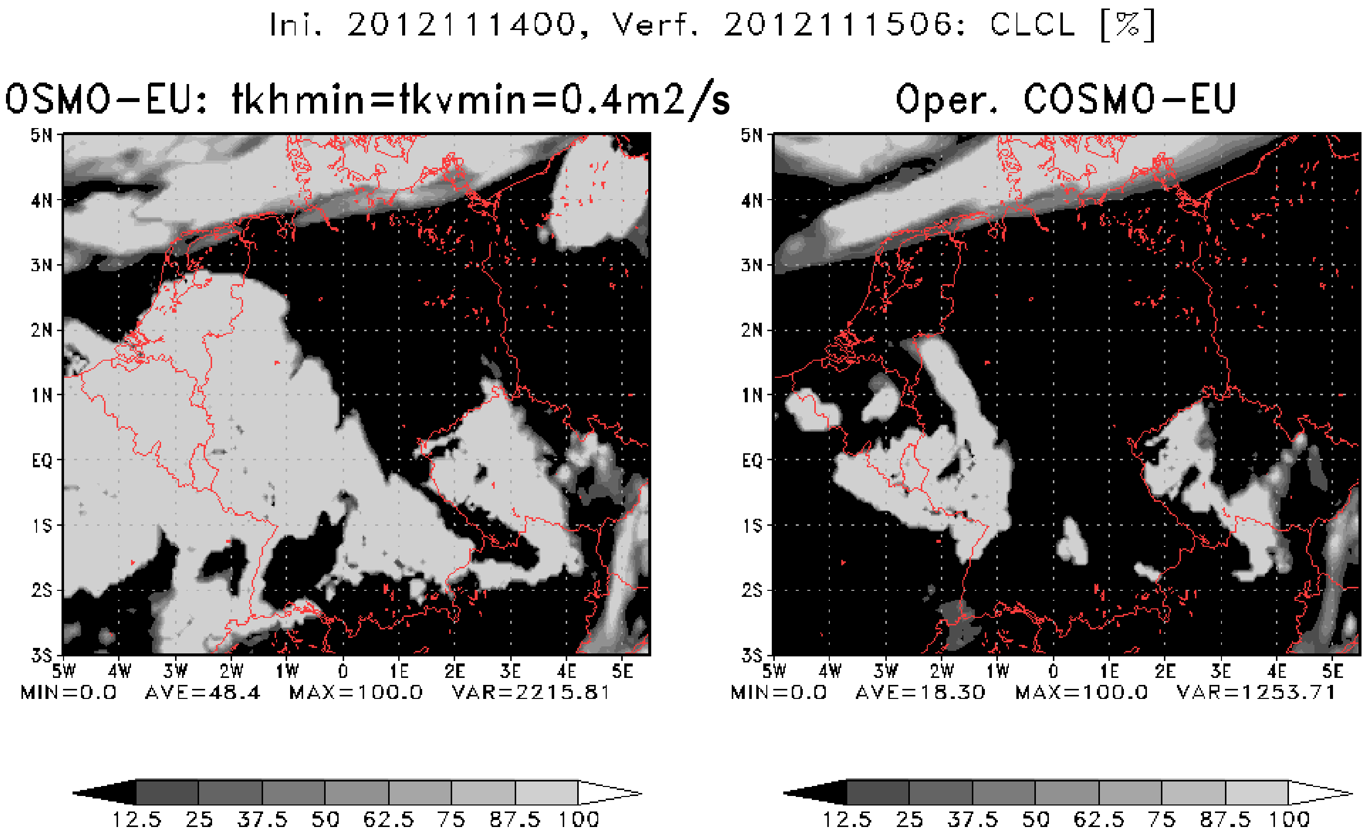
Consequences of the new solution:

- **More physical based TKE and mixing in the stable BL**
  - Is already beneficial for **CAT-forecast** needed for **aviation** (s. previous reports)
  - Should be beneficial also for near surface **SBL** as well.
  - **Previous artificial security measures needs to be adopted!**

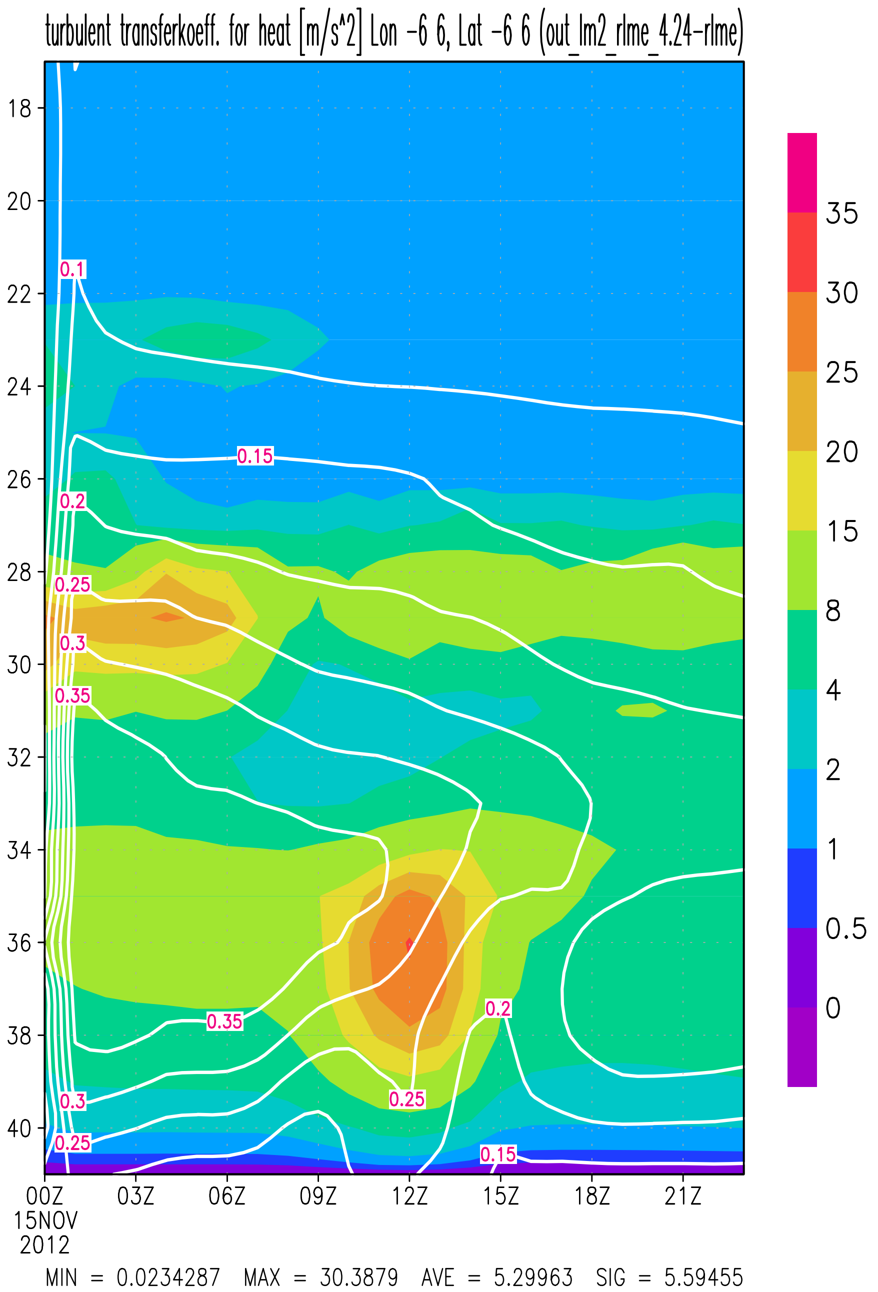
- **First candidate: the minimal diffusion coefficient**
  - Previous value: **tkv[h,m]min = 1.0 m^2/s** (same for scalars and momentum)
  - Seems to **dissolve BL clouds much to early** now (and was presumably always a bit too large)
  - Previous attempts to decrease it has **not** been successful
  - After lots of **general numerical improvement** of the model and the introduction of at least the **SSO-source term** a further attempt has now been tried
  - New value: **tkv[h,m]min = 0.4 m^2/s**


2012-11-15 12:00
Meteosat-MSG - Courtesy Eumetsat
Earth at Large
15.11.2012 12 UTC

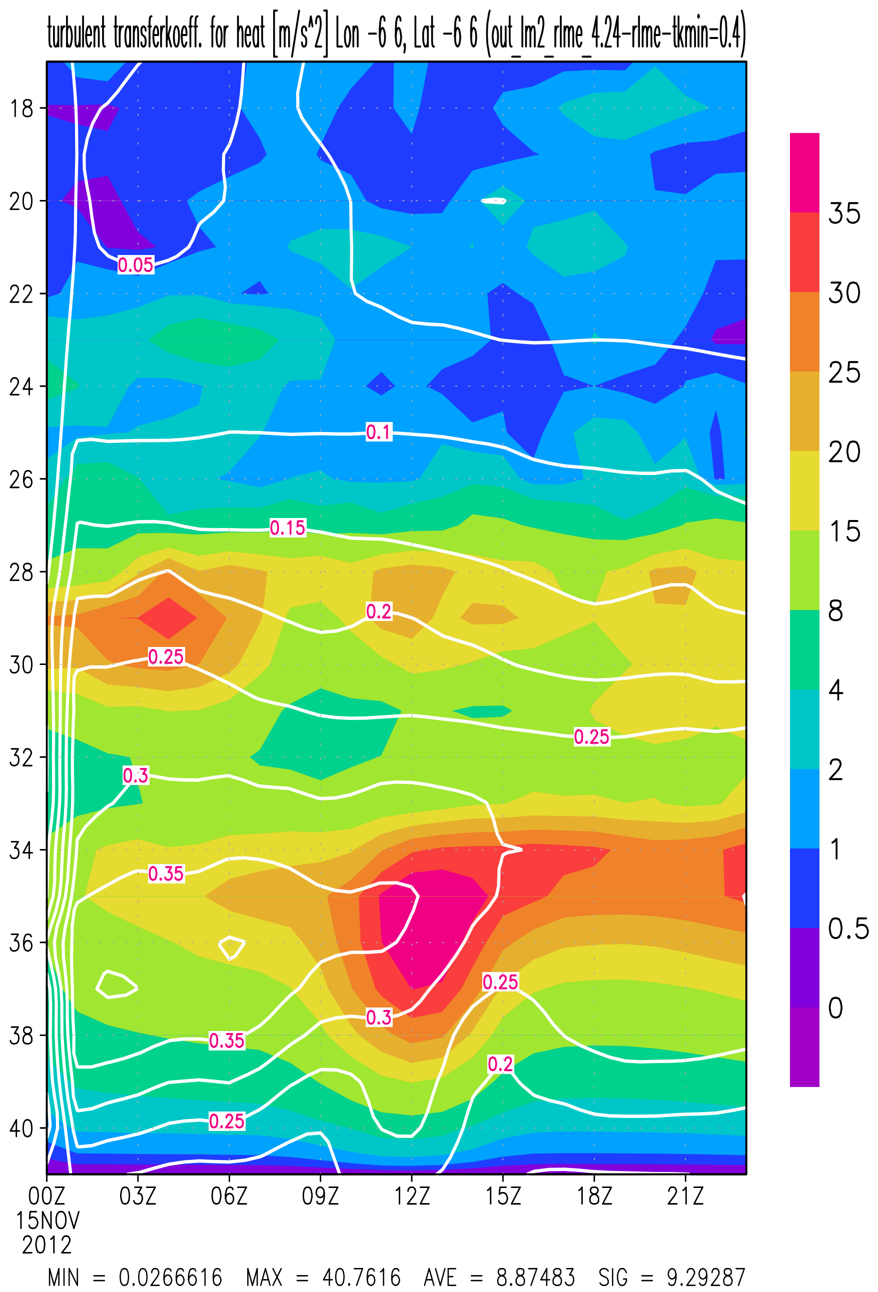
Low level cloud cover CLCL



Experiment **Routine**



turbulent transferkoeff. for heat [m/s^2] Lon -6 6, Lat -6 6 (out_lm2_rlme_4.24-rlme)
00Z 15NOV 2012
03Z
06Z
09Z
12Z
15Z
18Z
21Z
MIN = 0.0234287 MAX = 30.3879 AVE = 5.29963 SIG = 5.59455



turbulent transferkoeff. for heat [m/s^2] Lon -6 6, Lat -6 6 (out_lm2_rlme_4.24-rlme-tkmin=0.4)
00Z 15NOV 2012
03Z
06Z
09Z
12Z
15Z
18Z
21Z
MIN = 0.0266616 MAX = 40.7616 AVE = 8.87483 SIG = 9.29287

```
ERROR: typecheck
OFFENDING COMMAND: setmatrix

STACK:

1
[0.0 1.0 1.0 0.0 0.0 0.92125 ]
```