Operational version of turbulence scheme TOUCANS

Ivan Bašták Ďurán

ČHMÚ ONPP Prague,
ivanbastak@gmail.com

ČHMÚ

LACE
nwp central europe

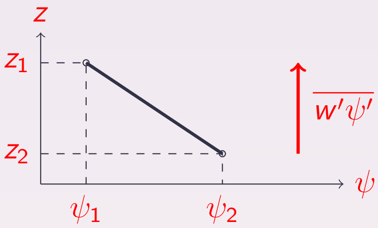
1. Turbulent diffusion
2. Framework of stability dependency functions
3. Scheme with prognostic TKE
4. Scheme with prognostic TKE and TTE/TPE
5. Third Order Moments parametrisation
6. Code organisation
7. Scores
8. Summary

TOUCANS

- T - Third
- O - Order moments (TOMs)
- U - Unified
- C - Condensation
- A - Accounting and
- N - N-dependent
- S - Solver (for turbulence and diffusion)

Turbulent flux

- $\overline{w'\psi'} = -K_\psi \frac{\partial\bar{\psi}}{\partial z}$ -upper air
- $\overline{w'\psi'} = C_\psi \sqrt{u^2 + v^2}\,(\psi - \psi_s)$ - surface layer



$\bar{}$ - average, $'$ - fluctuation, u, v, w - wind components, z - height, ψ - diffused variable

Diffused variables

- u, v - horizontal wind components
- q_t -total specific moisture
- $s_{sL} = c_{pd}\left(1 + \left[\frac{c_{pv}}{c_{pd}} - 1\right] q_t\right) T + g\,z - (L_v\,q_l + L_s\,q_i)$ - moist static energy
- K_M, K_H - coefficients of turbulent diffusion for momentum and heat
- C_D, C_H - drag coefficients for momentum and heat

$q_{l/i}$ - specific humidity of air for liquid or ice water, $L_{s/v}$ latent heat latent heat of sublimation/vaporization, g - acceleration of gravity, T - air temperature, c_{pd} and c_{pv} specific heat values for dry air and water vapour

Turbulent diffusion

$$\frac{\partial \psi}{\partial t} = -g\frac{\partial \rho \overline{\psi' w'}}{\partial p}$$

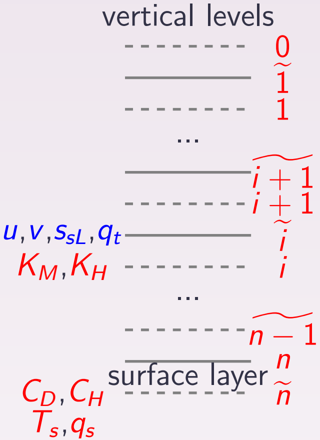
$$\text{upper air}: \frac{\partial \psi}{\partial t} = -g\frac{\partial \rho K_\psi \frac{\partial \psi}{\partial z}}{\partial p},$$

$$\text{surface}: \frac{\partial \psi}{\partial t} = -g\frac{\partial \rho C_\psi \left(\psi_n - \psi_s\right)}{\partial p}$$

$$\widetilde{\psi_i^+} - \widetilde{\psi_i^-} = -g\frac{\Delta t}{\delta p_i}[K'_{\psi,i}\left(\widetilde{\psi_i^+} - \widetilde{\psi_{i+1}^+}\right) - K'_{\psi,i-1}\left(\widetilde{\psi_{i-1}^+} - \widetilde{\psi_i^+}\right)]$$

leads to inversion of 3-diagonal matrix

$$K'_\psi = -\frac{\rho K_\psi}{\Delta z}$$



Δt - time step, ρ - density, p - pressure

Exchange coefficients

$$K_M = \frac{\nu^4}{C_\epsilon} L \chi_3 \sqrt{e_k}, \qquad K_H = C_3 \frac{\nu^4}{C_\epsilon} L \phi_3 \sqrt{e_k}$$

- $\chi_3(\Pi, \nu, C_\epsilon, C_3, O_\lambda)$, $\phi_3(\Pi, \nu, C_\epsilon, C_3, O_\lambda)$
  - stability dependency functions
  (Bašták, Ď. I., J.-F. Geleyn , and F. Váňa , 2014)
- $e_k = \frac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right)$
  - Turbulence Kinetic Energy
- $\Pi = \frac{e_t - e_k}{e_k}$, e_t- Turbulence Total Energy
  - based on Zilitinkevich et al.(2013)
- ν, C_ϵ, C_3, O_λ - free parameters
- L - length scale

Drag coefficients

$$C_D = \left(\frac{\kappa}{\ln\left(1 + \frac{z}{z_0}\right)} \right)^2 F_M(Ri_B),$$

$$C_H = \left(\frac{\kappa^2}{\ln\left(1 + \frac{z}{z_0}\right) \ln\left(1 + \frac{z}{z_{0h}}\right)} \right)^2 F_H(Ri_B)$$

$$F_M(Ri_B) = \chi_3(Ri_B).f(Ri_B)$$

$$F_H(Ri_B) = C_3 \frac{\phi_3(Ri_B)}{\chi_3(Ri_B)}.F_M(Ri_B)$$

$$Ri_B > 0 \; : \; f(Ri_B) = \chi_3(Ri_B) - C_3\,\phi_3(Ri_B)\; Ri_B$$

$$Ri_B \leq 0 \; : \; f(Ri_B) = 1$$

Ri_B - bulk Richardson number, κ - Von Karman constant, $z_{0/0h}$ - roughness lengths

Stability functions χ_3,ϕ_3:

- derived from TKE and TTE equations at equilibrium
- no existence of critical Ri - Ri_{cr}
- anisotropy of turbulence:
  - $\frac{\partial \chi_3}{\partial Ri} \neq 0$
  - $\phi_3 = \underbrace{\phi_Q(Ri)}_{\text{anisotropy}} \underbrace{\left(1 - \frac{2\, O_\lambda\, e_k}{C_4\, \overline{w'^2}} \Pi\right)}_{\text{energy conversion}}, \; \frac{\partial \phi_Q}{\partial Ri} \neq 0$
- valid for whole range of Ri

(Ri -gradient Richardson number, C_4 - coefficient)

Framework of stability functions:

- based on Cheng et al. (2002) scheme:
  - anisotropy included
  - with Ri_{cr}
- modification that avoid existence of Ri_{cr} result in general shape:

$$\chi_3(Ri) = \frac{1-\frac{Ri_f}{R}}{1-Ri_f} \quad , \phi_3(Ri) = \frac{1-\frac{Ri_f}{P}}{1-Ri_f} \quad ,$$

$$\phi_Q(Ri) = \frac{1-\frac{Ri_f}{Q}}{1-Ri_f} \quad , \frac{Ri}{Ri_f} = \frac{P(R-Ri_f)}{C_3\, R\,(P-Ri_f)}$$

$$0 < \lim_{Ri\to\infty} P = Ri_{fc} < 1,\ Ri_{fc} < \lim_{Ri\to\infty} R \equiv R_\infty \leq 1,\ Ri_{fc} \leq \lim_{Ri\to\infty} Q \equiv Q_\infty \leq 1.$$

($Ri_f = Ri\, K_H/K_M$ - flux Richardson number, $Ri_{fc} = \lim_{Ri\to\infty} Ri_f$ - critical Ri_f)

Framework of stability functions:

- the turbulent scheme then depends on:
  - 4 free parameters - (C_ϵ, C_3 , ν, O_λ),
    - following Schmidt and Schumann (1989)
    we assume: $C_\epsilon = \pi \, \nu^2$
  - 3 "functional dependencies" (P, R, Q)
- 4 possible realisations:

	Model I	Model II	eeQNSE	eeEFB
P	Const.	Const.	Const.	Ri fun.
R	Const.	Const.	Ri fun.	Ri fun.
Q	Const.	Ri fun.	Ri fun.	Ri fun.

- emulation and extension
  eeQNSE : of QNSE - Sukoriansky et al. (2005)
  eeEFB : of EFB - Zilitinkevich et al.(2013)

Prognostic TKE - e_k equation:

- $$\begin{aligned} \frac{de_k}{dt} &= -g\,\frac{\partial}{\partial p}\left(\rho\,K_{e_k}\frac{\partial e_k}{\partial z}\right) + I + II - \frac{2\,e_k}{\tau_k} \\ I &= -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z}, \\ II &= E_{s_{sL}}\,(SCC)\;\overline{w's'_{sL}} + E_{q_t,s_{sL}}\,(SCC)\;\overline{w'q'_t} \end{aligned}$$

- influence of moisture via $E_{s_{sL}}\,(SCC)$ and $E_{q_t,s_{sL}}\,(SCC)$ - weights according to Marquet and Geleyn (2013)
- SCC - Shallow Convection Cloudiness - currently implicitly given by shallow convection parametrisation according to Geleyn (1987)
- SCC used also in turbulent diffusion of $q_{l/i}$

(K_{e_k} - turbulent exchange coefficients for TKE, $\tau_k = \frac{2\,L}{C_\epsilon\,\sqrt{e_k}}$ - dissipation time scale for TKE)

Stability dependent adjustment for turbulent energy modelling - TKE:

$$\frac{d e_k}{dt} = -g \frac{\partial}{\partial p}\left(\rho K_{e_k} \frac{\partial e_k}{\partial z}\right) + \overbrace{\frac{1}{\tau_\epsilon}\left(\widetilde{e_k} - \widehat{e_k}\right)} \quad ,$$

$$\widetilde{e_k} = \frac{\tau_k}{2}\left(I + II\right), \quad K_{e_k} = \frac{\nu^2}{C_\epsilon} L \sqrt{\widehat{e_k}},$$

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

full level variables, half level variables

($\tau_\epsilon = 0.5\tau_k$ -relaxation time scale, $\overbrace{\quad}$ 'overbrace' operator - interpolation from half levels to full levels, $\widehat{\quad}$ 'hat' operator - interpolation from full levels to half levels.)

Stability dependent adjustment for turbulent energy modelling - TKE:

- enables a fully consistent treatment of the prognostic TKE
- enables longer times steps
- avoids difficulties with vertical staggering
  - TKE placed on full levels

Prognostic TTE/TPE

- based on Zilitinkevich et al.(2013)
- addition of second prognostic turbulent energy: Turbulent Potential Energy (TPE), or Turbulent Total Energy(TTE) = TKE+TPE
- stability parameter based on energy ratio (linked to fluxes) rather than on local gradients (Ri)
- enables modelling of counter-gradient heat transport maintained by velocity shear in very stable stratification

Prognostic TTE - e_t equation:

$$\frac{de_t}{dt} = -g\frac{\partial}{\partial p}\left(\rho K_{e_t}\frac{\partial e_t}{\partial z}\right) + I - \frac{2\,e_t}{\tau_t}$$

$$\tau_t \equiv \tau_k \frac{C_4\,(1+\Pi)}{C_4 + 2\,C_3\Pi},$$

$$\Pi \equiv \frac{e_p}{e_k} = \frac{e_t}{e_k} - 1, \quad e_p = \frac{g}{\theta}\frac{\overline{\theta'^2}}{2\frac{\partial\theta}{\partial z}},$$

$$Ri_f = \frac{\Pi}{\frac{C_4}{2\,C_3} + \Pi},$$

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

(e_p - TPE, K_{e_t} - turbulent exchange coefficient for TTE, τ_t - dissipation time scale for TTE, $Ri_f = Ri\,K_H/K_M$ - flux Richardson number, C_4 - coefficient)

Stability dependent adjustment for turbulent energy modelling - TTE:

$$\frac{de_t}{dt} = -g\frac{\partial}{\partial p}\left(\rho K_{e_t}\frac{\partial e_t}{\partial z}\right) + \overbrace{\frac{2}{\tau_t}\left(\widetilde{e}_t - \widehat{e}_t\right)}$$

$$\widetilde{e}_t = \frac{\tau_t}{2} I, \quad K_{e_t} = \frac{\nu^2}{C_\epsilon} L\sqrt{\widehat{e_k}}$$

$$\tau_t = \tau_k \frac{C_4\left(1+\widehat{\Pi}\right)}{C_4 + 2\,C_3\widehat{\Pi}}, \quad Ri_f = \frac{\widehat{\Pi}}{\frac{C_4}{2\,C_3}+\widehat{\Pi}}$$

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

full level variables, half level variables

Third Order Moments(TOMs) parametrisation

- based on Canuto et al., (2007)
- enables modelling of distant turbulent transport of heat caused by presence of semi-organised large eddies
- two step approach - local (down-gradient term only) solution is a reference
- stable and accurate algorithm immune against singularities
- requires iterations to improve accuracy
- influence of time-tendency terms parametrized via scaling factor

TOMs parametrisation:

$$\overline{w's'_{sL}} + A_t \frac{\partial \overline{w'\,s'_{sL}}}{\partial t} = -K_H \frac{\partial s_{sL}}{\partial z} + A_1^{s_{sL}} \frac{\partial \overline{w'^3}}{\partial z} + A_2^{s_{sL}} \frac{\partial \overline{w's'^2_{sL}}}{\partial z} + A_3 \frac{\partial \overline{w'^2 s'_{sL}}}{\partial z}$$

$$\overline{w'q'_t} + A_t \frac{\partial \overline{w'\,q'_t}}{\partial t} = -K_H \frac{\partial q_t}{\partial z} + A_1^{q_t} \frac{\partial \overline{w'^3}}{\partial z} + A_2^{q_t} \frac{\partial \overline{w'q'^2_t}}{\partial z} + A_3 \frac{\partial \overline{w'^2 q'_t}}{\partial z}$$

$$\overline{w's'^2_{sL}} = -\tau_k \overline{w's'_{sL}} \frac{\partial \overline{w's'_{sL}}}{\partial z}, \quad \overline{w'q'^2_t} = -\tau_k \overline{w'q'_t} \frac{\partial \overline{w'q'_t}}{\partial z}$$

$$\overline{w'^2 s'_{sL}} = -0.3\tau_k \overline{w'^2} \frac{\partial \overline{w's'_{sL}}}{\partial z}, \quad \overline{w'^2 q'_t} = -0.3\tau_k \overline{w'^2} \frac{\partial \overline{w'q'_t}}{\partial z}$$

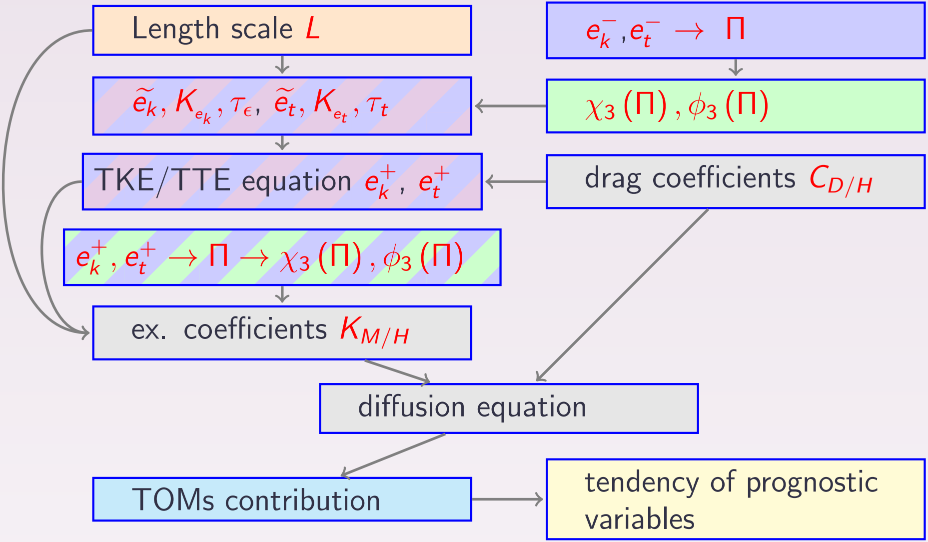
$$\overline{w'^3} = -0.06\tau_k^2 \overline{w'^2} \left(E_{s_{sL}} \frac{\partial \overline{w's'_{sL}}}{\partial z} + E_{q_t, s_{sL}} \frac{\partial \overline{w'q'_t}}{\partial z} \right)$$

($\overline{w'^2}$ - twice the vertical component of TKE, $A_{1/2}^{s_{sL}}$, $A_{1/2}^{q_t}$, A_3, A_t - weights resulting from equations for $\overline{w'^2}$, $\overline{w'\theta'}$ and $\overline{\theta'^2}$)

TOMS - two step solver

- local diffusion: $\frac{\partial \theta^{\mathrm{loc}}}{\partial t} = \frac{\partial\left(-g\rho K_H \frac{\partial \theta^{\mathrm{loc}}}{\partial z}\right)}{\partial p}$
- TOM s contribution computed in terms of :
  - $\delta s_{sL}^{+} = s_{sL}^{+} - s_{sL}^{\mathrm{loc}}$
  - $\delta q_t^{+} = q_t^{+} - q_t^{\mathrm{loc}}$

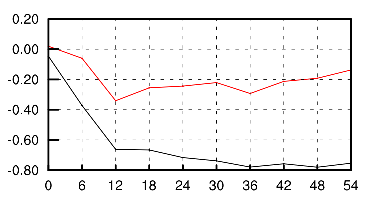
Code organisation



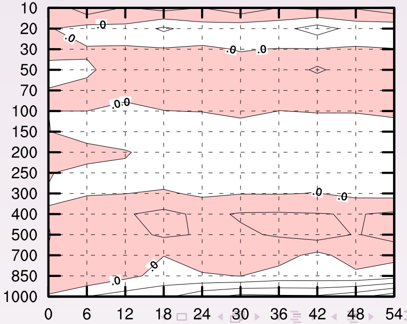
TOUCANS+ACANEB2+update of microphysics

- period:03-23.1.2015, start: 0UTC
- black: ALARO0, red: ALARO1
- score: BIAS

Temperature 2m



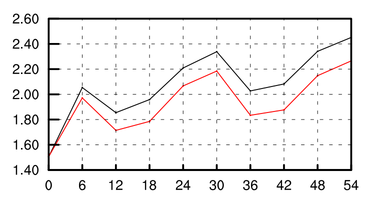
Temperature cross section



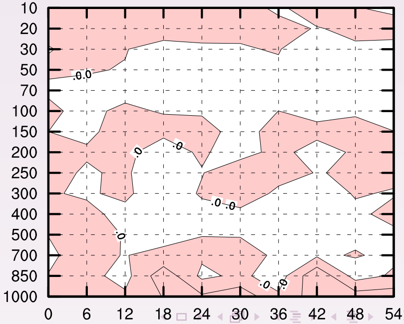
TOUCANS+ACANEB2+update of microphysics

- period:03-23.1.2015, start: 0UTC
- black: ALARO0, red: ALARO1
- score: RMSE

Temperature 2m



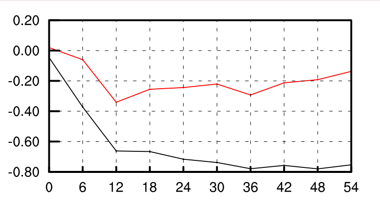
Temperature cross section



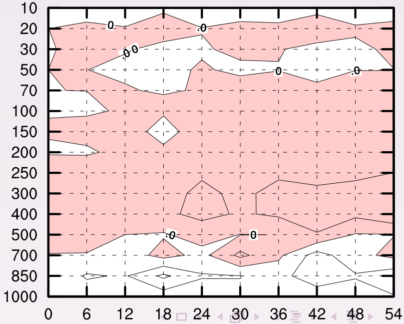
TOUCANS+ACANEB2+update of microphysics

- period:03-23.1.2015, start: 0UTC
- black: ALARO0, red: ALARO1
- score: BIAS

Relative humidity 2m



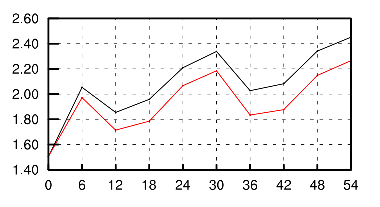
Relative humidity cross section



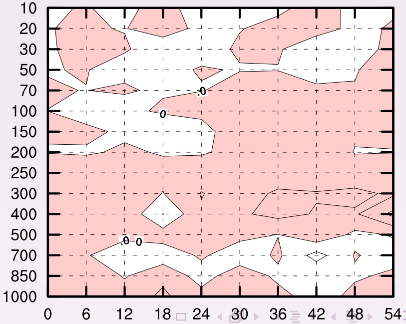
TOUCANS+ACANEB2+update of microphysics

- period:03-23.1.2015, start: 0UTC
- black: ALARO0, red: ALARO1
- score: RMSE

Relative humidity 2m



Relative humidity cross section



Summary:

- operation setup with TOUCANS scheme
  - stability dependency functions χ_3 and ϕ_3 - include anisotropy, no $Ri_c r$
  - 2 prognostic turbulent energies - TKE and TTE
  - moisture influence via definition of moist buoyancy term - SCC influence
  - TOMs parametrisation
- in winter cases increases mixing in PBL - prog.TTE + stab. functions

Thank you for your attention!