A TKE-Scalar Variance Mixing Scheme for COSMO

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Outline

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- Formulation of the TKE-Scalar Variance scheme, comparison with TKE scheme
- Single-column tests
- Implementation into the COSMO model
- Future challenges

Towards a Unified Description of Turbulence and Boundary-Layer Convection

A TKE-Scalar Variance Scheme

Key features

- prognostic treatment of TKE and of scalar variances with due regard for the third-order transport
- account for non-local, skewed nature of convective motions
- account for turbulence anisotropy (via advanced parameterizations of pressure scrambling effects)
- improved coupling with statistical cloud scheme

Treatment of Scalar Variances

Prognostic equations for $<u_i'^2>$ (kinetic energy of SGS motions) and for $<\theta_l'^2>$, $<q_t'^2>$, $<q_t'\theta_l'>$ (potential energy of SGS motions) including third-order transport.

Convection/stable stratification =

Potential Energy ↔ Kinetic Energy.

No reason to prefer one form of energy over the other!

The scalar-variance equation

$$\frac{1}{2}\frac{\partial\overline{\theta'^2}}{\partial t} = -\overline{w'\theta'}\frac{\partial\overline{\theta}}{\partial z} - \frac{1}{2}\frac{\partial}{\partial z}\overline{w'\theta'^2} - \varepsilon_\theta$$

non-stationarity

non-homogeneity

Algebraic (equilibrium) formulations for scalar fluxes, Reynolds-stress components, and turbulence length scale

Comparison with One-Equation TKE Schemes
(Draft Horses of Geophysical Turbulence Modelling)

Equation for $<\theta'^2>$

$$\frac{1}{2}\frac{\partial\overline{\theta'^2}}{\partial t} = -\overline{w'\theta'}\frac{\partial\overline{\theta}}{\partial z} - \frac{1}{2}\frac{\partial}{\partial z}\overline{w'\theta'^2} - \varepsilon_\theta$$

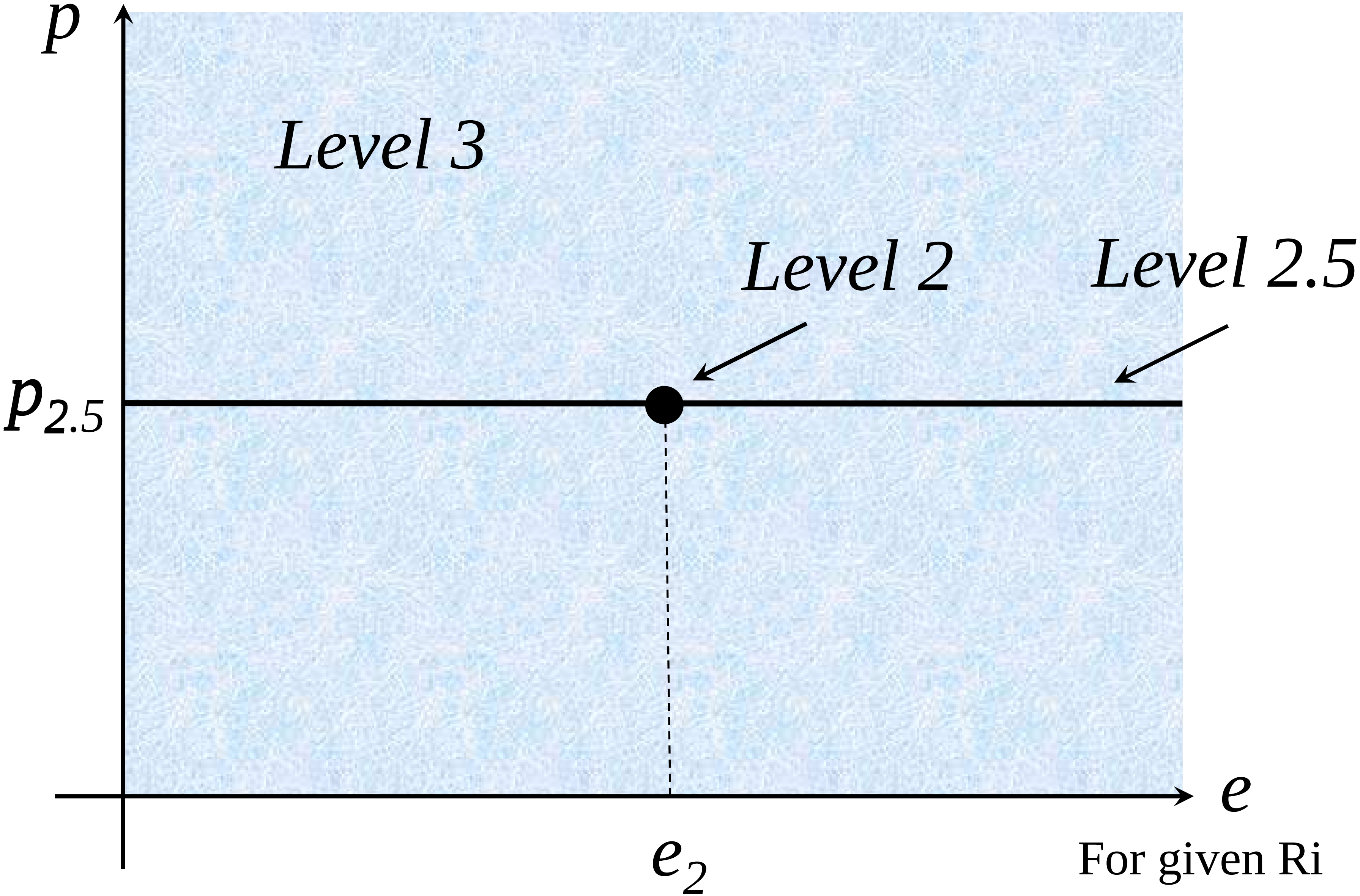
Production = Dissipation (implicit in all models that carry the TKE equations only).

Equation for $<w'\theta'>$

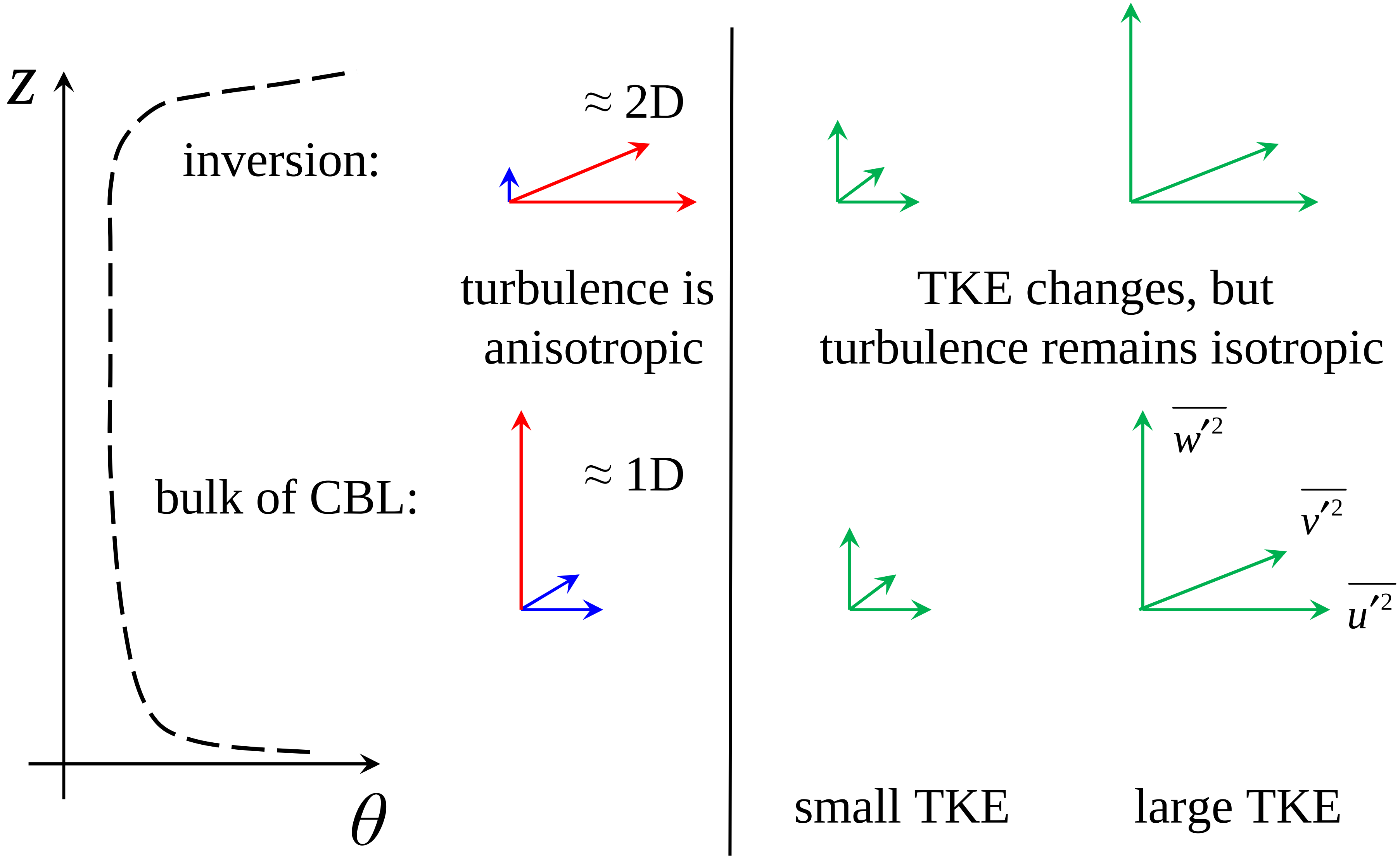
$$\overline{w'\theta'} = -C_{\theta g}\tau_\varepsilon e\frac{\partial\overline{\theta}}{\partial z} + C_{\theta h}\tau_\varepsilon g\alpha\overline{\theta'^2}$$

No way to get counter-gradient scalar fluxes in convective flows unless third-order scalar-variance transport is included (cf. turbulence schemes using "counter-gradient corrections" heuristically).

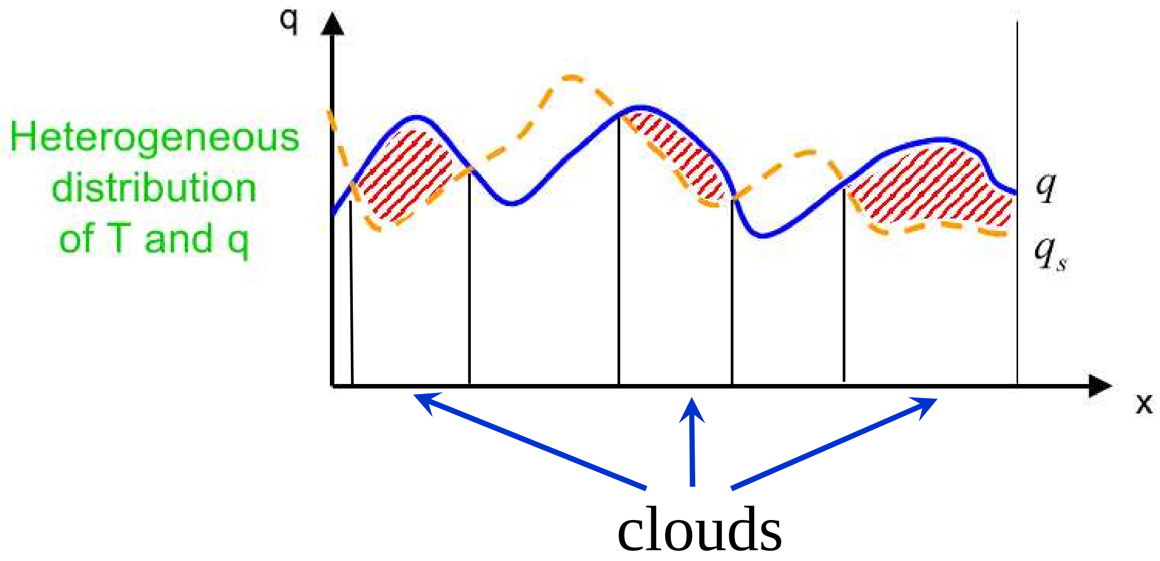
TKESV and TKE Schemes within the Mellor-Yamada Hierarchy



Turbulence Anisotropy

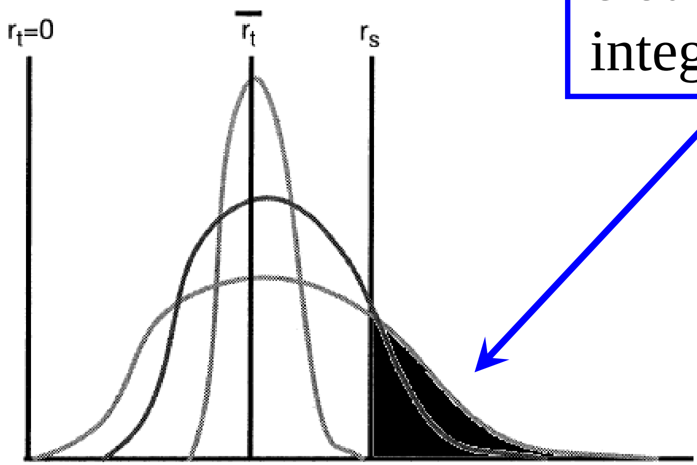


Coupling with Statistical Cloud Scheme



SGS fluctuations of ***q*** and ***q***

after Tompkins (2002)



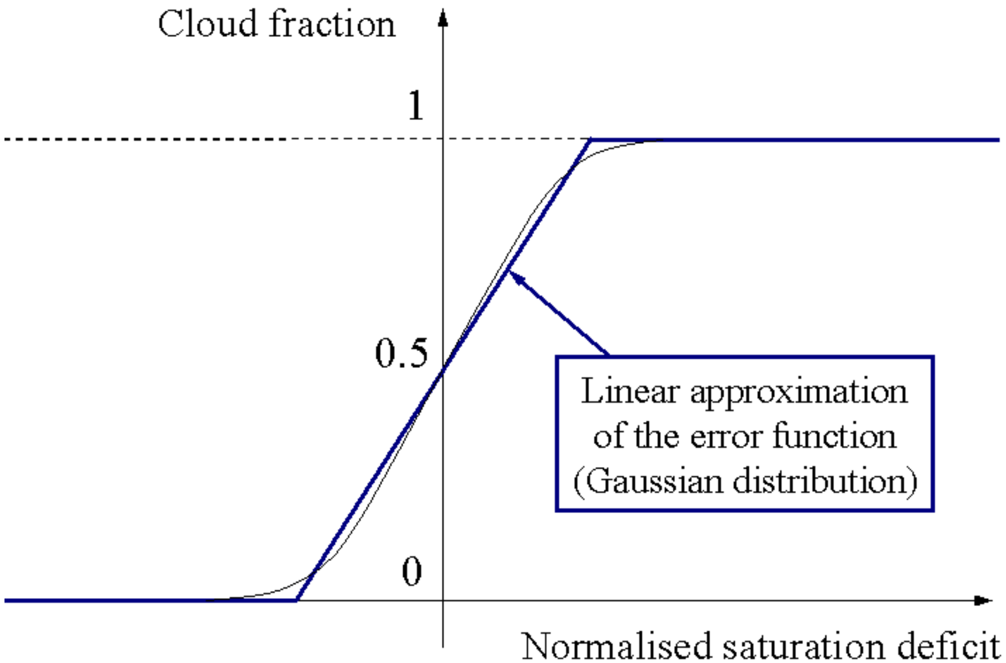
cloud cover, cloud condensate = integrals over supersaturated part of PDF

If a family of PDF is assumed, the only remaining problem is to determine its parameters

Coupling with Statistical Cloud Scheme

Many cloud schemes use (at least) two moments of distribution of θ_l and q_t. Then estimates of scalar variances are required.

For Gaussian cloud scheme, the only predictor is the normalized saturation deficit (combines mean and variance)



$$Q_1 = \frac{\overline{q_t} - q_s(\overline{T_l})}{\sigma_s},$$

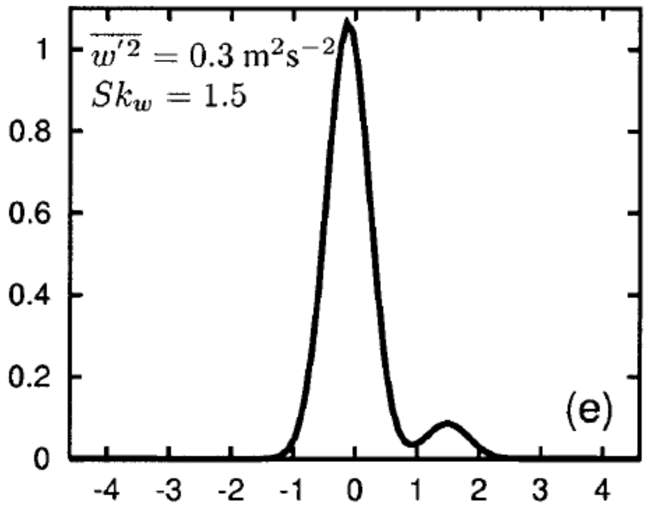
$$\sigma_s^2 = a\left(\overline{q_t'^2} + P^2\overline{\theta_l'^2} - 2P\overline{q_t'\theta_l'}\right)$$

A more accurate estimate of σ_s provided by a mixing scheme will (hopefully) lead to a better cloud forecast.

Coupling with Statistical Cloud Scheme

For shallow cumuli regime (highly localized motions) the Gaussian distribution works badly. Skewness is very important!

A three-moment (mean, variance, and skewness) statistical SGS cloud scheme that is based on the double Gaussian distribution and accounts for non-Gaussian effects (c/o Axel Seifert and Ann Kristin Naumann, Hans Ertel Centre on Cloud and Convection (HErZ), Hamburg) is developed.



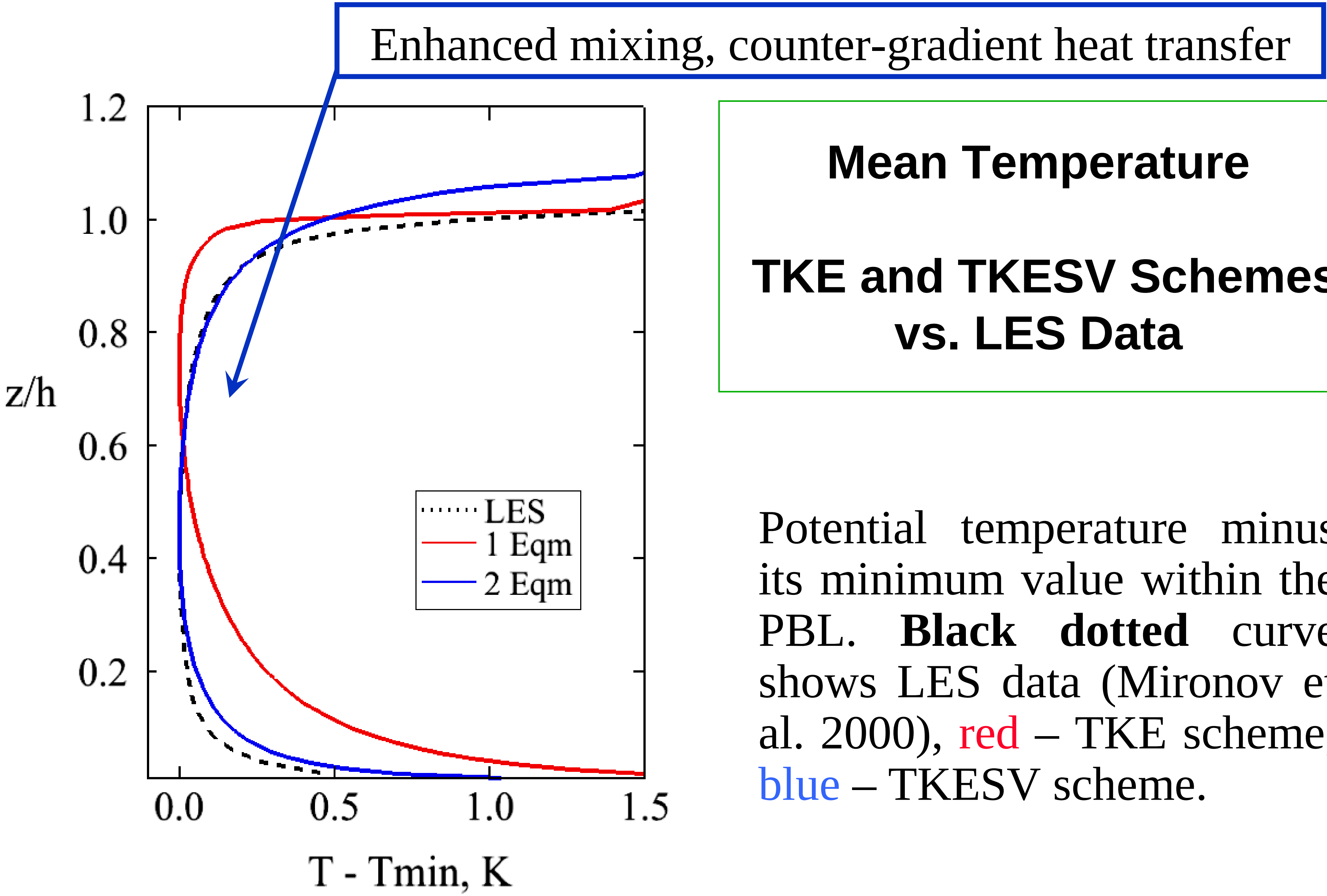
(Golaz et al., 2002)

Scalar variances and skewnesses obtained from TKESV scheme can be used as an input to this clous scheme.

Single Column Tests

- TKESV scheme is favourably tested through single-column numerical experiments (outperforms one-equation TKE scheme)
- Dry PBL: enhanced mixing, up-gradient heat transfer
- Cloudy PBLs (shallow cumuli, stratocumuli): better prediction of scalar variances and TKE, slight improvements with respect to the vertical buoyancy flux and the mean temperature and humidity

Dry Convective PBL

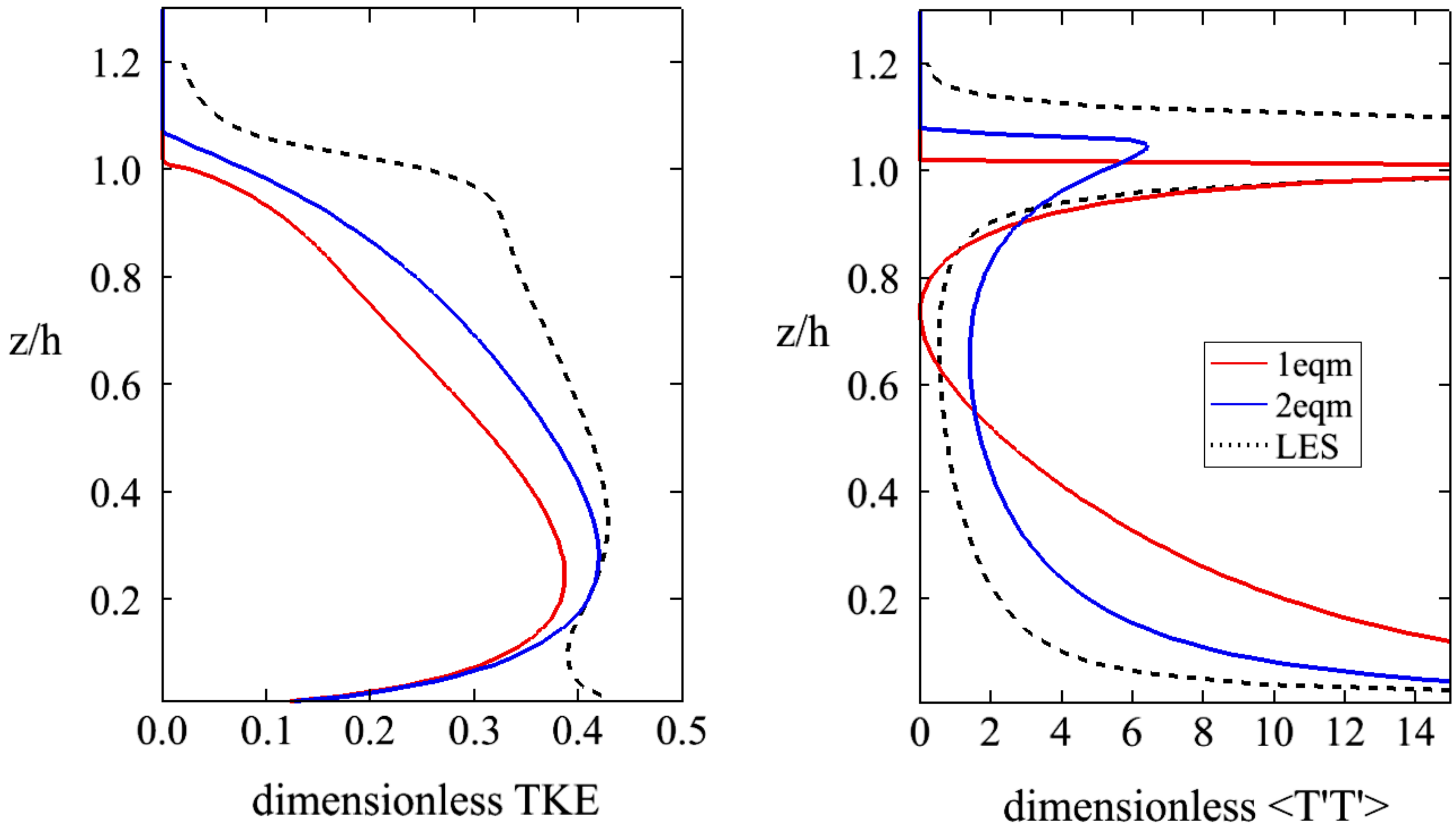


Mean Temperature

TKE and TKESV Schemes vs. LES Data

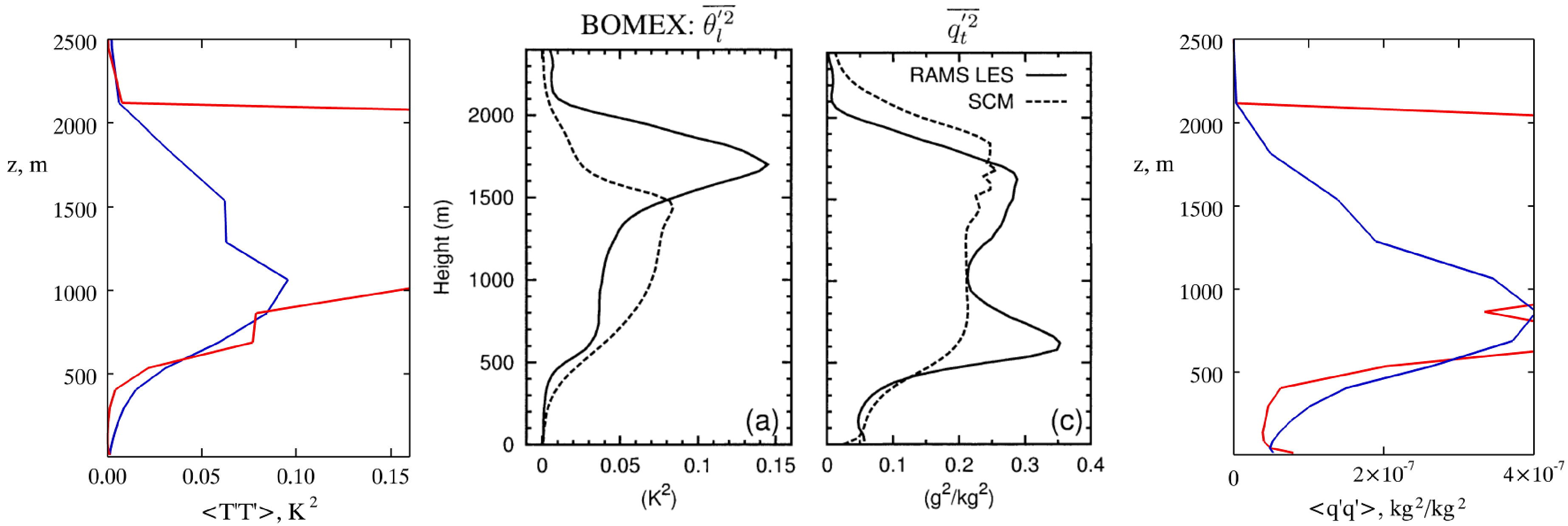
Potential temperature minus its minimum value within the PBL. **Black dotted** curve shows LES data (Mironov et al. 2000), red – TKE scheme, blue – TKESV scheme.

TKE and Potential-Temperature Variance in Convective PBL
TKE and TKESV Schemes vs. LES Data



TKE (left panel) and $<\theta'^2>$ (right panel) made dimensionless with w_*^2 and θ_*^2, respectively **Black dotted** curves show LES data, red – one-equation scheme, blue – two-equation scheme.

Shallow Cumuli (low vertical resolution)



Potential temperature variance (two left panels) and total water variance (two right panels) in BOMEX. Red – TKE scheme, blue – TKESV scheme. **Black solid** curves in the middle figures show LES data.

TKE-Scalar Variance Scheme within 3d COSMO Model

- Prognostic equations for $<u_i'^2>$ and for $<\theta_l'^2>$, $<q_t'^2>$ and $<\theta_l' q_t'>$ including third-order transport
- Algebraic (diagnostic) formulations for scalar fluxes and Reynolds-stress components (with due regard for anisotropy), and for turbulence length (time) scale
- Statistical SGS cloud scheme, either Gaussian or skewed (ad hoc correction)
- Optionally, prognostic equations for scalar skewness (affects fractional cloud cover and buoyancy production of TKE)

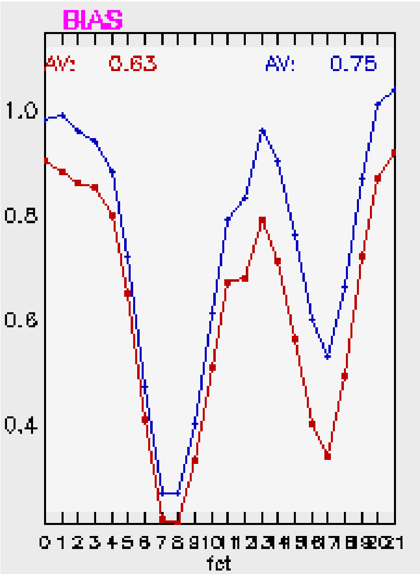
NB! A scheme should be reasonably inexpensive in terms of computation cost (hence diagnostic treatment of Reynolds stress and scalar fluxes)

TKESV vs. COSMO Oper

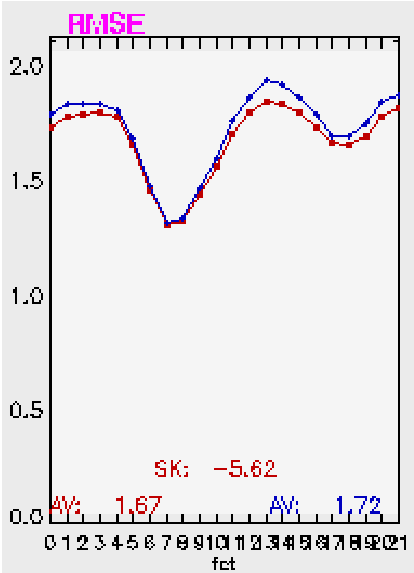
COSMO-DE, July – September 2011

2m temperature

Bias

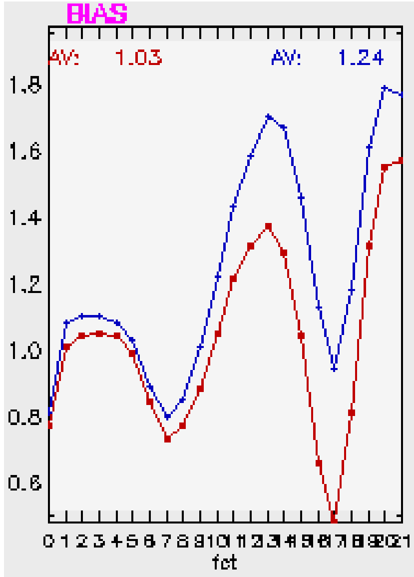


RMSE

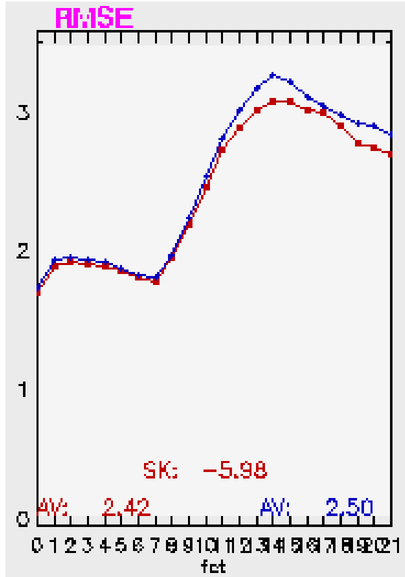


2m dew point depression

Bias



RMSE

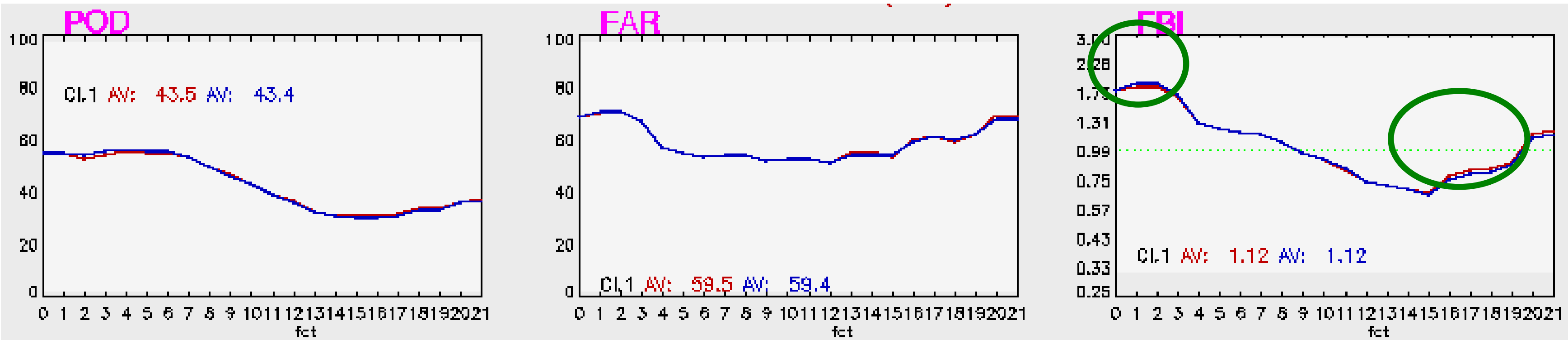


Experiment vs. **Operational**

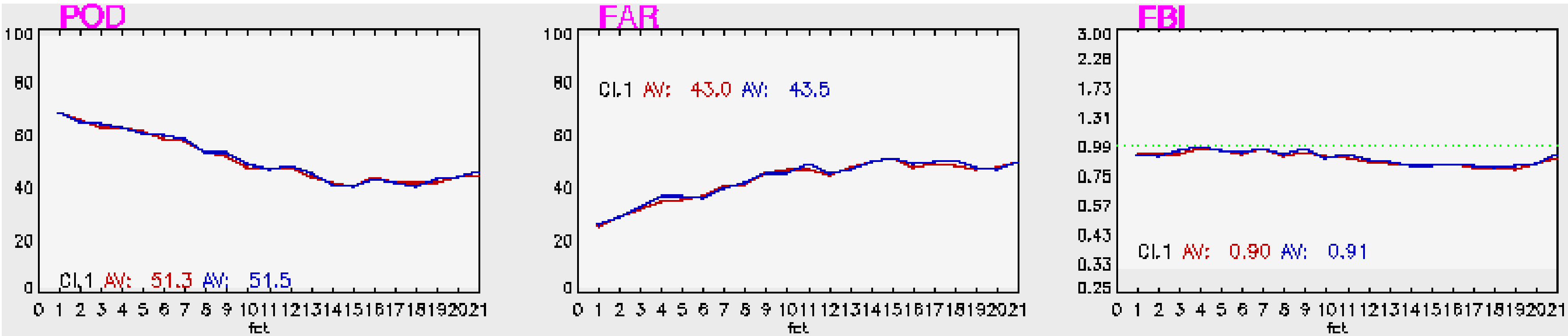
TKESV vs. COSMO Oper

COSMO-DE, July – September 2011

Low clouds



Precipitation



Future Challenges

Skewness-dependent “diffusion + advection” parameterizations of the third-order moments in the scalar-variance equations

- The skewness-dependent parameterizations are developed and tested and are available as an option within the TKESV scheme. These parameterizations require smaller time step (numerical stability) and are not recommended for immediate implementation into COSMO.

Coupling with the three-moment statistical cloud scheme

- Further development and comprehensive testing of transport equations for the skewness of scalar quantities, coupling the skewness equations with the three-moment statistical cloud scheme (mean, variance, and skewness; co-operation with Axel Seifert and Ann Kristin Naumann, HErZ on Cloud and Convection, Hamburg)

Thanks for your kind attention!

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Features of TKESV Scheme Pertinent to Stably Stratified PBLs

- accounts for two-component states of turbulence (fluctuations in the vertical direction are suppressed by gravity) through the use of advanced formulations for pressure scrambling terms in the Reynolds-stress and scalar-flux equations
- accounts for enhanced mixing due to horizontal heterogeneity of the underlying surface through the use of tile approach to determine grid-box mean fluxes and variances, where individual profiles of soil temperature and humidity are computed for each tile