The two-energies turbulence scheme coupled to the assumed PDF method

Ivan Bašták Ďurán (1,2), Mirjana Sakradzija (2,3), and Juerg Schmidli (1,2)

Goethe University Frankfurt[1], Hans Ertel Centre for Weather Research [2], Deutscher Wetterdienst[3]

Overview

1. 2TE scheme
2. Update of the 2TE scheme
3. Results
4. Summary

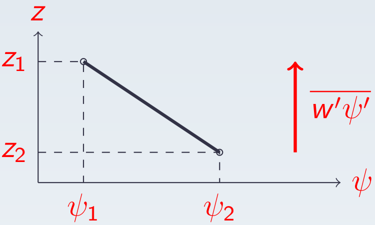
- Separate modelling of turbulence and clouds in Atmospheric Boundary Layer (ABL) causes inconsistencies.
- Unified parameterization of turbulence and clouds should improve the representation of interactions and transition of processes.
- A parameterization based on two prognostic energies and the Assumed Probability Density Function (APDF) approach for modelling both turbulence and clouds is presented here.

Local down-gradient turbulent diffusion

$$\overline{u'w'} = -K_M \frac{\partial u}{\partial z}, \quad \overline{v'w'} = -K_M \frac{\partial v}{\partial z},$$

$$\overline{\theta_l' w'} = -K_H \frac{\partial \theta_l}{\partial z}, \quad \overline{q_t' w'} = -K_H \frac{\partial q_t}{\partial z},$$

K_M and K_H - turbulent diffusion coefficients for momentum and heat/moisture



Turbulent diffusion coefficients in TKE scheme

$$K_M = \frac{\nu^4}{C_\epsilon}\chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3\frac{\nu^4}{C_\epsilon}\phi_3(Ri_f^*)\sqrt{e_k}L$$

Turbulent diffusion coefficients in TKE scheme

$$K_M = \frac{\nu^4}{C_\epsilon}\chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3\frac{\nu^4}{C_\epsilon}\phi_3(Ri_f^*)\sqrt{e_k}L$$

- TKE - measure of turb. intensity

Turbulent diffusion coefficients in TKE scheme

$$K_M = \frac{\nu^4}{C_\epsilon}\chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3\frac{\nu^4}{C_\epsilon}\phi_3(Ri_f^*)\sqrt{e_k}L$$

- TKE - measure of turb. intensity
- length scale - scale of the problem

Turbulent diffusion coefficients in TKE scheme

$$K_M = \frac{\nu^4}{C_\epsilon}\chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3\frac{\nu^4}{C_\epsilon}\phi_3(Ri_f^*)\sqrt{e_k}L$$

- TKE - measure of turb. intensity
- length scale - scale of the problem
- stability functions - influence of stratification

Turbulent diffusion coefficients in TKE scheme

$$K_M = \frac{\nu^4}{C_\epsilon}\chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3\frac{\nu^4}{C_\epsilon}\phi_3(Ri_f^*)\sqrt{e_k}L$$

- TKE - measure of turb. intensity
- length scale - scale of the problem
- stability functions - influence of stratification
- closure constants

ν - free parameter, C_3 - inverse Prandtl number at neutrality, Ri_f^* - stability parameter in the form of flux Richardson number: $Ri_f \equiv (\frac{g}{\theta_v}\overline{\theta_v' w'})/(\overline{u'w'}\frac{\partial u}{\partial z} + \overline{v'w'}\frac{\partial v}{\partial z})$

Prognostic TKE equation

$$\frac{d e_k}{dt} = \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) + I + II - \epsilon_k,$$

$$e_k \equiv \frac{\overline{u'u'} + \overline{v'v'} + \overline{w'w'}}{2} \quad \text{-Turbulence Kinetic Energy (TKE)}$$

$$I \equiv -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} \quad \text{-Shear term},$$

$$II \equiv \frac{g}{\theta_v}\overline{\theta'_v w'} = E_{q_t}\overline{q'_t w'} + E_{\theta_l}\overline{\theta'_l w'} \quad \text{-Buoyancy term}$$

$$\epsilon_k \equiv \frac{2\, e_k}{\tau_k} \quad \text{-Dissipation term}$$

K_{e_k} - turb. exchange coefficients for e_k; τ_k and τ_s - are dissipation time scales; E_{q_t} and E_{θ_l} are cloud-dependent weights.

The two-energies turbulence scheme (2TE)

$$\frac{d e_k}{dt} = \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) + \boxed{I + II - \frac{2\,e_k}{\tau_k}},$$

$$\frac{d e_s}{dt} = \frac{\partial}{\partial z}\left(K_{e_s}\frac{\partial e_s}{\partial z}\right) + \boxed{I - \frac{2\,e_s}{\tau_s}},$$

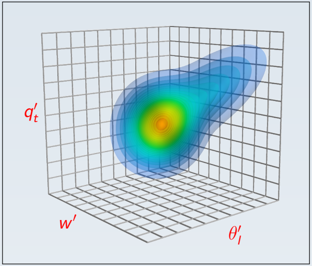
$$e_s \equiv e_k + \frac{E_{q_t}\overline{q_t'^2}}{2\frac{\partial q_t}{\partial z}} + \frac{E_{\theta_l}\overline{\theta_l'^2}}{2\frac{\partial \theta_l}{\partial z}},$$

$$Ri_f^{TE} = \frac{e_s - e_k}{e_s + e_k\left(\frac{C_4}{2\,C_3} - 1\right)}$$

K_{e_s} - turb. exchange coefficients for e_s; τ_s - dissipation time scale

APDF method

Trivariate PDF



PDF shape given

C - Cloud fraction, θ_v - virtual potential temperature

APDF method

Input

Available

$\overline{w}$ $\overline{q_t}$ $\overline{\theta'_l}$

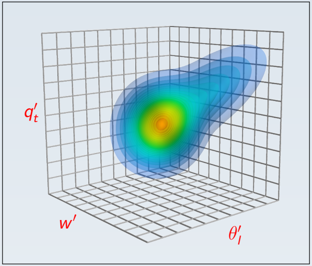
$\overline{w'\theta'_l}$ $\overline{w'q'_t}$ $\overline{w'^2}$

Additional

$\overline{\theta_l'^2}$ $\overline{q'_t\theta'_l}$

$\overline{q_t'^2}$ $\overline{w'^3}$

Trivariate PDF



estimate PDF from model state

PDF shape given

C - Cloud fraction, θ_v - virtual potential temperature

APDF method

Input

Available

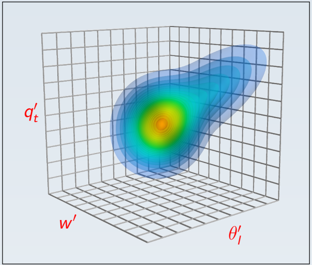
$\overline{w}$, $\overline{w'\theta_l'}$, $\overline{q_t}$, $\overline{w'q_t'}$, $\overline{\theta_l'}$, $\overline{w'^2}$

Additional

$\overline{\theta_l'^2}$, $\overline{q_t'^2}$, $\overline{q_t'\theta_l'}$, $\overline{w'^3}$

estimate PDF from model state

Trivariate PDF



PDF shape given

Output

Cloud related variables

C, $\overline{w'\theta_v'}$, ...

Higher order Moments

$\overline{w'^2q_t'^2}$, $\overline{w'^3q_t'}$, $\overline{w'^4}$, ...

analytical integration of PDF

C - Cloud fraction, θ_v - virtual potential temperature

2TE+APDF (1)

- the buoyancy term, *II*, is computed via APDF
- The stability parameter is computed from local gradients (Ri_f^{GR}) and turbulence energies: $Ri_f^{*} = C_{Ri_f}\, Ri_f^{\mathrm{GR}} + (1 - C_{Ri_f})\, Ri_f^{\mathrm{TE}}$
- Turbulence exchange coefficient for TOMs:

$$K_{e_k} = K_{e_s} = \left(C_{e_k} \overline{w'^2} + C_{\theta_s} \frac{g}{\theta_0} \overline{w'\theta'_s} \tau_k \right) \tau_k,$$

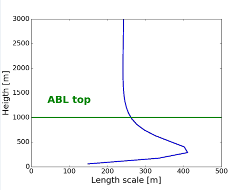
$$\overline{w'^3} = -K_{e_k} \frac{\partial \overline{w'^2}}{\partial z}$$

C_{e_k}, C_{θ_s}, and C_{Ri_f} - closure constants, $Ri_f^{GR} \equiv Ri \frac{K_H}{K_M}$ - computed from conventional gradient Richardson number, $\overline{w'\theta'_s}$ turbulent flux of the entropy potential temperature (Marquet and Geleyn, 2014)

- Canuto et al. (2007) - dry case:
  $$\overline{w'^3} = -A_1 \frac{\partial \overline{w'^2}}{\partial z} - A_2 \frac{\partial \overline{w'\theta'}}{\partial z} - A_3 \frac{\partial \overline{\theta'^2}}{\partial z}$$
  $$A_1 = \left(a_1 \overline{w'^2} + a_2 \frac{g}{\theta_0} \tau \overline{w'\theta'} \right) \tau$$
- simplification for moist 2TE+APDF:
  $$A_2 = A_3 = 0, \ \overline{w'\theta'} = \overline{w'\theta'_s}$$

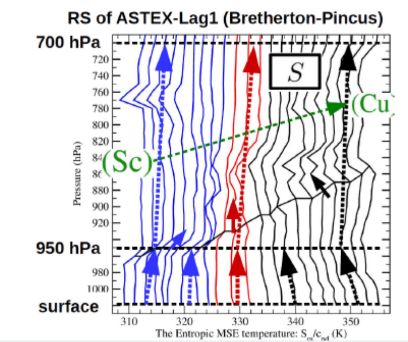
2TE+APDF (2)

- Turbulence length scale:



$$
\begin{aligned}
L &= \frac{\left(C_K\, C_\epsilon\right)^{\frac{1}{4}}}{C_K} \frac{\kappa z}{1+\frac{\kappa z}{\lambda_m}\left[\frac{1+\exp\left(-a_m\sqrt{\frac{z}{H_{\rm abl}}}+b_m\right)}{\beta_m+\exp\left(-a_m\sqrt{\frac{z}{H_{\rm abl}}}+b_m\right)}\right]}, \\
H_{\rm abl} &= C_{ablh}\sqrt{\int_z L_{up} dz}, \\
\Delta\theta_s \leq -C_{\beta_m} &: \quad \beta_m = \beta_m^u, \\
\left(\Delta\theta_s \geq -C_{\beta_m}\right) \& \left(\Delta\theta_s \leq C_{\beta_m}\right) &: \quad \beta_m = \frac{\beta_m^u}{2}\left(1-\frac{\Delta\theta_s}{C_{\beta_m}}\right), \\
\Delta\theta_s > C_{\beta_m} &: \quad \beta_m = 0, \\
\Delta\theta_s &= \theta_s\left(z=1.5H_{\rm abl}\right)-\theta_s\left(z=0\right)
\end{aligned}
$$

- $\beta_m \sim$ entrainment
- $\Delta\theta_s \sim$ entrainment

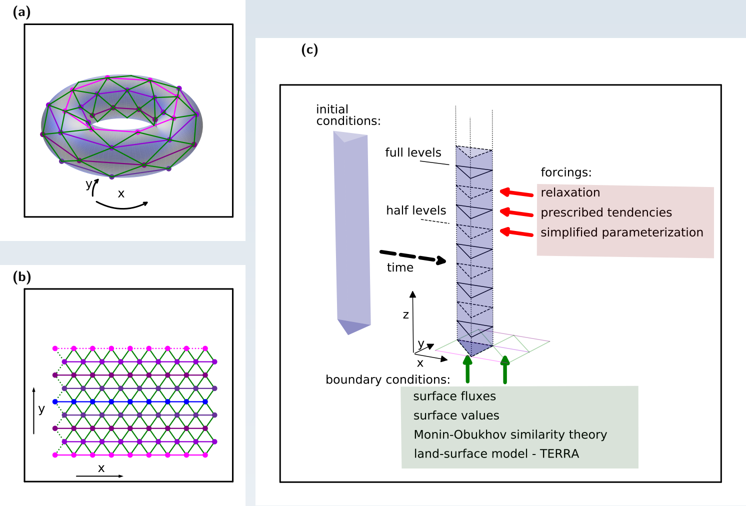


Marquet and Bechtold (2021)

ICON experiments

- Two modes:
  - Single Column Mode (SCM) : Torus grid (8x8), no dynamics
  - Cloud Resolving Mode (CRM) : Torus grid(100x100, 2.5km), with dynamics
- Two setups:
  - NWP : ICON operational turbulence and convection scheme
  - 2TE+APDF : Two-energies scheme with APDF (without convection par.)

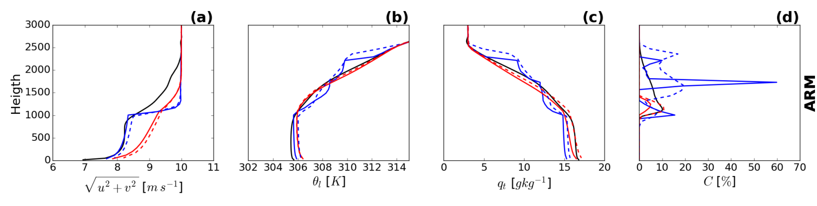
ICON SCM and ICON CRM-PER

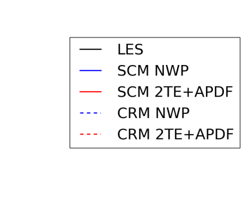


ICON experiments (2)

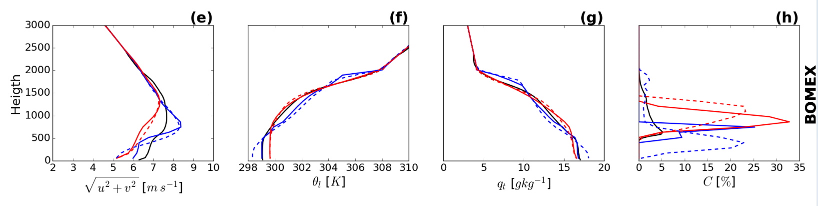
- MicroHH (van Heerwaarden et al., 2017) LES is used as reference.
- Four idealized cases:
  - ARM: Continental shallow,
  - BOMEX: Non-precipitating trade cumulus,
  - DYCOMS-II: Stratocumulus,
  - GABLS(1): weakly stable stratification

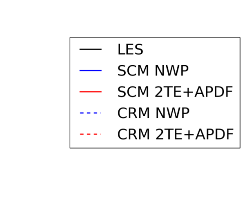
Vertical profiles after 8 hours if integration ARM



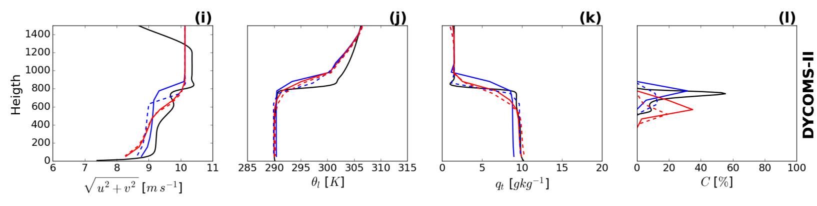


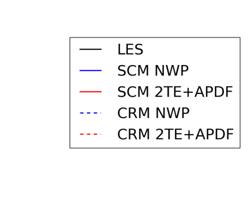
Vertical profiles after 8 hours if integration BOMEX



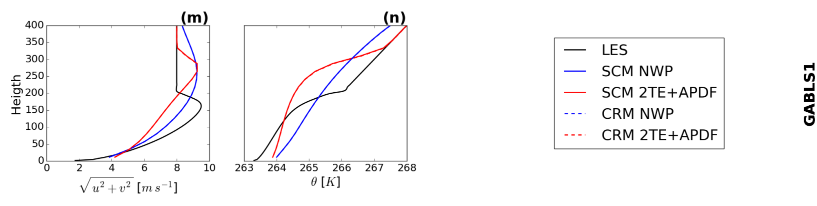


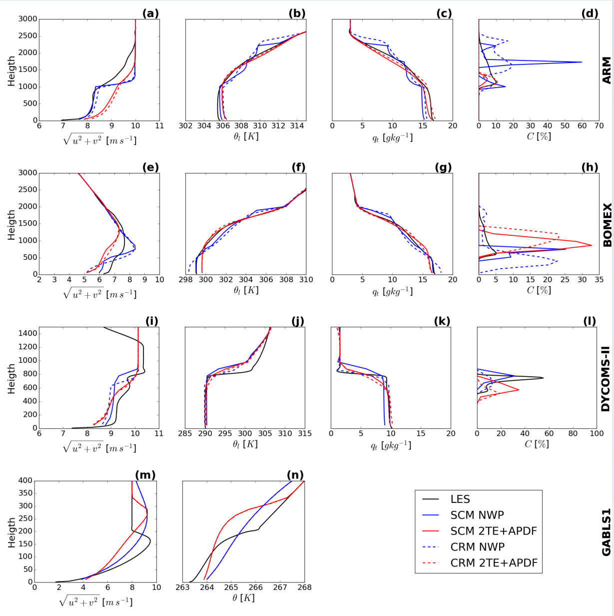
Vertical profiles after 8 hours if integration DYCOMS-II



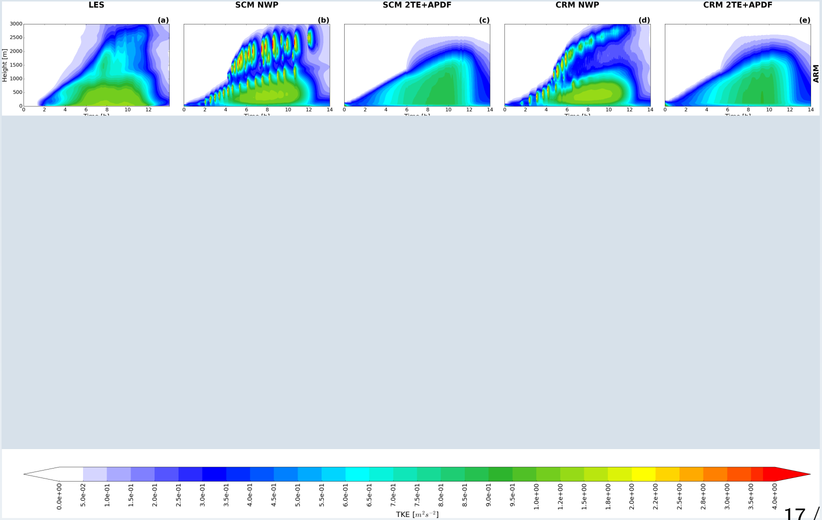


Vertical profiles after 8 hours if integration GABLS(1)

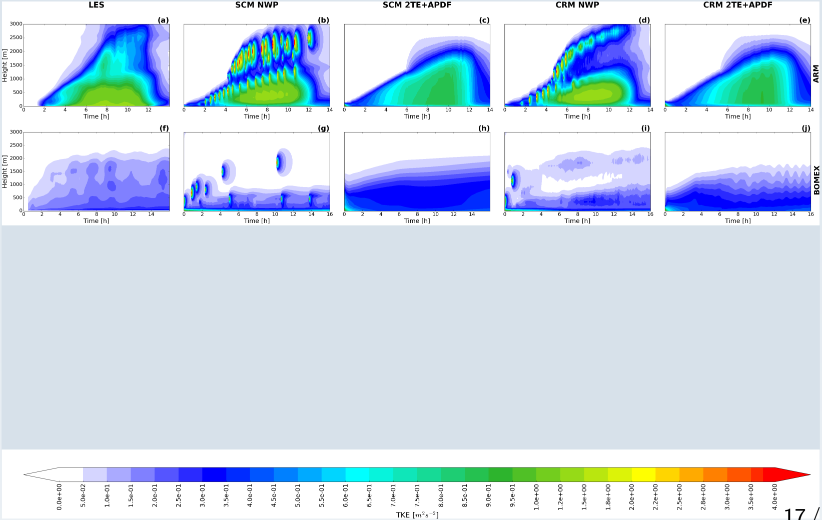



(a)
(b)
(c)
(d)
ARM
(e)
(f)
(g)
(h)
BOMEX
(i)
(j)
(k)
(l)
DYCOMS-II
(m)
(n)
GABLS1
Heigth
$\sqrt{u^2+v^2}$ $[m\,s^{-1}]$
θ_l $[K]$
q_t $[gkg^{-1}]$
C $[\%]$
θ $[K]$
LES
SCM NWP
SCM 2TE+APDF
CRM NWP
CRM 2TE+APDF

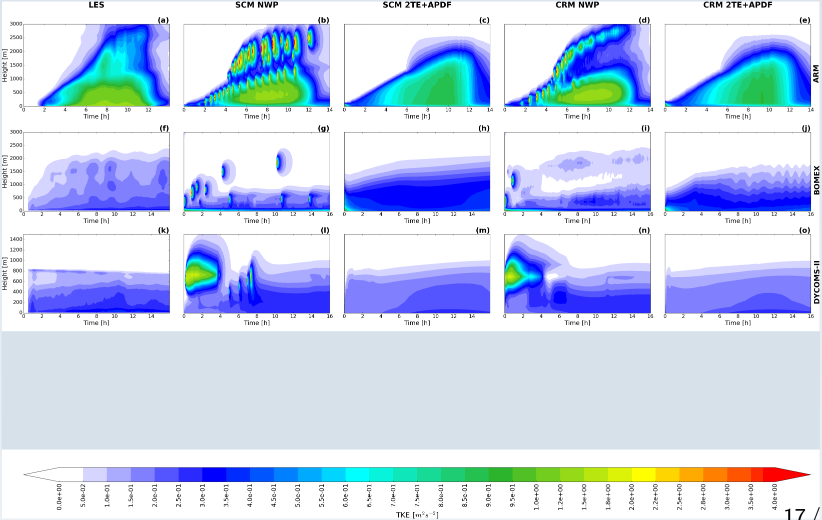
Evolution of TKE



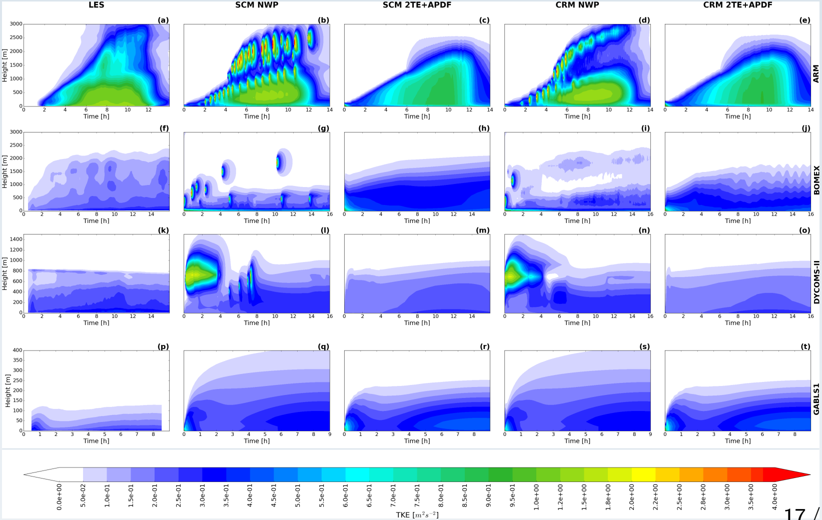
Evolution of TKE



Evolution of TKE

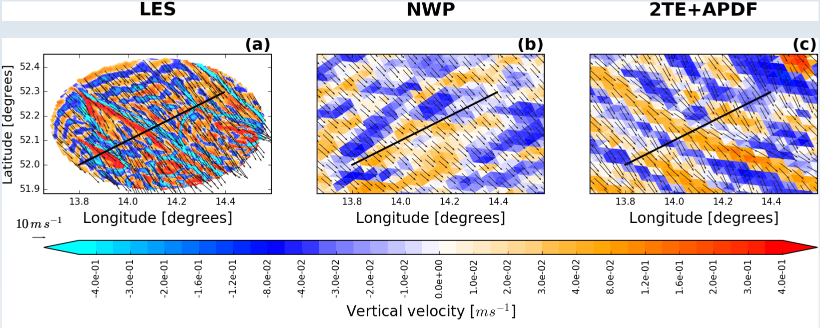


Evolution of TKE



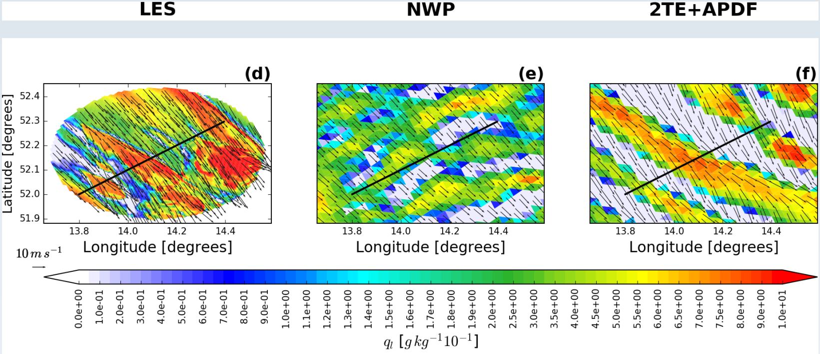
Real case - 13.06.2021 : cloud streets

Horizontal cross section at 1900 m



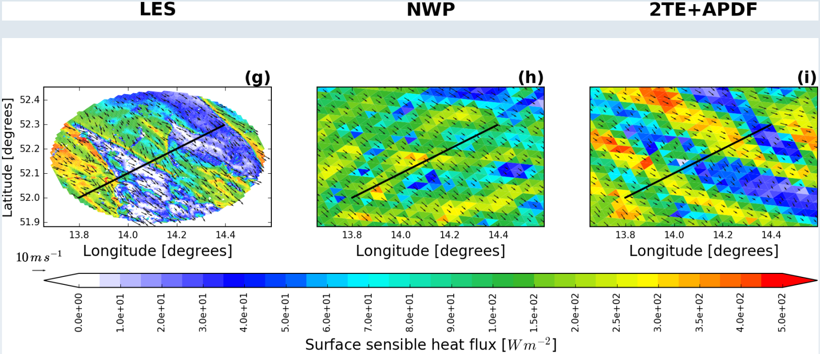
Real case - 13.06.2021 : cloud streets

Horizontal cross section at 1900 m



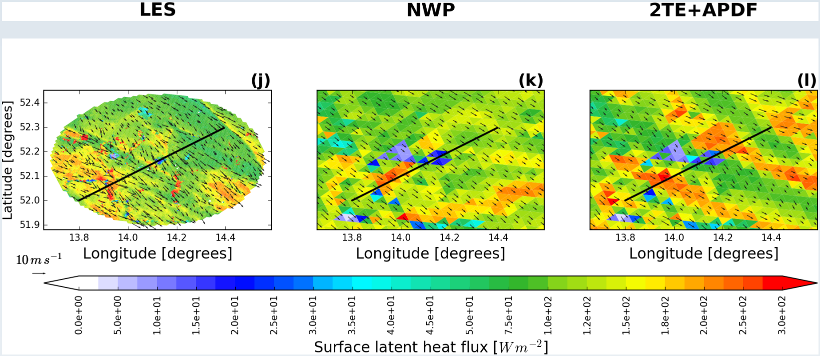
Real case - 13.06.2021 : cloud streets

Horizontal cross section at 1900 m



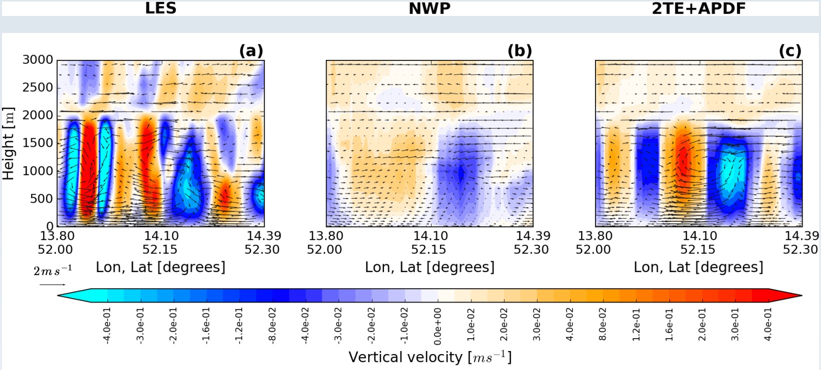
Real case - 13.06.2021 : cloud streets

Horizontal cross section at 1900 m



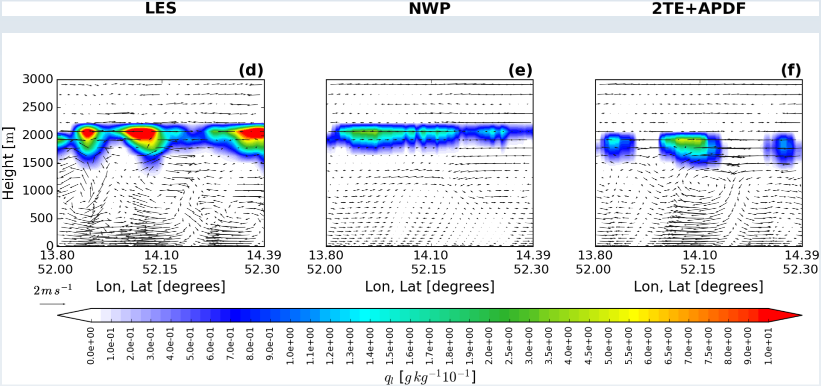
Real case - 13.06.2021 : cloud streets

Vertical cross section



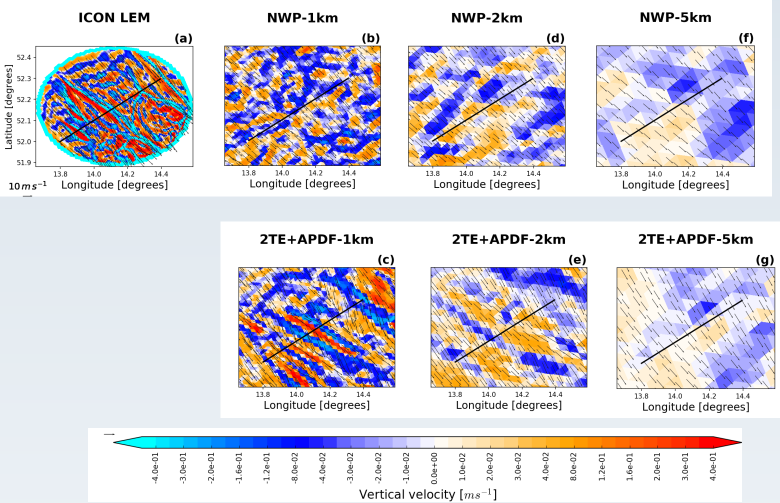
Real case - 13.06.2021 : cloud streets

Vertical cross section



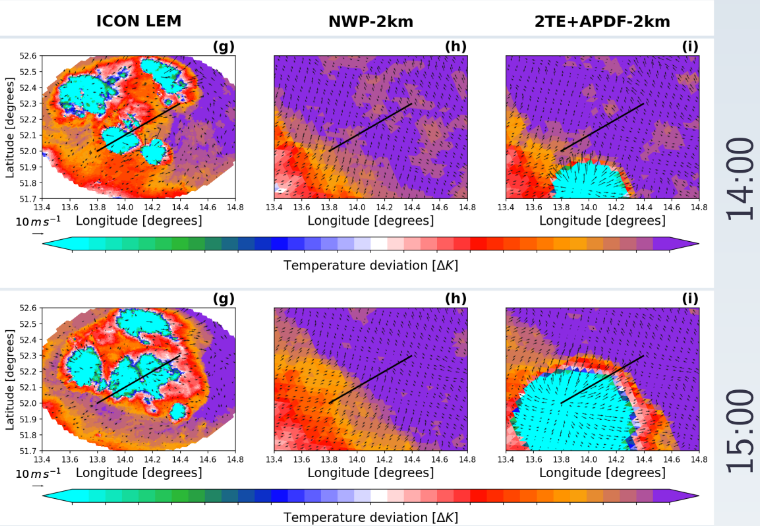
Real case - 13.06.2021

Resolution dependence



29.06.2021 14:00 and 15:00 - cold pool

Horizontal cross sections - 10 m



Conclusion (1)

- 2TE+APDF scheme is implemented in full ICON code
- 2TE+APDF scheme has been updated to correct over-estimation of mixing:
  - combination of the non-local stability parameter with a local stability parameter
  - bulk vertical gradient of the entropy potential temperature is used to distinguish between a shallow convection and a stratocumulus
  - an update of the turbulence length scale formulation

Conclusion (2)

- based on selected cases, the 2TE+APDF scheme can be considered as an alternative to the operational turbulence and shallow convection scheme in ICON
- 2TE+APDF scheme improves the coupling with dynamics, which is beneficial for the modeling of coherent flow structures in the ABL

Thank you for your attention!