Towards a better simulation of the stably stratified boundary layer

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The problem with the stable boundary layer (SBL):

- Almost no production term in a classical TKE equation

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

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 is usually 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) — already 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

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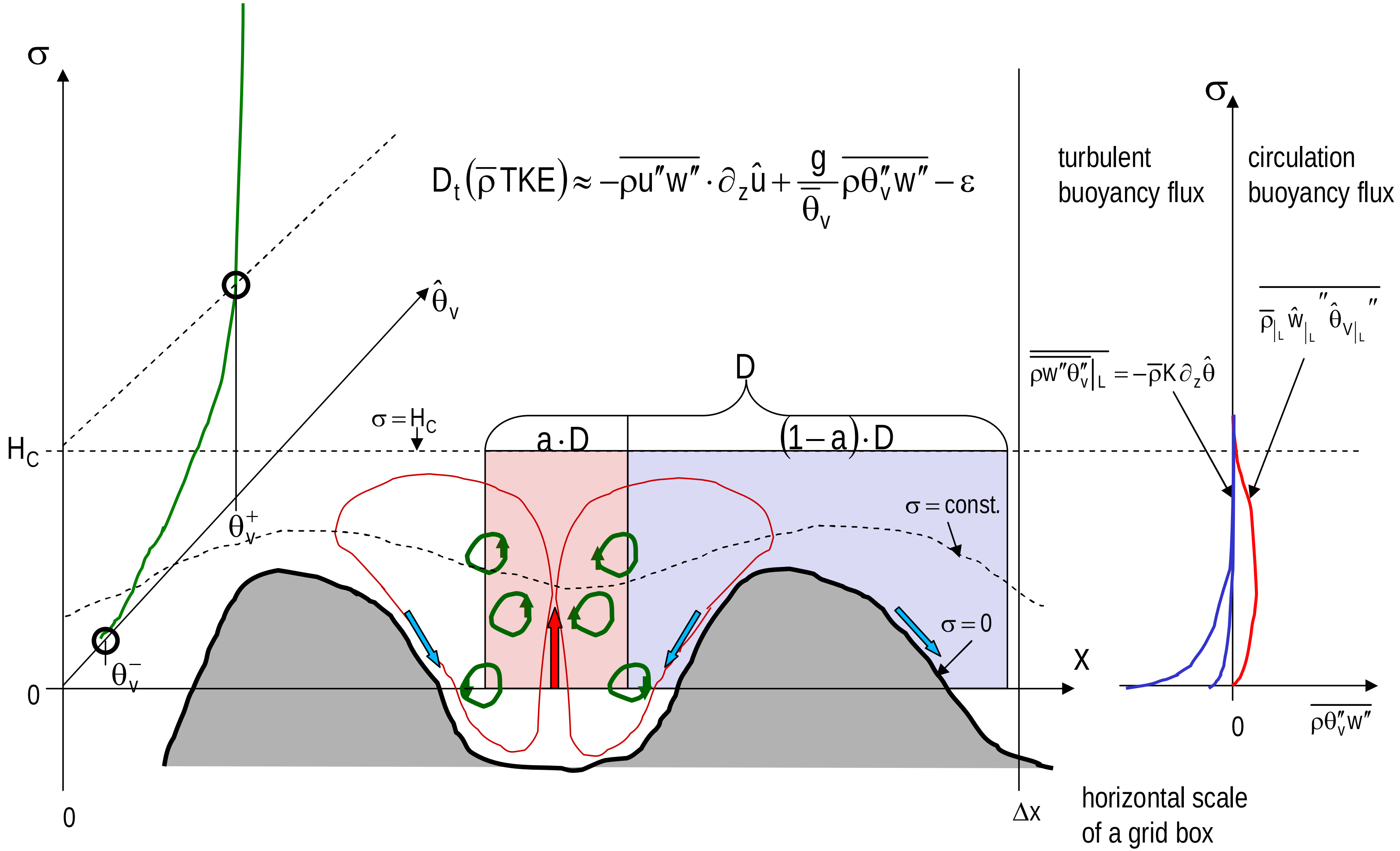
Effect of the density flow driven circulation term for stabile stratification:



- 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 $-\overline{v''\cdot\nabla p|_L}$

expressed by turbulent flux gradient solution

mean (horizontal) shear production of circulations,

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

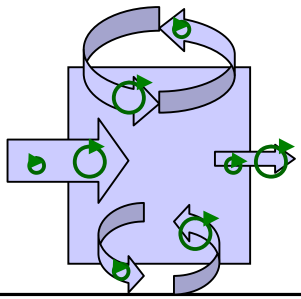
to be parameterized by a non turbulent approach

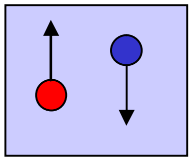
$-\mu\sum_{i=1}^{3}\overline{|\nabla v_i|^2}$

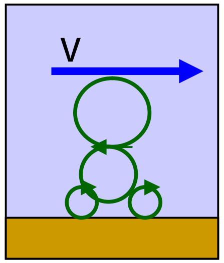
according Kolmogorov

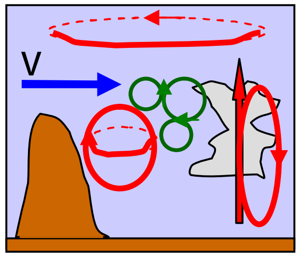
$$\partial_t\left(\frac{1}{2}\bar{\rho}\cdot\overline{q|_L}^2\right) = \frac{1}{2}\overline{\nabla}\cdot\left(\bar{\rho}\,\overline{q^2|_L}\,\hat{\tilde{v}} + \sum_{i=1}^{3}\overline{\left(\rho v_i''^2\tilde{v}''\right)|_L}\right) + \frac{g}{\hat{\theta}_v}\overline{\rho\theta_v''w''|_L} + \left[-\sum_{i=1}^{3}\overline{\overline{\rho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

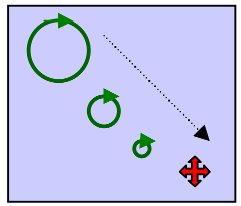
time tendency	transport (advection + diffusion)	buoyancy production	shear production by the mean flow	shear production by sub grid scale circulations	eddy-dissipation rate (**EDR**)
		labil: >0 neutral: $=0$ stabil: <0	≥ 0	≥ 0	<0







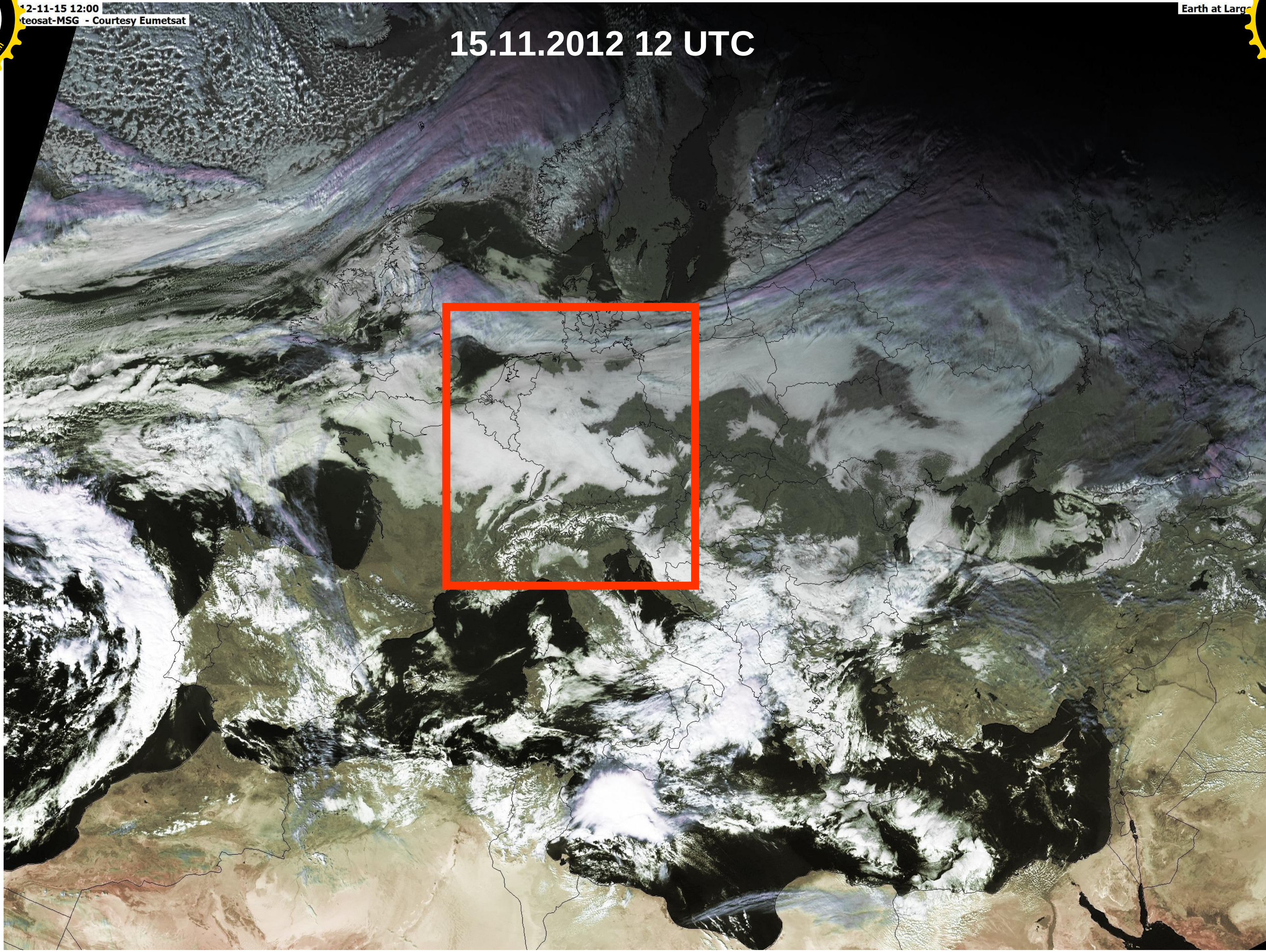




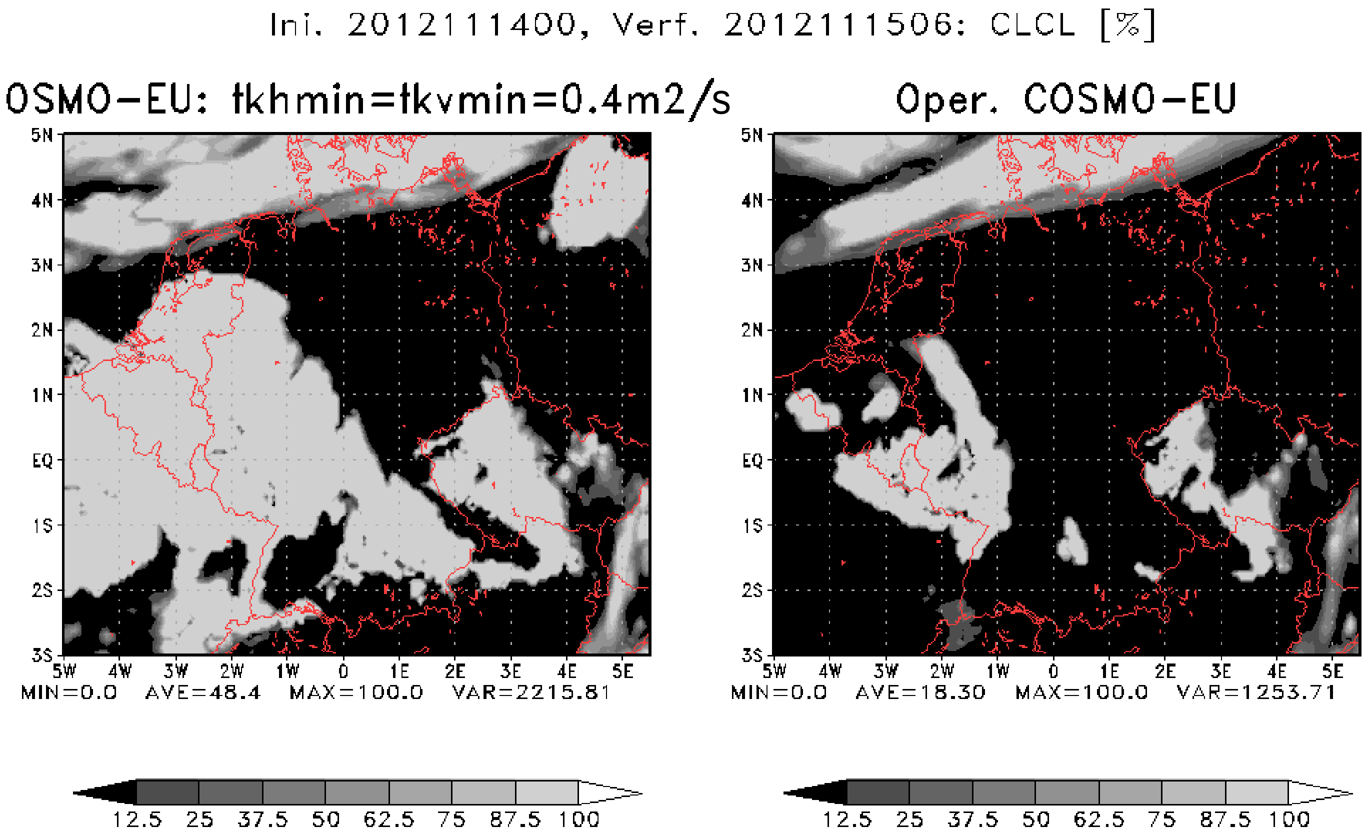
Consequences of the new solution:

- 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


15.11.2012 12 UTC
12-11-15 12:00
teosat-MSG - Courtesy Eumetsat
Earth at Larg

Low level cloud cover CLCL

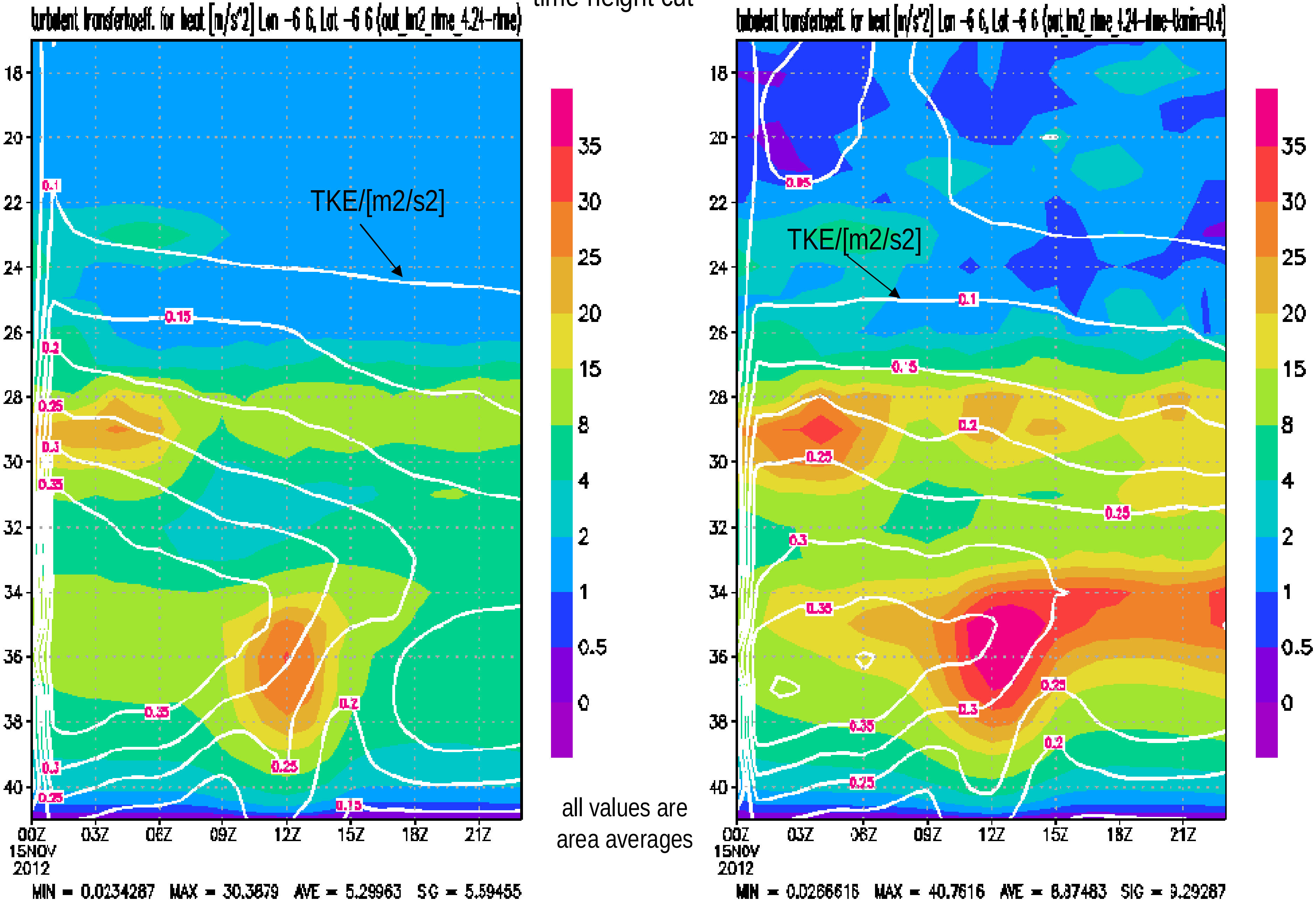


Experiment **Routine**

diffusion-coefficient/[m2/s]:
time-height cut

Routine

Experiment

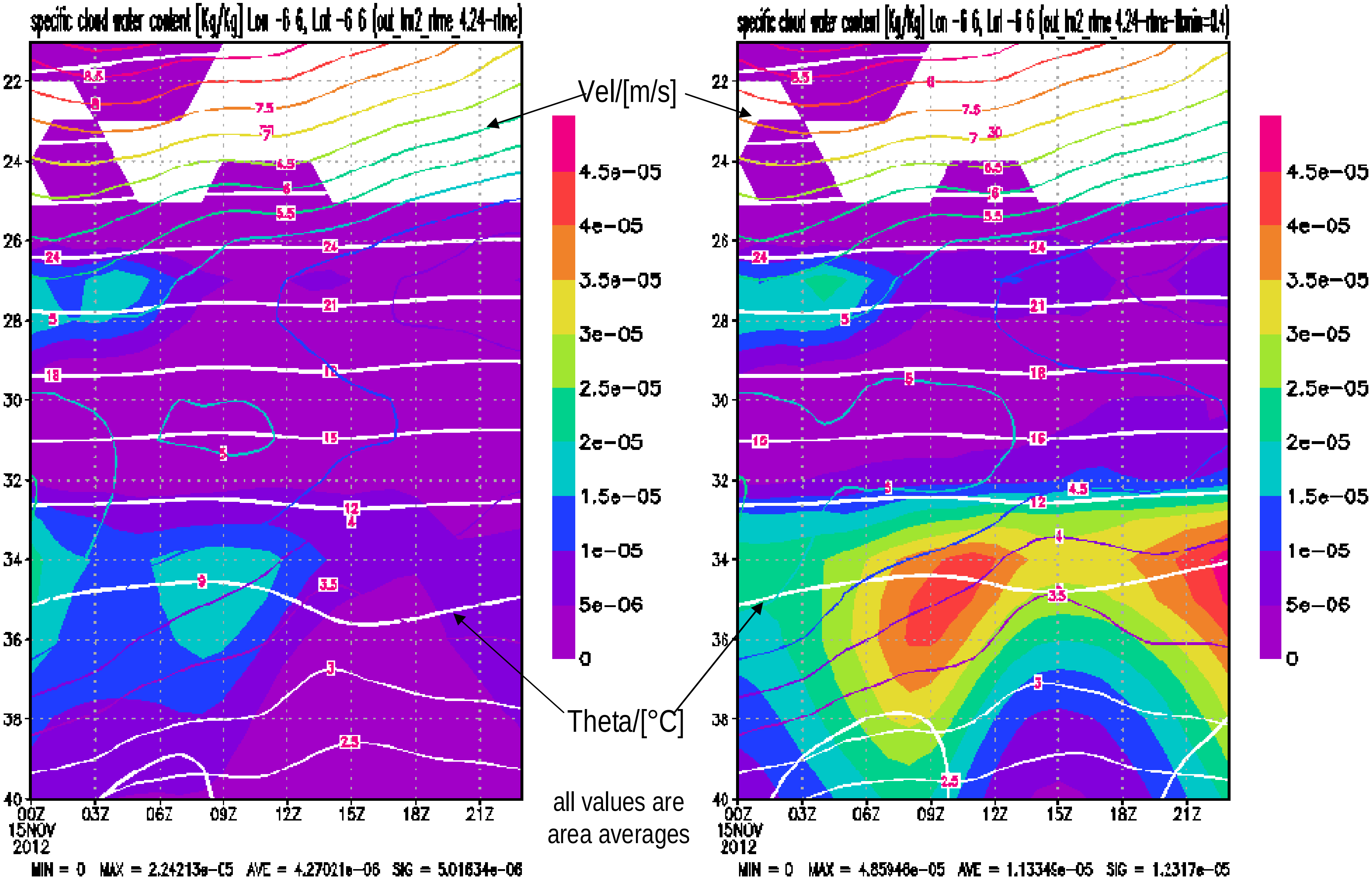


cloud-water-content/[Kg/Kg]:

Routine

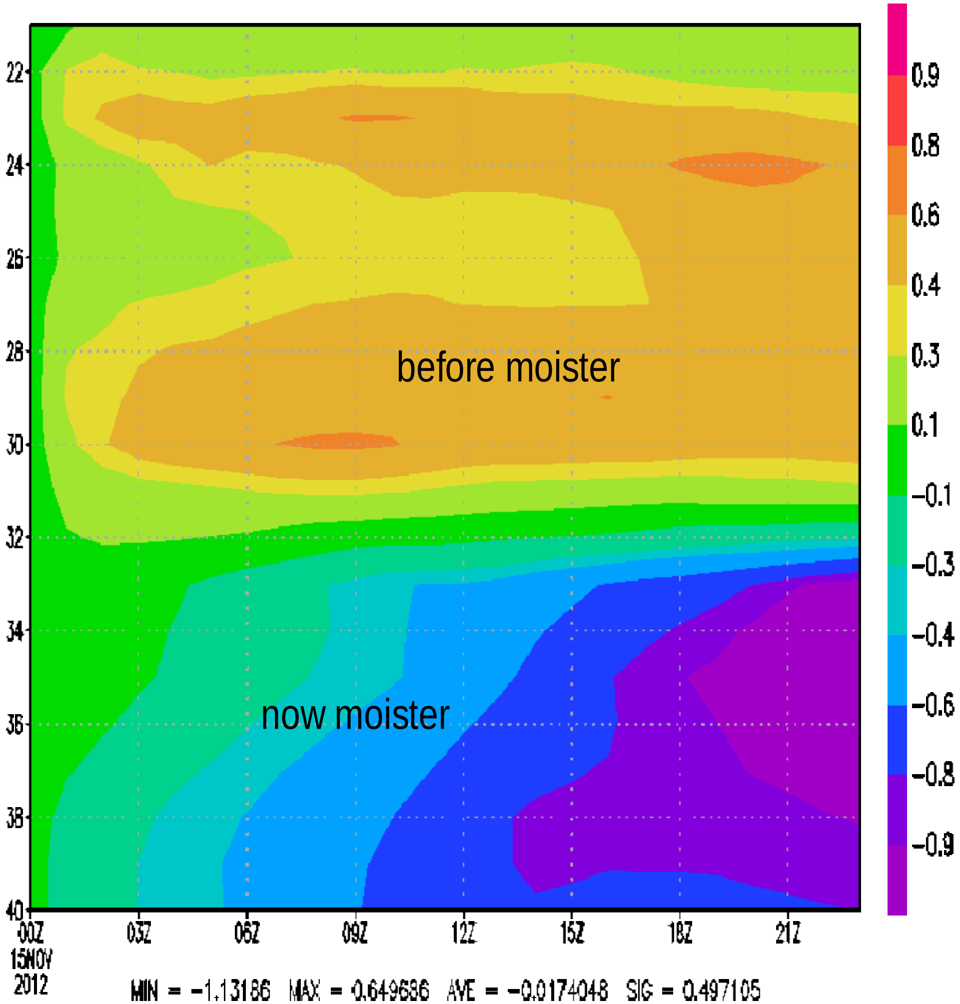
time-height cut

Experiment



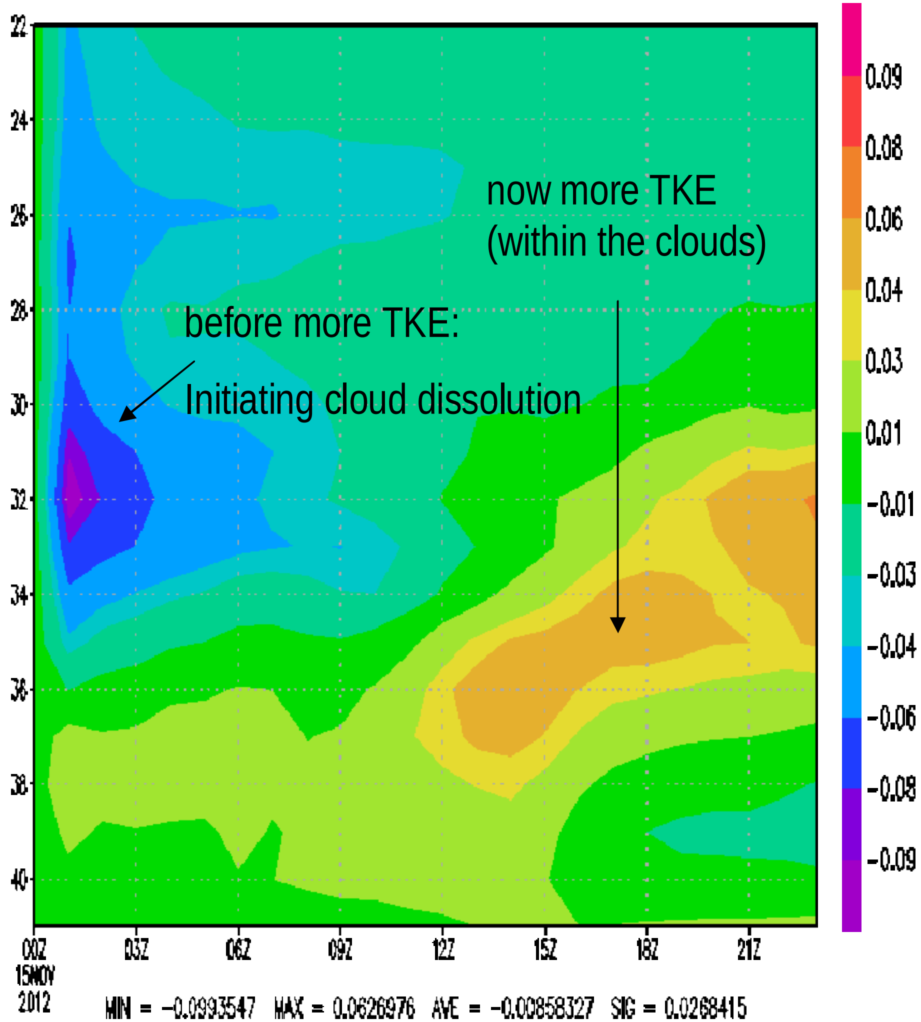
time-height cut

dif (Spread [C])
Experiment - Routine
out_lm2_rlme_4.24−rlme−tkmin=0.4



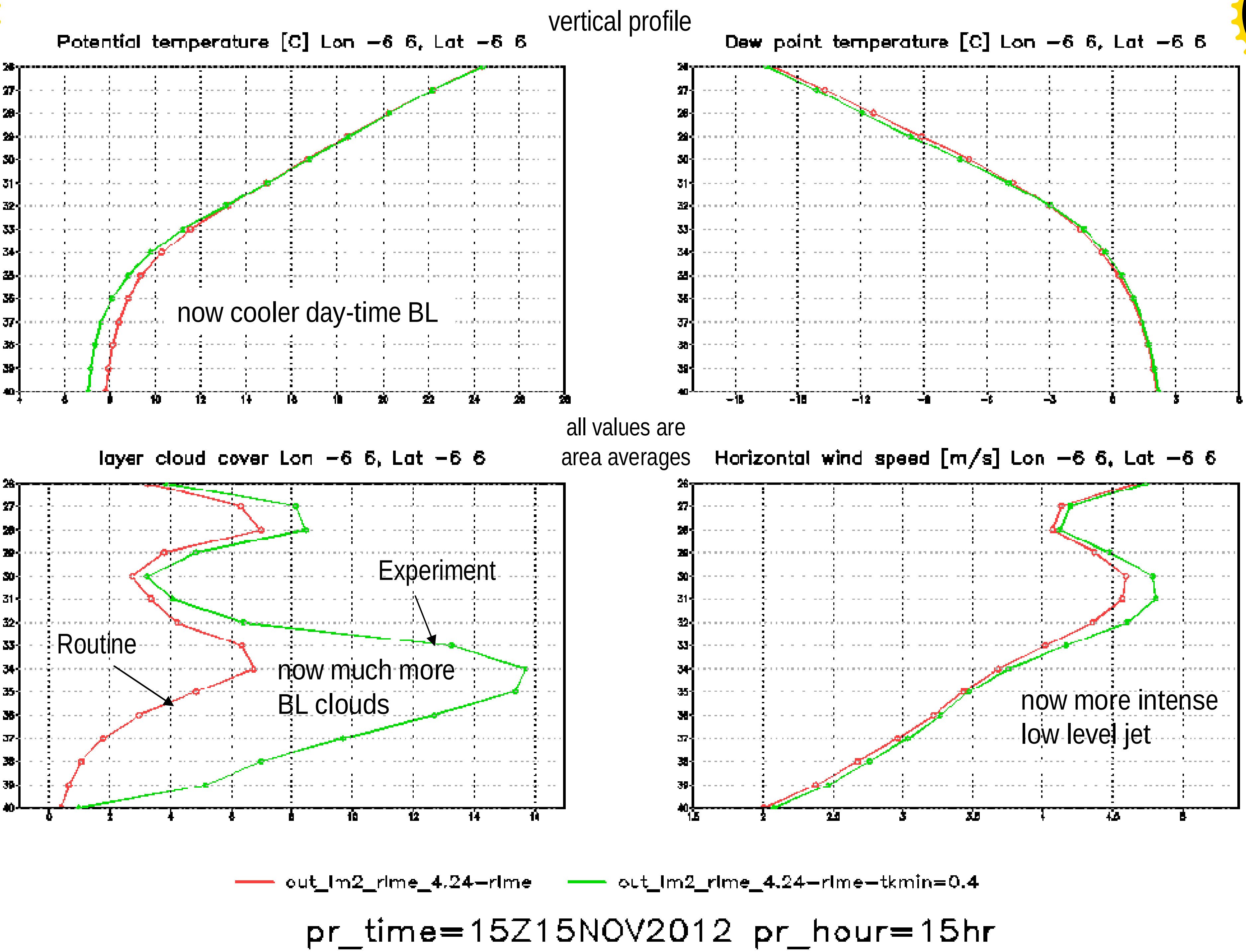
Lon −6 6, Lat −6 6

dif (turbulent kinetic energy (TKE) [m^2/s^2])
Experiment - Routine
out_lm2_rlme_4.24−rlme−tkmin=0.4



Lon −6 6, Lat −6 6

all values are
area averages



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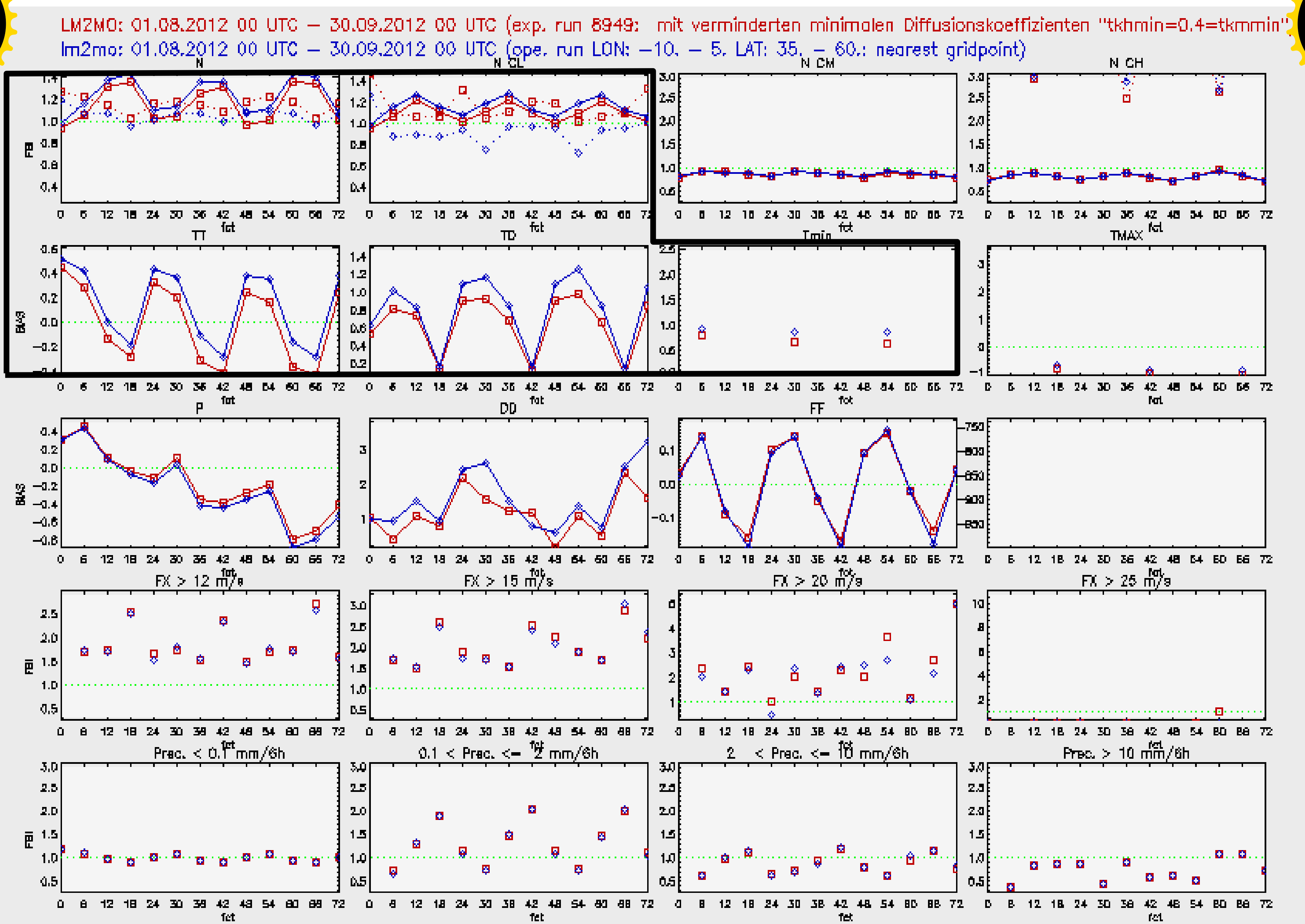
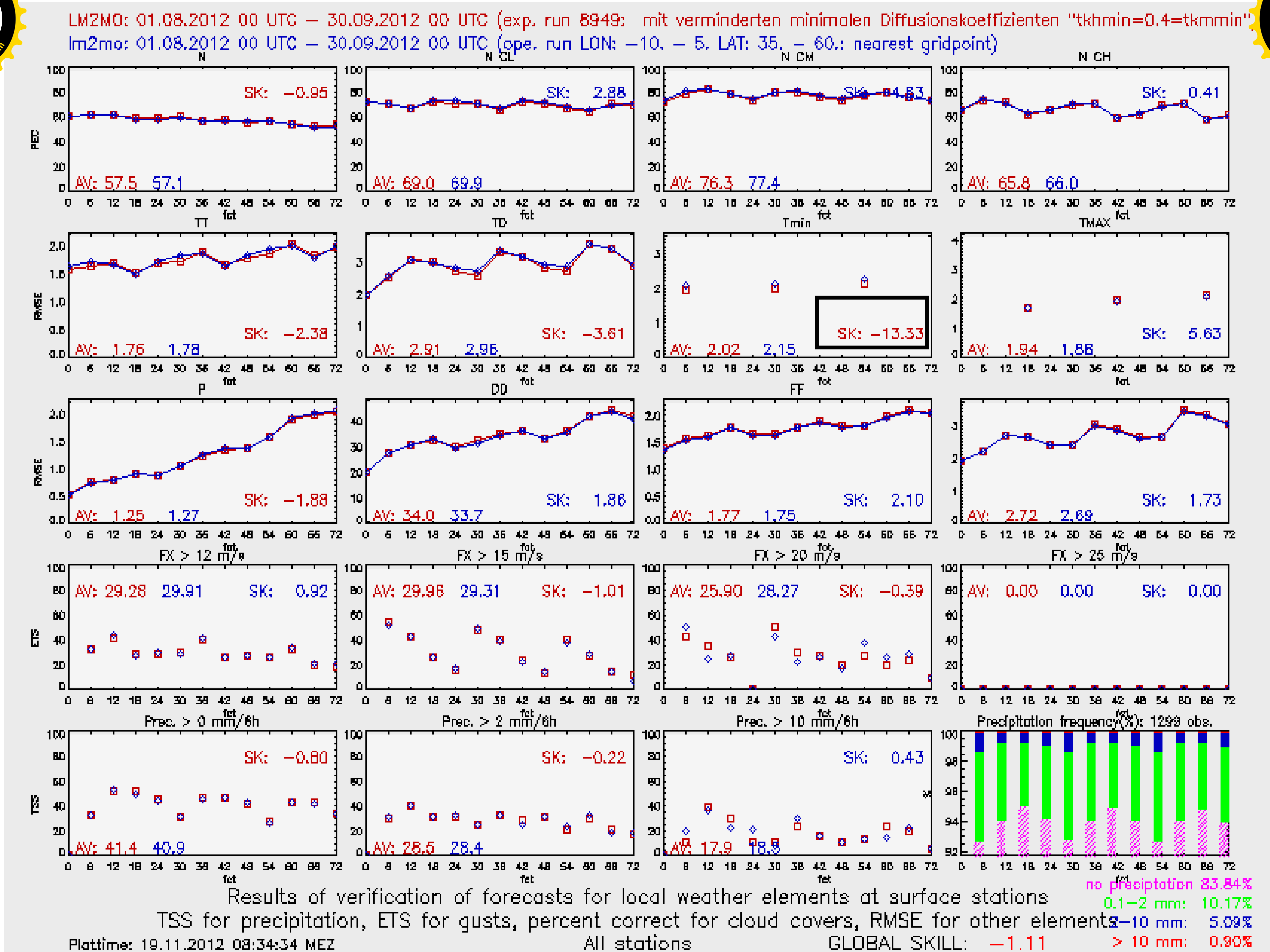


Results of verification of forecasts for local weather elements at surface stations

FBI for cloud covers gusts and precipitation (cloud covers dotted: below 3 octa, solid: above 6 octa), BIAS for other elements

All stations

Plottime: 19.11.2012 08:34:34 MEZ


LM2MO: 01.08.2012 00 UTC – 30.09.2012 00 UTC (exp. run 8949: mit verminderten minimalen Diffusionskoeffizienten "tkhmin=0.4=tkmmin")
lm2mo: 01.08.2012 00 UTC – 30.09.2012 00 UTC (ope. run LON: –10. – 5. LAT: 35. – 60.: nearest gridpoint)
N
SK: –0.95
AV: 57.5 57.1
N CL
SK: 2.88
AV: 69.0 69.9
N CM
SK: 4.53
AV: 76.3 77.4
N CH
SK: 0.41
AV: 65.8 66.0
TT
SK: –2.38
AV: 1.76 1.78
TD
SK: –3.61
AV: 2.91 2.96
Tmin
SK: –13.33
AV: 2.02 2.15
TMAX
SK: 5.63
AV: 1.94 1.86
P
SK: –1.88
AV: 1.25 1.27
DD
SK: 1.86
AV: 34.0 33.7
FF
SK: 2.10
AV: 1.77 1.75
SK: 1.73
AV: 2.72 2.69
FX > 12 m/s
AV: 29.28 29.91 SK: 0.92
FX > 15 m/s
AV: 29.96 29.31 SK: –1.01
FX > 20 m/s
AV: 25.90 28.27 SK: –0.39
FX > 25 m/s
AV: 0.00 0.00 SK: 0.00
Prec. > 0 mm/6h
SK: –0.80
AV: 41.4 40.9
Prec. > 2 mm/6h
SK: –0.22
AV: 28.5 28.4
Prec. > 10 mm/6h
SK: 0.43
AV: 17.9 18.3
Precipitation frequency(%): 1299 obs.
PEC
RMSE
ETS
TSS
fct
no precipitation 83.84%
0.1–2 mm: 10.17%
2–10 mm: 5.09%
> 10 mm: 0.90%
Results of verification of forecasts for local weather elements at surface stations
TSS for precipitation, ETS for gusts, percent correct for cloud covers, RMSE for other elements
Plottime: 19.11.2012 08:34:34 MEZ
All stations
GLOBAL SKILL: –1.11

Conclusion:

- In the SBL pure turbulence would completely disappear, unless non-turbulent sub-grid processes are interacting.
- Introduction of scale interaction terms was the reason that previous security measures for the SBL could and must be degraded.
- Reduction of tkv[h,m]min diminishes excessive dissolution of inversion layer clouds that seemed to get increasingly worse lately and causes more BL clouds now.
  - Less often completely wrong simulation of BL clouds
  - cooler BL also during daytime => slightly negative BIAS of T2m_max
  - we expect also less systematic radiative cooling of the soil during winter time

    (needs to be verified)
- Reduction of tkv[h,m]min diminishes night-time heat transfer towards the soil.
  - cooler clear sky surface layer during night => reduction of positive BIAS of T2m_min
- Operational at DWD since December 2012

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Next steps:

- Investigation of the other security measures in the scheme
  - Reformulation of the numerical sub schemes to allow for less restrictions (running)
  - Less restrictive security measures to avoid singularities in the turbulent budget equations (running)

- Further development of the scheme
  - Verification of the already implemented source terms and using them operationally (first experiments can start)
  - Reformulation of the thermal circulation term into a thermal SSO-source term (prepared)
  - Reformulation of the surface-to-atmosphere transfer in order to be more sensitive for stable stratification (ConSAT)

Thank you for attention