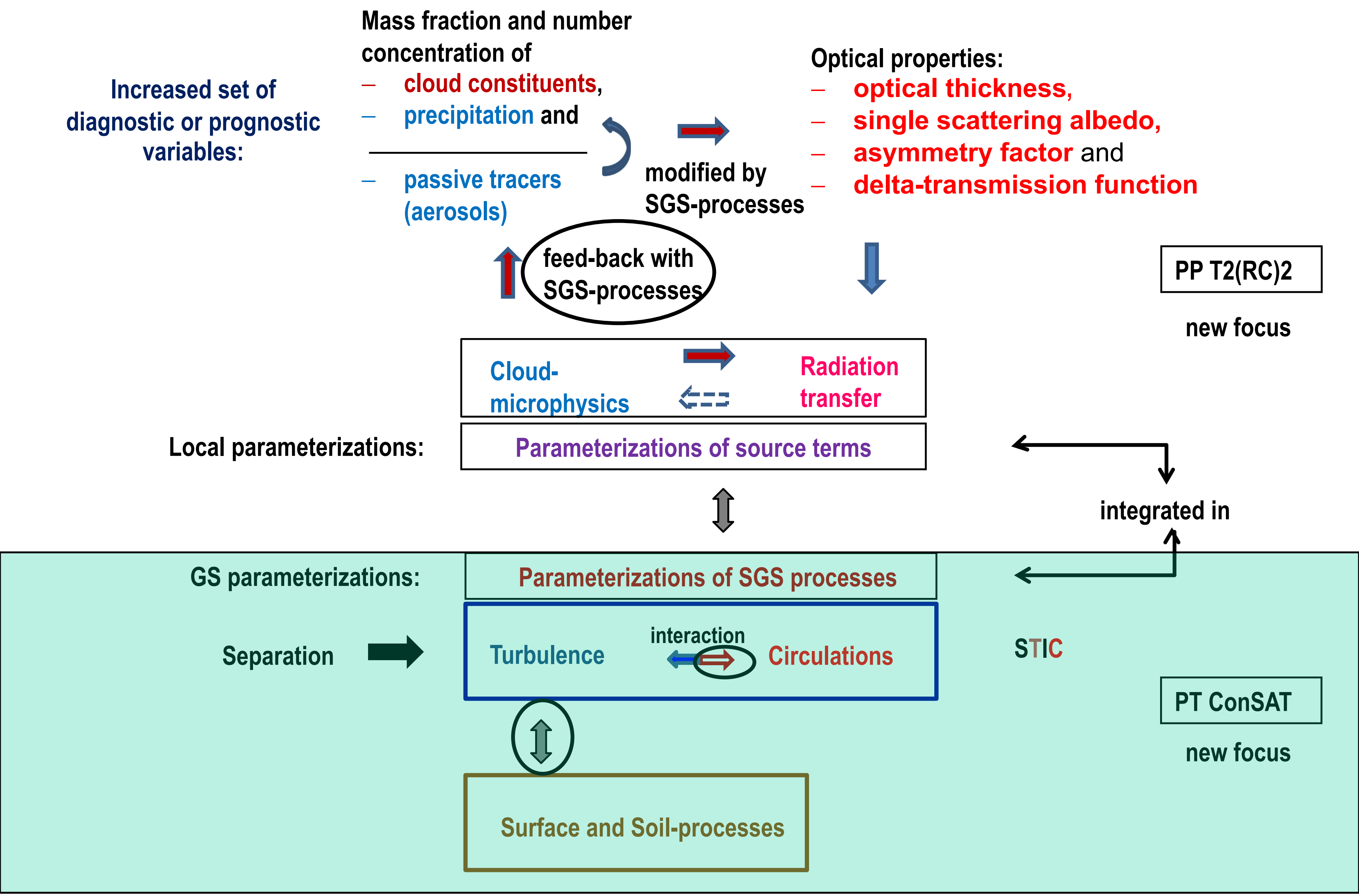
# Along the aim of COSMO-SP to consider missing interactions:



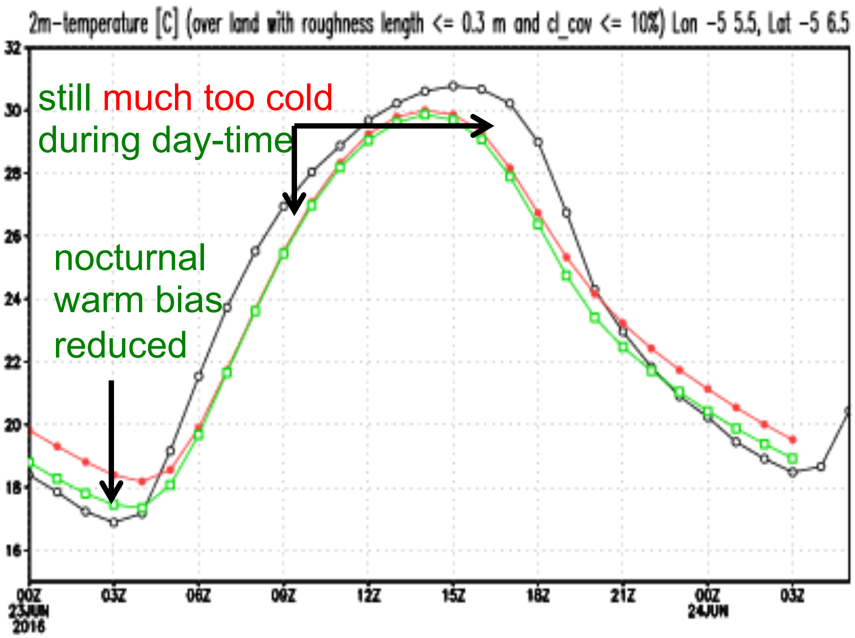
# Case study: 23.06.2016

## COSMO-DE with lateral boundaries from ICON-EU

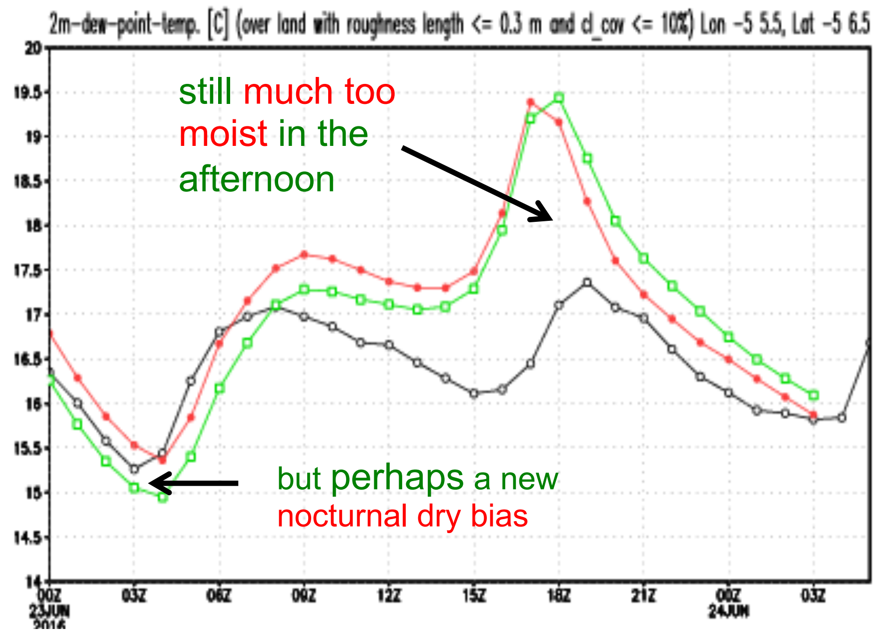
- ✓ only for rather smooth surfaces; applied filter
- ✓ almost saturated soil due to long standing rain period before
- ✓ almost no clouds due to high pressure situation; + applied filter

domain averaged daily cycles of near−surface variables

**T_2m**

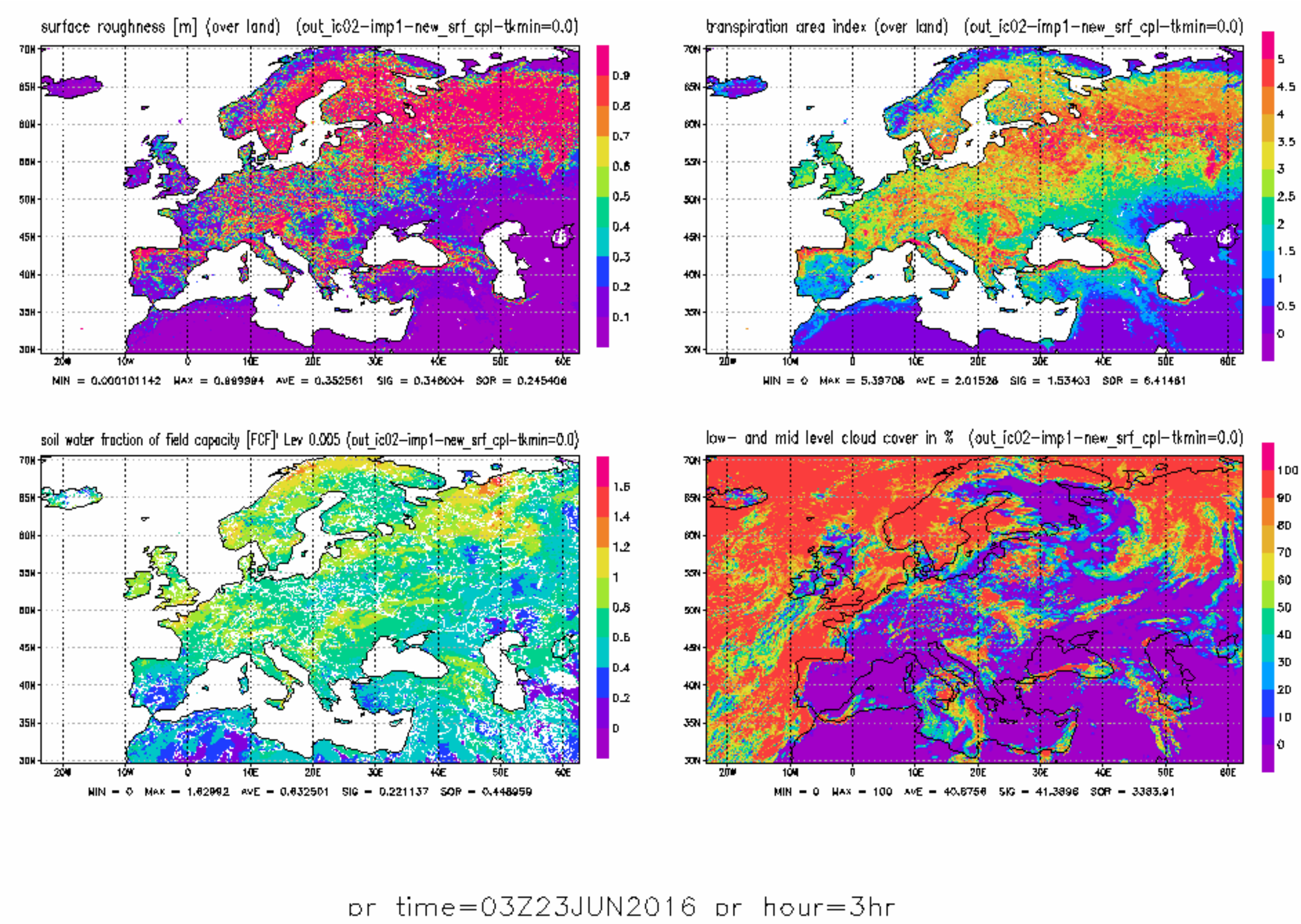



**TD_2m**



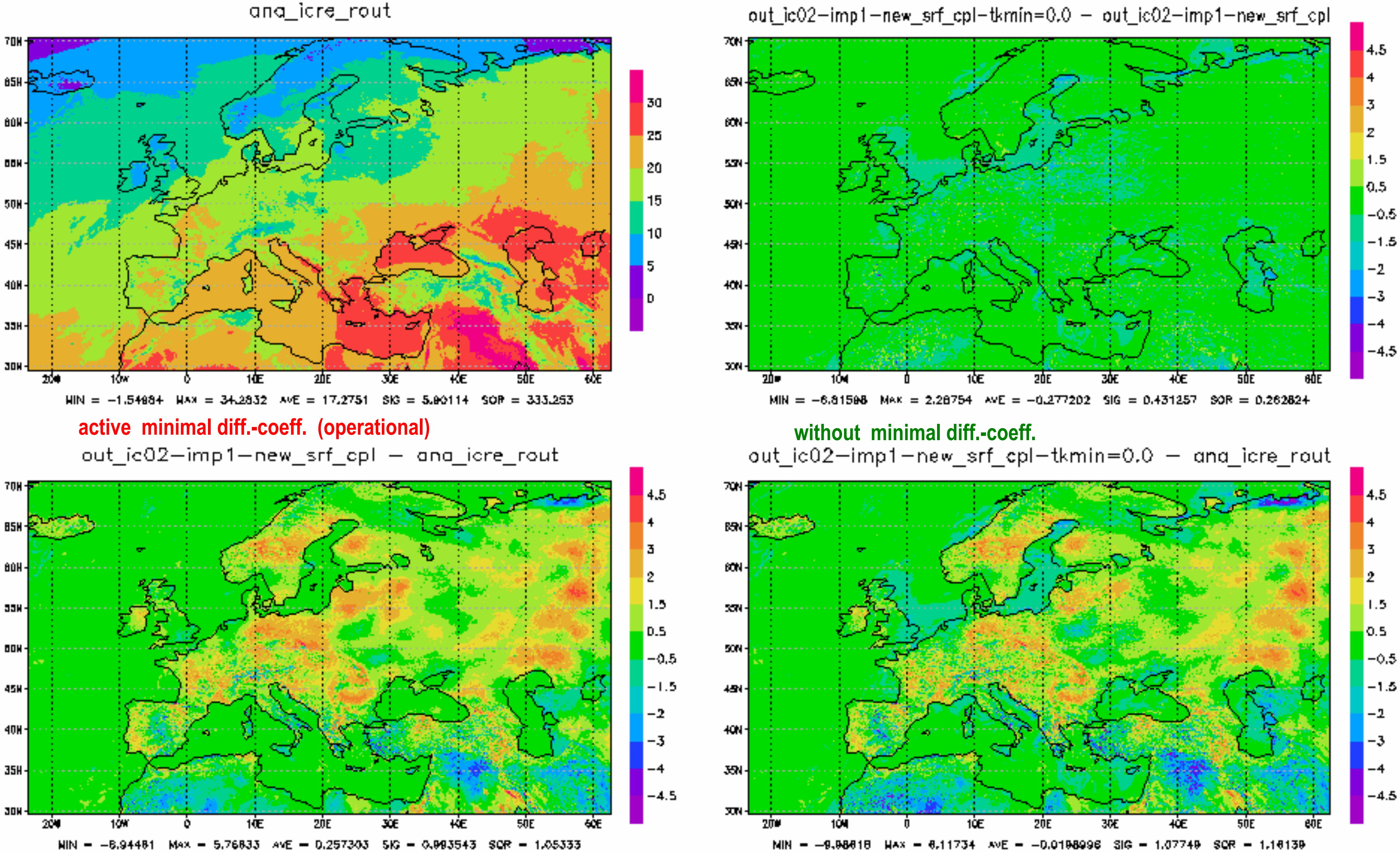

| ana_lm3_exp_10279 | out_lm3_rout | out_lm3_exp_10279 |
|---|---|---|
| direct analysis of T_2m and TD_2m | operational configuration | revised TURBDIFF imported from ICON |

# <u>ICON-EU-Simulations: Same Testcase</u>



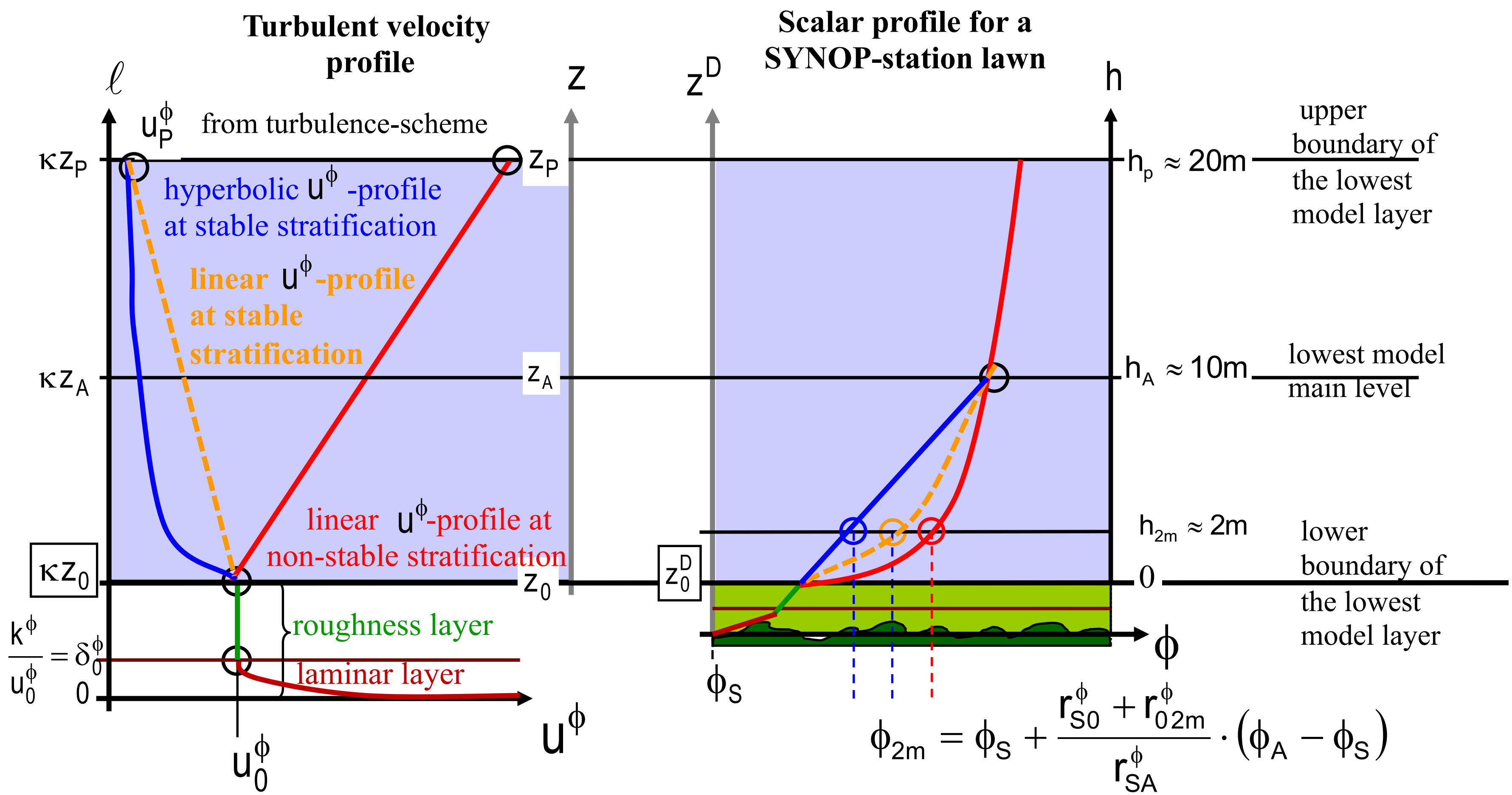
# 2m−temperature [C]

## Nocturnal effect of minimal diffusion coefficients in ICON




or time=03Z23JUN2016 or hour=3hr

# STIC-effect on the Profile-Function on near-surface values:




$$\phi_{2m} = \phi_S + \frac{r_{S0}^\phi + r_{02m}^\phi}{r_{SA}^\phi} \cdot (\phi_A - \phi_S)$$

$$r_{SA}^\phi = \frac{1}{u_{SA}^\phi} = \frac{1}{\kappa} \int_0^{\ell_A} \frac{d\ell}{\ell \cdot u^\phi}$$

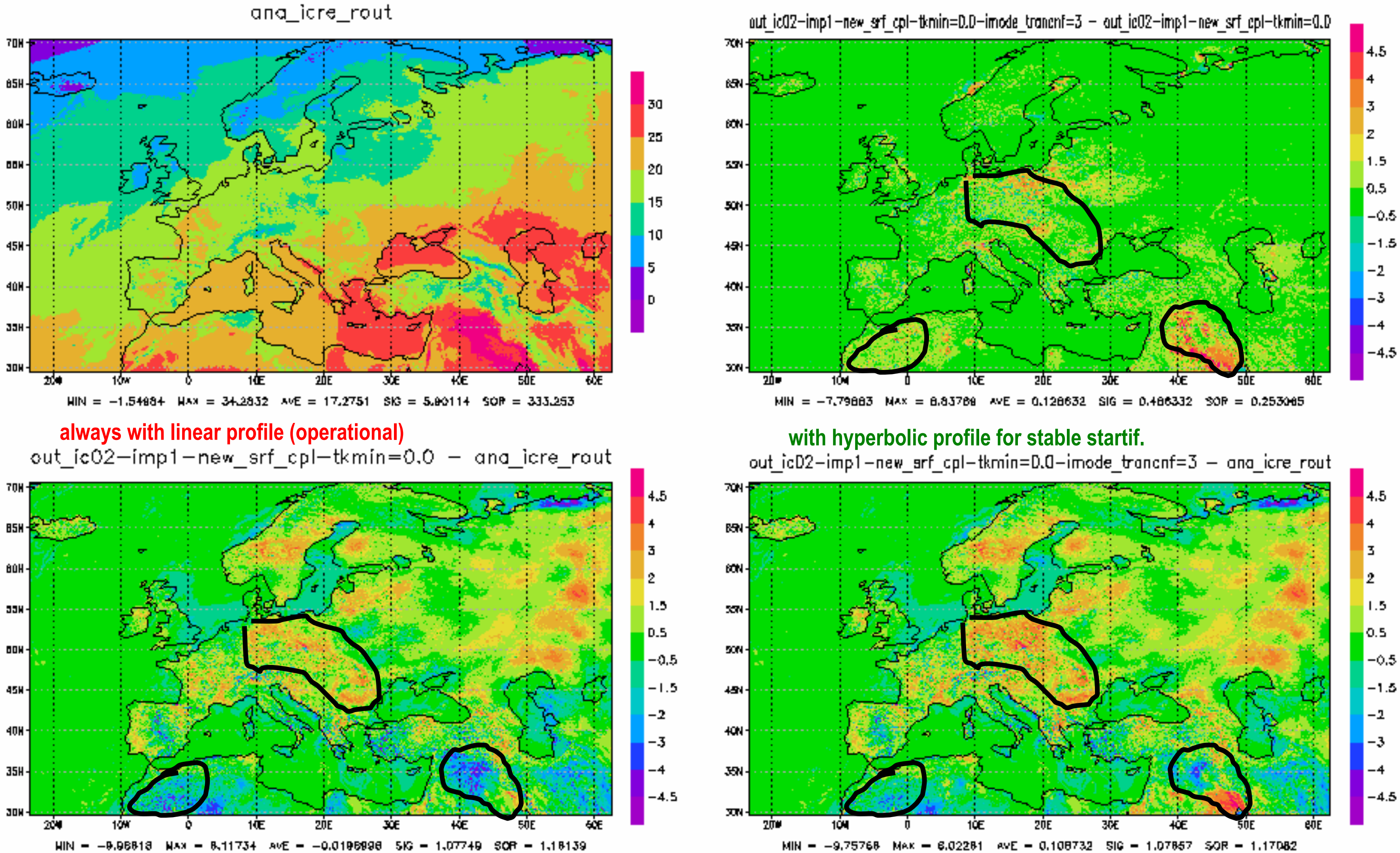
$$SHF_S = \overline{\rho}_S u_{SA}^H \cdot c_{p_d} \left( \hat{\theta}_A - \hat{T}_S \right)$$

$$LHF_S = \overline{\rho}_S u_{SA}^H \cdot L_{ev} \left( \hat{q}_{vA} - \hat{q}_{vS} \right)$$

- **Effect of Kmin:**
  - **Increased transfer-velocity**
  - **Non-stable profile shape**

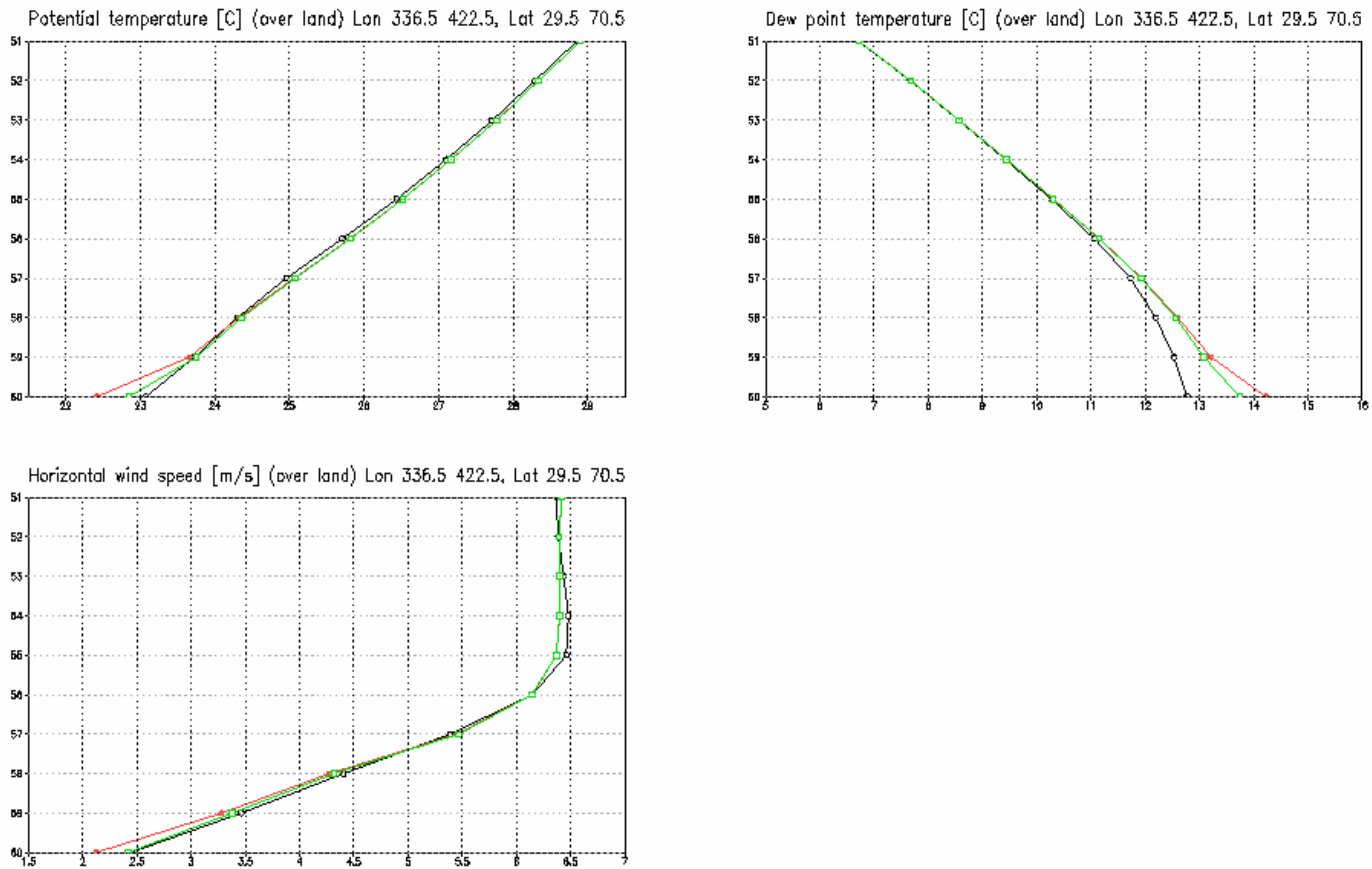
# 2m−temperature [C]

## Nocturnal effect of hyperbolic profile for stable turbulent velocity scale




pr time=03Z23JUN2016 pr hour=3hr

# Nocturnal effect of hyperbolic profile for stable turbulent velocity scale




**assimilation** — ana_icre_rout

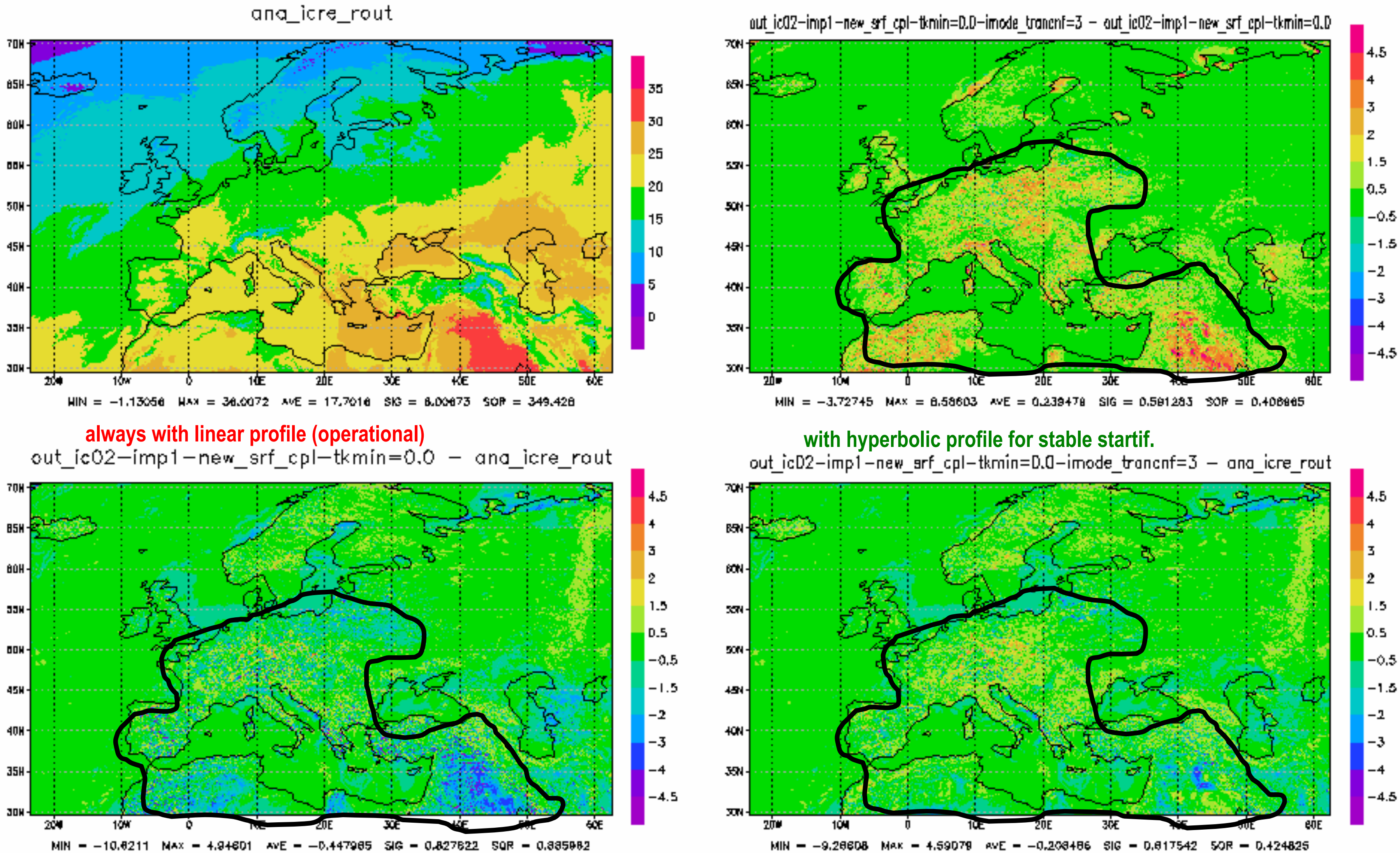
**always with linear profile (operational)** — out_ic02-imp1-new_srf_cpl-tkmin=0.0

**with hyperbolic profile for stable startif.** — out_ic02-imp1-new_srf_cpl-tkmin=0.0-imode_trancnf=3

pr time=03Z23JUN2016 pr hour=3hr

temperature [C]

# Nocturnal effect of hyperbolic profile for stable turbulent velocity scale




pr time=03Z23JUN2016 pr hour=3hr Lev 60

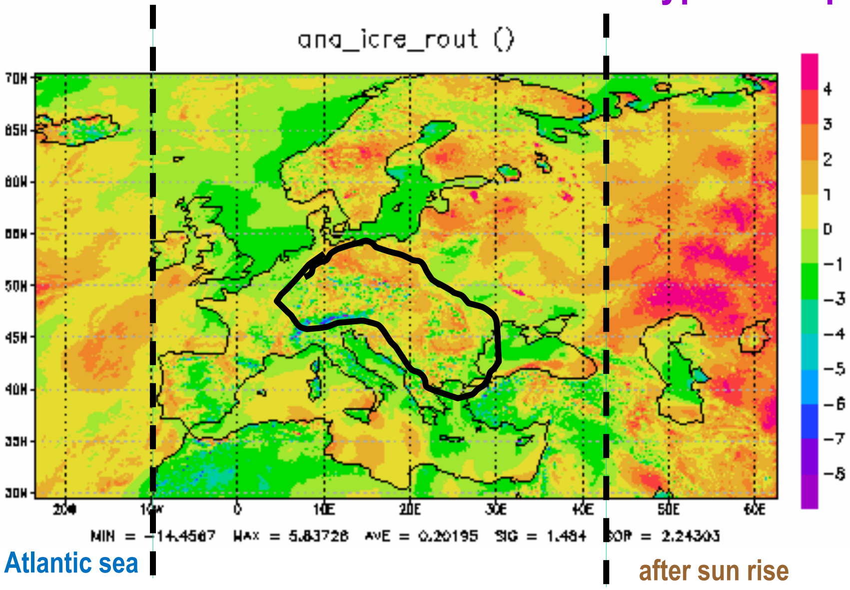
# Effect of hyperbolic profile for turbulent velocity at stable stratification:

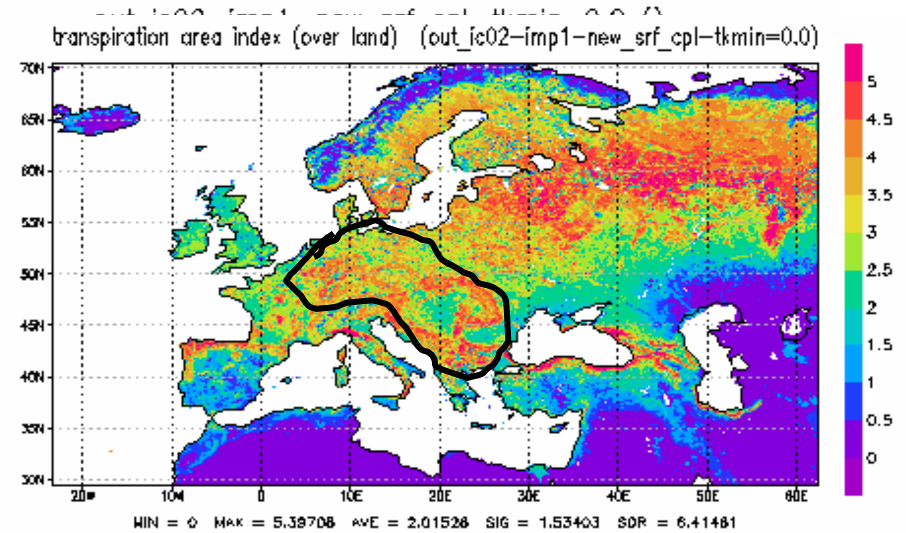
- **Right correction for nocturnal coupling**
  - **Smaller transfer velocities**
  - **Reduction of too excessive nocturnal BL-cooling**

- **Below clouds and at vegetated surfaces during summertime**
  - **positive nocturnal T2m-bias gets even larger!**

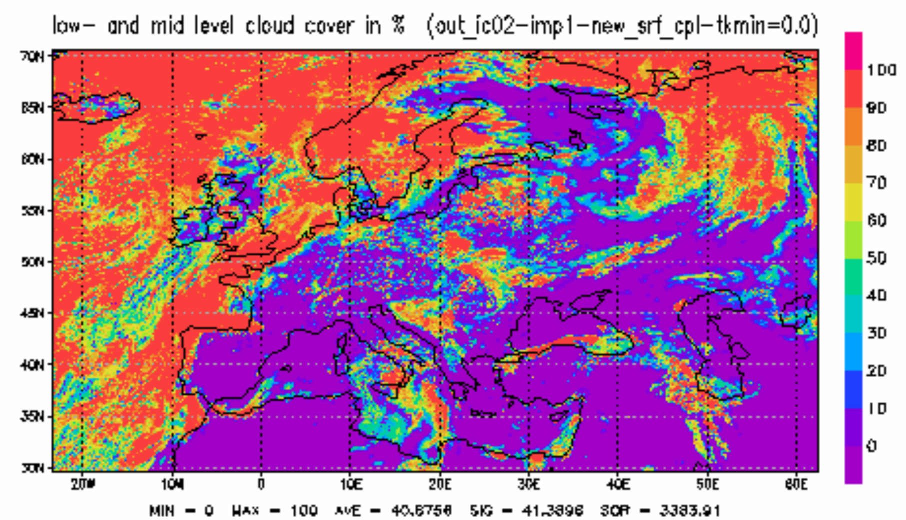
# t_g – t_2m [C]

## Nocturnal effect of hyperbolic profile for stable turbulent velocity scale




- Attention:
  - Nocturnal surface-temperature during the assimilation run is warmer than measured T2m!
  - Not only below some sheltering clouds
  - But correlated with the amount of leaves
    - ➢ Missing decoupling of plant-surfaces with the still warm soil mass!?
    - ➢ Radiative cooling is almost compensated by heat form the soil
    - ➢ Warmer nocturnal BL with hyperbolic profiles causes (although this is an improvement) an even increased positive T2m-bials.




➢ Semi-transparent and decoupled cover-layer in TERRA -> is being done

pr time=03Z23JUN2016 pr hour=3hr

- **An lessen from previous ConSAT tasks:**

> – **Pure modifications in the description of the turbulent Prandtl-layer can hardly correct the main sources of current model-errors of the diurnal cycle of near surface variables and of numerical instability of near-surface temperatures!**
>
> – **The description of surface processes promises to provide by far the largest potential for improvement!**

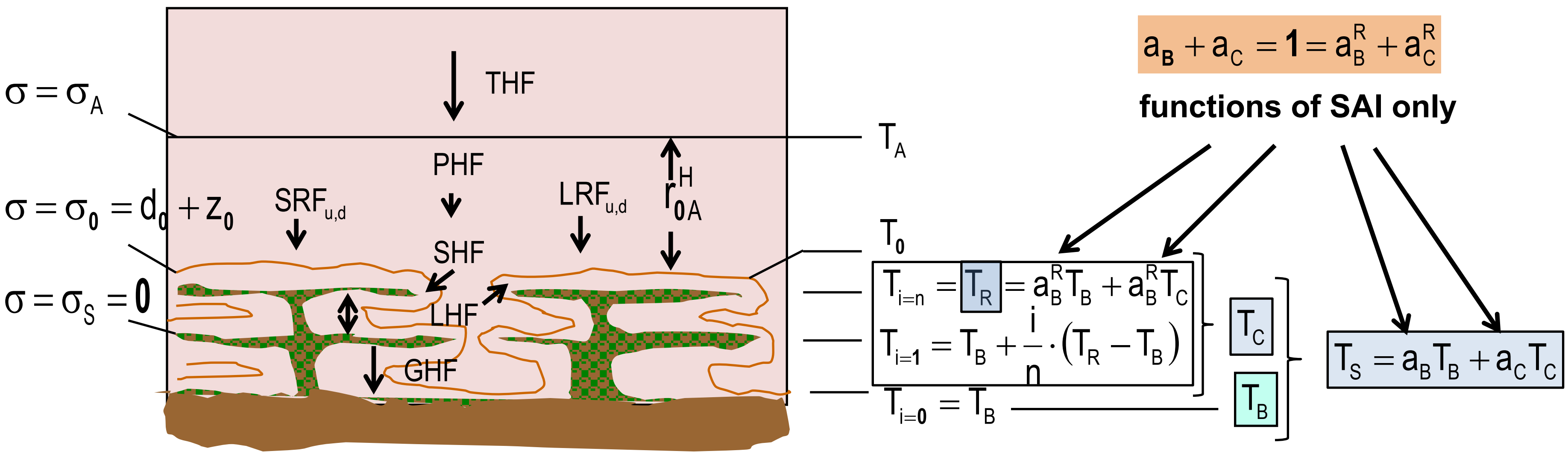
⇩

**Efforts towards a substantial, semi-transparent cover-layer (canopy) thermally loosely coupled to the dense soil:**

- **A canopy-extension of TERRA has been developed already 2 years ago in COSMO-TERRA:**

**Sequence of connected semi-transparent and substantial cover layers**

- **Coupled by long-wave radiation and atmospheric heat-transfer**
- **Linear cover-layer T-profile**
- **Without consideration of snow**
- **Common heat-budget of the cover-layers with implicit surface temperature**
- **The direct coupling of surfaces with the atmosphere becomes as smaller as more surface-layers are above**
- **The soil-surface is the lowest surface**
- **Controlled by present external parameters and 2->3 tuning parameters**

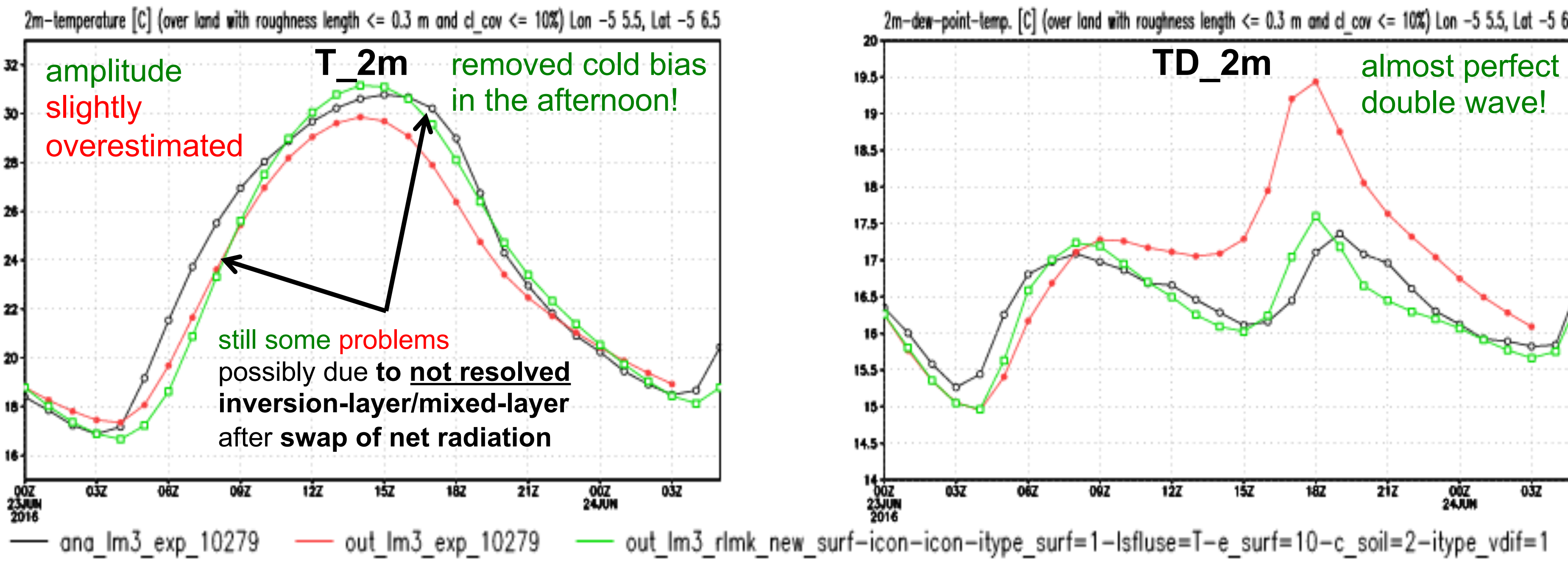


- A more advanced **semi-transparent C-layer extension** (by M. Raschendorfer) with **parameterized heat-conduction** and **heat storage** of the **full roughness cover** (e.g. plant canopy) is **being adapted** from an existing test-version prepared last year within COSMO.
  - The **final combination** with the **reformulated budgets** will **include all related partial development!**

2) Experiment with **the existing test-version in COSMO:**
   - **COSMO-DE with lateral boundaries from ICON-EU**
   - **domain averaged daily cycles of near-surface variables**
   - **almost saturated soil due to long standing rain period before**
   - **only for rather smooth surfaces: applied filter**
   - **almost no clouds due to high pressure situation + applied filter**

already shown last year

**conditional diagnostic**




**direct analysis of T_2m and TD_2m**

**revised TURBDIFF imported from ICON**

**full C-layer treatment : semi-transparent + loosely coupled + heat-storage + adapted evapo-transpiration**

❖ **Implementation strategy for ICON:**

**Solving the problem of oscillating surface-temperatures first**

- **Necessary implicit treatment of surface-temperature is also matches with the structure of the heat-budget for the cover-layer**
- **Treatment of a partial snow-cover is included**
- **Separation of formal modifications from physical extensions**

1. **Additional thermal equation for snow-free skin**
2. **Linearization of surface processes**
3. **Thermal equations for skin, snow and soil coupled through implicit temperatures => extended linear system of equations**
4. **Related adaptations for snow-cover diagnostic, dynamic tiles, initialization (of nested domains) and organization of model-restart**
5. **Cleaning the code from detrimental limitations**
6. **Necessary restructuring of code**
7. **Correction of various inconsistencies with respect to the treatment of water interception and phase transitions of surface water**
8. **Merge with various work-arounds and extensions in ICON-TERRA**

(items 4–8: **a very large effort!**)

9. **Including phase-transitions of precipitation (as well as soil water and the snow-cover) into the implicit treatment** — **already prepared!**
10. **Merge with canopy-extension, prepared 2 years ago in COSMO-TERRA**
11. **Canopy-interception of snow and related adaptation of snow-tiles**
12. **Transfer of ICON-development into COSMO?**

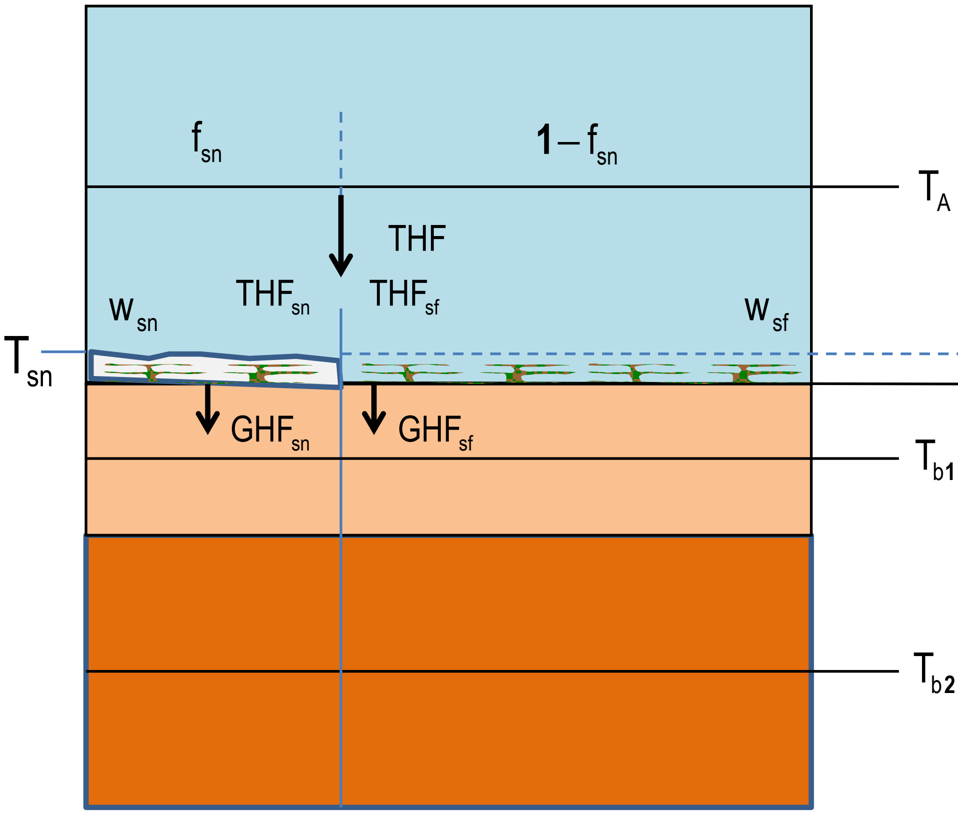
# Some of Günthers Workarounds:

- **Forcing the effect of a closed snow-cover of melting snow below a snow-free canopy by generation of an artificial sf surface-fraction of the soil and by a reduced snow-albedo**
  - The artificial sf sub-tile can be warmer than Tmelt and can heat the near surface air
  - Necessary corrections of this measure:
    - **Avoiding soil-evaporation of this tile, since real soil is snow-covered**
    - **Artificial reduction of day-time snow-temperature (since snow should be colder than the roughness elements), in order to avoid too excessive snow evaporation**
    - **Artificial reduction of heat-capacity of the artificial sf sub-tile, since it has to represent sf roughness elements being loosely coupled with the compact soil**
  - **This had to be adapted and partly substituted**

- **Reduction of roughness-length above a snow-cover**
  - **This caused jumps in transfer-velocity after aggregation of new dynamic sub-tiles**
  - **Now R-elements get sunk in an increasing snow-cover**

- **Interception of rime has been considered**
  - Larger interception storage and longer lasting potential evaporation
  - Phase transitions between rime and dew are not considered, which creates artificial heat sources
  - **This could be adapted by treating super-cooled interception water**

# New linear-implicitly coupled budget equations at the surface : (completely implemented)




mean cover-temp. (of lin. vert. prof.).

$$THF_{sf} - GHF_{sf} = [\rho_c c_c]^0 \frac{T_{cm} - T_{cm}^0}{\Delta t} \rightarrow 0$$

mean snow-temp. (of lin. vert. prof.)

$$THF_{sn} - GHF_{sn} = [\rho_{sn} c_{sn}]^0 \frac{T_{sm} - T_{sm}^0}{\Delta t} \xrightarrow[h_{sn \to 0}]{} 0$$

$\left.\begin{matrix} T_{sf} \\ T_b \end{matrix}\right\}$ **substantial, loosely coupled, semi-transparent C-layer** ➡ **idealized, infinite-thin S-layer** $T_b \rightarrow T_{sf}$

$$GHF_{sf} = -\alpha_{b1}^{b} \cdot \left(T_{sf} - T_{b1}\right)$$

**so far** substituted by $T_{sf} = T_{b1}$

$$GHF_{sn} = -\frac{\alpha_b^{sn}}{\alpha_b^{sn} + \alpha_{b1}^{b}} \cdot \left(T_{sn} - T_{b1}\right)$$

**so far** only explicit and resistance of soil-half-layer not considered

⬇

singularity for vanishing snow-depth

$$\partial_{T_{sx}} [LRF_u]_{sx}^0 = -4\sigma\varepsilon_0 [T_{sx}^3]^0$$

$$THF_{sx} = [PHF + SRF + LRF_d + LRF_u + SHF + LHF]_{sx}$$

$$= THF_{sx}^0 + \partial_{T_{sx}} [LRF_u + SHF + LHF]_{sx}^0 \cdot \left(T_{sx} - T_{sx}^0\right)$$

$$\partial_{T_{sx}} [SHF]_{sx}^0 = -[\rho_s u_{SA}^H]^0 \cdot c_p$$

$$\partial_{T_{sx}} [LHF]_{sx}^0 = -\left[\rho_s u_{SA}^H \cdot f_{sx}^{red} \cdot d_T q_v^{sat}(T_{sx}) \cdot L_{ev}(T_{sx})\right]_{sx}^0$$

so far only explicit contribution considered

➡ **so far** no budget equation for $T_{sf}$ in favour of setting $T_{sf} = T_{b1}$

# Implicit increments of atmospheric transfer velocities:
## (already implemented)

- Considering the **hidden $T_{Sx}$-dependency** of the **transfer velocity for heat** $u_{SA}^{H}$, which controls the **virtual conductivities** of $SHF_{Sx}$ and $LHF_{Sx}$:

$$\partial_{T_{Sx}}[SHF]_{Sx}^{0} = -\left[\rho_S u_{SA}^{H}\right]^{0} \cdot c_p \qquad \partial_{T_{Sx}}[LHF]_{Sx}^{0} = -\cdot\left[\rho_S u_{SA}^{H} \cdot f_{Sx}^{red} \cdot d_T q_v^{sat} \cdot L_{ev}\right]^{0}$$

$$\left[u_{SA}^{H}\right]^{0} \rightarrow u_{SA}^{H} := \left[u_{SA}^{H}\right]^{0} + \partial_{T_{Sx}}\left[u_{SA}^{H}\right]^{0} \cdot \left(T_{Sx} - T_{Sx}^{0}\right)$$

- The implicit heat budgets for Sf and Sn become **quadratic** in $T_{Sx}$ :

- From **solutions** $T_{Sx}^{*}$ of the **decoupled** versions of these **implicit quadratic** equations:

$$\left[u_{SA}^{H}\right]^{*} = \left[u_{SA}^{H}\right]^{0} + \partial_{S_{sx}}\left[u_{SA}^{H}\right]^{0} \cdot \left(T_{Sx}^{*} - T_{Sx}^{0}\right)$$

- This **updated transfer velocity** $\left[u_{SA}^{H}\right]^{*}$ is used in the **subsequent linear system**.

- The factor of the **linear $T_{Sx}$-dependency of the transfer-velocity** is estimated by **registration**:

$$\partial_{T_{sx}}\left[u_{SA}^{H}\right]^{0} \approx \frac{\left[u_{SA}^{H}\right]^{0} - \left[u_{SA}^{H}\right]^{-1}}{T_s^{0} - T_s^{-1}} \qquad T_s := \left(1 - f_{Sn}\right) \cdot T_{Sf} + f_{Sn} \cdot T_{Sn}$$

# Resulting matrix of the extended linear system:

altered

created

- All 2 + k_soil budgets are always present (even for f_sn=0 or f_sn=1)
- They are linearly coupled in the temperatures:

| | Sn | Sf | B1 | B2 | B3 | ... | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| isc | $a_{Sn}^{Sn}$ | | $a_{Sn}^{B1}$ | | | | | $T_{Sn}$ | | $d_{Sn}$ |
| fes | | $a_{Sf}^{Sf}$ | $a_{sf}^{b1}$ | | | | | $T_{Sf}$ | | $d_{Sf}$ |
| ifb | $a_{B1}^{Sn}$ | $a_{B1}^{Sf}$ | $a_{B1}^{B1}$ | $a_{B1}^{B2}$ | | | • | $T_{B1}$ | = | $d_{B1}$ |
| | | | $a_{B2}^{B1}$ | $a_{B2}^{B2}$ | $a_{B2}^{B1}$ | | | $T_{B2}$ | | $d_{B2}$ |
| | ⋮ | | | $a_{B3}^{b2}$ | $a_{B3}^{B3}$ | $a_{B3}^{B4}$ | | ⋮ | | ⋮ |

- Can easily be tri-diagonalized by matrix-operations and solved by the standard solver
- Partly reducible by parameters:

**isc:** degree of corrected implicit coupling of $T_{Sn}$ to the soil- and atm. temperatures

**fes:** degree of considered flux-equilibrium in diagnostics of $T_{Sf}$

**ifb:** degree of implicitness for effective surface fluxes used in the heat budgets

**Default for test: isc=1; fes=1; ifb=1 (full implicit solution active) - modified for diagnostic points**

# Scheme for snow-covered fraction and snow-depth :

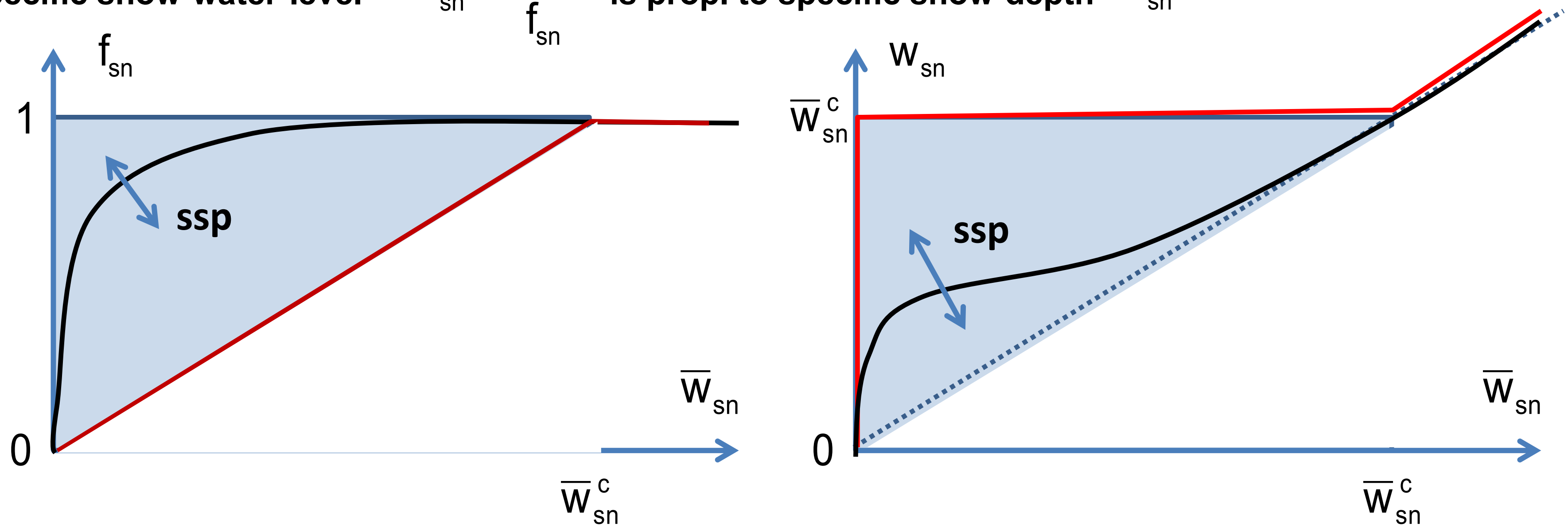
- Snow is not equally distributed along the grid-cell surface, due to various sources of inhomogeneity:

  Snow-covered fraction $f_{sn}$

  increases monotonically with mean snow-water level of a grid cell $\overline{W}_{sn}$

  until a critical mean snow-water level $\overline{W}_{sn}^{c}$ is reached.

- Specific snow-water-level $W_{sn} = \dfrac{\overline{W}_{sn}}{f_{sn}}$ is prop. to specific snow-depth $h_{sn}$



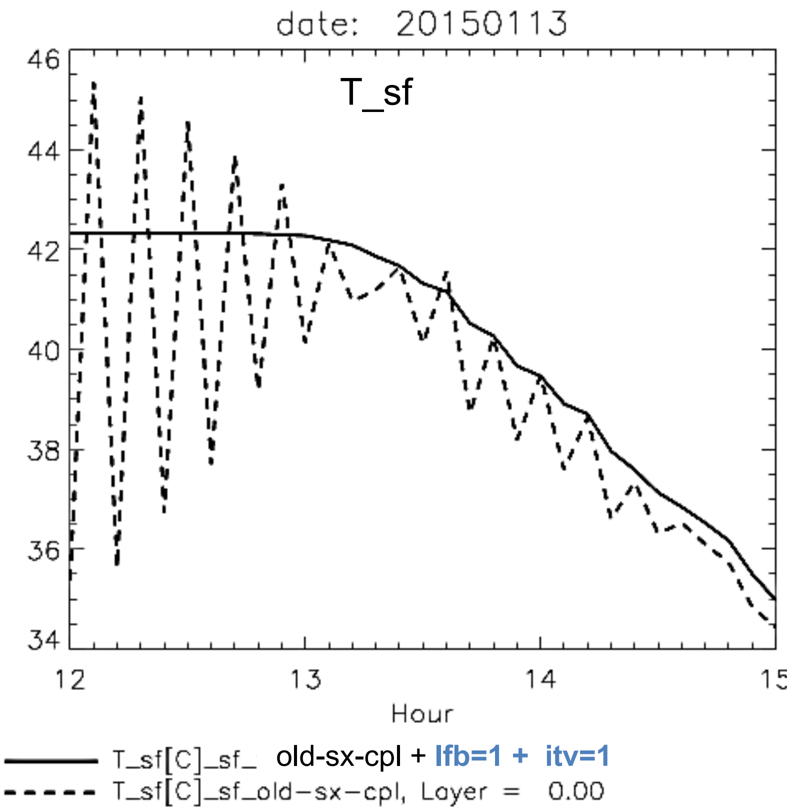

- New control-parameter : ssp: spreading efficiency

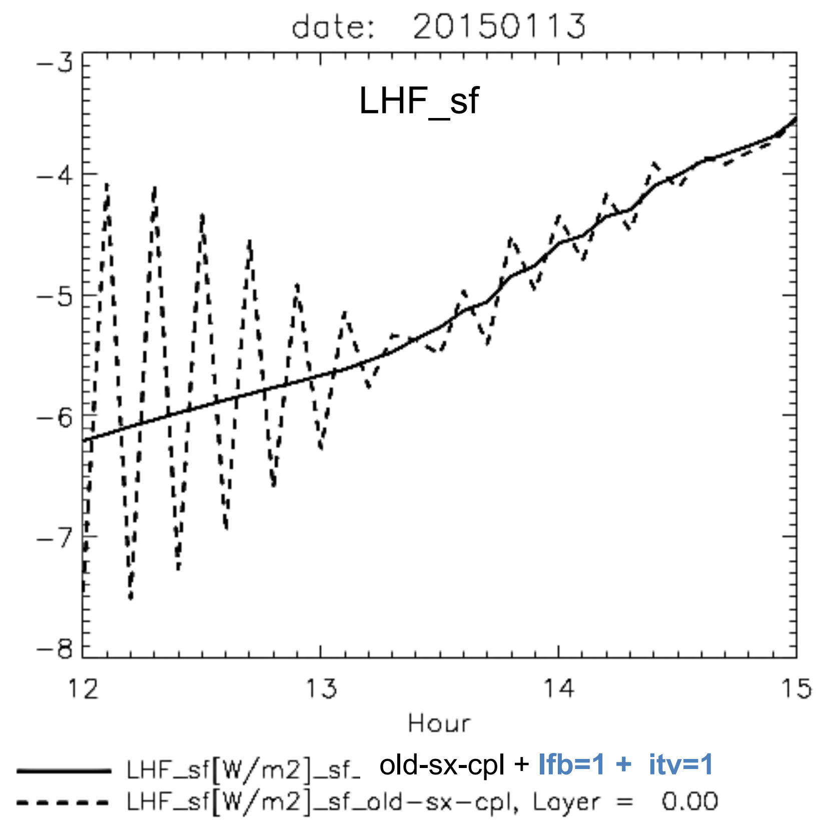
  ssp=0: so far operational version; not steady; it is always $W_{sn} \geq \overline{W}_{sn}^{c}$ !!

  ssp=1: full snow-spreading; always full snow-cover!!

# Test-grid-point Kenia (+33.71_+7.89) :

- After-noon situation; tropical hot with strong radiation forcing
- 3 hour ICON-global test-run (R2B6, dt=6min) with
- implicit defaults of the new development version of SAT-formulation (mainly TERRA)
- Emulation of so far operational explicit surface coupling only for a special grid-point




- Oscillations almost completely eliminated by ifb=1 + itv=1
- Similar result but a bit larger daily amplitudes ifb=1 + itv=1 + fes=1 (not shown)

itv=1: full consideration of implicit T_sx-dependency in atmospheric transfer velocity

fes=1: full consideration of flux-equilibrium at the sf surface

# Current state :

- **Major adaptations** in TERRA, TURBTRAN (and related interfaces) introduced into **ICON-branch**:
  - **Restructuring** the sequence of processes
  - **Removal** of various, now detrimental limitations all over the code
  - **Reformulations** related to variable-redistribution for dynamic snow-tiles
  - **Generalization** of snow-cover diagnostics
  - **Adaptation and extension of** **various empirical extension implemented by Günther Z**

- **Sanity-checks** performed:
  - **numerically stable** even for **large time steps; a couple of technical ICON-testsuites**
  - some **remaining oscillations** due to phase-transitions of snow or soil-water
  - almost minor differences compared to operational version
  - Technical test-suite of ICON passed

⇒

- **consistent formulation of a 2-phase interception-store**
- **together with the so far missing implicit formulation** of $\mathbf{w_{Sf}}$-evolution

# New implicit and simultaneous incrementation of interception water:

## (partly implemented)

$$\frac{w_{Sf} - w_{Sf}^{0}}{\Delta t} = PWF_{Sf} + VWF_{Sf} + DWF_{Sf}$$

$PWF$ : given precipitation-water flux-density

$$VWF_{Sf} = -f_{Sf}^{cov}(w_{Sf}) \cdot VWF_{Sf}^{pot}(T_{Sf}^{0})$$

: current water-vapour flux-density

explicit potential evaporation (negative for dew- or rime-fall, where $f_{Sf}^{cov}(w_{Sf}) \equiv 1$ )

linear cover-function: $f_{Sf}^{cov}(0) = 0$ $\quad f_{Sf}^{cov}(w_{Sf}^{max}) = 1$ (for real evaporation)

$$DWF_{Sf} = -f_{Sf}^{drp}(w_{Sf}) \cdot DWF_{Sf}^{ref}$$

: current drip-water flux-density

explicit reference value at $f_{Sf}^{dpr} = 1$ (parameter of the scheme)

rational drip-function: $f_{Sf}^{dpr}(0) = 0$ $\quad f_{Sf}^{dpr} \xrightarrow[w_{Sf} \to w_{Sf}^{max}]{} \infty$

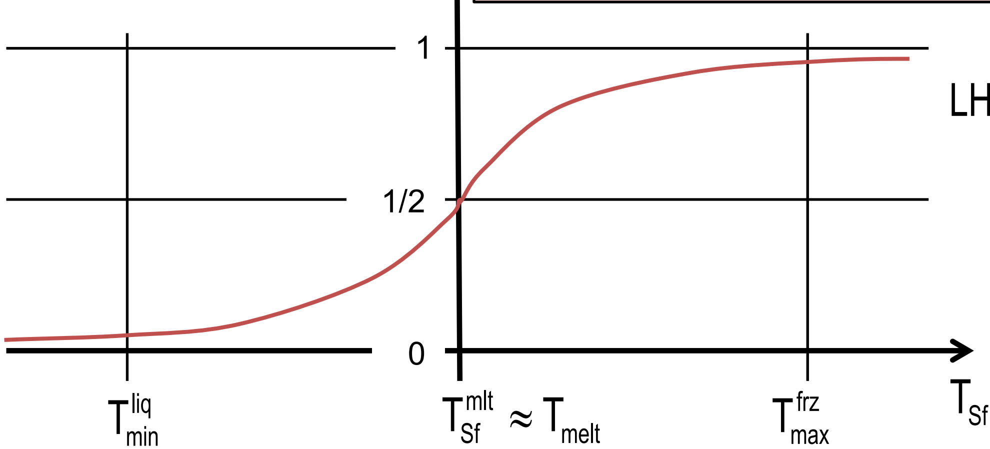
- ❖ **Quadratic equation for $0 \le w_{Sf} \le w_{Sf}^{max}$ ; automatically positive-definite and limited**
- ❖ **Simultaneous consideration of all sources and sinks**
- ❖ $VWF_{Sx}^{pot}$ **still depends on previous surface temperature** $T_{Sf}^{0}$
  - ➢ **No implicit coupling between hydrological and thermal equations yet!**
  - ➢ **Lower atmosph. BC**: **explicit** $VWF_{Sx}^{0}$ and **corrected** $SHF_{Sx} = SHF_{Sx}^{0} + \Delta THF_{Sx}$ !!

# Implicit freezing and melting of interception water and precipitation:
## (being implemented)

- At least for $T_{min}^{liq} \le T_{Sf} \le T_{max}^{frz}$ **liquid and frozen** interception-water **coexists** with a **smooth transition**.

$$f_{Sf}^{liq}(T_{Sf}) \approx f_{Sf}^{liq}(T_{Sf}^{0}) + d_T f_{Sf}^{liq}(T_{Sf}^{0}) \cdot (T_{Sf} - T_{Sf}^{0})$$

: **liquid fraction** of $w_{Sf}$ and its linearization




$$LHF_{Sf} = LHF_{Sf}^{0} + \partial_{T_{Sx}} [LHF]_{Sx}^{0} \cdot (T_{Sx} - T_{Sx}^{0})$$

$$\partial_{T_{Sf}} [LHF]_{Sf}^{0} = -\cdot \left[\rho_s u_s^H \cdot f_{Sf}^{red} \cdot d_T q_v^{sat} \cdot L_{ev}\right](T_{Sf}^{0})$$

$$L_{ev}(T_{Sf}^{0}) \rightarrow L_{ev}(T_{Sf}) = L_{lv} \cdot f_{Sf}^{liq}(T_{Sf}) + L_{fv} \cdot \left[1 - f_{Sf}^{liq}(T_{Sf})\right]$$

generalized latent heat of vaporization

$$PHF_{Sf} = PHF_{Sf}^{0} + \partial_{T_{Sf}} [PHF]_{Sf}^{0} \cdot (T_{Sf} - T_{Sf}^{0})$$

: latent heat flux-density due to rain<->snow transition including implicit extension

$$PHF_{Sf}^{0} = L_{fl} \cdot \left[RWF_{Sf} - (RWF_{Sf} + SWF_{Sf}) \cdot f_{Sf}^{liq}(T_{Sf}^{0})\right]$$

: related explicit part

$$\partial_{T_{Sx}} [PHF]_{Sx}^{0} = -L_{fl} \cdot \left( RWF_{Sf} + SWF_{Sf} + \frac{w_{Sf}^{0}}{\Delta t} \right) \cdot d_T f_{Sf}^{liq}(T_{Sf}^{0})$$

: related virtual conductivity including associated phase transition of present interception water $w_{Sf}^{0}$

- Introducing $\mathbf{LHF_{sf}}$ and $\mathbf{PHF_{sf}}$ in **decoupled** $\mathbf{T_{Sf}}$**-equation** and solving this in **quadratic approximation**:
  - **Correct** and **implicit** treatment of **liquid and frozen interception water**
  - Final $\mathbf{T_{sf}}$ is in **dynamical accordance** with **complete turnover of latent heat.**

# Next steps:

- **Operationalization of my development branch in ICON**

  → ❖ **1-st official ICON-release -> COSMO**

- **Adding** melting of snow and freezing/melting of soil-ice into the implicit heat budgets

  → ❖ **2-nd official ICON-release -> COSMO**

- **Incorporation** of a multi-layer snow-model

- **Introducing** the extension with a decoupled, substantial and semi-transparent **cover-layer**, including
  - the partitioning of fluxes into those related to B and C
  - expressions for the additional conductivity $\alpha_B^C$

    and the additional heat capacity $c_c$ :

$$THF_C - GHF_C = [\rho_c c_c]^0 \frac{T_{Cm} - T_{Cm}^0}{\Delta t}$$

$$T_{Cm} = \frac{1}{2} \cdot (T_C + T_B)$$ linear vertical T-profile of R-layer

$$GHF_C = -\frac{\alpha_B^C \cdot \alpha_{B1}^B}{\alpha_B^C + \alpha_{B1}^B} \cdot (T_C - T_{B1})$$

$c_c$ due to the mass of R-elements and interception water

$\alpha_B^C$ due to the exchange of SH and LR between B and C

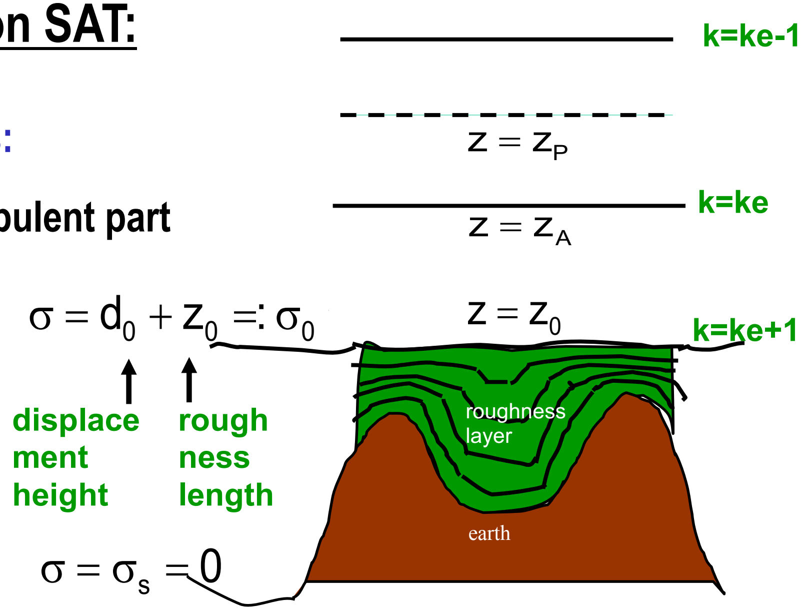
➢ based on an **already developed prototype**, present in an **older test-version of COSMO**!

➢ largely **prepared just by the current implementations** into ICON!

➢ **removal of remaining conceptual deficiencies!**

➢ **significant impact on simulated properties!**

# Direct STIC-impact on SAT:




- **In TURBTRAN, the SAT-resistance has a two contributions:**
  - **Roughness-layer resistance with a laminar and a turbulent part (only for scalars):**

$$r_{S0}^H = \frac{1}{\kappa S_0 \cdot u_0^H} \cdot \left( \lambda^H + \ln \frac{\kappa z_0 u_0^H}{k^H} \right) = \frac{1}{\kappa u_0^H} \cdot \ln \left[ \frac{z_0}{z_0^H} \right]$$

  - **Turbulent Prandtl-layer resistance with an unstable and a stable branch:**

$$\gamma_s^\phi := \frac{z_0}{h_P} \left[ \left( \frac{u_P^\phi}{u_0^\phi} \right)^s - 1 \right] \qquad s = \begin{cases} 1 & \text{unstable} \\ -1 & \text{stable} \end{cases} \qquad \phi \in \{H, M\} \qquad h_X := z_X - z_0$$

$$u_X^\phi := \frac{K_X}{\ell}$$ **turbulent velocity**

$$r_{0A}^\phi = \frac{1}{\kappa} \int_{\ell_0}^{\ell_A} \frac{d\ell}{\ell \cdot u^H} = \frac{1}{\kappa u_0^\phi} \cdot \begin{cases} \dfrac{1}{1-\gamma_1^\phi} \ln \left( \dfrac{z_A}{z_0 + \gamma_1^\phi \cdot h_A} \right) \xrightarrow{\gamma_1^\phi \to 0\,(\text{neutral})} \ln \left( \dfrac{z_A}{z_0} \right) & u_p^\phi \geq u_0^\phi \quad (\text{unstable}) \\ \left(1 - \gamma_{-1}^\phi\right) \ln \left( \dfrac{z_A}{z_0} \right) + \gamma_{-1}^\phi \dfrac{h_A}{z_0} & u_p^\phi < u_0^\phi \quad (\text{stable}) \end{cases}$$

operationally deactivated

$$u_{SA}^\phi := \frac{1}{r_{S0}^\phi + r_{0A}^\phi}$$ **transfer velocity**

$$SHF_S = \overline{\rho}_S u_{SA}^H \cdot c_{p_d} \left( \hat{\theta}_A - \hat{T}_S \right)$$

$$LHF_S = \overline{\rho}_S u_{SA}^H \cdot L_{ev} \left( \hat{q}_{vA} - \hat{q}_{vS} \right)$$

# Iterative solution for TKE and the stability-functions:

$$r_p = \left(\frac{\bar p}{p_r}\right)^{\frac{R_d}{c_{pd}}} \qquad r_v := 1 + \left(\frac{R_v}{R_d} - 1\right)\hat q_v - \hat q_c \qquad T_c = \frac{L_c}{c_{p_d}} \qquad \alpha := \partial_T q_{vs}(\hat T) \qquad r_T := \frac{1}{1+\alpha T_c}$$

saturation fraction

$$\vartheta_v := r_T \cdot \left(r_v \vartheta_c - \frac{R_v}{R_d}\hat T\right) \qquad \vartheta_w := \left(\frac{R_v}{R_d} - 1\right)\cdot\hat\theta + \frac{r_c}{r_p}\cdot\vartheta_v \qquad r_\theta := r_v - r_c \alpha \vartheta_v$$

$$F_T^M := (\partial_z \hat u)^2 + (\partial_z \hat v)^2 \quad + F_C^M \qquad F^H := \frac{g}{\hat\theta_v}\cdot\left(\vartheta_w \partial_h \hat q_w + r_\theta \partial_h \hat\theta_w\right) \qquad \frac{1}{\ell(z)} \approx \frac{1}{\kappa z} + \frac{1}{\ell_m} + a_{stab}\frac{\sqrt{F^H}}{q}$$

normal to grid scale surface — **additional shear** — normal to horizontal surface

$$\partial_t\left(\frac{1}{2}\bar\rho q^2\right) + \partial_z\left[-\bar\rho\,\ell S^q q \partial_z\left(\frac{1}{2}q^2\right)\right] = \bar\rho q \ell \cdot \left[S^M r^M F_T^M - S^H F^H\right] - \frac{q^3}{\alpha^{MM}\ell} \rightarrow G_T^M := \frac{\ell^2}{q^2}\cdot F_T^M \geq 0 \qquad G^H := \frac{\ell^2}{q^2}\cdot F^H$$

$$\underbrace{\left[\frac{1}{\alpha^H} + \left(3 r^H \alpha^{HH} + 12\alpha^M\right)\cdot G^H\right]}_{=:a_{HH}} \cdot S^H + \underbrace{6 r^M \alpha^M G_T^M}_{=:a_{HM}} \cdot S^M = 1 - 3c^H =: b_H$$

$$\underbrace{\left[\left(9 r^H \alpha^H + 12\alpha^M\right)\cdot G^H\right]}_{=:a_{MH}} \cdot S^H + \underbrace{\left[\frac{1}{\alpha^M} + 9 r^M \alpha^H G^H + 6 r^M \alpha^M G_T^M\right]}_{=:a_{MM}} \cdot S^M = 1 - 3c^M =: b_M$$

$$\alpha^M = 0.92,\quad \alpha^H = 0.74,\quad c^M = 0.08,\quad c^H = 0.0,\quad \alpha^{MM} = 16.6,\quad \alpha^{HH} = 10.1$$

SAI — LCF — DAI

$$r^\phi := \Gamma \cdot \left(1 + \frac{k^\phi}{K^\phi}\right)\cdot\begin{cases} 1 & ,\ \phi \text{ a scalar} \\ (1 + c_{di} s^2) & ,\ \phi = v_i \end{cases}$$

$$S^H = \frac{b_H a_{MM} - b_M a_{HM}}{a_{HH} a_{MM} - a_{HM} a_{MH}} \qquad S^M = \frac{b_M a_{HH} - b_H a_{MH}}{a_{HH} a_{MM} - a_{HM} a_{MH}}$$

# The STIC-scheme including empirical parameterization extensions:

Matthias Raschendorfer, Günther Zängl (DWD)

with optional positive definite solution of prognostic TKE-equation and optional vertical smoothing of $F_T^M$ $F^H$

*laminar-, tilted surface- and roughness-layer-correction*

partly substituting artificial security limits and related stratification damping

**STIC-impact:**

$r_M \cdot (F^M + F_C^M)$ additional SGS shear by :

Ri-number dependent scaling factor

- SHS circulation
- SSO wakes,
- SSO density currents
- *plumes of SGS convection*

optionally contributing to physical horizontal diffusion

- $$\frac{q^2 - q_0^2}{2 \cdot \Delta t} \approx [Adv(q_0) + Dif(q_0) + \ell \cdot (S^M F_T^M - S^H F^H)] \cdot q - \frac{q_0}{\alpha^{MM} \ell} q^2$$

$S^M F_T^M \geq 0$; $\frac{q_0}{\alpha^{MM} \ell} q^2 < 0$

including non-gradient diffusion

restrictions for very stable stratification

now more flexible

potentially reducing stable stratification-damping

$$q = \max\{v_{min}, q\}$$

minimal turbulent velocity scale with a stability dependent correction (near the surface)

artificial treatment of possible singularities

- **diagnostic (linear) system** dependent on TKE=$q^2/2$ and **mean vert. gradients** $F_T^M$ $F^H$

(for all other 2-nd order moments) => **stability functions**: $S^M$ $S^H$

- **Implicit vertical diffusion** update for **mean vert. gradients** using **restricted** **vertical diffusion coefficients** $K^{M,H} = \max\{k^{M,H}, \ell q S^{M,H}\}$

Ri.number dependent minimal diffusion coefficients