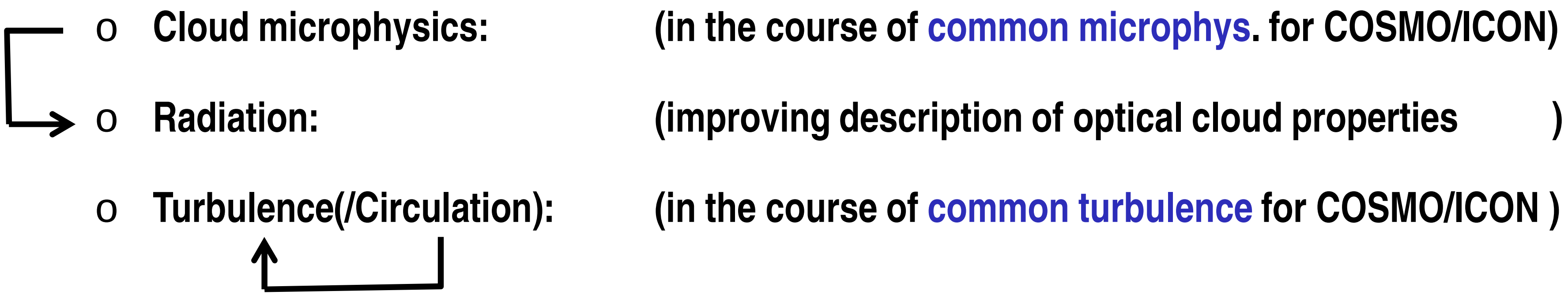
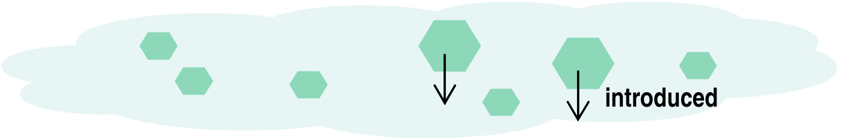
Recent developments in COSMO physics

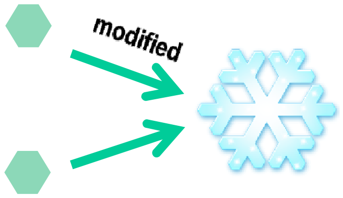


- **Cloud microphysics:** (in the course of **common microphys**. for COSMO/ICON)
- **Radiation:** (improving description of optical cloud properties)
- **Turbulence(/Circulation):** (in the course of **common turbulence** for COSMO/ICON)

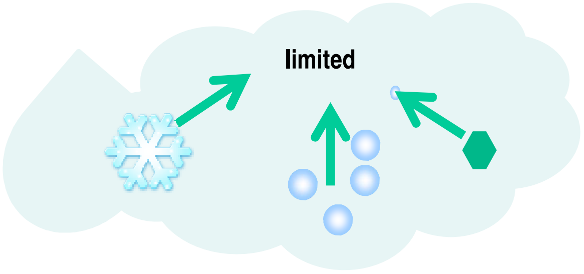
Modification in the unified cloud microphysics (1):



- Cloud Ice Sedimentation (F. Köhler/Rieper, G. Zängl):
  - – Counteracts our too persistent cirrus clouds (also in graupel-scheme
  - – With an modified formulation of sticking efficiency of cloud ice to snow
  - ➢ Modifications have been beneficial in ICON:
    - o Reduction of overestimated ice water content
  - ➢ Impact on COSMO rather neutral

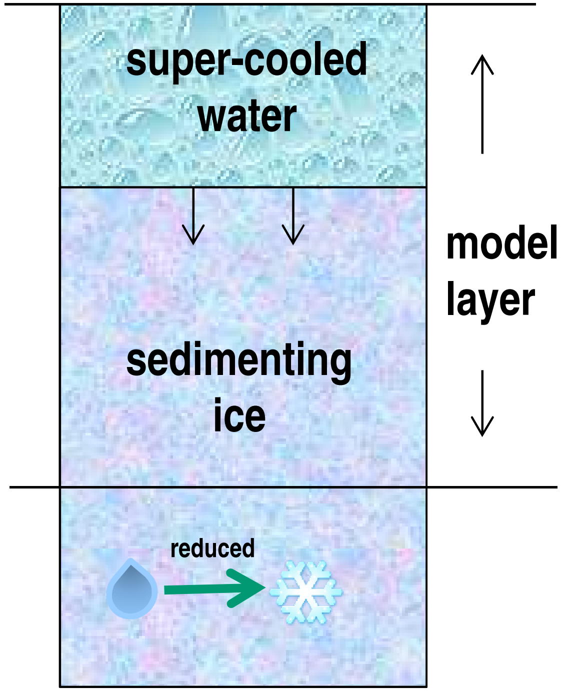


- Limitation of evaporation from falling precipitation (G. Zängl):
  - – Avoids overshoots of evaporation within a time step towards super-saturation
  - – Removes a source of numerical instability
  - ➢ Modification was necessary for ICON
  - ➢ Impact on COSMO rather neutral

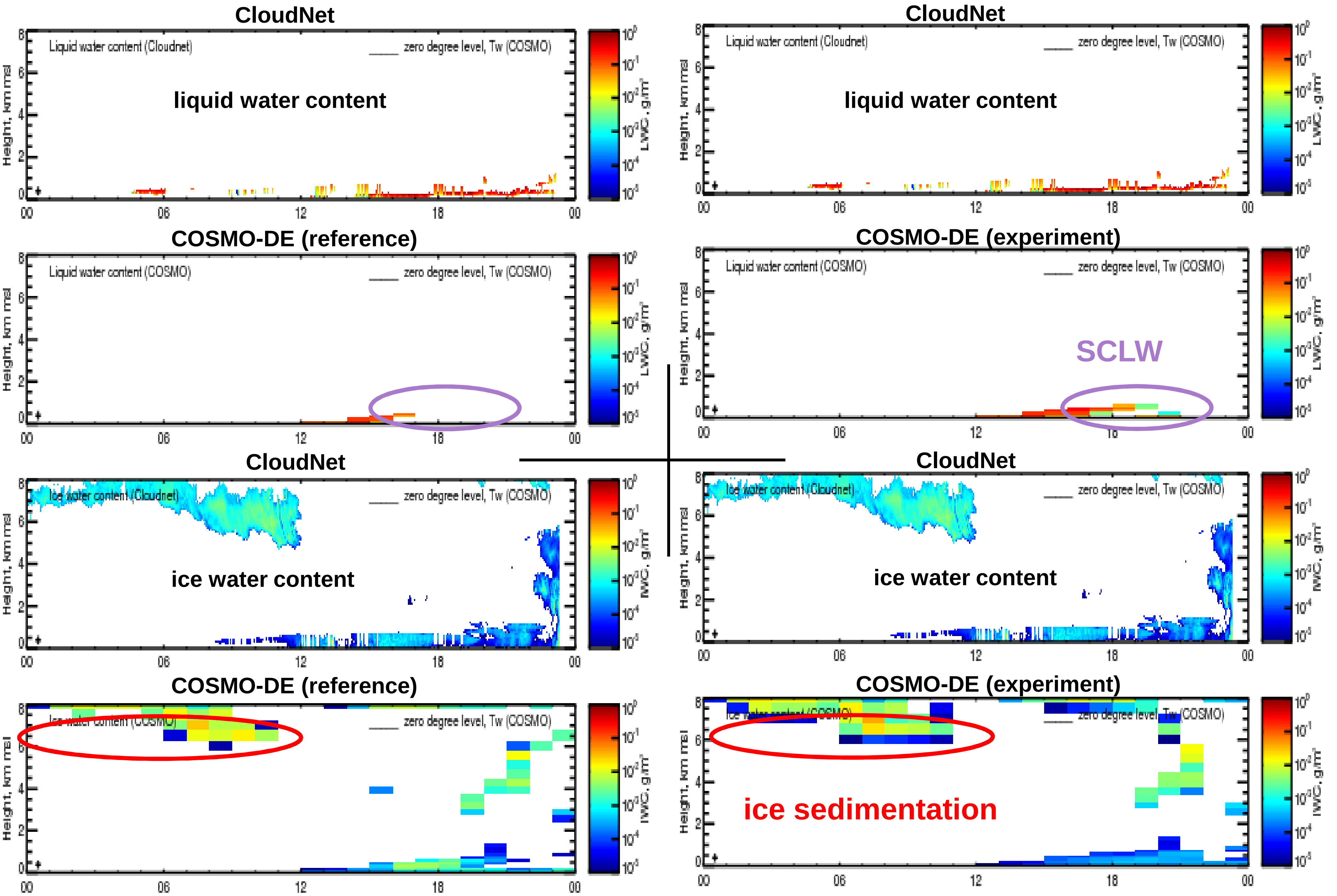


Modification in the unified cloud microphysics (2):

- Improved simulation of Super-Cooled Liquid Water (SCLW) and some bug-fixes (by F. Rieper)
  - Liquid water sub layer on top of ice cloud layer due to ice sedimentation and a
  - reduction of freezing rate of in-cloud and below-cloud water below temperature threshold of homog. freezing
  - ➢ Reduction of overestimated number of ice particle as a function of time
  - ➢ Much improved forecast of aircraft icing (for aviation)
  - ➢ Tested in COSMO and ICON



Comparison with Observations at Lindenberg by U. Görsdorf (DWD):



CloudNet

liquid water content

CloudNet

liquid water content

COSMO-DE (reference)

COSMO-DE (experiment)

SCLW

CloudNet

ice water content

CloudNet

ice water content

COSMO-DE (reference)

COSMO-DE (experiment)

ice sedimentation

Notes and further steps:

- All over impact of modification in COSMO-verification is quite neutral
- Some modifications are necessary in ICON (mainly due to its higher atmosphere)
- SCLW is a main impact for improved forecast of air craft icing with COSMO

- An improved cloud ice treatment (prognostic number concentration of activated ice nuclei, more sophisticated representation of homogeneous and heterogeneous nucleation) prepared by C. Köhler needs to be further investigated within the ICON framework

- The full 2-moment microphysics needs to be considered mainly with respect to its numerical expense

- …

Work on improved cloud-radiation coupling (U.Blahak):

- In the COSMO radiation scheme (Ritter & Geleyn 1992)
  - Optical properties of the air (extinction coeff. β_{ext} , single scattering albedo ω , asymmetry factor g) depend only on the mass fractions qc or qi.
  - Effect of inhomogeneity is taken into account by means of a constant reduction factor k=0.5 applied to the mass fractions.

➔ Modern parameterizations based on an effective radius R_e have been investigated

  - R_e has been deduced from inherent assumptions about the particle size distribution N(D), mass size relation and particle shapes in both the 1-moment and 2-moment microphysical scheme.
    - Assuming hexagonal (randomly distributed) particles in case of cloud ice
    - Dependent on tuning parameters
  - Optical properties are formulated as fct (qx, $R_{e,}$) specific for each considered spectral band
    - For cloud droplets according to Hu and Stammnes (1993)
    - For cloud ice according to Fu et al. (1996, 1998)

➔ qx now also includes (falling) hydrometeors like rain and snow, with analogue R_e -modelling

  - Extrapolation of regression functions fct based on “large-size approximation”

➔ Effect of SGS clouds is investigated:

  - Treating reduction factor k and other fixed parameters at least as a tuning parameters
    - k has been increased according to estimates based on an assumed PDF of cloud water

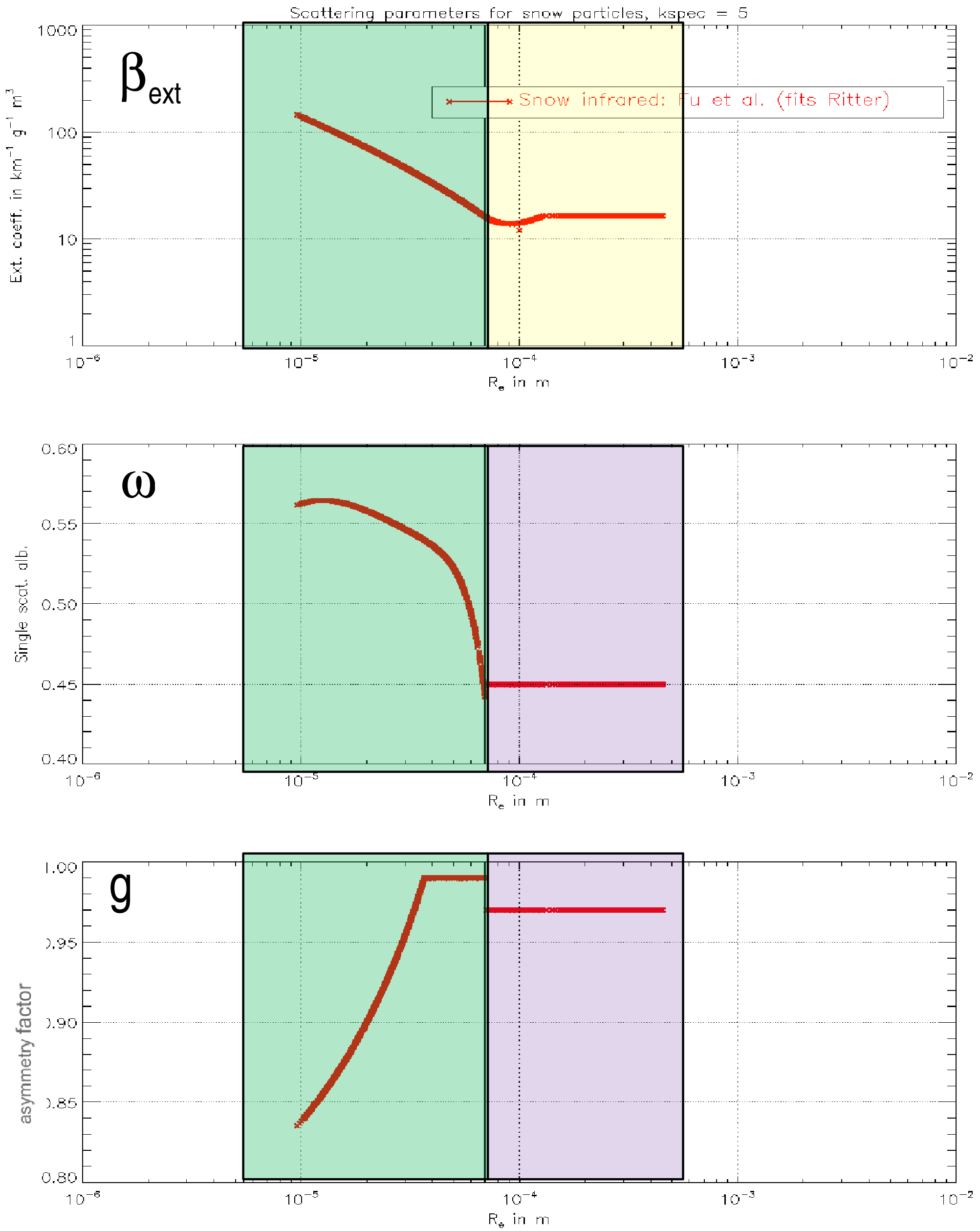
Large-size approximation for scattering parameters by (U.Blahak):

🟩 **Range of fits from literature**

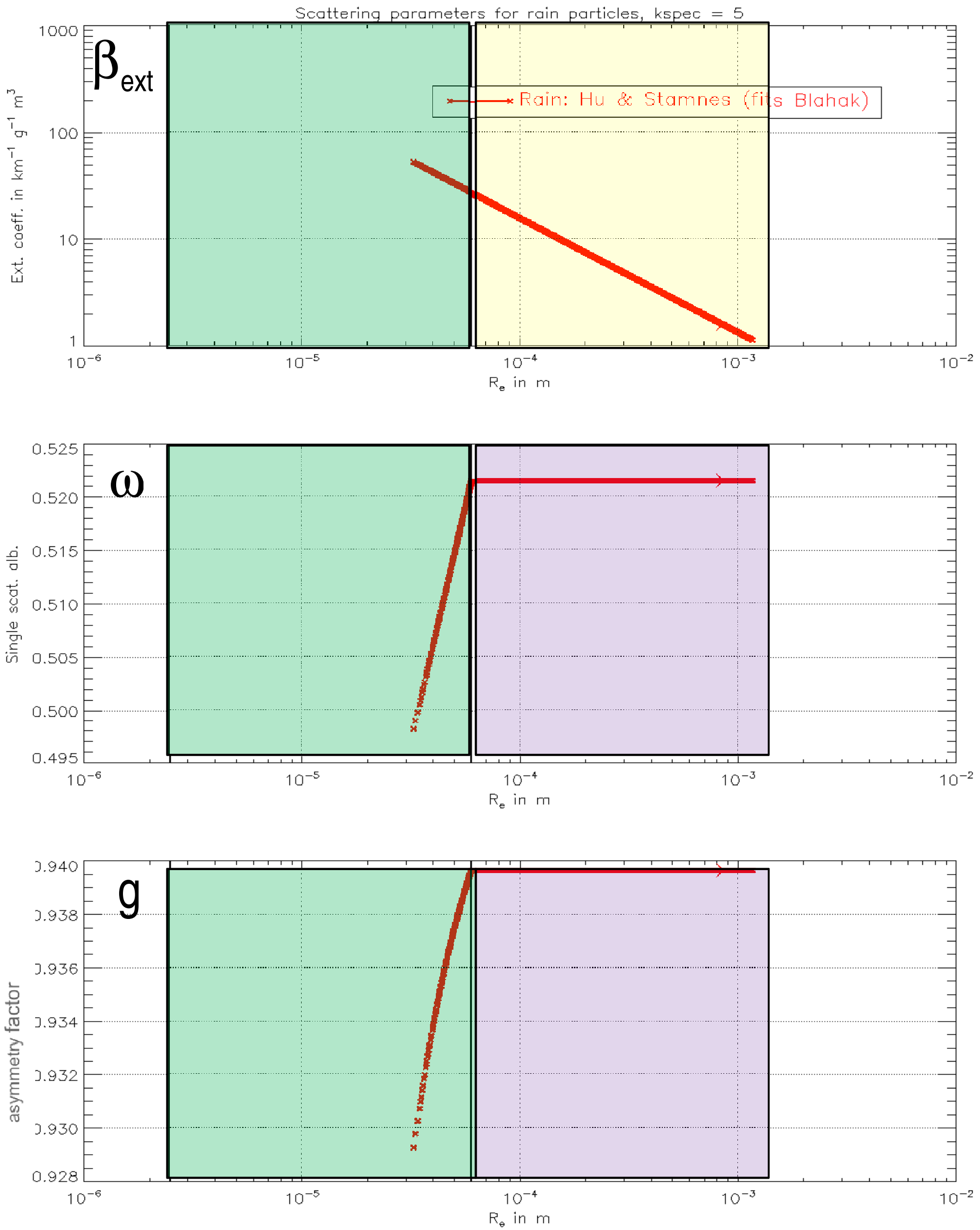
🟪 **large-size approximation by constant extrapolation**

🟨 **large-size approximation by blending**

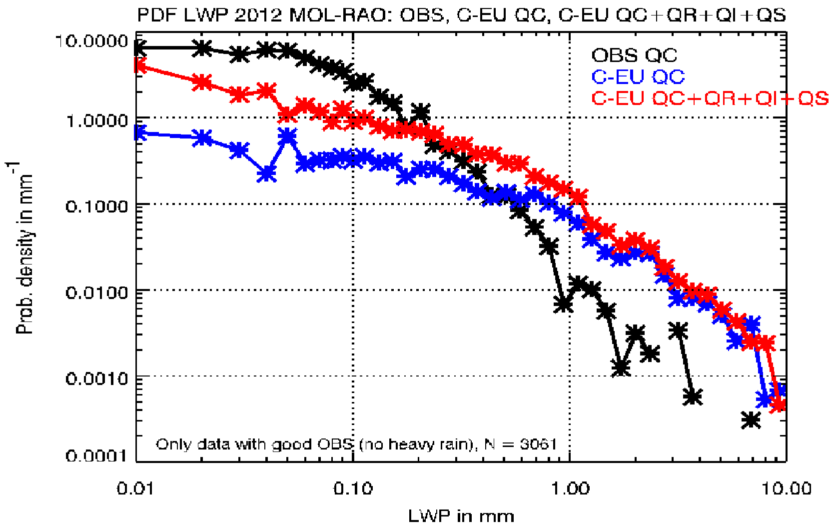
Snow:



Rain:

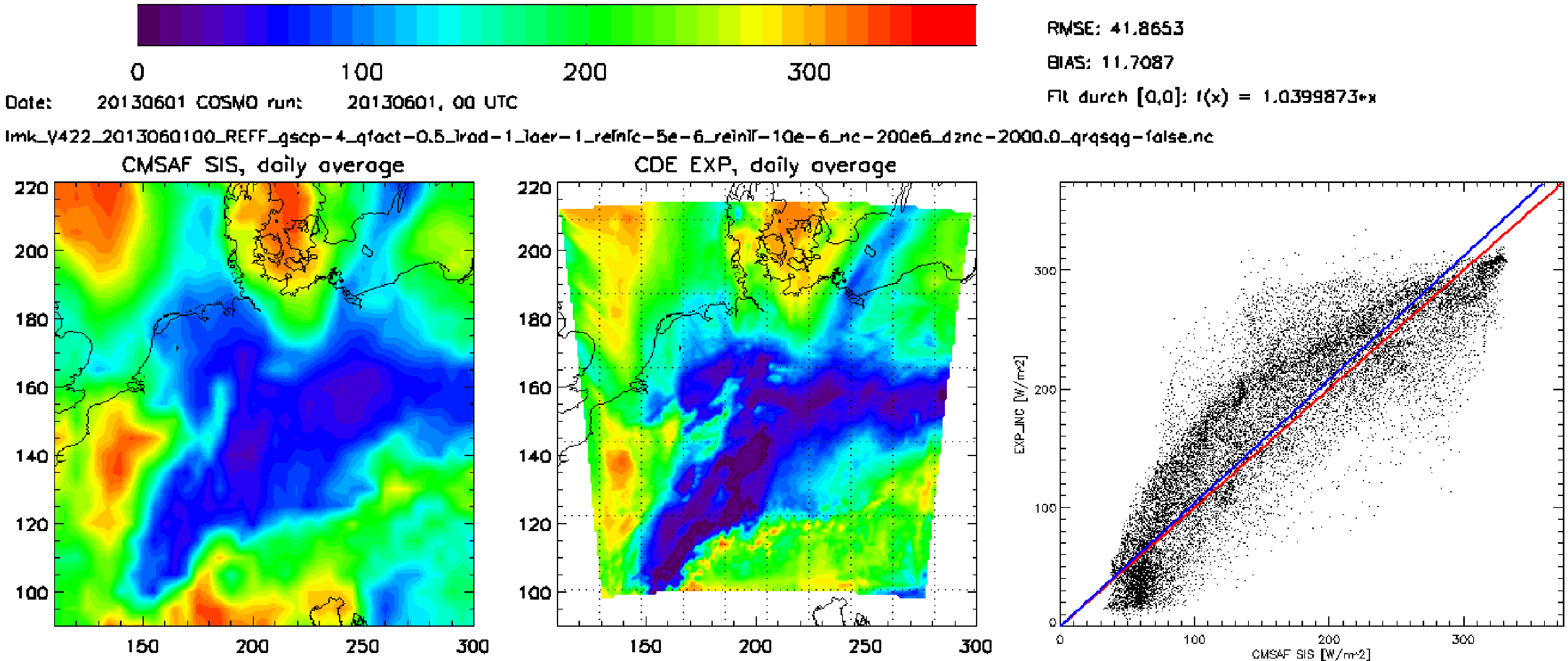


- **Comparison of PDFs of Liquid Water Path with observations form Lindenberg** (by U. Blahak)**:**



- **Model seems to show more very high and less moderate values of LWP**
- **Low values of shortwave downward fluxes overrepresented and moderate values underrepresented**
- **Has considerable impact on near surface temperature**
- **Tuning of various new parameters may improve the situation**

- **Comparison of shortwave downward radiation fluxes at the ground with CMSAF satellite product**



RMSE: 41.8653

BIAS: 11.7087

Fit durch [0,0]: f(x) = 1.0399873*x

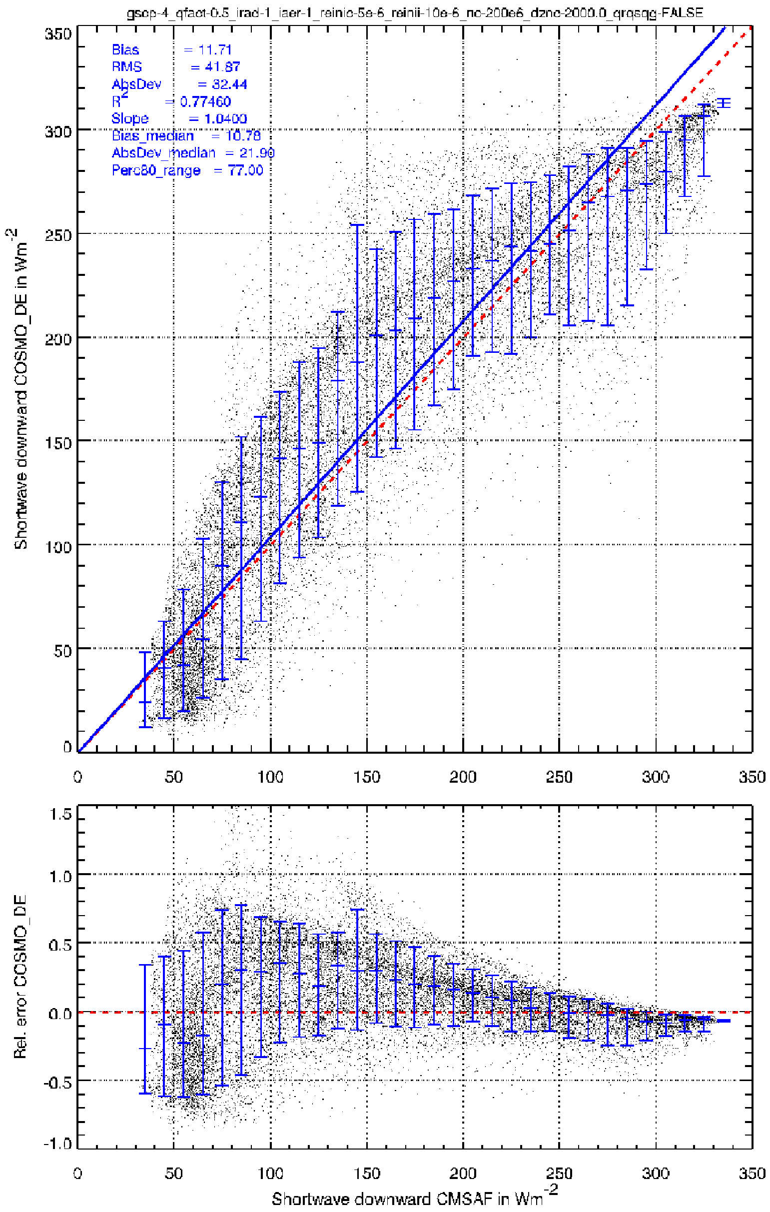
Date: 20130601 COSMO run: 20130601, 00 UTC

lmk_V422_2013060100_REFF_gscp-4_qfact-0.5_lrad-1_laer-1_refnfc-5e-6_reinif-10e-6_nc-200e6_dznc-2000.0_qrqsqg-false.nc

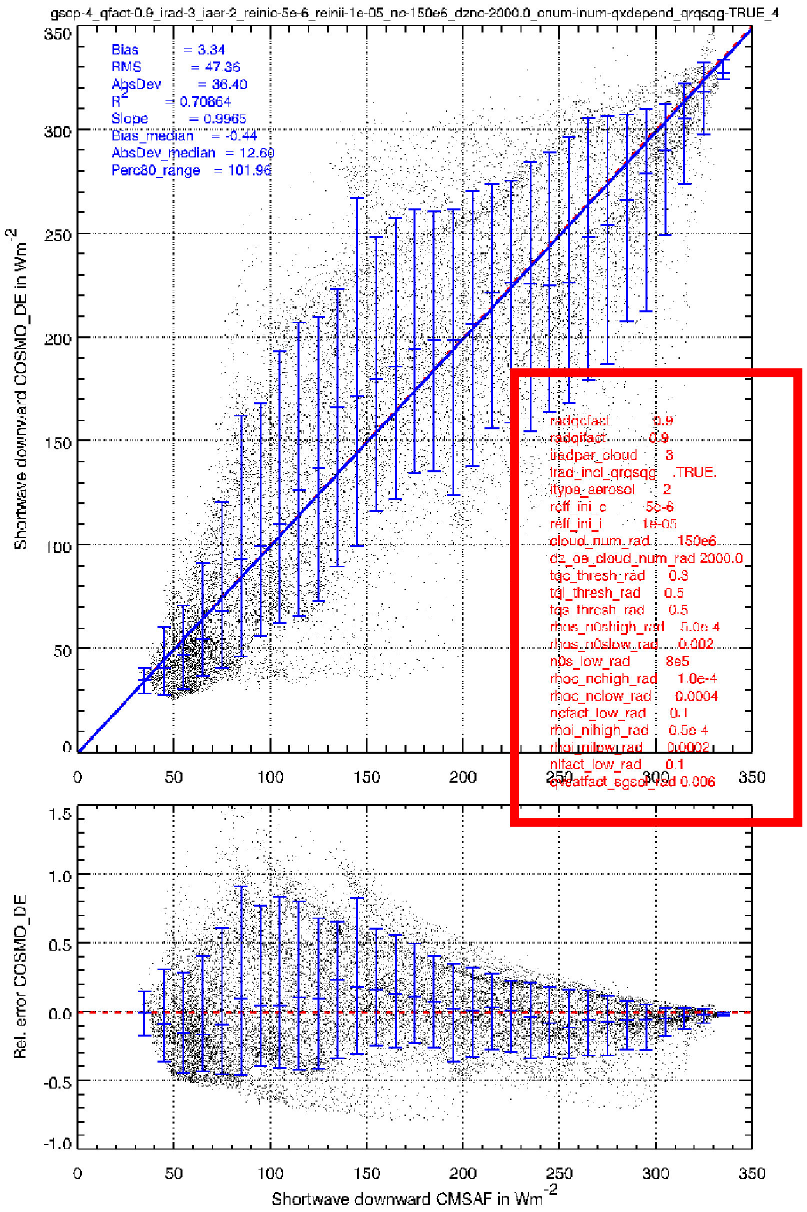
- **Adaptation of shortwave downward radiation by parameter tuning applied to the new scheme:**

(by U. Blahak)

Old formulation



New formulation after some tuning



radqcfact 0.9
radqifact 0.9
iradpar_cloud 3
irad_incl_qrqsqg .TRUE.
itype_aerosol 2
reff_ini_c 5e-6
reff_ini_i 1e-05
cloud_num_rad 150e6
dz_oe_cloud_num_rad 2000.0
tqc_thresh_rad 0.3
tqi_thresh_rad 0.5
tqs_thresh_rad 0.5
rhos_n0shigh_rad 5.0e-4
rhos_n0slow_rad 0.002
n0s_low_rad 8e5
rhoc_nchigh_rad 1.0e-4
rhoc_nclow_rad 0.0004
ncfact_low_rad 0.1
rhoi_nihigh_rad 0.5e-4
rhoi_nilow_rad 0.0002
nifact_low_rad 0.1
qvsatfact_sgscl_rad 0.006

List of tuning parameters

Notes and further steps:

- ➔ Implemented R_e –parameterizations make ice clouds optically thinner in the visible and infrared, but the consider of falling hydrometeors and the increased reduction factor k counteracts at all wave length ranges.

- ➔ Changes in cloud microphysics causes more directs impact on radiation now.

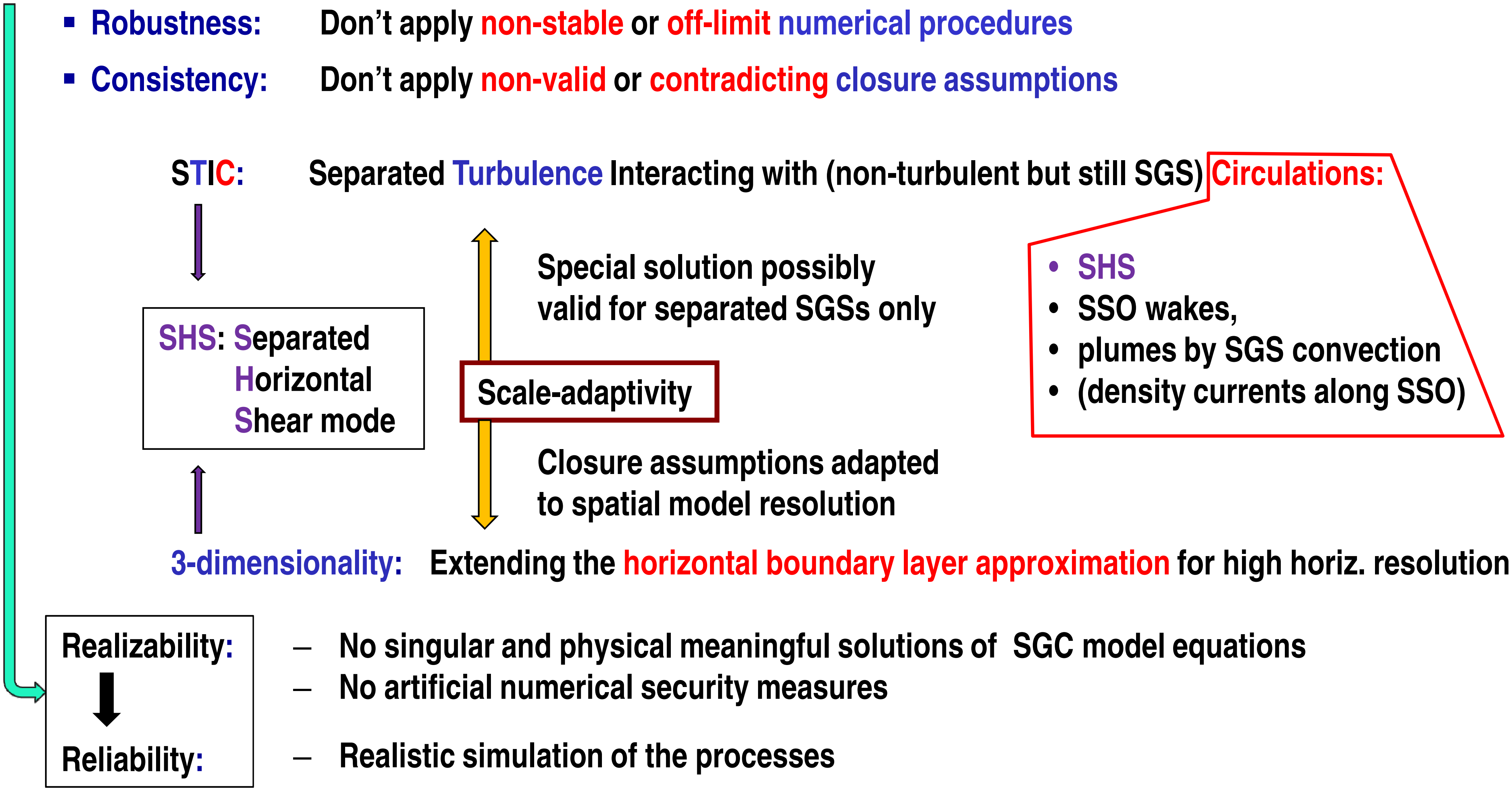
- ➔ The whole parameterization of optical properties needs to be retuned.
  - Reduction of tuning parameters by means of internal relationships or additional relations

- ➔ Improved representation of heterogeneity needs to be investigated
  - Employing an assumed a PDF of GS and SGS cloud water
  - Introducing a parameterization of R_e for SGS clouds dependent on mass fraction and SGS statistics).

- ➔ …

Turbulence/Circulations:

- Purpose: Parameterizations of SGS processes (generated by non-linearity and a finite numerical resolution) in terms of GS model variables
- Main strategy: Truncation of infinite expansion by introduction of closure assumptions



- **Robustness:** Don’t apply non-stable or off-limit numerical procedures
- **Consistency:** Don’t apply non-valid or contradicting closure assumptions

STIC: Separated Turbulence Interacting with (non-turbulent but still SGS) Circulations:

- SHS
- SSO wakes,
- plumes by SGS convection
- (density currents along SSO)

SHS: Separated
Horizontal
Shear mode

Special solution possibly valid for separated SGSs only

Scale-adaptivity

Closure assumptions adapted to spatial model resolution

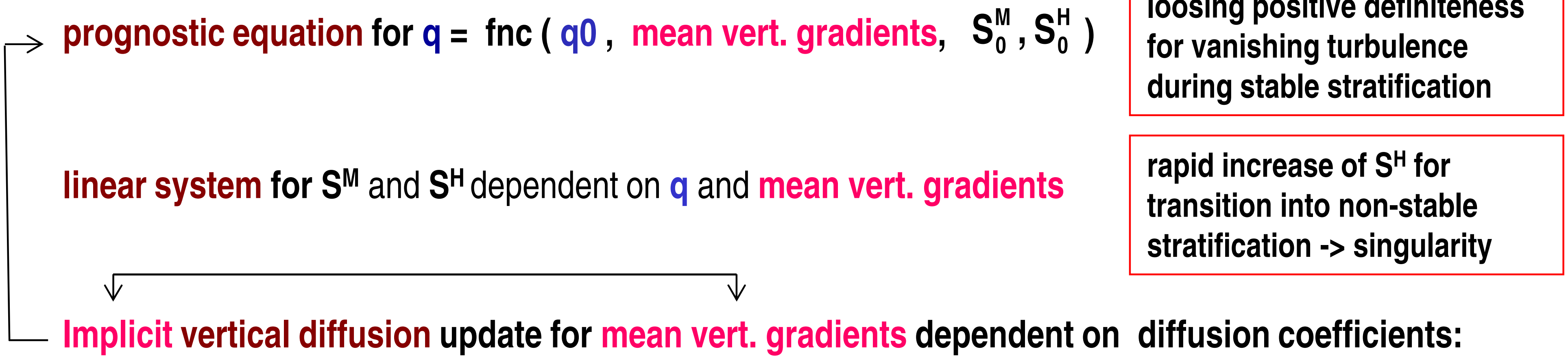
3-dimensionality: Extending the horizontal boundary layer approximation for high horiz. resolution

Realizability:
- No singular and physical meaningful solutions of SGC model equations
- No artificial numerical security measures

Reliability:
- Realistic simulation of the processes

Numerical procedures of M/Y schemes of level 2.5 (and 3):

- closed turbulent 2-nd order budgets for
  - trace of turbulent stress tensor (q^2=2*TKE) : prognostic (**level =2.5**)
  - **S**calar **V**ariances: prognostic (**level =3.0**)
  - all other 2-nd order moments: diagnostic source term equilibrium
- diagnostic equations build linear system for at least 15 2-nd order moments
  - Horizontal BLA -> Reduction to only 2 equations for stability functions **S^M and S^H**
- Iterative time step solution for operational TURBDIFF (**level 2.5**):



prognostic equation for q = fnc (q0 , mean vert. gradients, S_0^M, S_0^H)

loosing positive definiteness for vanishing turbulence during stable stratification

linear system for S^M and **S^H** dependent on **q** and **mean vert. gradients**

rapid increase of S^H for transition into non-stable stratification -> singularity

Implicit vertical diffusion update for mean vert. gradients dependent on diffusion coefficients:

$$K^{M,H}=q\,S^{M,H}\,\ell$$

Approximated 3D-solution for pure turbulence:

- **Complete linear system of all 2-nd order equations needs to be solved without BLA in principal**

- **Simplification by an analog extension of the SC-solution (similar to Smagorinsky-type schemes):**

$$\overline{\rho\phi_k'' v_j''}^{\,*} = \begin{cases} \overline{\rho\phi_k'' v_j''} \approx -\overline{\rho} K^H \partial_j \hat{\phi}_k & , \phi_k \ \text{is a scalar} \\ \overline{\rho v_i'' v_j''} - \delta_{ij}\overline{\rho}\cdot\left(\frac{q^2}{3} + K^M \frac{2}{3} \cancel{\nabla\cdot\underline{\hat{v}}}\right) \approx -\overline{\rho} K^M \left(\partial_i \hat{v}_j + \partial_j \hat{v}_i\right) & , \phi_k = v_i \end{cases}$$

trace-less stress tensor

$$Q_{3DS}^{TKE} = -\sum_{i,j} \overline{\rho v_i'' v_j''}\, \partial_i \hat{v}_j \approx \overline{\rho} K^M \left[\underbrace{\frac{1}{2}\sum_{i\neq j}\left(\partial_i \hat{v}_j + \partial_j \hat{v}_i\right)^2 + 2\sum_i \left(\partial_i \hat{v}_i\right)^2}_{F^M \leftrightarrow F^M_{3D}} - \frac{2}{3}\cancel{\left(\nabla\cdot\underline{\hat{v}}\right)^2} \right] - \overline{\rho}\frac{q^2}{3}\cancel{\nabla\cdot\underline{\hat{v}}}$$

complete direct 3D shear by the GS flow

$K^{M,H} = qS^{M,H}\ell$ **turbulent isotropic diffusion coefficients with stability functions similar to HBA but** $F^M \leftrightarrow F^M_{3D}$

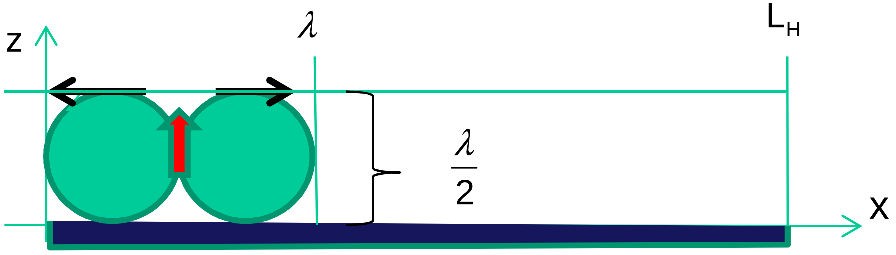
- **Turbulent length scale restriction by horizontal grid scale** L_H **:**

scale adaptivity

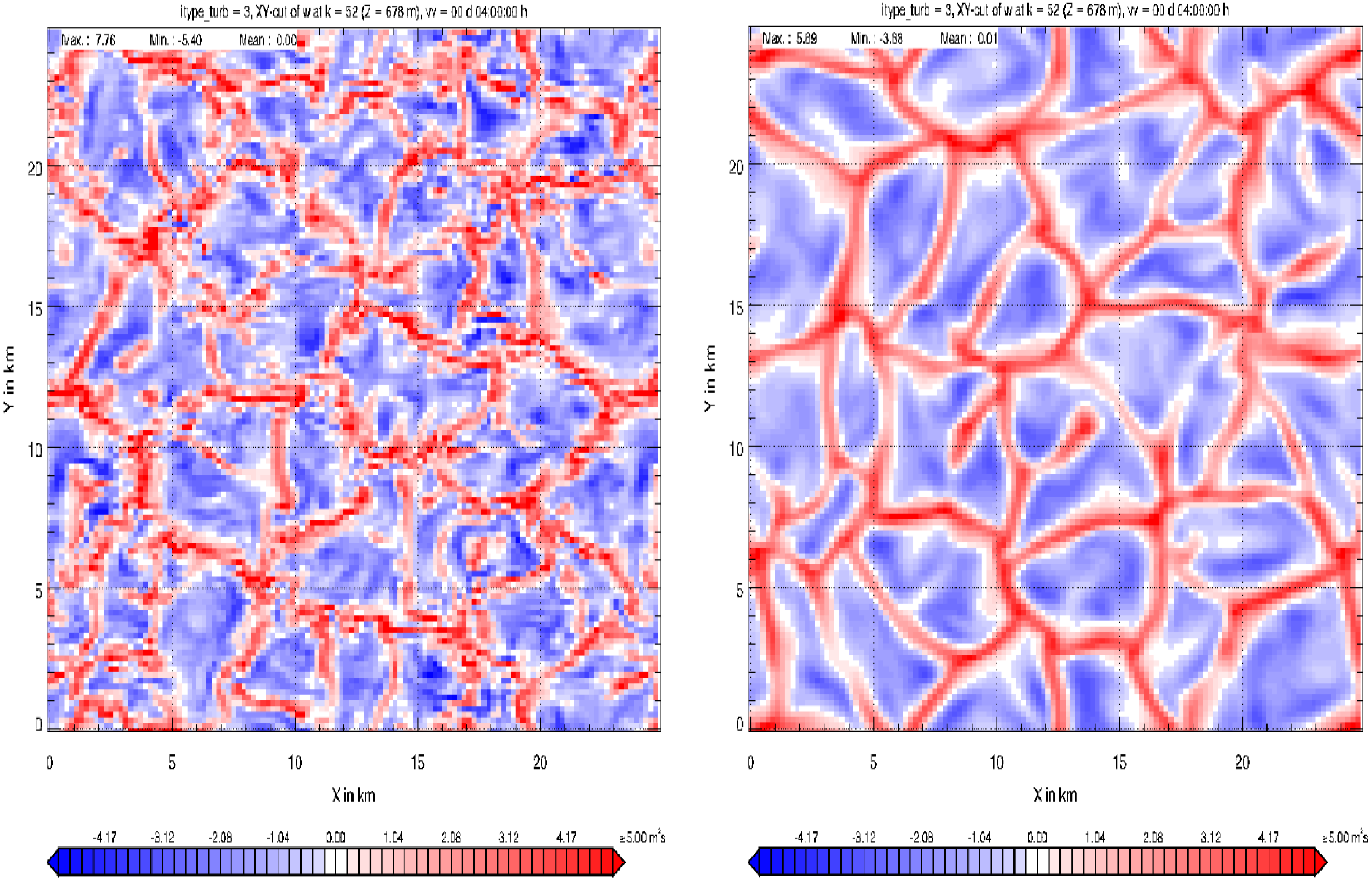
$\Updownarrow$

$$\ell = \kappa\cdot \mathrm{MAX}\left\{\frac{z\cdot z_m}{z+z_m}, \frac{L_H}{2}\right\}$$

z_m : **maximal asymptotic turbulent distance**



- Additional terms in budgets of ϕ_k by **convergence of additional horizontal fluxes** and (a not yet implemented) kinematic pressure correction



Test of horizontal diffusion (and TKE advection) for itype turb=3 done by U. Blahak:
LES-run with dX = 200m, heating by 300 W/m2
Vertical velocity after 4 h forecast time
Left: 1D-turbulence (and no horizontal diffusion), Right: 3D-turbulence (and horizontal diffusion)

Notes and further steps:

- LES-Runs (U. Blahak):
  - ➢ Reasonable results for some idealized test cases
- COSMO-1-Runs (Meteo-Swiss):
  - ➢ No significant impact due to TKE-advection and turbulent horizontal diffusion
- Operational COSMO-Runs:
  - – Possible positive impact for EDR-forecast (used by aviation) to be investigated

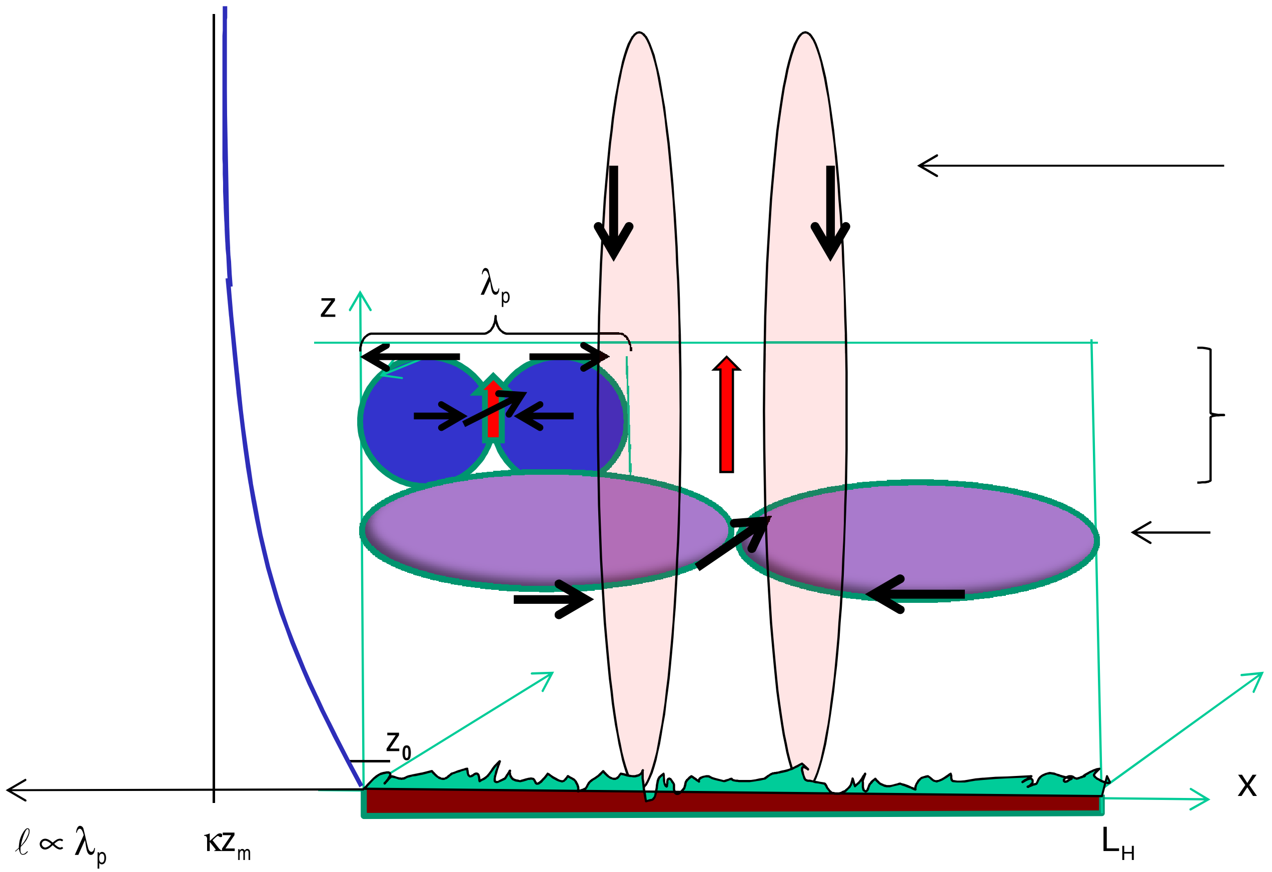
- Further development:

– Correcting the implemented restriction of the turbulent length scale

– Implementation and investigation of kinematic pressure corrections

– …

The concept of STIC:



$$\ell \propto \lambda_p = \kappa \cdot \frac{z \cdot z_m}{z + z_m}$$

turbulent length scale

	closure framework:
Non-isotropic convection - **vertically accelerated**	**mass flux or alternative**
3D isotropic turbulence - **dependent on single length scale profile**	**2-nd order**
2D separated shear circulation - **vertically damped** - **dependent on specific horizontal diffusion coefficients** - **much more effective horizontal mixing compared to pure turbulence**	**simplified 2-nd order**
⋮ **SSO-wakes, ...**	

- **Scale separation** with **adapted closure assumptions** for **scale classes**
- Related with new **Scale Transfer (ST) terms** in budget equations for 2-nd order moments of **turbulence**
  - In form of **additional shear terms** (marked by F_C^M): $\boxed{C(irculation)KE \rightarrow T(urbulent)KE}$

The separated horizontal shear mode:

- **Separated horizontal shear diffusion: only for** $i, j \in \{1, 2\}$

$$\overline{\bar{\rho}_{|_L}\hat{\phi}_{k_{|_L}}''\,\hat{v}_{j_{|_L}}''}^{*} = \begin{cases} \overline{\bar{\rho}_{|_L}\hat{\phi}_{k_{|_L}}''\,\hat{v}_{j_{|_L}}''} \approx -\bar{\rho}K^{H}_{SHS}\,\partial_j\hat{\phi}_k & ,\ \phi_k = w \text{ or a scalar (incl TKE)} \\ \overline{\bar{\rho}_{|_L}\hat{v}_{i_{|_L}}''\,\hat{v}_{j_{|_L}}''} - \delta_{ij}\bar{\rho}\dfrac{q_{SHS}^{2}}{2} \approx -\bar{\rho}K^{M}_{SHS}\left(\partial_i\hat{v}_j + \partial_j\hat{v}_i - \delta_{ij}\nabla_h\cdot\hat{\underline{\mathbf{v}}}_h\right) & ,\ \phi_k = v_i \end{cases}$$

guaranteeing the proper tensor trace

- **GS horizontal shear production equals scale transfer towards turbulence by SGS shear production :**

$$Q^{CKE}_{SHS} := \bar{\rho}K^{M}_{SHS}\underbrace{\left[\left(\partial_1\hat{v}_2+\partial_2\hat{v}_1\right)^2 + \mathbf{2}\sum_{i=1,2}\left(\partial_i\hat{v}_i\right)^2 - \left(\nabla_h\cdot\hat{\underline{\mathbf{v}}}_h\right)^2\right]}_{\left(\partial_1\hat{v}_2+\partial_2\hat{v}_1\right)^2+\left(\partial_1\hat{v}_1-\partial_2\hat{v}_2\right)^2} - \bar{\rho}\frac{q_{SHS}^{2}}{2}\nabla_h\cdot\hat{\underline{\mathbf{v}}}_h \approx \frac{q_{SHS}^{3}}{\alpha^{MM}\beta_{SHS}L_H} =: K^{M}F^{M}_{SHS}$$

additional TKE-production

$$K^{M,H}_{SHS} := \bar{\rho}\,q_{SHS}\,S^{M,H}_{SHS}\underbrace{\beta_{SHS}L_H}$$

effective mixing length of diffusion by horizontal shear eddies

velocity scale of the separated horizontal shear mode

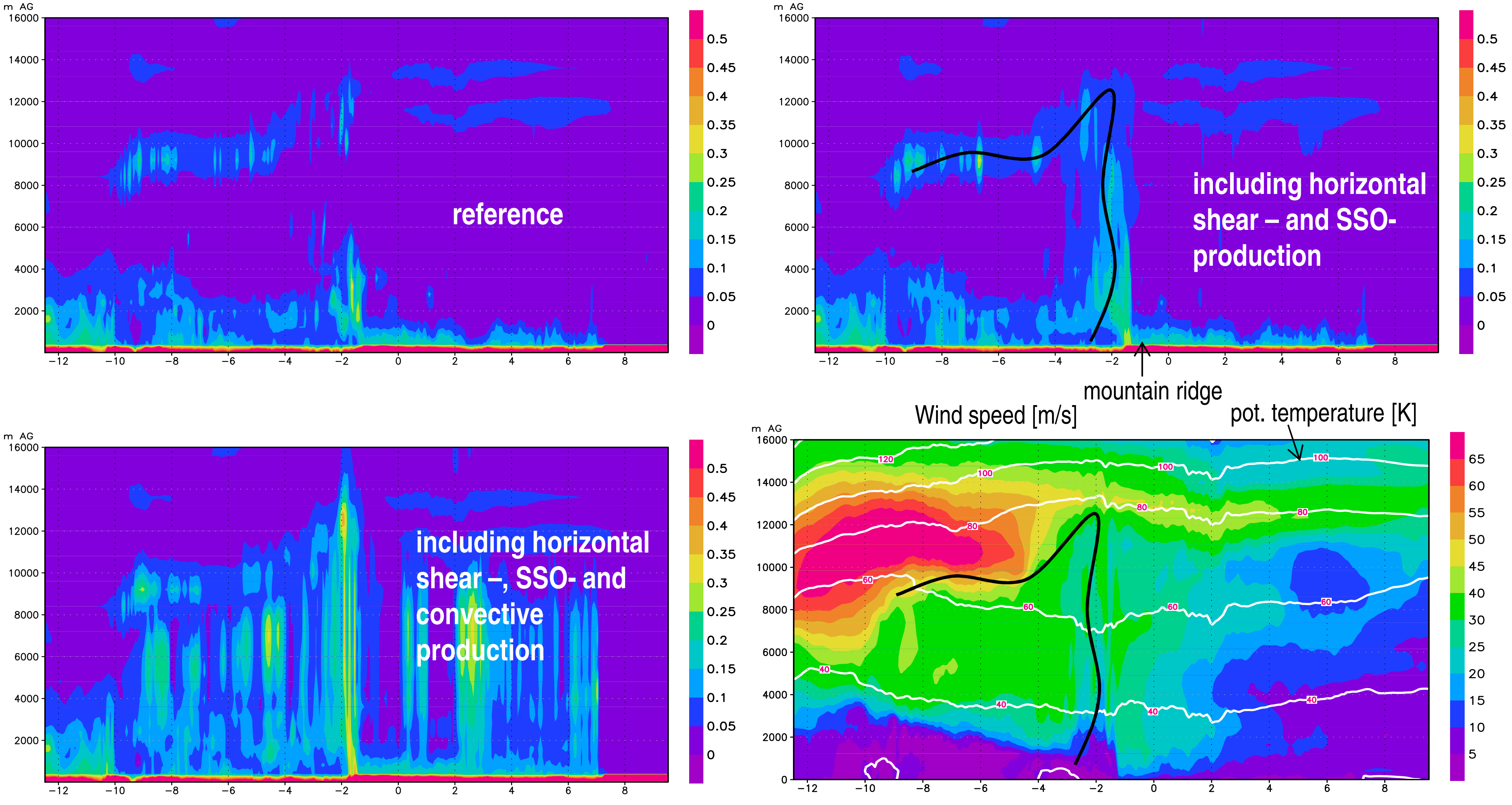
F^{M}_{SHS} **shear by SGS separated horizontal shear circulation; contributes to** F^{M}_{C}

$S^{M,H}_{SHS}$ **stability parameter for neutral stratification**

$1 > \beta_{SHS}$ **scaling parameter**

- **Additional horizontal diffusion by separated shear circulation related to** $K^{M,H}_{SHS}$ **:**
  - Including a related additional kinematic pressure correction not yet implemented!
  - Contributes also for coarse horizontal resolution not yet investigated!

pow_1/3 (eddy dissipation rate (EDR) [m^2/s^3])

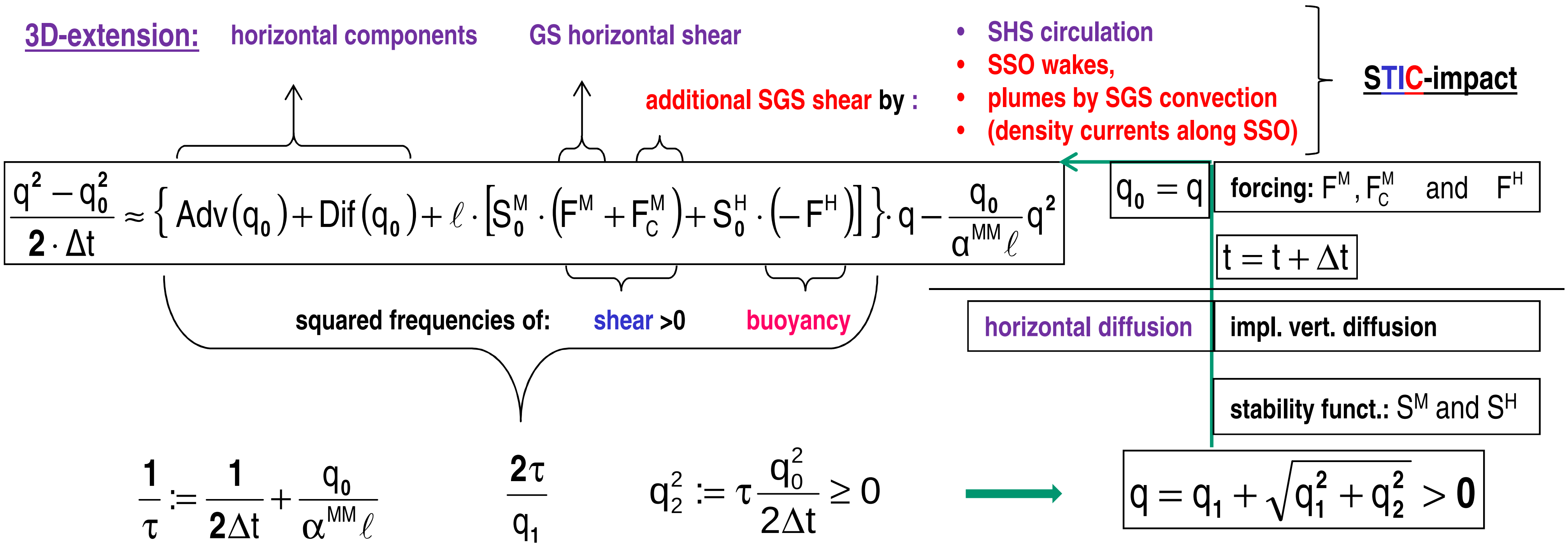


COSMO-US: cross section across frontal line with COSMO-EU

Notes and further steps:

- Further generalization of turbulence parameterization along the lines of STIC
  - SHS-Production of TKE is the main contributor to an improved CAT-forecast with COSMO
  - Preoperational ICON already employs (somewhat modified) SHS-production of TKE
    - Including an empirical Ri-dependency introduced by G. Zängl
  - Introducing a missing dependency on turbulence properties in the ST–detrainment terms
  - Fixing the remaining scaling parameter in the SHS-parameterization
  - Introduction/Investigation of missing diffusion by non-turbulent SGS circulations:
    - Testing the impact of horizontal diffusion by SHS-eddies
  - Reformulation of the current very crude estimate of thermal SSO production of CKE

Positive definite solution of prognostic TKE-equation:



3D-extension: horizontal components   GS horizontal shear

additional SGS shear by :

- SHS circulation
- SSO wakes,
- plumes by SGS convection
- (density currents along SSO)

STIC-impact

$$\frac{q^2 - q_0^2}{2\cdot\Delta t} \approx \left\{ \mathrm{Adv}(q_0) + \mathrm{Dif}(q_0) + \ell\cdot\left[S_0^M\cdot\left(F^M + F_C^M\right) + S_0^H\cdot\left(-F^H\right)\right]\right\}\cdot q - \frac{q_0}{\alpha^{MM}\ell}q^2$$

squared frequencies of: shear >0   buoyancy

$q_0 = q$

forcing: F^M, F_C^M and F^H

$t = t + \Delta t$

horizontal diffusion

impl. vert. diffusion

stability funct.: S^M and S^H

$$\frac{1}{\tau} := \frac{1}{2\Delta t} + \frac{q_0}{\alpha^{MM}\ell} \qquad \frac{2\tau}{q_1} \qquad q_2^2 := \tau\frac{q_0^2}{2\Delta t} \geq 0$$

$$\boxed{q = q_1 + \sqrt{q_1^2 + q_2^2} > \mathbf{0}}$$

- **Numerical security measures and further possible extensions under investigation**:

➢ Explicit lower limit for q:

➢ Exponential time smoothing filter for q:

➢ Limiting negative buoyancy relative to shear:

➢ Vertical smoothing of source due to shear and buoyancy:

➢ Minimal vertical diffusion coefficient:

may cause too much mixing for stable stratification

can possibly be avoided/reduced

in prognostic TKE-equation

for implicit vertical diffusion

➢ Relaxation towards a maximal deviation from TKE-equilibrium: **current method**

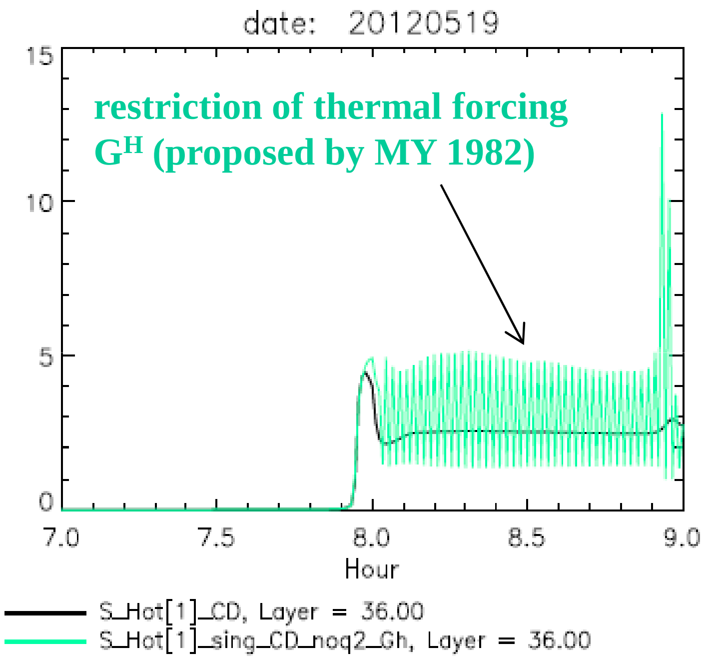
➢ Relaxation of $G^H := \left(\frac{\ell}{q}\right)^2 F^H$ towards its critical value: **possible alternative**

➢ Emulation of neglected transport- and trend-terms equations: **possible alternative**

in linear diagnostic equations resulting in S^M and S^H

Effect of potential singularity of the MY-level-2.5 scheme for growing turbulence and its interception:

SC experiments gained by Ines Cerenzia (Univ. of Bologna)



restriction of thermal forcing G^H (proposed by MY 1982)

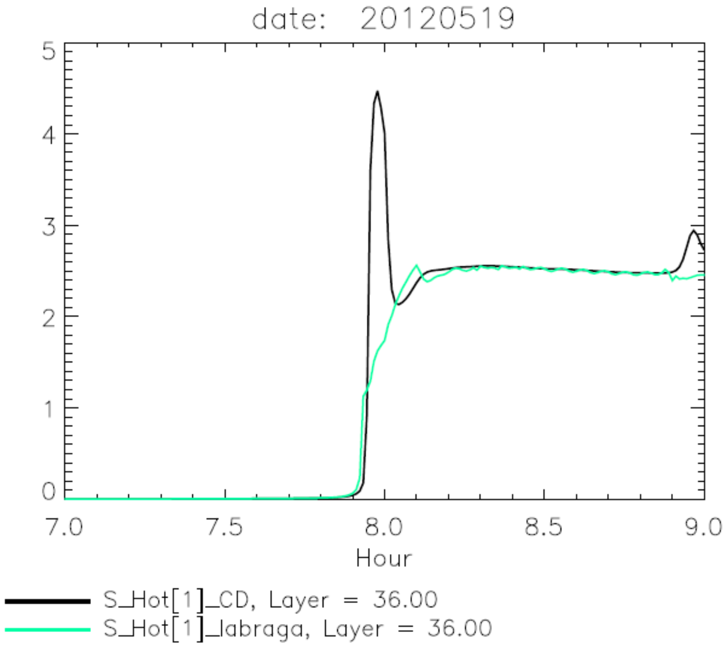
black line:

operational method by formulating the stability parameters as functions of deviation from TKE-equilibrium (γ) and Ri for non-stable situations (according to Raschendorfer)

green line lower right:

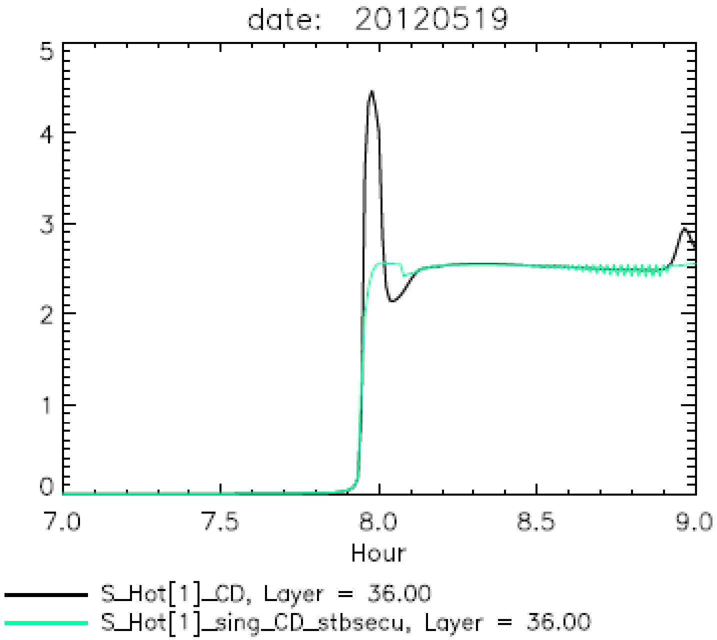
alternative operational method with a modified γ-relaxation (according to Raschendorfer)

S_Hot: stability function S^H for heat flux



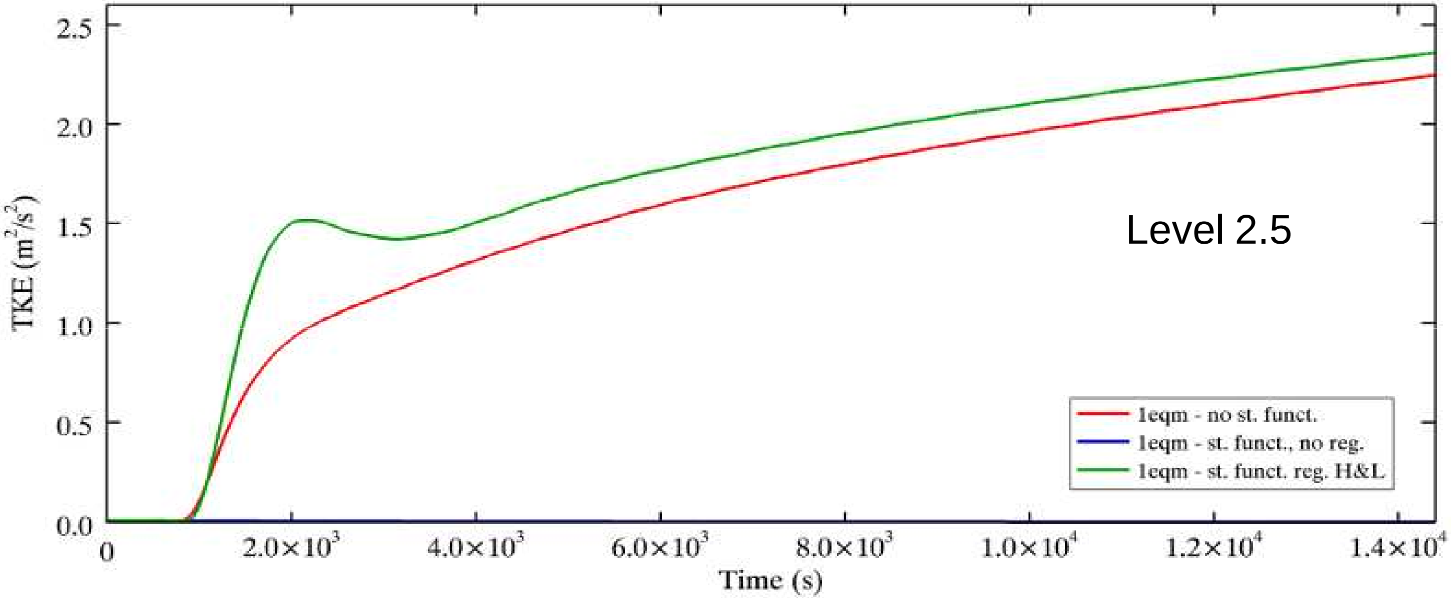
green line lower left:

account for deviation from source term equilibrium for 2-nd order moments apart form TKE (according to Helfand et Labraga 1988)



Regularized Stabiloity Functions for levels 2.5 & 3

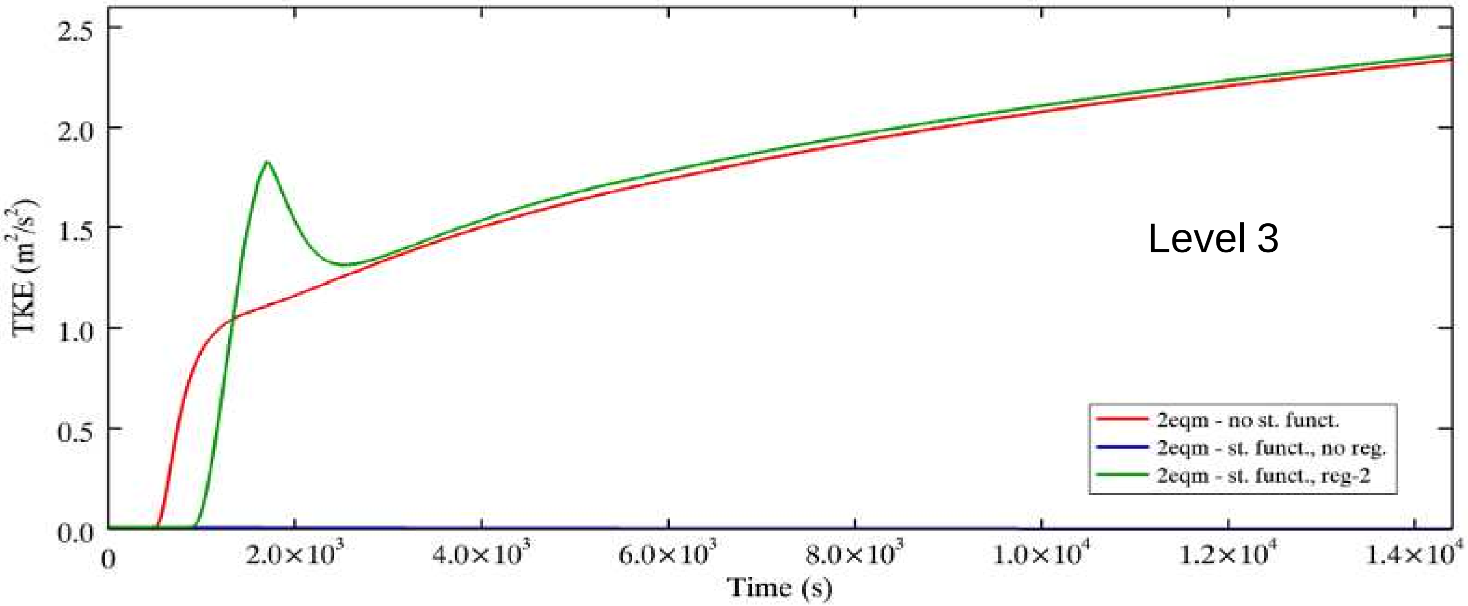
SC-experiments
by E. Maschulskaya
and D. Mironov



Without stab. functions

Without regularization

With regularization



Notes and further steps:

- Consolidation of employed security limits and numerical methods
  - Getting rid of no more necessary limits **->** more realistic simulation of the SBL
  - ➢ ICON-version of TURBDIFF already contains the major reformulations
  - ➢ Automatically influencing the TKE-based **S**urface-to-**A**tmosphere-**T**ransfer (SAT) scheme

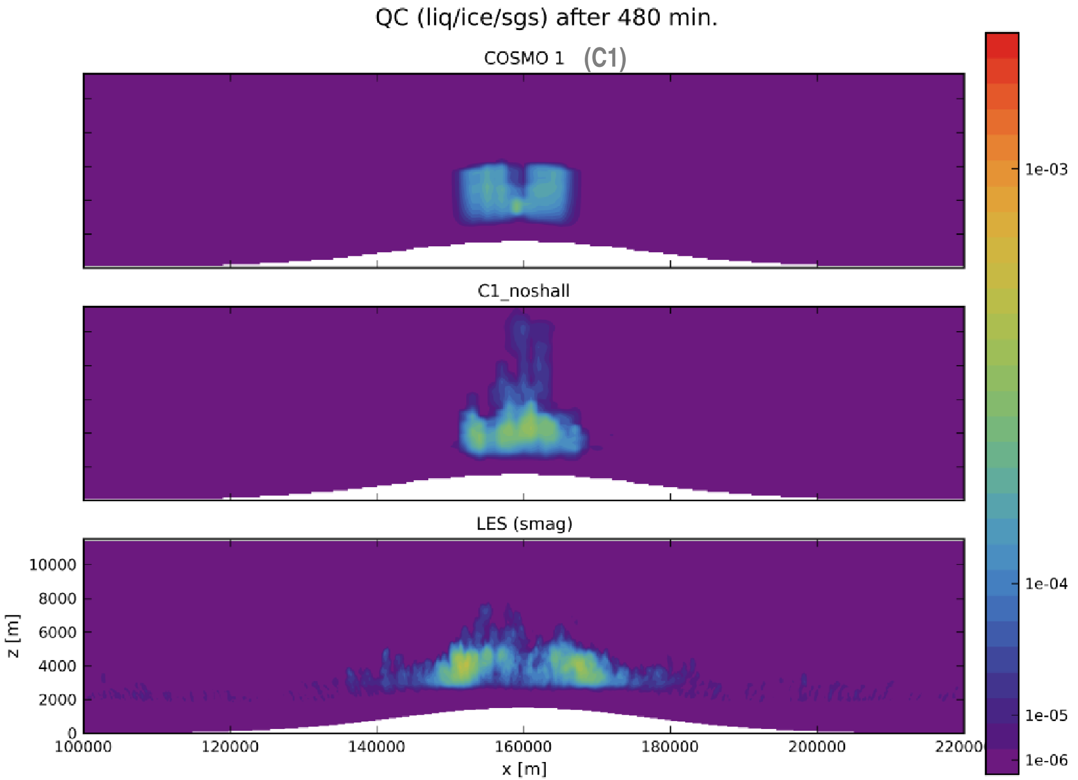
- Investigating further generalization of pure turbulence parameterization
  - Considering more transport terms (explicitly: TKESV or emulated: H/L-approach) in 2-nd order equ.

Work convection permitting model runs:

Tub-i-sim-project : Jürg Schmidli/Steef Böing (MeteoSwiss/ETH Zürich)

- One task of others: Systematic comparison of COSMO-1 with COSMO-LES:
  - Investigation of idealized test cases and real cases
    - o here: initialization of convection above a bell-shape topography (Kirshbaum 2011):

1) x-z chart of total water content by S. Böing)**:**



COSMO-1 with 1 Km horizontal resolution;

prognostic TKE scheme;

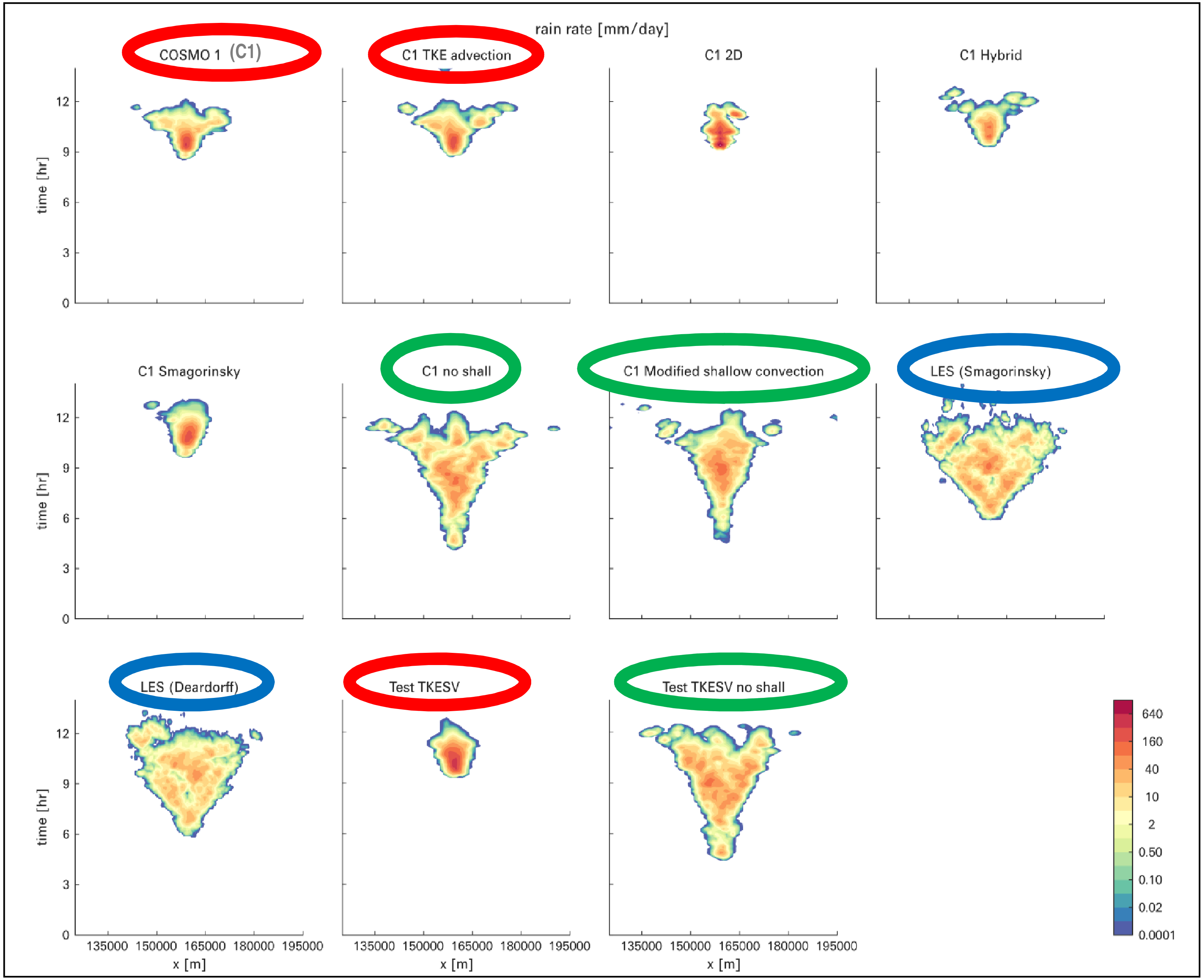
shallow convection scheme active

C1; no shallow convection

COSMO_LES with 100m resolution;

3D-turbulence (here pure Smagorinsky)

2) **t-x charts of rain-rate** (by S. Böing):



- C1 with operational shallow convection too localized precipitation
- runs without or with reduced shallow convection performs better
- no configuration satisfying

Scale Adaptive precipitating convection scheme interacting with turbulence may be the missing link

TKESV: C1 and level 3 turbulence (with progn. Scalar Variances)

Notes and further steps:

- Adequate representation of SGS (shallow) convection
  - Introducing some scale adaptivity
  - Investigating scale interaction with turbulence
  - Testing alternative convection schemes or possible generalizations of turbulence closure
  - …

Thank you for your attention