

# Improvement of the TOUCANS two-energy scheme

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# Introduction

- ALARO-1 uses the TOUCANS turbulence parameterization with the so-called **two-energy scheme**, operational at CHMI since January 2015
- two prognostic turbulence energies are involved:
  - 1) TKE – turbulence kinetic energy,  $e_k$
  - 2) TTE – turbulence total energy,  $e_s$
- **advantages** of the two-energy scheme over the TKE scheme are **deeper mixing** and **smoother space-time behaviour** (confirmed by LES results)
- **non-locality** of the two-energy scheme, beneficial in unstable environment, **tends to penetrate stable layers**

# The problem

- despite its long operational history, a problem with **noisy turbulent fluxes** in the two-energy scheme was discovered by Luc Gerard only in April 2019
- further investigation showed that the noise is connected to the horizontally uncorrelated  **$\sim 2\Delta t$  oscillations**, occurring in stable stratification
- at first glance the problem resembled **fibrillations** cured by Bénard et al. (2010), but there are some important **differences**:

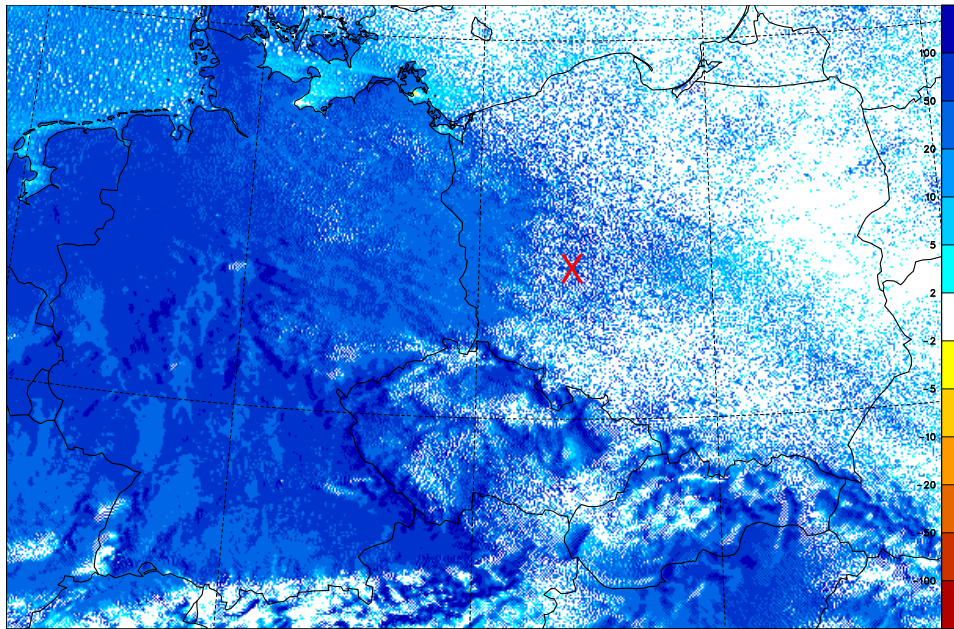
	<b>fibrillations</b>	<b>two-energy scheme oscillations</b>
period	$\sim 4\Delta t$ (leapfrog) $\sim 2\Delta t$ (two-time level)	$\sim 2\Delta t$
occurrence	$\Delta t \gtrsim 100$ s	observed even at $\Delta t = 20$ s
vertical structure	$2\Delta z$ wave	smooth
manifestation	turbulent fluxes, momentum and thermodynamic variables	turbulent fluxes, prognostic turbulence energies

- late discovery of  **$\sim 2\Delta t$  oscillations** in the two-energy scheme was caused by their weak coupling with the momentum and thermodynamic variables

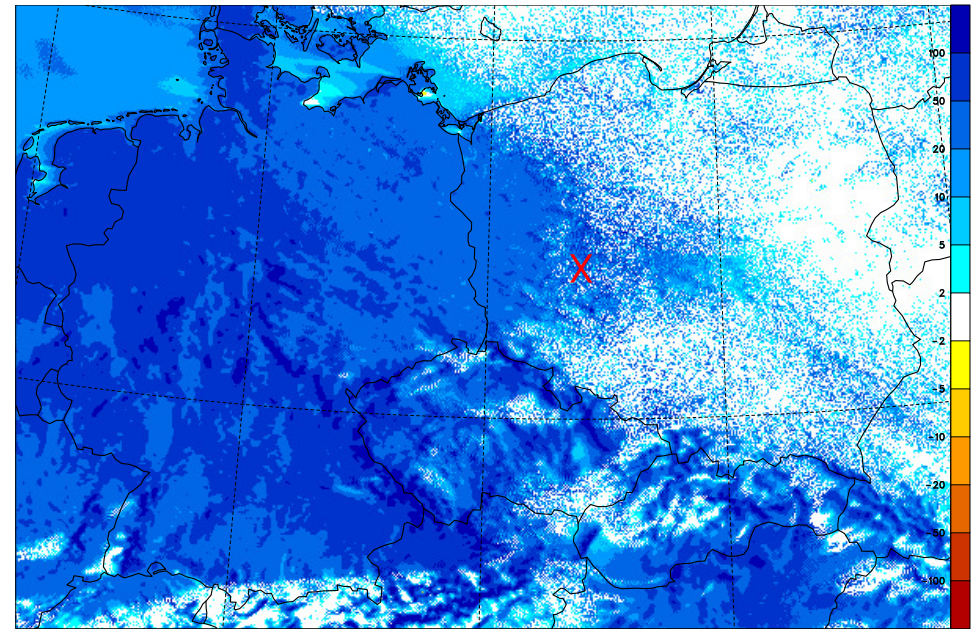
# Short scale noise in the turbulent heat flux

$\Delta x = 2.3 \text{ km}$ , 87 levels

$\Delta t = 90 \text{ s}$



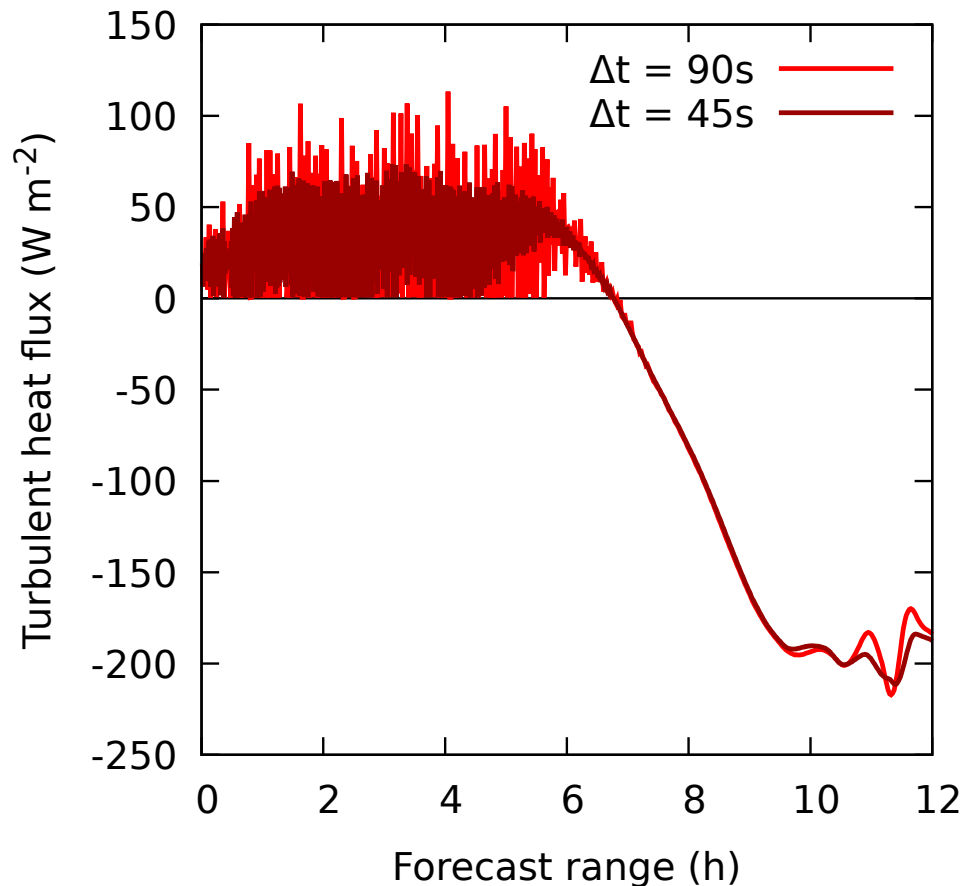
$\Delta t = 45 \text{ s}$



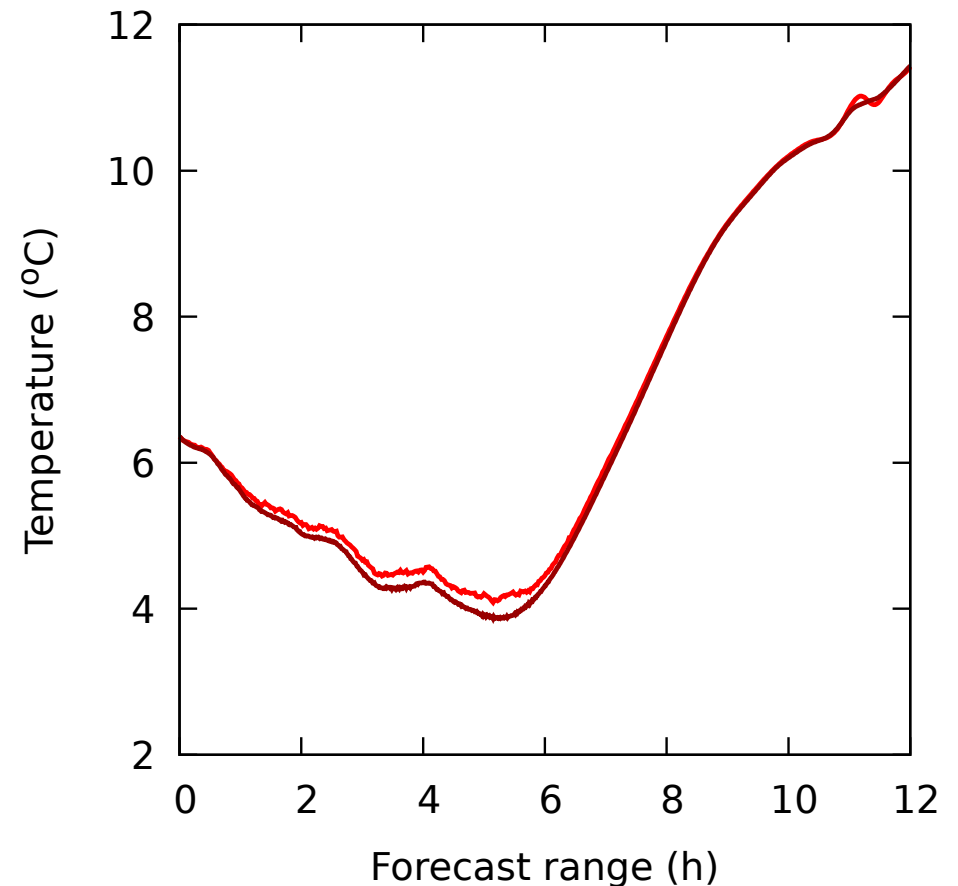
*Turbulent heat flux on the model half level 82 ( $\sim 130 \text{ m}$  above the ground) for 3-hour forecast valid at 0300 UTC 21 April 2020. The flux is positive downwards (blue colors). The red cross denotes point ( $17^\circ \text{ E}$ ,  $52^\circ \text{ N}$ ), inspected on the subsequent plots.*

# Spurious $\sim 2\Delta t$ oscillations

## Turbulent heat flux



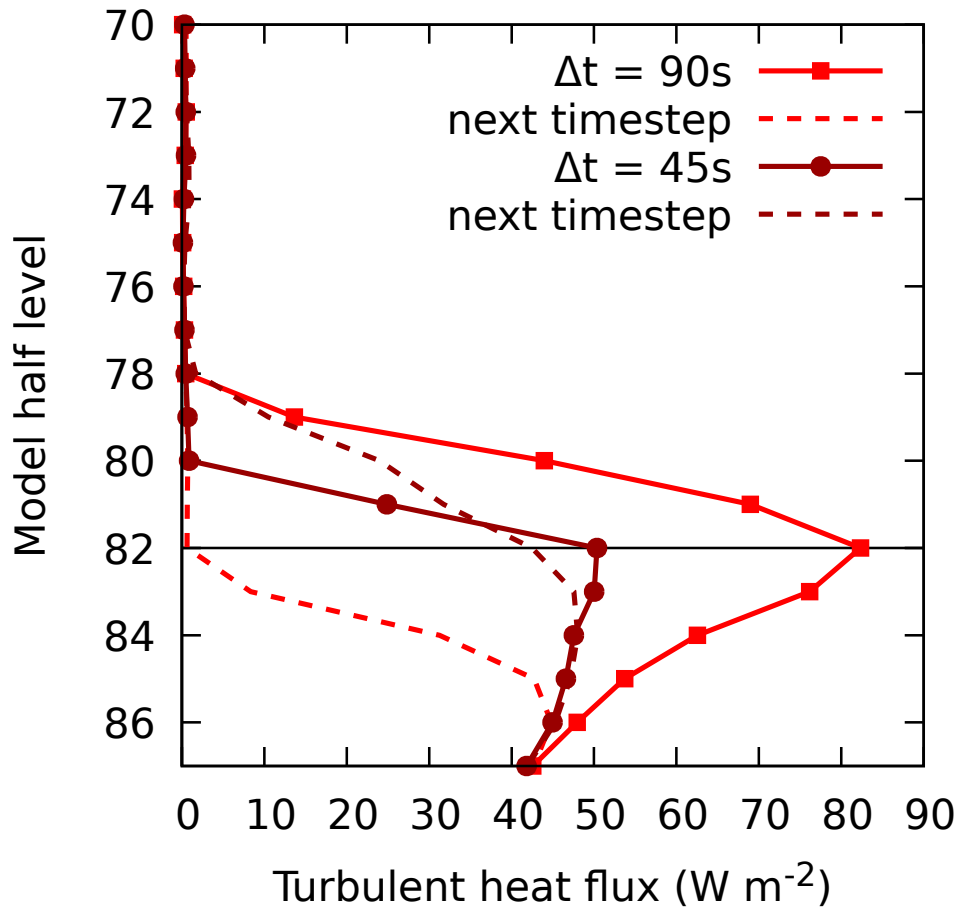
## Temperature



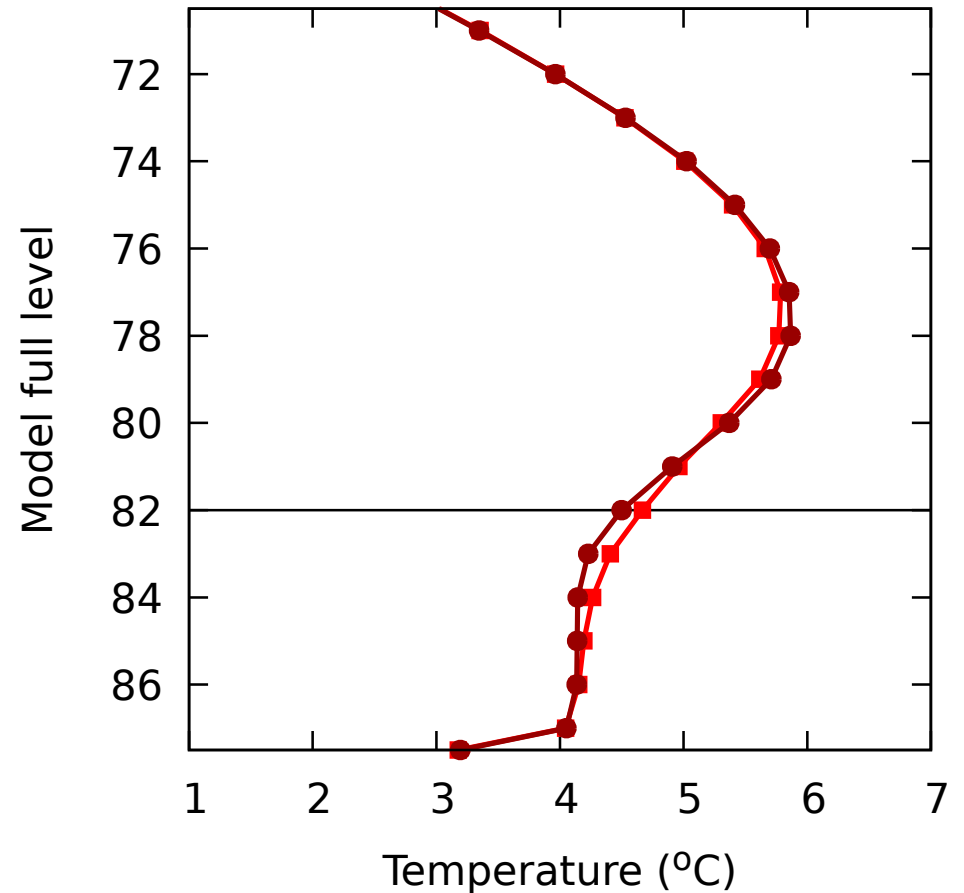
*Evolutions in point ( $17^{\circ}\text{E}$ ,  $52^{\circ}\text{N}$ ) during 12-hour forecast starting at 0000 UTC 21 April 2020. The turbulent heat flux is shown on the model half level 82 ( $\sim 130\text{ m}$  above the ground), temperature on the model full level 82 ( $\sim 150\text{ m}$  above the ground).*

# Vertical structure

## Turbulent heat flux



## Temperature



Vertical profiles in point ( $17^{\circ}\text{E}$ ,  $52^{\circ}\text{N}$ ) for 3-hour forecast valid at 0300 UTC 21 April 2020.

# Cause of $\sim 2\Delta t$ oscillations

- oscillations in the two-energy scheme do not react to the transport terms
- problem thus comes from evolution driven by the **relaxation terms**, representing TKE and TTE shear production  $I$ , buoyant production/destruction  $II$  (TKE only), and dissipation:

$$\frac{\partial e_{k|s}}{\partial t} = \overbrace{I(+II)}^{\text{source term (shear \& buoyancy)}} - \underbrace{\frac{2e_{k|s}}{\tau_{k|s}}}_{\text{dissipation term}} = \frac{2}{\tau_{k|s}} \left( \tilde{e}_{k|s} - e_{k|s} \right)$$

relaxation term
relaxation term

- equilibrium energies**  $\tilde{e}_{k|s}$  and **dissipation time scales**  $\tau_{k|s}$  have non-linear dependences on the prognostic energies  $e_{k|s}$ , that is why they are **discretized explicitly**:

$$\frac{e_{k|s}^+ - e_{k|s}^0}{\Delta t} = \frac{2}{\tau_{k|s}^0} \left[ \tilde{e}_{k|s}^0 - \beta_\tau e_{k|s}^+ - (1 - \beta_\tau) e_{k|s}^0 \right]$$

- prognostic energies**  $e_{k|s}$  in the dissipation term are **discretized over-implicitly** with factor  $\beta_\tau = 1.5$
- explicit discretization of equilibrium energies** causes  $\sim 2\Delta t$  oscillations

# The solution

- linearization around the equilibrium point  $\tilde{e}_{k|s}(e_k, e_s) = e_{k|s}$  suggests that  $2\Delta t$  oscillations appear when the following two conditions are met:
  - 1) Jacobian matrix  $\partial(\tilde{e}_k, \tilde{e}_s)/\partial(e_k, e_s)$  has **eigenvalue smaller than  $(1 - \beta_\tau)$**
  - 2) the model timestep  $\Delta t$  **exceeds certain critical value**
- to avoid the oscillations, **implicit treatment of equilibrium energies** is needed
- it can be achieved by **one corrective iteration of the TKE and TTE solvers**:
  - first call of the solvers provides preliminary prognostic energies  $e_{k|s}^{(+)}$
  - second time the solvers are called with **updated equilibrium energies**:

$$\tilde{e}_{k|s} = \delta \cdot \tilde{e}_{k|s}^{(+)} + (1 - \delta) \cdot \tilde{e}_{k|s}^0$$

- **implicitness factor  $\delta$**  for the equilibrium energies was introduced; due to the interaction with non-locality its **optimal value is between 0.25 and 0.5**
- once the  $\sim 2\Delta t$  oscillations are avoided, **prognostic energies** in the dissipation term can be **discretized implicitly** ( $\beta_\tau = 1$  increases the accuracy)

# Non-local aspect

- the two-energy scheme calculates the shear and buoyancy terms using the turbulent fluxes from the previous model timestep:

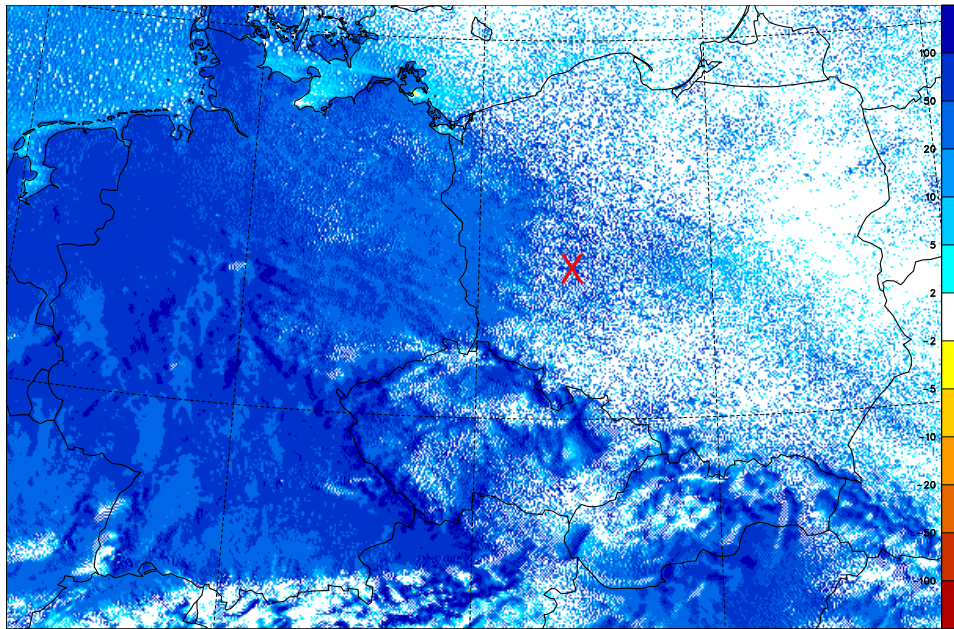
$$I^0 = -\frac{\partial u^0}{\partial z} \overline{u'w'}^0 - \frac{\partial v^0}{\partial z} \overline{v'w'}^0 \quad II^0 = E_{sL}^0 \overline{w's'_L}^0 + E_{qt}^0 \overline{w'q'_t}^0$$
$$\tilde{e}_k^0 = \frac{\tau_k^0}{2} (I^0 + II^0) \quad \tilde{e}_s^0 = \frac{\tau_s^0}{2} I^0$$

- turbulent fluxes result from the **implicit vertical diffusion solver**, which propagates local forcing vertically within a single timestep  $\Rightarrow$  **non-locality of  $\tilde{e}_{k|s}^0$**
- corrective iteration of the TKE and TTE solvers uses **updated  $\tilde{e}_{k|s}^{(+)}$** , computed from the turbulent fluxes reevaluated using **local down-gradient formulation**
- combining the **non-local values  $\tilde{e}_{k|s}^0$**  with the **locally updated values  $\tilde{e}_{k|s}^{(+)}$**  **decreases non-locality:**
  - less penetration of stable layers
  - unstable stratification not much influenced

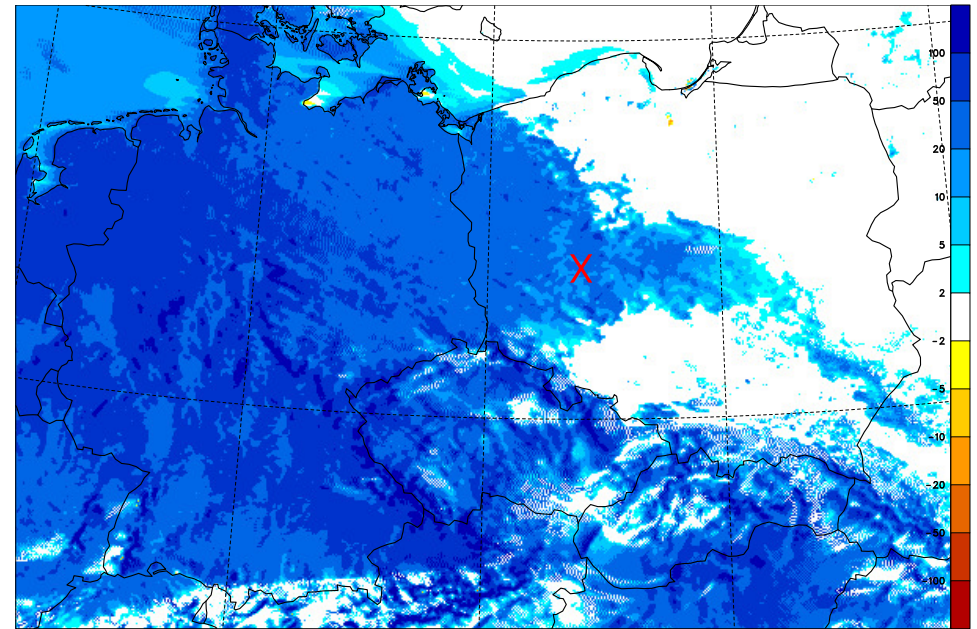
# Proposed treatment – impact on the turbulent heat flux

$\Delta t = 90 \text{ s}$ ,  $\Delta x = 2.3 \text{ km}$ , 87 levels

$\delta = 0.00$ ,  $\beta_{\tau} = 1.5$



$\delta = 0.25$ ,  $\beta_{\tau} = 1.0$

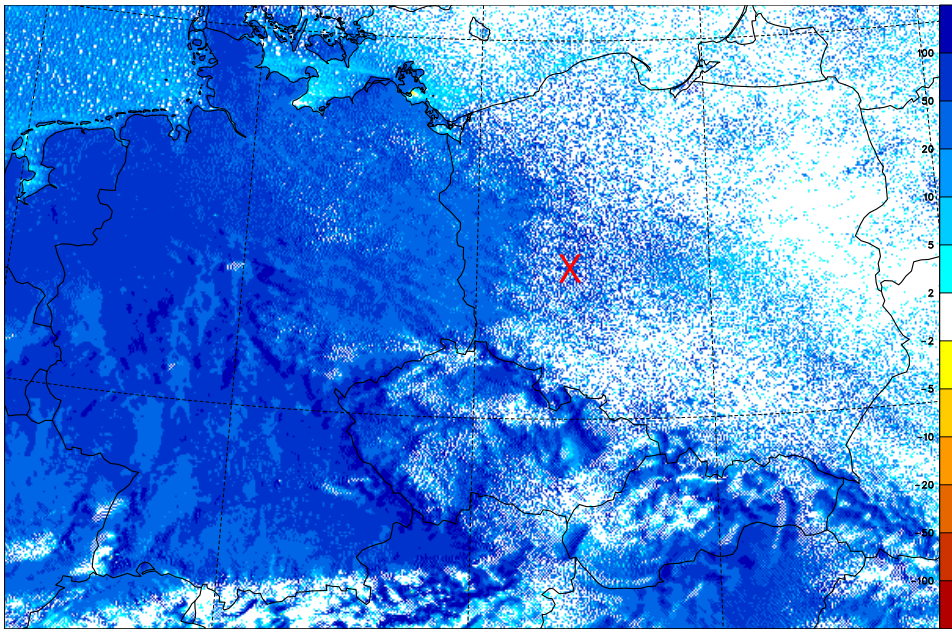


*Turbulent heat flux on the model half level 82 (~130 m above the ground) for 3-hour forecast valid at 0300 UTC 21 April 2020. The reference with  $\delta = 0.00$  (left), and the treatment with  $\delta = 0.25$  (right).*

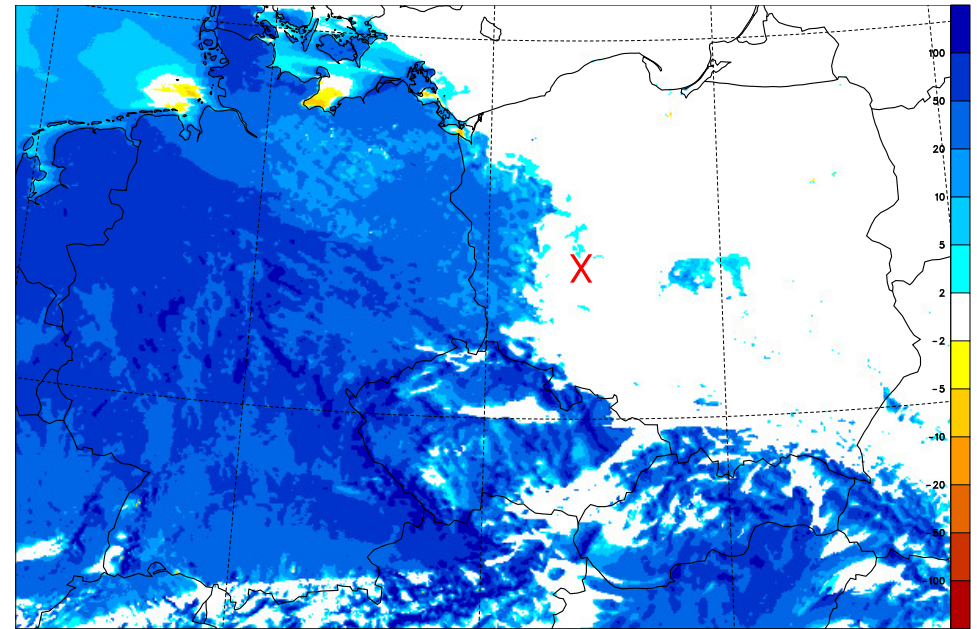
# Proposed treatment – impact on the turbulent heat flux

$\Delta t = 90 \text{ s}$ ,  $\Delta x = 2.3 \text{ km}$ , 87 levels

$\delta = 0.00$ ,  $\beta_{\tau} = 1.5$

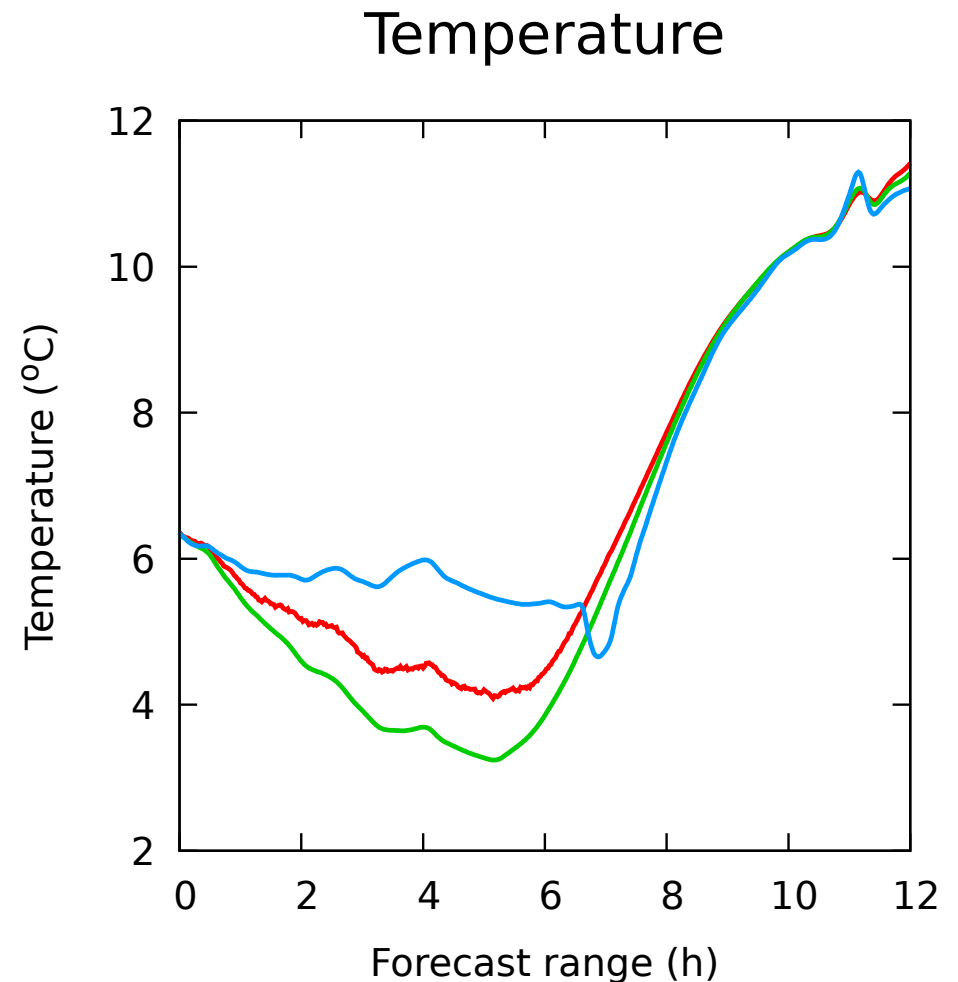
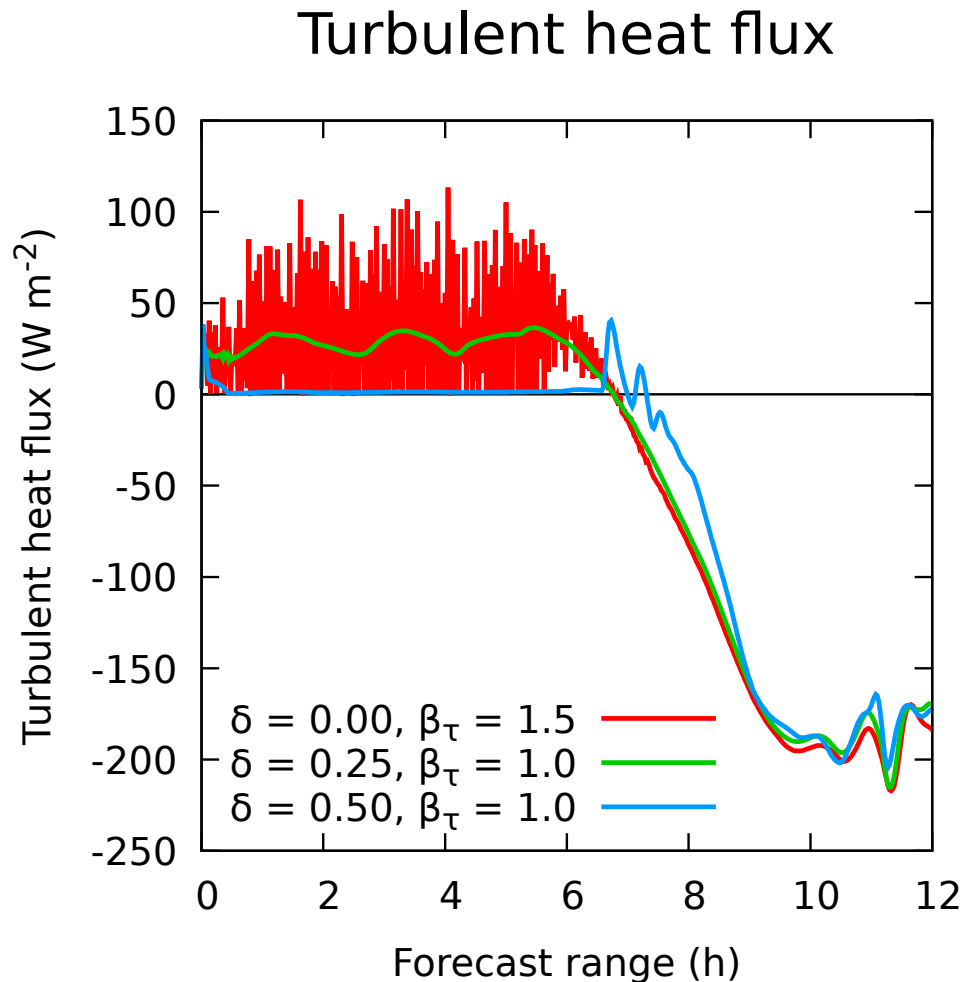


$\delta = 0.50$ ,  $\beta_{\tau} = 1.0$



*Turbulent heat flux on the model half level 82 ( $\sim 130 \text{ m}$  above the ground) for 3-hour forecast valid at 0300 UTC 21 April 2020. The reference with  $\delta = 0.00$  (left), and the treatment with  $\delta = 0.50$  (right).*

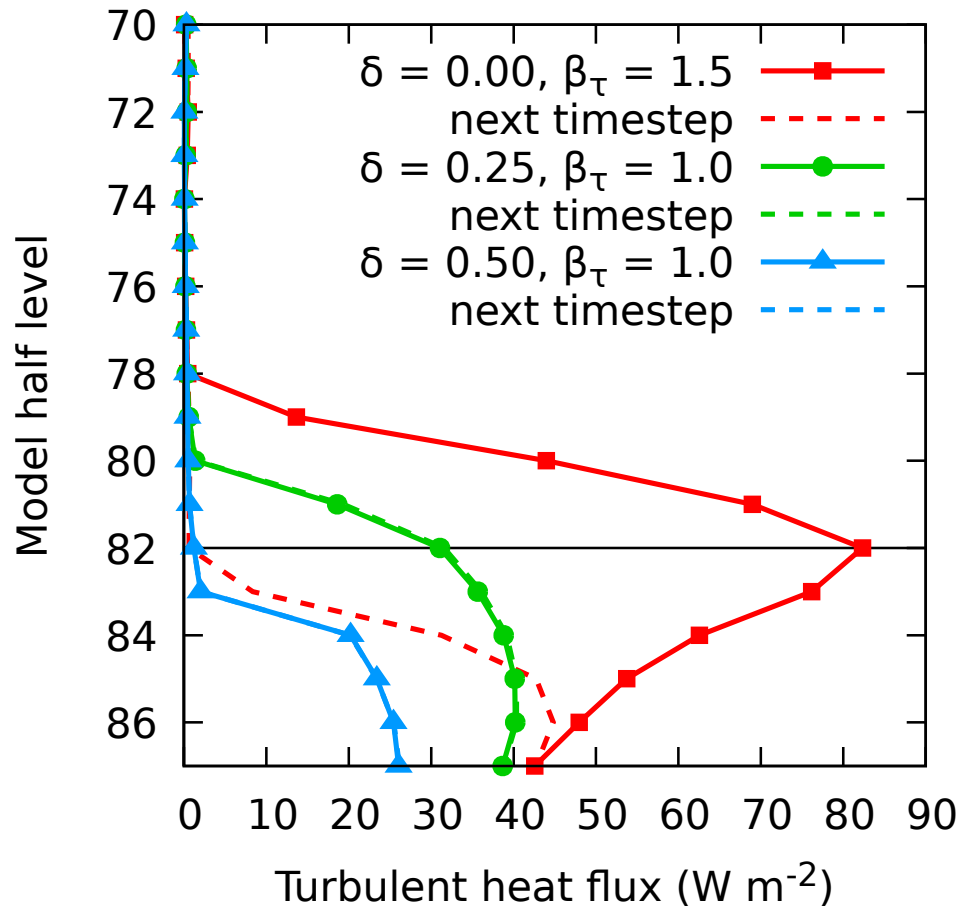
# Proposed treatment – smoothness versus drift



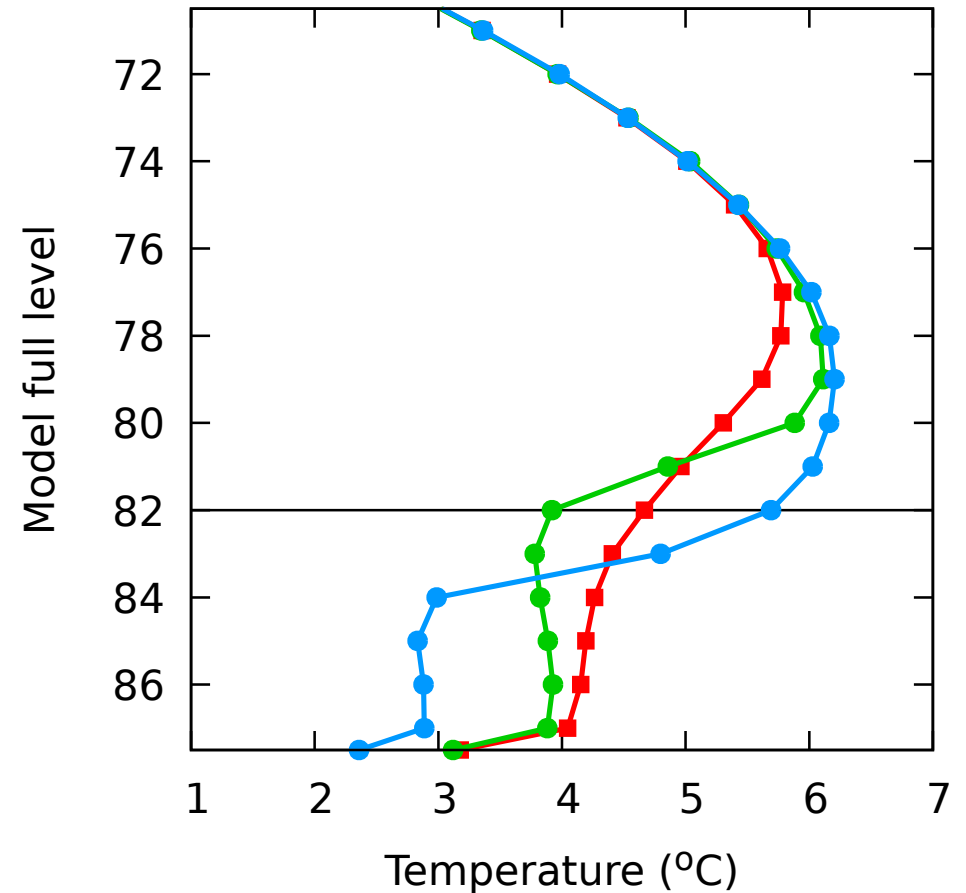
*Evolutions in point ( $17^{\circ}\text{E}$ ,  $52^{\circ}\text{N}$ ) during 12-hour forecast starting at 0000 UTC 21 April 2020. The turbulent heat flux is shown on the model half level 82 ( $\sim 130$  m above the ground), temperature on the model full level 82 ( $\sim 150$  m above the ground).*

# Proposed treatment – impact on the stratification

## Turbulent heat flux



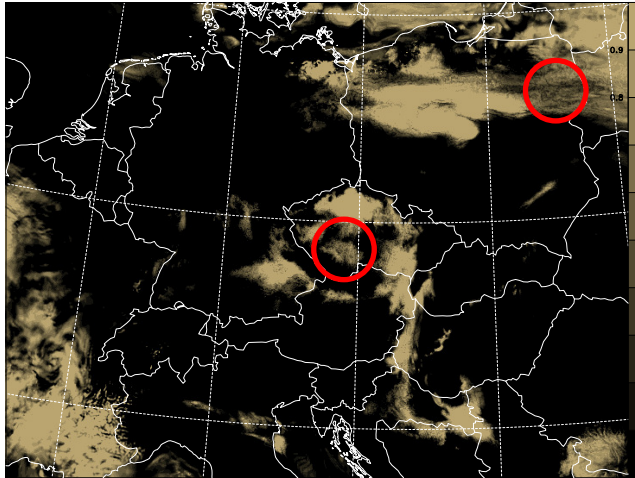
## Temperature



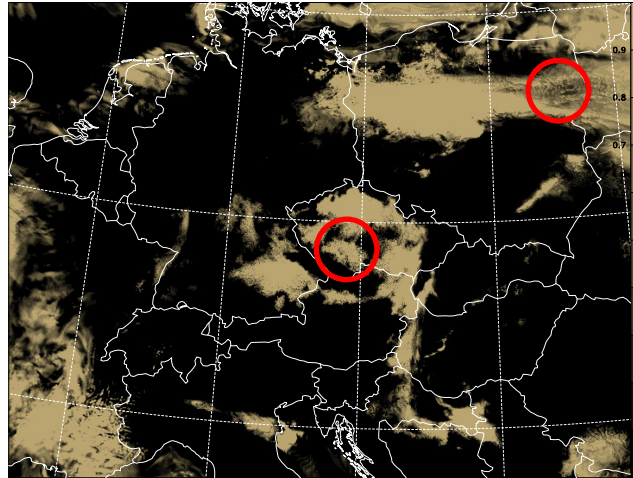
*Vertical profiles in point ( $17^{\circ}\text{E}$ ,  $52^{\circ}\text{N}$ ) for 3-hour forecast valid at 0300 UTC 21 April 2020.*

# Proposed treatment – impact on the low level clouds

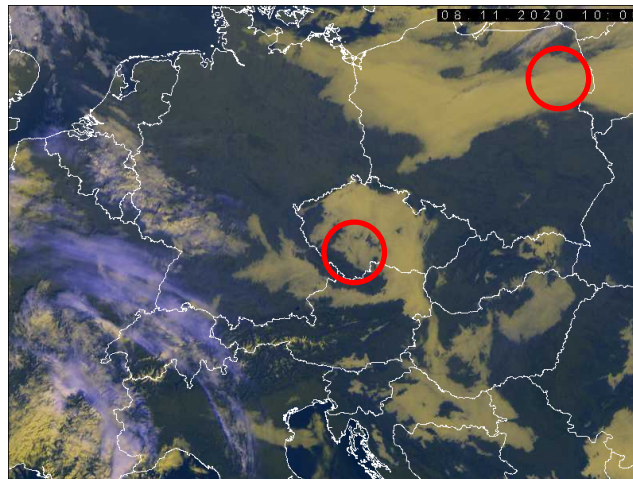
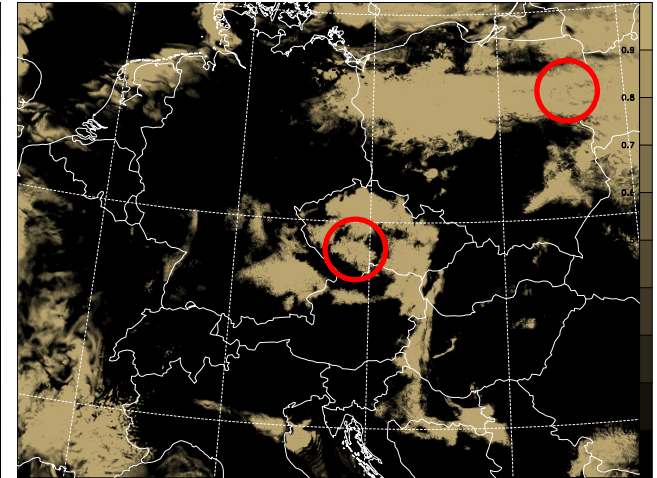
$\delta = 0.00, \beta_{\tau} = 1.5$



$\delta = 0.25, \beta_{\tau} = 1.0$



$\delta = 0.50, \beta_{\tau} = 1.0$



*The low level cloud cover for 10-hour forecasts valid at 1000 UTC 08 November 2020. Bottom panel contains verifying Meteosat VIS-IR combination, with the low clouds in beige color.*

# Conclusions

- original implementation of the **two-energy scheme**, available as an option in the TOUCANS turbulence parameterization, suffered from **two unrelated shortcomings**:
  - 1) **tendency to penetrate stable layers** due to a too intense non-local mixing
  - 2) **spurious  $\sim 2\Delta t$  oscillations** due to the explicit temporal discretization of the equilibrium energies
- **solving the second problem** via iterated TKE and TTE solvers **addressed also the first one**, by combining the non-local values of the equilibrium energies at time  $t$  with their local estimates at time  $t + \Delta t$



☺ **win-win situation** ☺

- the proposed treatment entered t-codes in CY48t1
- scientific paper describing the treatment is in preparation

**Thank you for your attention**

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