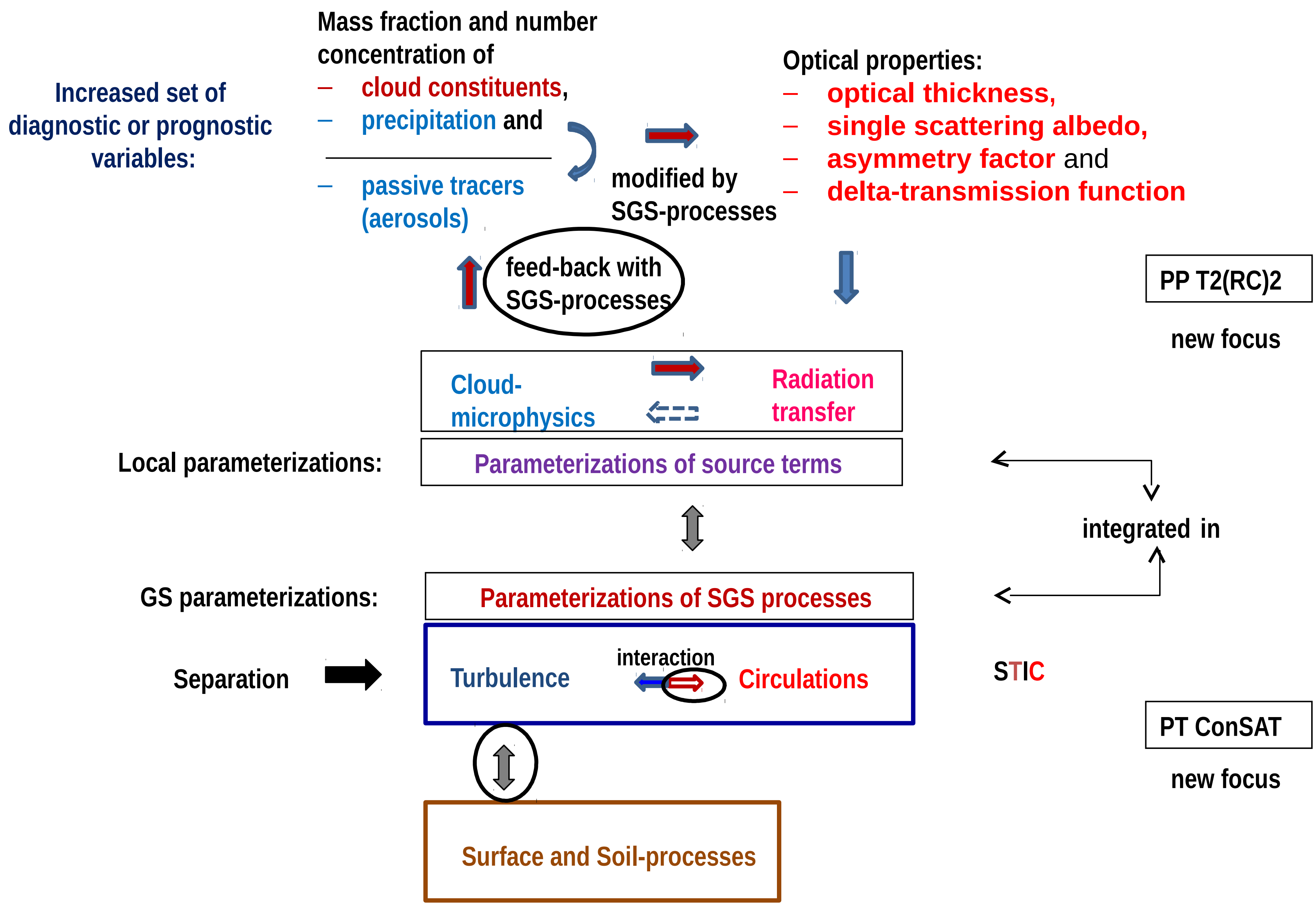
Along the aim of COSMO-SP to consider missing interactions:



Scale Interaction (STIC) and its essential effect on Surface-to-Atmosphere Transfer (SAT)

Matthias Raschendorfer, DWD

Outline:

- A lessen from previous ConSAT tasks:

  - Background-diffusion (BD), introduced, e.g., by minimal diff.-coeff., is a substitute of missing STIC terms (acting due to non-turbulent heterogeneity).
  - If BD of non-adaptive STIC terms are applied in the BL even above a homogeneous surface, this partly destroys the stability reduction of SAT-velocity.
    - ➢ too large heat-fluxes in those situations

⇓ one branch of ConSAT

- ❖ more complete STIC-terms being better adapted to external parameters and to the local model state
- ❖ adapted relaxation of hidden numerical security measures
- ❖ activation of prepared extensions
- ❖ transfer of related ICON-development into COSMO?

- I'm explaining the idea of STIC and the status of current development

The filtered model equations:

GS flux density — molecular flux density — GS source term

$$\partial_t\left(\bar\rho\hat\phi_i\right) + \nabla\cdot\left(\underbrace{\bar\rho\hat\phi_i\hat{\mathbf{v}}}_{\text{GS flux density}} + \underbrace{\overline{\rho\phi_i''\mathbf{v}''}}_{\text{SGS flux density}} - \underbrace{k^{\phi_i}\nabla\hat\phi_i}_{\text{molecular flux density}}\right) + \overline{\nabla'\cdot\left(\rho\phi_i\mathbf{v} - k^{\phi_i}\nabla\phi_i\right)'} = \underbrace{Q_{\underline{\lambda}}^{\phi_i}\left(\hat{\underline{\phi}},\bar p\right)}_{\text{GS source term}} + \overline{Q_{\underline{\lambda}}^{\phi_i}\left(\underline{\phi}'',p'\right)}'$$

SGS flux density

roughness layer modification of transport

non-linear function

SGS source term including roughness layer effects (form drag)

$$\overline{Q_{\underline{\lambda}}^{v_i}\left(\underline{\phi}'',p'\right)}' = -\overline{\partial_i' p'}$$

form drag: non-commutability of filter and spatial differentiation ➡ contribution by SGS slopes of model layers or non-atmospheric intersections

$$\overline{Q_{\underline{\lambda}}^{q_k}\left(\underline{\phi}'',p'\right)}'$$

SGS contribution by cloud microphysics

$$\overline{Q_{\underline{\lambda}}^{T}\left(\underline{\phi}'',p'\right)}'$$

SGS contribution by cloud microphysics and radiation

} functions in various covariance terms of scalar variables

$$\bar p = \bar\rho R_d\left[1 + \left(\frac{R_v}{R_d} - 1\right)\bar q_v - \bar q_c\right]\bar T + R_d\left[\left(1 + \frac{R_v}{R_d} - 1\right)\overline{\rho q_v''T''} - \overline{\rho q_c''T''}\right]$$

$\underline{\phi}$: vector of all 1[st]-order prognostic model variables

$\bar\varsigma$: grid-scale filtered (mean) variable with fluctuation $\varsigma' = \varsigma - \bar\varsigma$

$\hat\varsigma = \dfrac{\overline{\rho\varsigma}}{\bar\rho}$: corresponding density weighted mean with fluctuation $\varsigma'' = \varsigma - \hat\varsigma$

2nd-order (SO) budgets:

$\phi, \psi \cdots \in \{\phi_1, \phi_2, \cdots\}$ **prognostic model variables**

influenced by pressure force, microphysics and radiation

$$\partial_t\left(\overline{\rho\phi'\psi'}\right) = -\nabla\cdot\left(\overline{\rho\phi'\psi'}\,\hat{\mathbf{v}} + \overline{\rho\phi'\psi'\mathbf{v}'}\right) - \left(\overline{\rho\psi'\mathbf{v}'}\cdot\nabla\hat{\phi} + \overline{\rho\phi'\mathbf{v}'}\cdot\nabla\hat{\psi}\right) + \left(\overline{\mathbf{e}^{\psi}\cdot\nabla\phi'} + \overline{\mathbf{e}^{\phi}\cdot\nabla\psi'}\right) + \left(\overline{\phi' Q^{\psi}} + \overline{\psi' Q^{\phi}}\right)$$

GS flux density **SGS flux density** **shear production** **dissipation sink** **source term correlation**

$+ \cdots$

to be parameterized

laminar transport

roughness layer modification of transport

Parameterizations in terms of grid scale (GS) variables :

- **Further information** (**assumptions**) about these **additional covariance terms** has to be introduced:

functions in all <u>GS</u> model variables $\overline{\rho}, \underline{\hat{\phi}}, \overline{p}$

dependent on a list of additional parameters $\underline{\beta}$

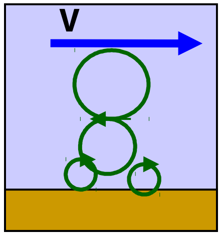
<u>GS</u> parameterizations due to

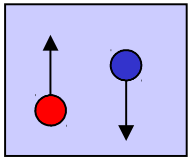
– *SGS variability*

- **Closure assumptions** are **additional constraints** that **<u>can't be general valid</u>**

➢distinguish **different SGS flow structures** more or less according to the **length scales of their motions**

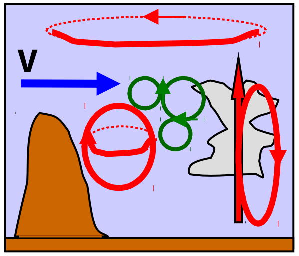
➢each with **<u>specific</u> parameterization assumptions**





Turbulence: **isotropic**, **normal distributed**, only **<u>one</u>** characteristic **length scale** at each grid point, forced by **shear and buoyancy**

SGS Circulation: **non isotropic**, arbitrarily **skewed** and **coherent** structures of **<u>several</u> length scales,** supplied by **various pressure forces**



Convection: large vertical scales of coherence, full microphysics, forced by buoyancy feed back

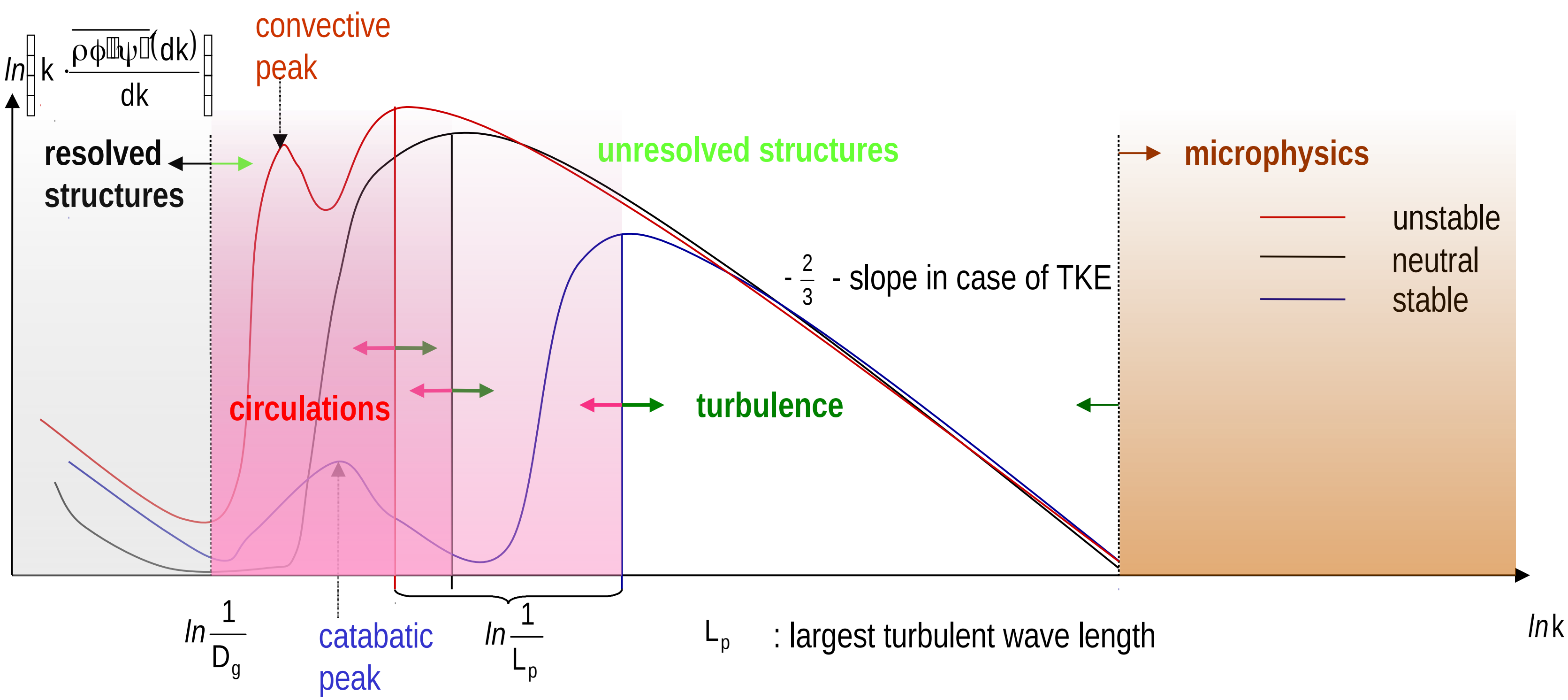
Kata- and anabatic density circulations: direct thermal circulation forced by lateral cooling or heating by sloped surfaces of the earth; dominated by SGS surface structures like SSO

Horizontal shear eddies: produced by strong horizontal shear e.g. at frontal zones; dominated by horizontal grid scale

Wake eddies: produced by blocking at SGS surface structures (form drag forces)

Breaking gravity wave eddies: belong to wave length of instable gravity waves of arbitrary scales

Spectral characteristics of turbulence and circulations:



- **circulations** generally are related with …………………………………… **additional spectral peaks**
- or they cause **different peak wavelengths** in **vertical** direction compared to the **horizontal** directions: …. **anisotropic peak wave length**
  - **larger** **peak wavelength** in **vertical** direction in case of **unstable** stratification
  - **smaller** **peak wavelength** in **vertical** direction in case of **stable** stratification

– at least a **two-scale-problem**

– **different closure assumptions for turbulence and circulations**

The TKE-scheme including empirical parameterization extensions:

Matthias Raschendorfer Günther Zängl (DWD)

- o **TKE vanishes at stable stratification and vanishing vertical shear**
  - **Unrealistic decouple of surface and boundary layer**
  - **Missing stratospheric turbulence**
- **artificial limitations and empirical extensions are necessary**

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

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

including non-gradient diffusion

$\left(S^M F_T^M \right) \geq 0$; $\frac{q_0}{\alpha^{MM} \ell} q^2$: < 0

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

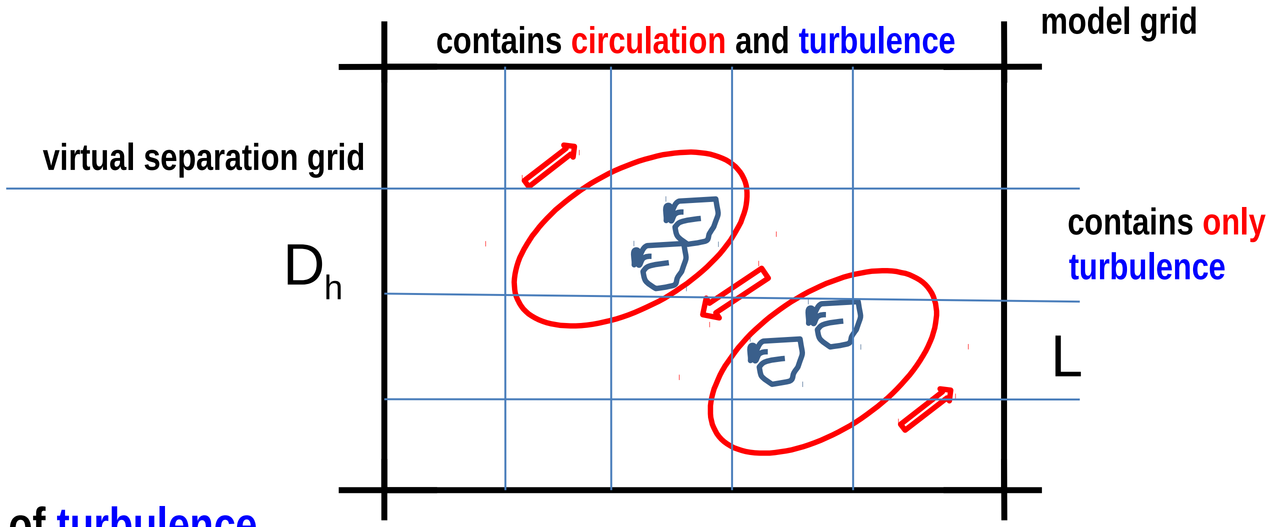
- **Implicit vertical diffusion** update for **mean vert. gradients** using **restricted vertical diffusion coefficients** $K^{M,H} = \max\{ k^{M,H}, \ell q S^{M,H} \}$

Ri.number dependent minimal diffusion coefficients

Current realization:

- **We usually apply parameterizations of effects on 1-st order budgets due to different processes (turbulence, convection, SSO wakes) without using a clear separation procedure**
  - **Each scheme for a specific SGS process would only be valid, if all the other sub grid scale processes were in accordance with the specific closure assumptions, what is in CONTRADICTION to the need of DIFFERENT SGS models!!**
- **This missing separation causes serious problems:**
  - **Non-realizability due to the application of not valid assumptions**
  - **Double-counting of effects from different scale regimes**
  - **Missing feedback between different scale regimes**
    - **No amplification of turbulence due to the action of circulations**
    - **No decrease of Circulation Kinetic Energy (CKE) by turbulent friction**
    - **No trigger of convective circulations by turbulent eddies**
    - **....**

Separated Turbulence Interacting with non-turbulent Circulations (STIC):



- **3D-shear production of turbulence**
  - **From the grid-scale flow**
  - **From non-turbulent sub-grid flow patterns (circulations)**
    - **Connected with coherent structures being not in accordance with turbulence closure**
    - **Will be expressed by grid-scale 3D shear, if the patterns are resolved by a smaller grid**
    - **<u>Extracts</u> kinetic energy from the circulation flow and <u>feeds</u> turbulence**

<u>The procedure of STIC:</u>

- **Assume that turbulence approximations can be assigned to all <u>horizontal scales</u> not smaller than a <u>maximal turbulent length scale</u>** L_p **(mainly dependent on the distance from the surface)**

- **Spectral separation** by
  - considering **budgets** with respect to the **separation scale** $L = min\{L_p, D_g\}$
  - **averaging** these budgets along the **whole control volume** (**double averaging**)

➢ **1-st order budgets with SGS contributions from turbulence and circulations**

$$\overline{\rho\phi\psi} = \overline{\rho}\hat{\phi}\hat{\psi} + \overline{\overline{\rho\phi'\psi'}|_L} + \overline{\overline{\rho}|_L \hat{\phi}|_L'' \hat{\psi}|_L''}$$

$|_L$: with respect to the separation scale L

➢ **Two sets of 2-nd order equations containing additional scale interaction terms:**

one set for pure turbulence and another for pure circulations

⇕

Mass flux equations describing initial conditions and lateral mixing of cells using properties of turbulence

Separated TKE equation contains additional shear term:

- **Semi-parameterized (neglecting laminar transport and roughness layer modification of transport)**

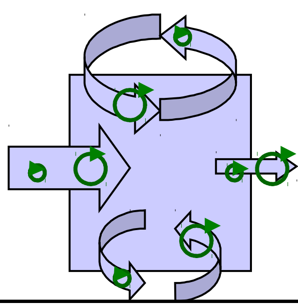
$$2\cdot TKE := q^2 := \frac{\overline{\bar{\rho}|_L\, q|_L^{\;2}}}{\bar{\rho}} \qquad q_C^2 := q|_L^{\;2} := \frac{1}{\bar{\rho}|_L}\sum_{i=1}^{3}\overline{\rho v_i''^2}\Big|_L$$

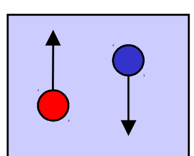
$|_L$: with respect to the separation scale L

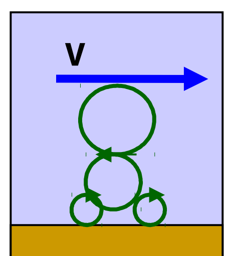
not yet considered

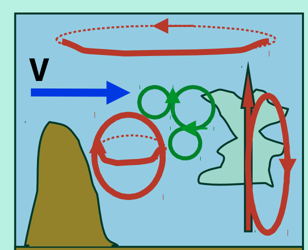
$$\partial_t\left(\frac{1}{2}\bar{\rho}\cdot q^2\right) = \frac{1}{2}\nabla\cdot\left(\overline{\bar{\rho}\, q^2\,\hat{\mathbf{v}}} + \overline{\hat{\rho}|_L\, q|_L^2\,\hat{\mathbf{v}}|_L}'' + \sum_{i=1}^{3}\overline{\left(\rho v_i''^2\,\mathbf{v}''\right)}\Big|_L\right) + \frac{g}{\hat{\theta}_v}\overline{\rho\theta_v'' w''}\Big|_L + \left(-\sum_{i=1}^{3}\overline{\rho v_i''\mathbf{v}''}\Big|_L\cdot\nabla\hat{v}_i\right) + \underbrace{\left(-\sum_{i=1}^{3}\overline{\overline{\rho v_i''\mathbf{v}''}\Big|_L{}'\cdot\left(\nabla\hat{v}_i\right)\Big|_L}'\right)}_{Q_C^{TKE}} + \left(-\bar{\rho}\,\frac{q^3}{\alpha^{MM}\ell}\right)$$

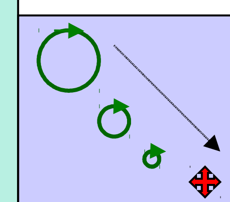
time tendency	transport: (advection + circ. diffusion + turb. diffusion)	buoyancy production	shear production by the mean flow	shear production by sub grid scale circulations	eddy-dissipation rate (**EDR**)
		labil: > 0 neutral: $= 0$ stabil: < 0	≥ 0	≥ 0	< 0







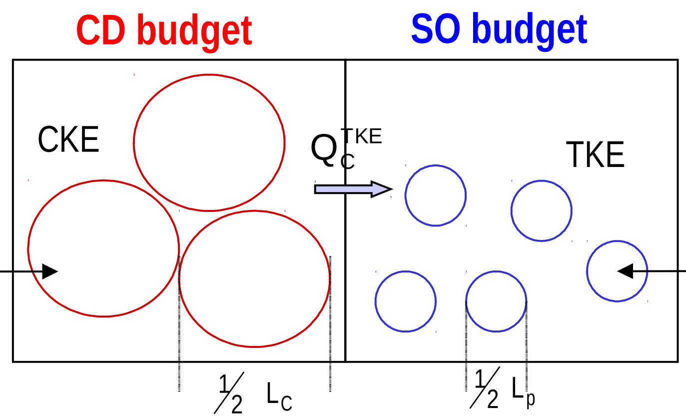




Towards a description of TKE-production by sub-grid circulations (SI-term):

production terms dependent on:

specific **length scales** L_C and a specific **velocity scale** (= $\sqrt{CKE}$)



production terms depend on:

turbulent **length scale** L_p and the turbulent **velocity scale** (= $\sqrt{TKE}$)

and other **circulation**-scale **turbulence**-scale moments

- **Simplified CD budget: Equilibrium of production and scale transfer towards turbulence:**

$$Q_C^{TKE}(q_C) \propto \frac{q_C^3}{L_C}$$

L_C **length scale** of the circulation

α_C **effective** scaling parameter

kinetic energy production of the circulation

solving for q_C **velocity scale** of the circulation

Current work on STIC:

- **dTKEshs “more realistic generalization”**
  - ✓ **SI dependent on thermal stability and height above ground**
    - ➢ **formulation SI-sink in CKE-budget of SHS-circulation also dependent on turbulent velocity scale.**

✓ new formulation in preparation

- **dTKEcnv “to be used not only for EDP-post-processing”**
  - • **Operational use in prognostic TKE-equation**
    - ➢ **removing sources of detrimental jumps in space and time**
  - • **Introduction of turbulence-feedback into convection-scheme**
    - ➢ **formulation of detrainment/entrainment also dependent on turbulent velocity scale**
    - ➢ **trigger of SGS convective plumes by turbulent vertical velocity**

✓ publications about EDP running
– derivation and validation

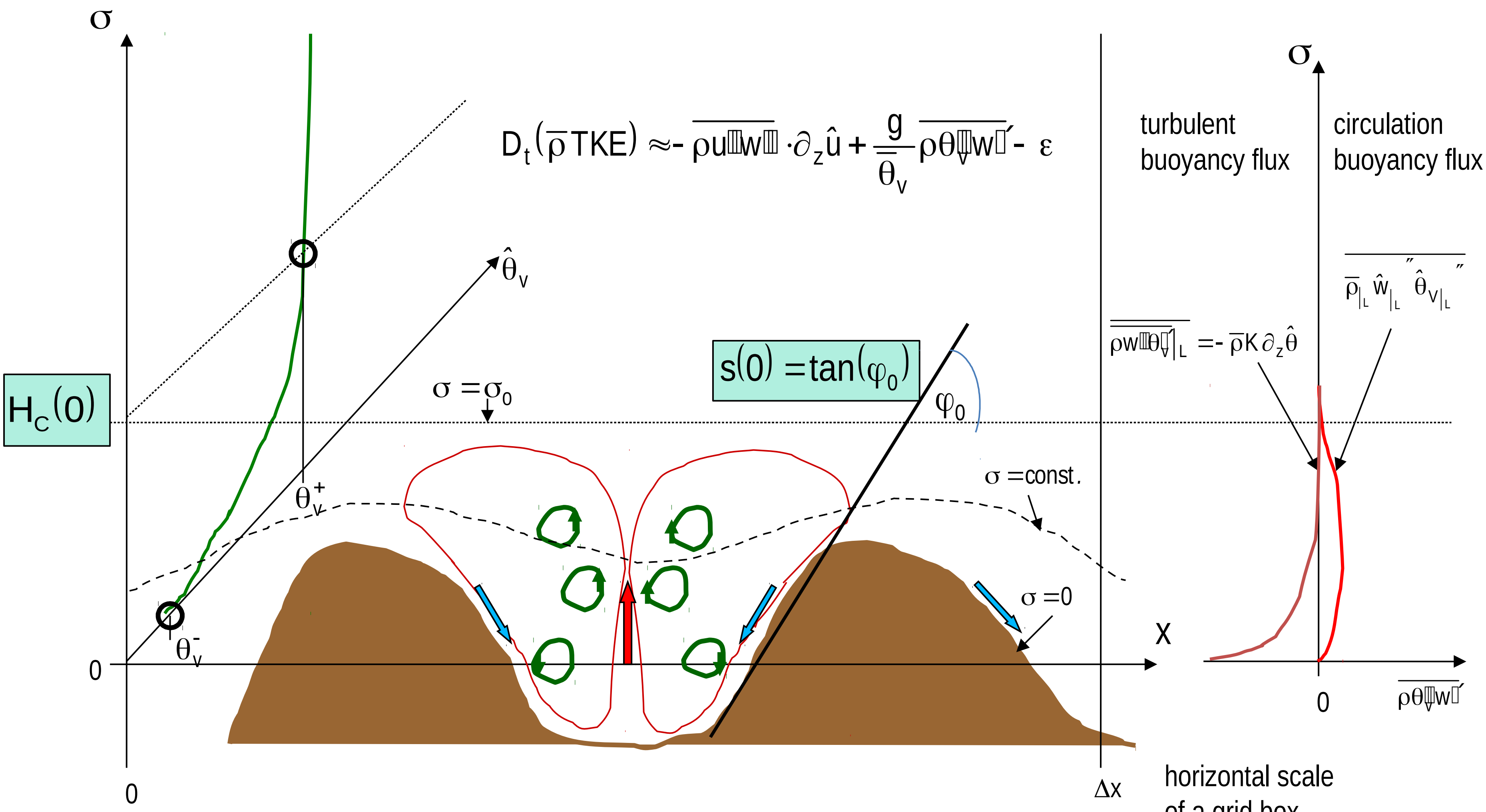
- **dTKEsso “empirical modifications”**
  - ✓ **SI with correction factor dependent on thermal stability**

✓ Introduced by Günther Z.

- **dTKEcrc “thermal SSO-term”**
  - ➢ **nocturnal katabatic down-valley circulation**
  - ➢ **daytime convective up-valley circulation**
  - ✓ **dependent on SSO-parameters (vanishing for a flat surface)**
  - ➢ **Thermal surface inhomogeneity surface-forcing of SGS convection**

✓ new formulation being tested
– substituting the current “circulation-term”

Effect of a sub-grid katabatic circulation for stabile stratification:



- Even for **vanishing mean wind** and **negative turbulent buoyancy** there remains a **positive definite source term**

⇨ TKE will **not** vanish ⇨ Solution even for **strong stability**

TKE-production by sub-grid circulations:

- **Equilibrium of production and spectral transfer towards turbulence:**

$$g\frac{\Delta\overline{\theta}_v}{\overline{\theta}_v}\sin(\varphi)\cdot q_C \approx Q_C^{TKE} \propto \frac{q_C^3}{L_C}$$

$$H_C(\sigma) \approx \max\{0, H_C(0) - \sigma\}$$ mean height-amplitude of a σ -surface

$$\tan[\varphi(\sigma)] = s(\sigma) \approx s(0)\cdot\frac{H_C(\sigma)}{H_C(0)}$$ mean slope of a σ -surface

$$L_C = \frac{H_C}{\sin(\varphi)}$$ coherence-length along the σ -slope

$$\Delta\overline{\theta}_v \approx \left|\partial_z\overline{\theta}_v\right|\cdot H_C$$ effective temperature difference

$$F^H = \frac{g}{\overline{\theta}_v}\partial_z\overline{\theta}_v$$

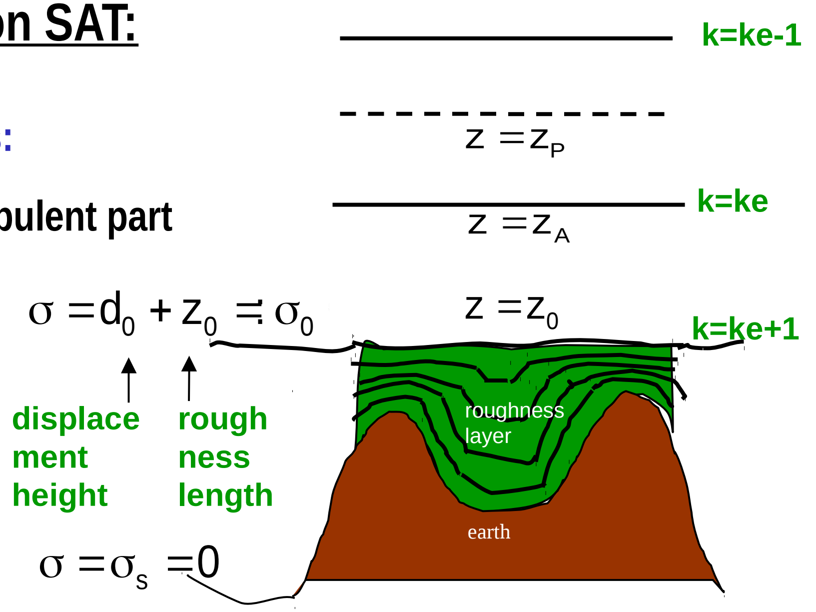
- <0: anabatic — q_C may trigger convection
- >0: katabatic — q_C ventilates the SBL

$$Q_C^{TKE} \approx \alpha_C\frac{(s\cdot H_C)^2}{1+s^2}\left|F^H\right|^{\frac{3}{2}}$$ resulting TKE-production

$H_C(0)$, $s(0)$: external 2D SSO-parameter

α_C: effective scaling parameter

Direct STIC-impact on SAT:



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

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

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

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

$$u_x^{\phi} := \frac{K_x}{\ell} \quad \text{turbulent velocity}$$

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

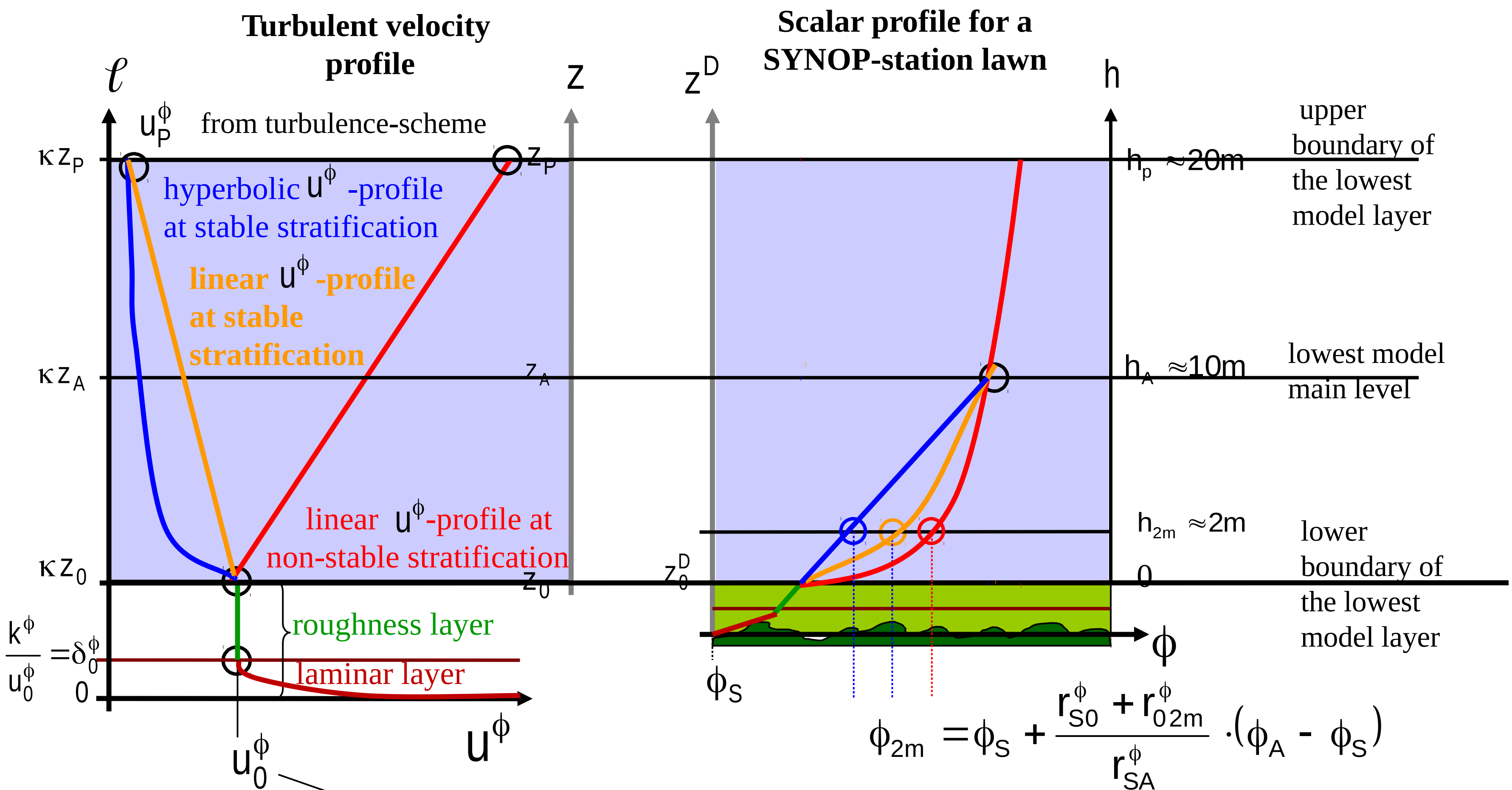
operationally deactivated

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

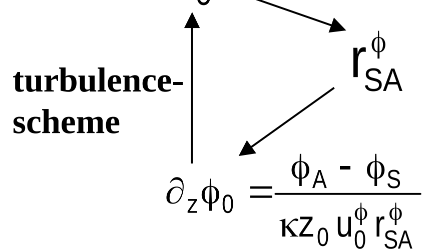
$$SHF_S = \bar{\rho}_S u_{SA}^H \cdot c_{p_d} \left(\hat{\theta}_A - \hat{T}_S \right)$$

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

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



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



- **Kmin or STIC-terms may increase u_P^ϕ compared to u_0^ϕ**
  - **stable -> non-stable characteristic**
  - **decreased r_{SA}^ϕ -> stronger coupling**

} **increased nocturnal T2m**

General STIC-Impact on SAT:

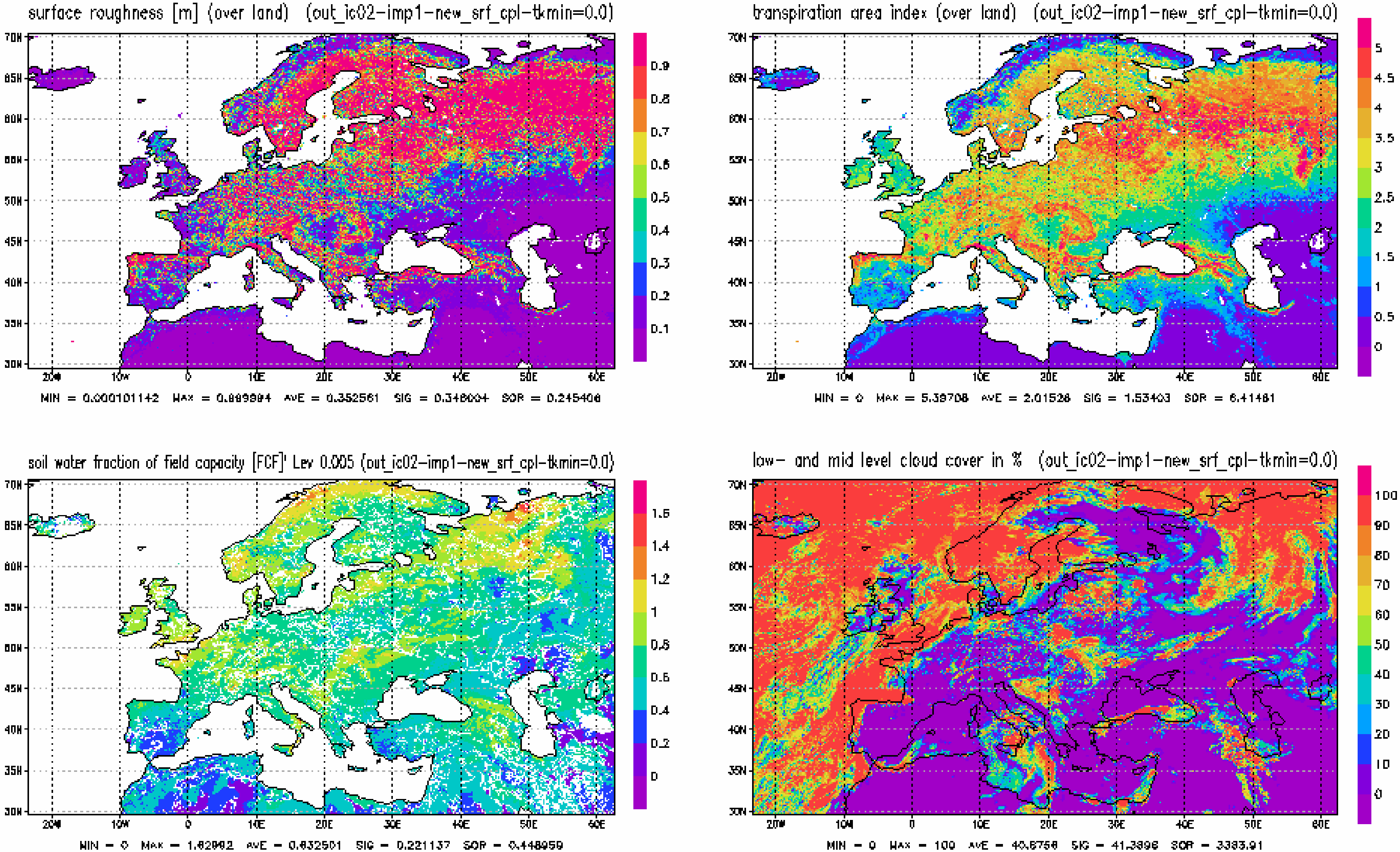
- Increased shear lowers Ri-number at stable stratification within the ABL
  and enters the calculation of stability functions
  - ➢ Avoids singularities of the solution
  - ➢ Substitutes the introduction of artificial "long-tale" stability functions

- Has a direct impact on transfer-velocities
  - o Due to the adapted construction of the transfer scheme
    solving TKE-equations at the roughness-layer top and the next higher half-level,
    where at least the latter can receive an impact by STIC-terms

- Generates additional physically based turbulent mixing
  - ➢ avoids unrealistic decoupling of a heterogeneous surface from the atmosphere
  - ➢ Substitutes (at least partly) the introduction of artificial minimal diffusion coefficients

A case-study:

- **An almost clear-sky mid-summer night with ICON-EU**



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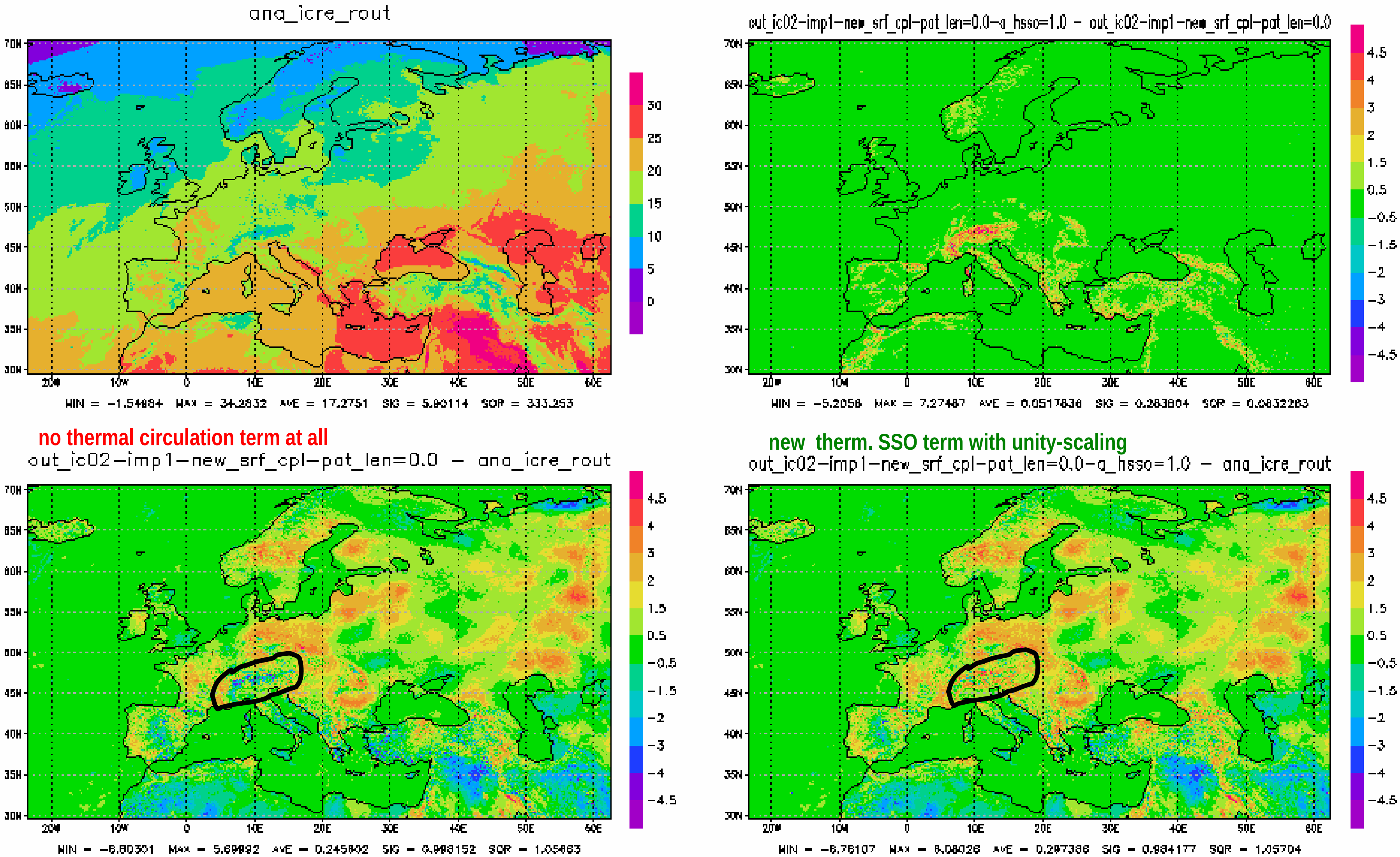
Effect of thermal SSO term:

- **Right correction for hilly surfaces**
  - **reduces negative nocturnal T2m-bias**
- **No effect at flat terrain**
  - **where only an decreased Kmin can lower the already present positive nocturnal T2m-bias**

2m-temperature [C]

Nocturnal effect of new SI-term from thermal SSO



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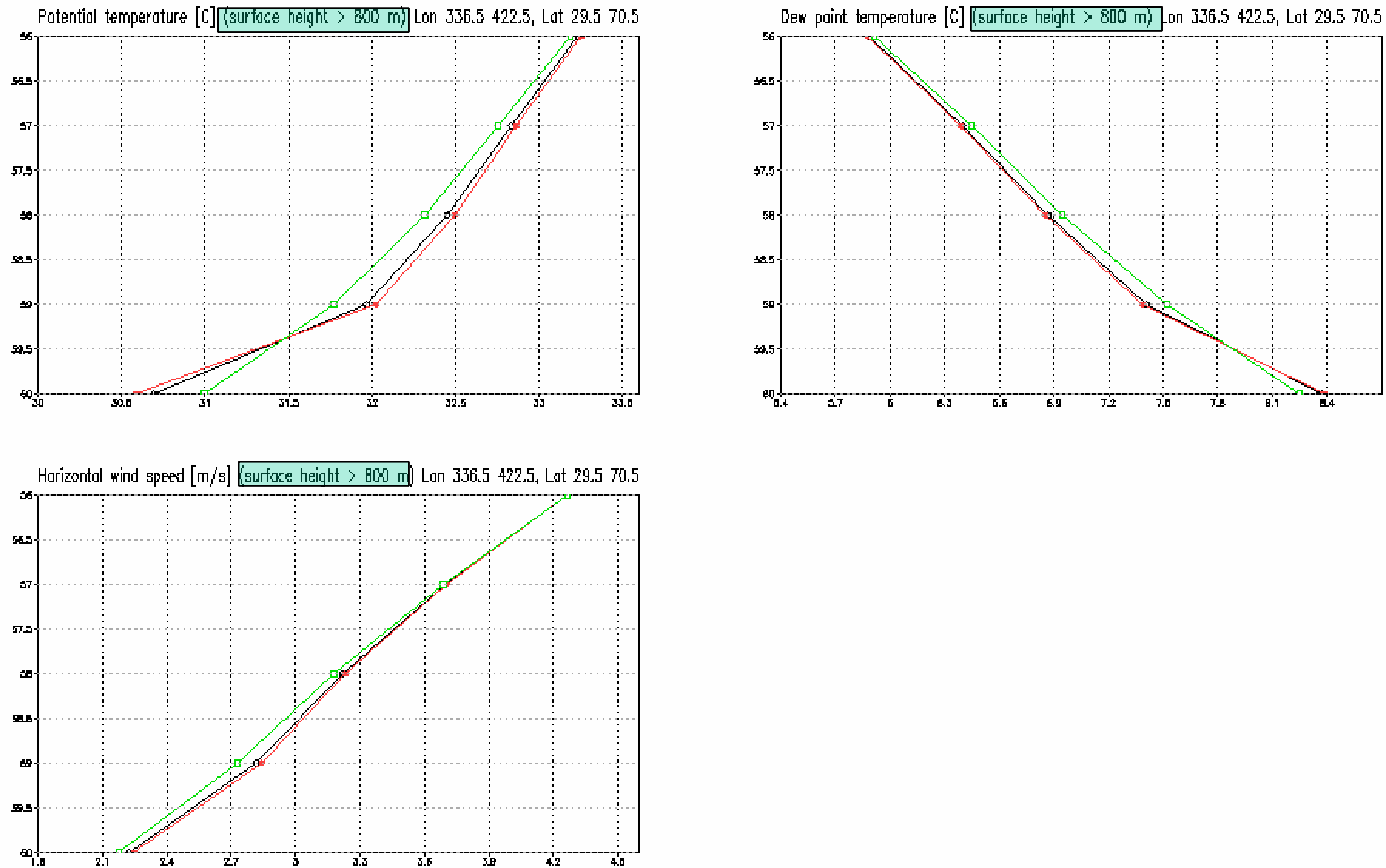
Nocturnal effect of new SI-term from thermal SSO



current circ.-term with strong SSO-limitation — out_ic02-imp1-new_srf_cpl

no thermal circulation term at all — out_ic02-imp1-new_srf_cpl-pat_len=0.0

new therm. SSO term with unity-scaling — out_ic02-imp1-new_srf_cpl-pat_len=0.0-a_hsso=1.0

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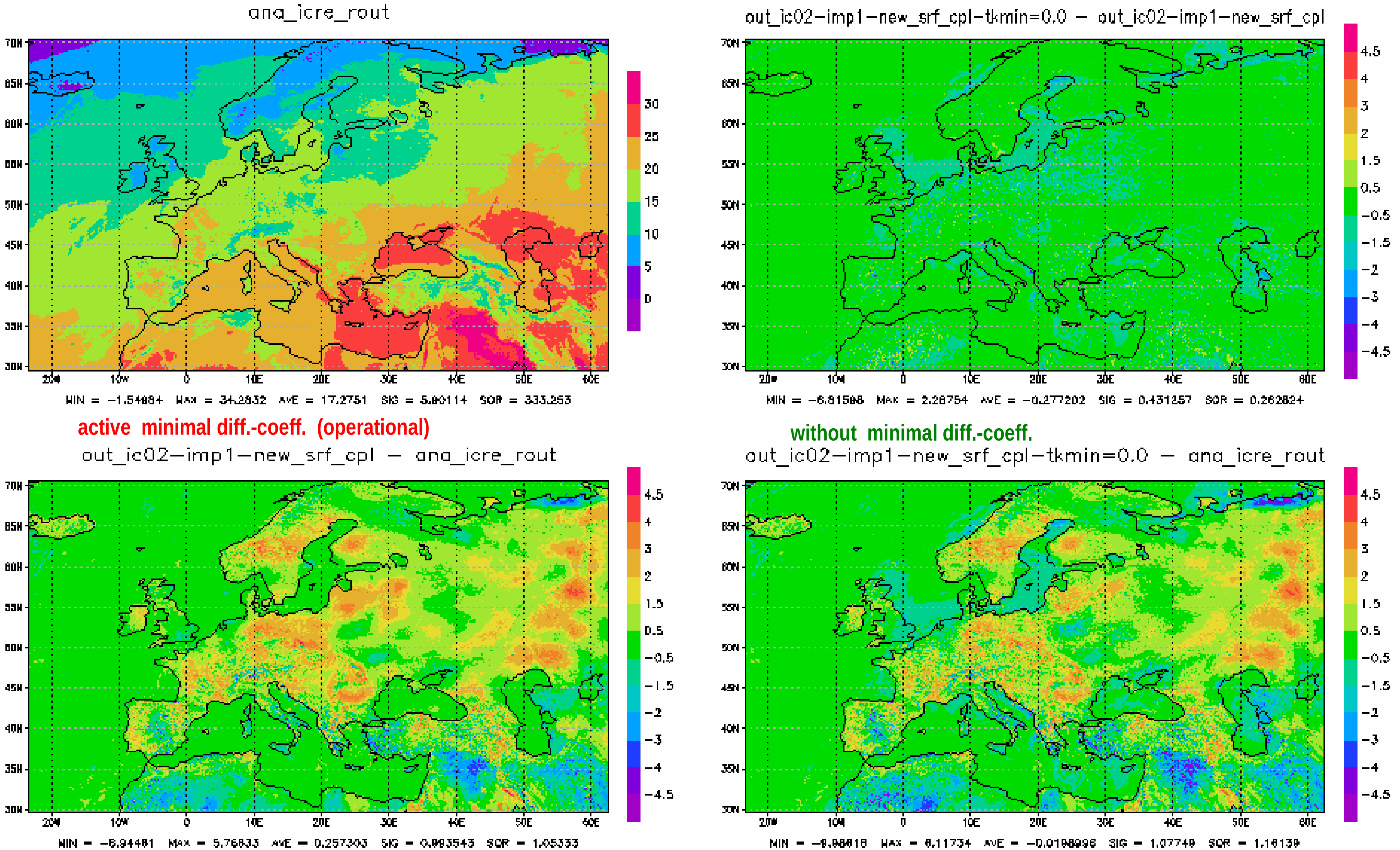
2m−temperature [C]

Nocturnal effect of minimal diffusion coefficients



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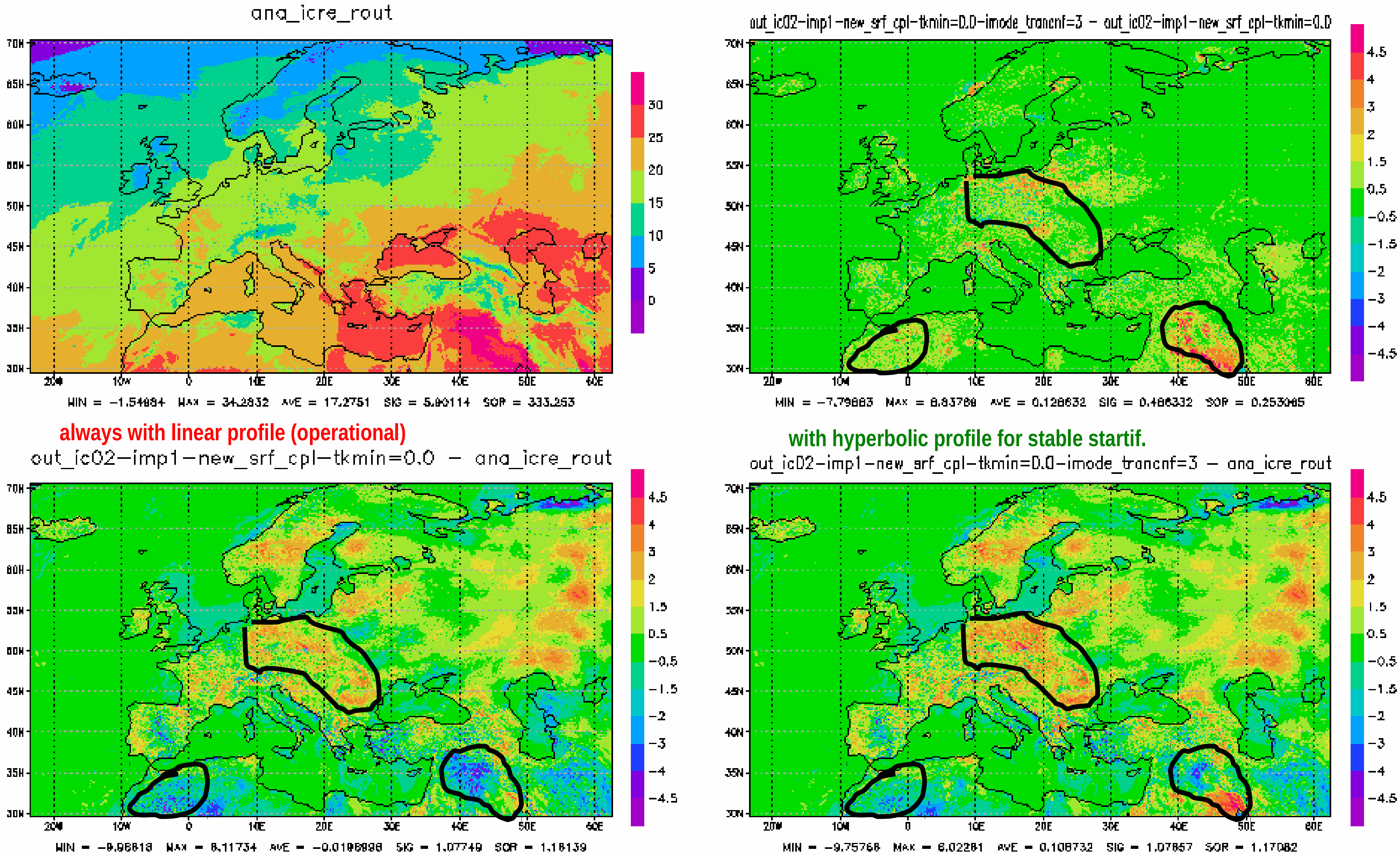
Effect of hyperbolic profile for turbulent velocity at stable stratification:

- **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**

2m−temperature [C]

Nocturnal effect of hyperbolic profile for stable turbulent velocity scale



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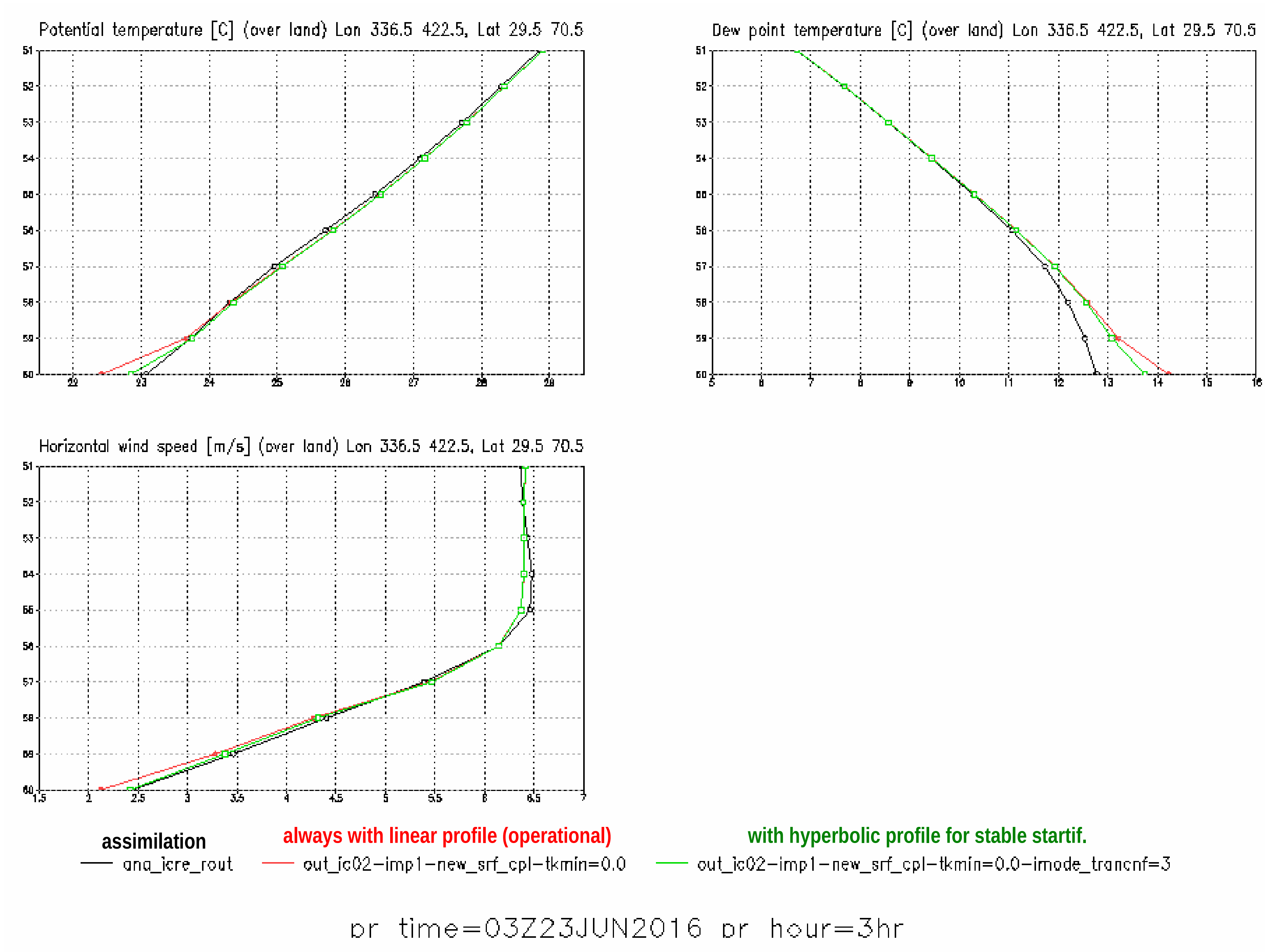
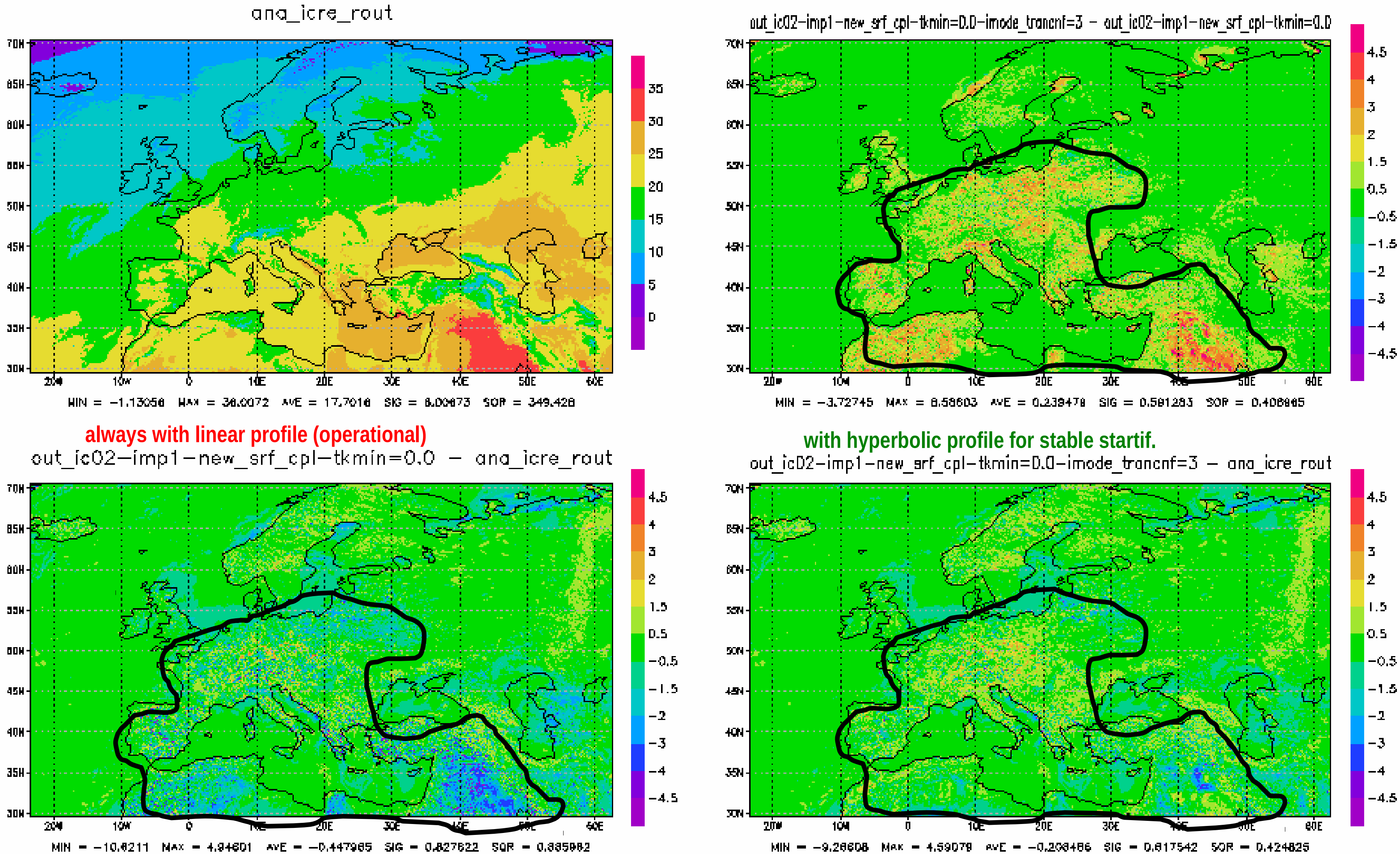
Nocturnal effect of hyperbolic profile for stable turbulent velocity scale



temperature [C]

Nocturnal effect of hyperbolic profile for stable turbulent velocity scale



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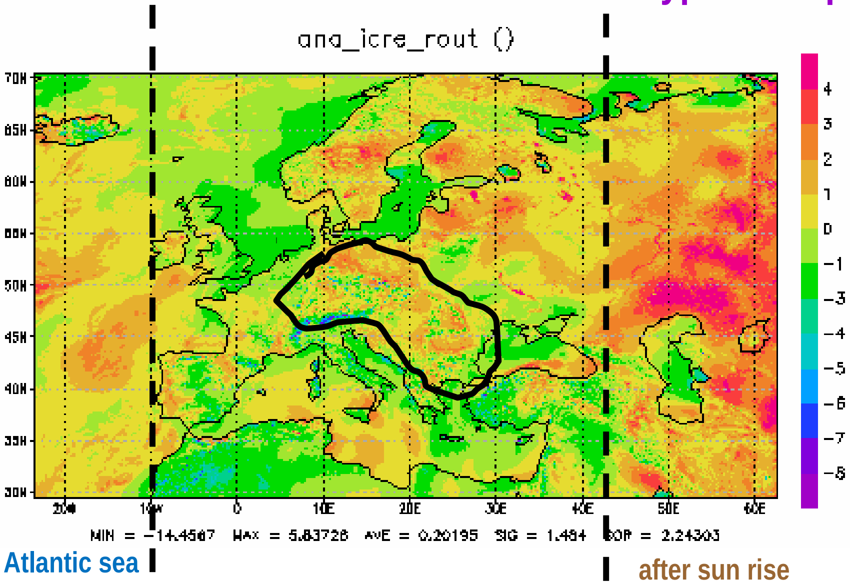
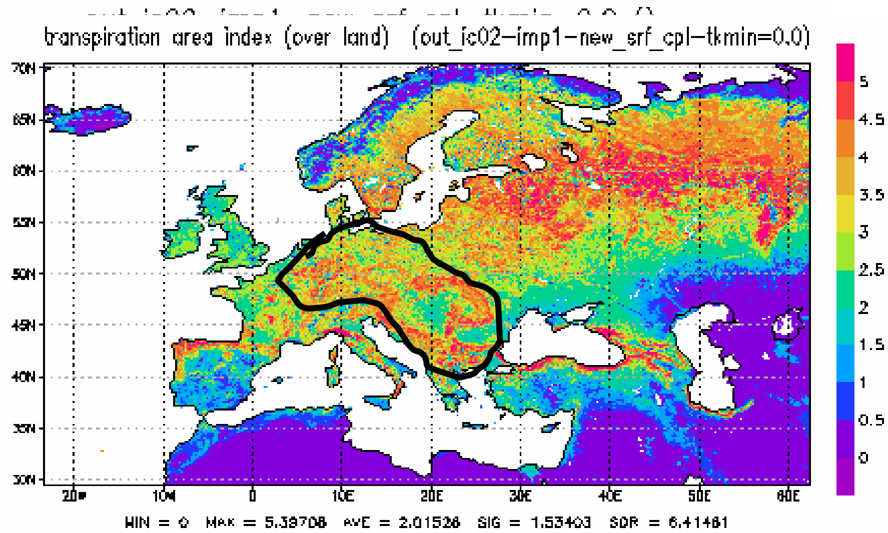
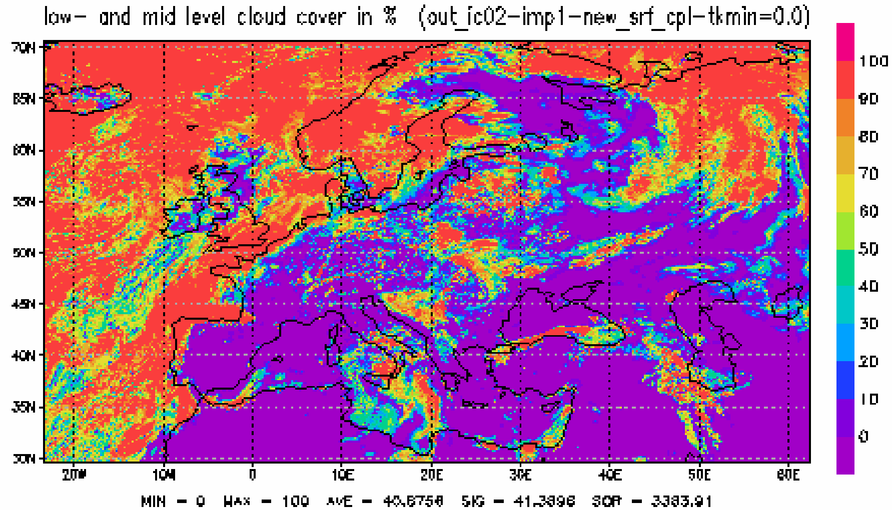
t_g – t_2m [C]

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

Outlook:

- Implementing a semi-transparent substantial cover-layer built from R-elements being thermally decoupled from the rigid soil
  - Larger amplitude of diurnal cycle
  - Reduction of evaporating surface
  - Treatment of snow below a plant canopy

- Expressing missing transport parameterized sub-grid circulations
  - Additional vertical and horizontal diffusion at circulation scales

- Expressing the effect of turbulence on circulations
  - Substitution of dissipation-like scale-transfer expressing the related shear term directly
  - Automatically introduces turbulent feedback:
    - Dependency on turbulent length scale and thermal stratification
- Describing near surface thermal circulations caused by land use roughness
  - Kata- and anabatic circulations at buildings and vegetation
    - Nocturnal labialization and daytime stabilization of transfer between soil and canopy

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

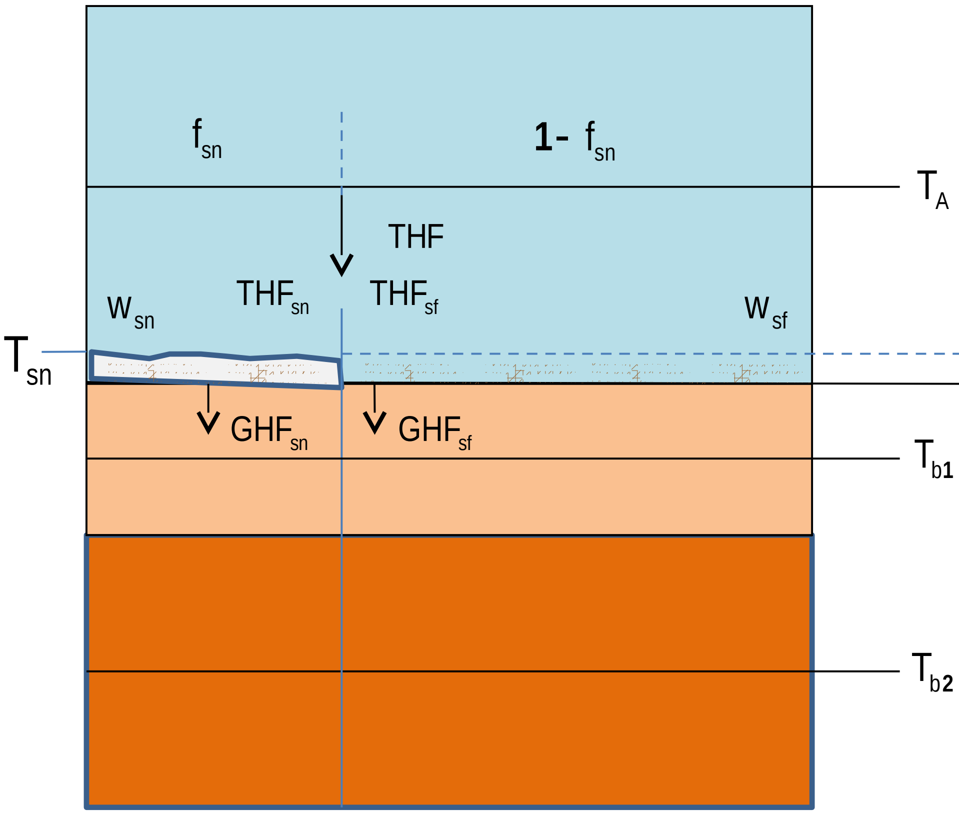
  - **Pure modifications in the description of the turbulent Prandtl-layer can hardly correct the main sources of current model-errors of the diurnal cycle of near surface variables and of numerical instability of near-surface temperatures!**
  - **The description of surface processes provides by far the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

⇩

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

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 and initialization**
5. **Merge with various work-arounds and extensions in ICON-TERRA**
6. **Including phase-transitions of precipitation (as well as soil water and the snow-cover) into the implicit treatment**
7. **Merge with prepared canopy-extension of skin-layer**
8. **Canopy-interception of snow and related adaptation of snow-tiles**
9. **Transfer of ICON-development into COSMO?**

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



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

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

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

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

T_{sf}, T_b } **substantial, loosely coupled, semi-transparent C-layer** ➡ **idealized, infinite-thin S-layer** $T_b \rightarrow T_{sf}$

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

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

$$GHF_{sn} = -\frac{\alpha^{sn}_b}{\alpha^{sn}_b + \alpha^b_{b1}} \cdot \left(T_{sn} - T_{b1}\right)$$

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

⇩

singularity for vanishing snow-depth

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

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

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

so far only explicit contribution considered

$$\partial_{T_{sx}}\left[SHF\right]^0_{sx} = -\left[\rho_s u^H_{SA}\right]^0 \cdot c_p$$

$$\partial_{T_{sx}}\left[LHF\right]^0_{sx} = -\left[\rho_s u^H_{SA} \cdot f^{red}_{sx} \cdot d_T q^{sat}_v\left(T_{sx}\right) \cdot L_{ev}\left(T_{sx}\right)\right]^0_{sx}$$

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

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

$$THF_{Sx} = \left[PHF + SRF + LRF_d + LRF_u + SHF + LHF\right]_{Sx}$$ total implicit heat flux-density towards the surface

$$= THF^0_{Sx} + \partial_{T_{Sx}}\left[LRF_u + SHF + LHF\right]^0_{Sx} \cdot \left(T_{Sx} - T^0_{Sx}\right)$$ explicit flux-density + implicit extension

total (virtual) conductivity

$$\partial_{T_{Sx}}\left[LRF_u\right]^0_{Sx} = -4\sigma\varepsilon_0 \cdot \left(T^0_{Sx}\right)^3$$

atmospheric transfer-velocity for scalars

specific humidity at saturation

$$\partial_{T_{Sx}}\left[SHF\right]^0_{Sx} = -\left[\rho_S u^H_{SA}\right]^0 \cdot c_p$$

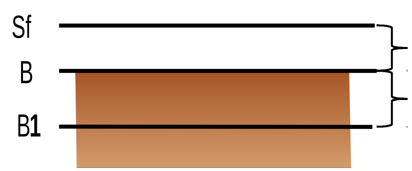
specific latent heat of evaporation

concatenation of resistances

$$\partial_{T_{Sx}}\left[LHF\right]^0_{Sx} = -\left[\rho_S u^H_{SA} \cdot f^{red}_{Sx} \cdot d_T q^{sat}_v \cdot L_{ev}\right]\left(T^0_{Sx}\right)$$

specific reduction of actual evaporation

$$GHF_{Sx} = -\frac{\alpha^{Sx}_B \cdot \alpha^B_{B1}}{\alpha^{Sx}_B + \alpha^B_{B1}} \cdot \left(T_{Sx} - T_{B1}\right)$$



α^{Sx}_B (due to exchange of SH and LR for Sx=Sf)

α^B_{B1}

α^y_x : conductivity between levels x and y

$$THF_{Sn} - GHF_{Sn} = \left[\rho_{Sn} c_{Sn}\right]^0 \frac{T_{Sm} - T^0_{Sm}}{\Delta t} \xrightarrow[h_{Sn} \to 0]{} 0$$

reduces to **implicit flux-balance** for vanishing snow-depth

$$T_{Sm} = \frac{1}{2} \cdot \left(T_{Sn} + T_B\right)$$ linear vertical T-profile of snow-pack

$$THF_{Sf} - GHF_{Sf} = \left[\rho_c c_c\right]^0 \frac{T_{Cm} - T^0_{Cm}}{\Delta t} \xrightarrow[C_c \to 0]{} 0$$

reduces to **implicit flux-balance** for **currently applied** **skin-layer approximation:**

$$C_c \to 0$$
$$\alpha^{Sf}_B \to \infty$$
$$T_C \to T_B$$

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

Implicit increments of atmospheric transfer velocities:
(already implemented)

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

$$\partial_{T_{Sx}}\left[SHF\right]^0_{Sx} = -\left[\rho_S u^H_{SA}\right]^0 \cdot c_p \qquad \partial_{T_{Sx}}\left[LHF\right]^0_{Sx} = -\cdot\left[\rho_S u^H_{SA} \cdot f^{red}_{Sx} \cdot d_T q^{sat}_v \cdot L_{ev}\right]^0$$

$$\boxed{\left[u^H_{SA}\right]^0 \rightarrow u^H_{SA} := \left[u^H_{SA}\right]^0 + \partial_{T_{Sx}}\left[u^H_{SA}\right]^0 \cdot \left(T_{Sx} - T^0_{Sx}\right)}$$

- 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:

$$\left[u^H_{SA}\right]^* = \left[u^H_{SA}\right]^0 + \partial_{S_{sx}}\left[u^H_{SA}\right]^0 \cdot \left(T^*_{Sx} - T^0_{Sx}\right)$$

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

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

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

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^{B1}_{Sn}					T_{Sn}		d_{Sn}
fes		a^{Sf}_{Sf}	a^{b1}_{sf}					T_{Sf}		d_{Sf}
ifb	a^{Sn}_{B1}	a^{Sf}_{B1}	a^{B1}_{B1}	a^{B2}_{B1}			•	T_{B1}	=	d_{B1}
			a^{B1}_{B2}	a^{B2}_{B2}	a^{B1}_{B2}			T_{B2}		d_{B2}
	⋮			a^{b2}_{B3}	a^{B3}_{B3}	a^{B4}_{B3}		⋮		⋮

- 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 :

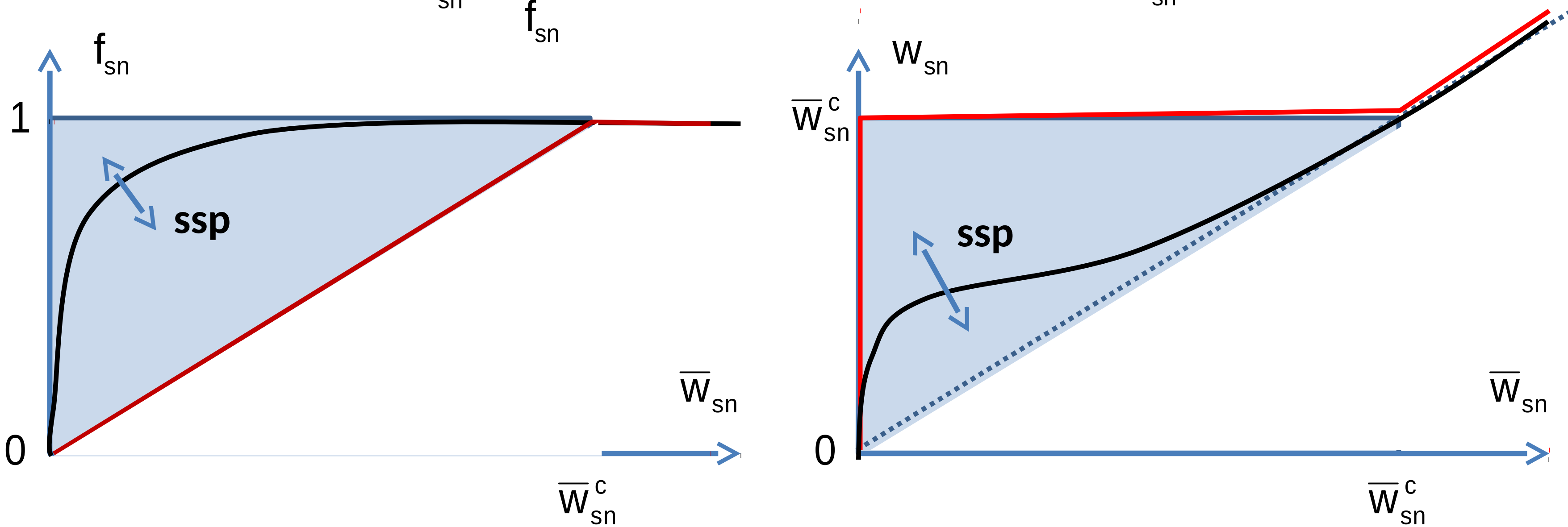
- **Snow is not equally distributed along the grid-cell surface, due to various sources of inhomogeneity:**

  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}



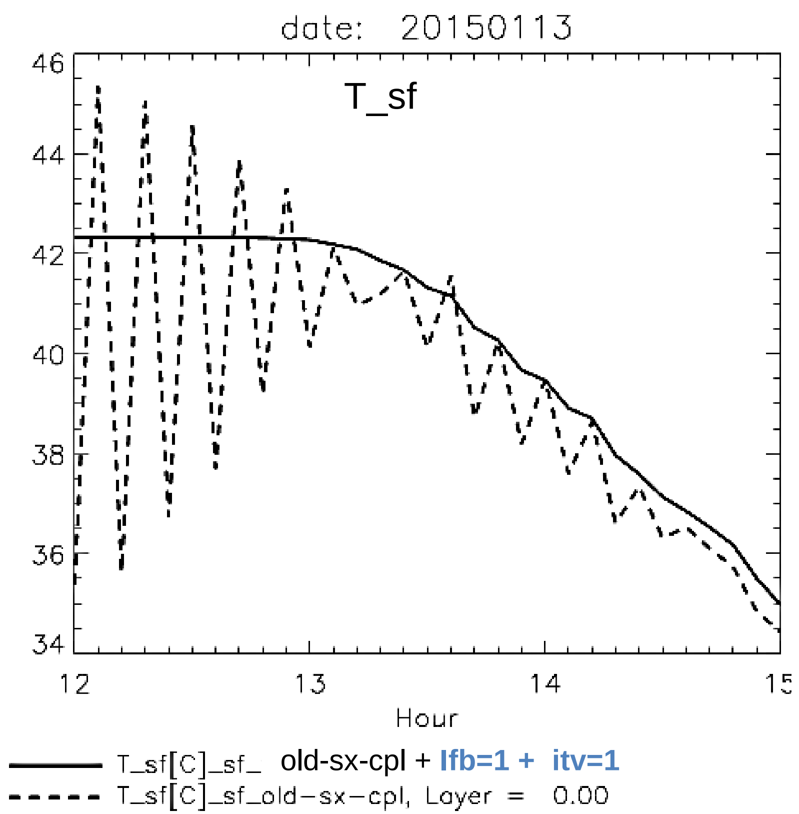
- **New control-parameter : ssp: spreading efficiency**

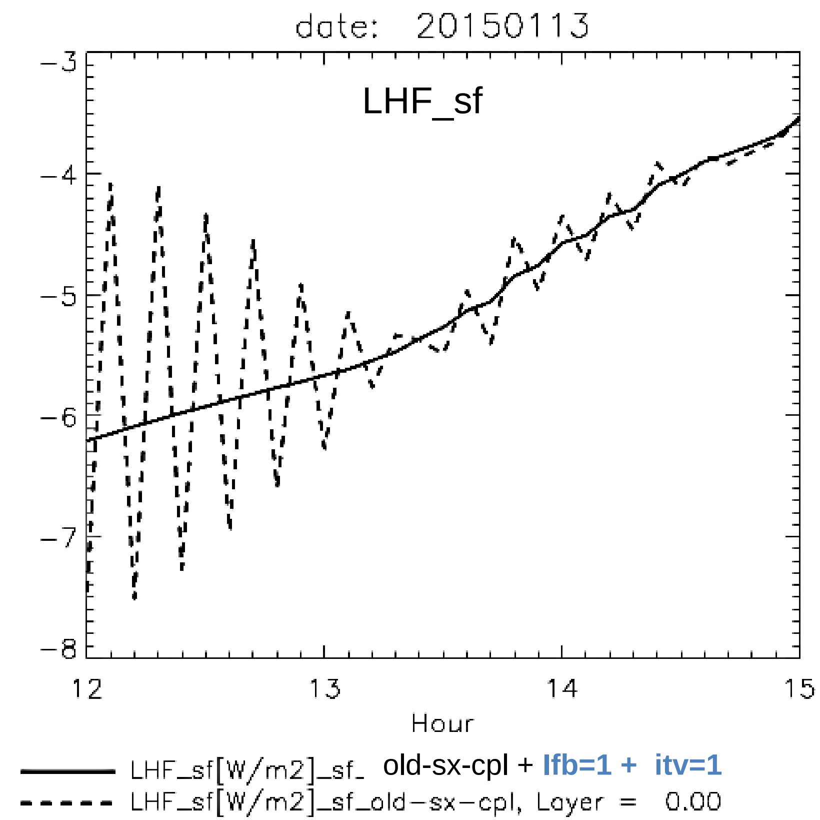
  ssp=0: **so far operational version; not steady; it is always** $w_{sn} \geq \overline{W}_{sn}^{c}$ **!!**

  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
  - **Substitution** of previous descriptions by new formulations
  - **Implementation** of new features
- **Sanity-checks** performed:
  - **numerically stable** even for **large time steps**
  - some **remaining oscillations** due to phase-transitions of snow or soil-water
  - almost minor differences compared to operational version, **but:**
  - the so far **inconsistent** treatment of **rime as part of w_{sf}** had to be **removed!**
    - **positive effect of this feature no longer present!**

⇒
- **consistent formulation of a 2-phase interception-store**
- **together with the so far missing implicit formulation** of 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

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

: current water-vapour flux-density

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

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

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

: current drip-water flux-density

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

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

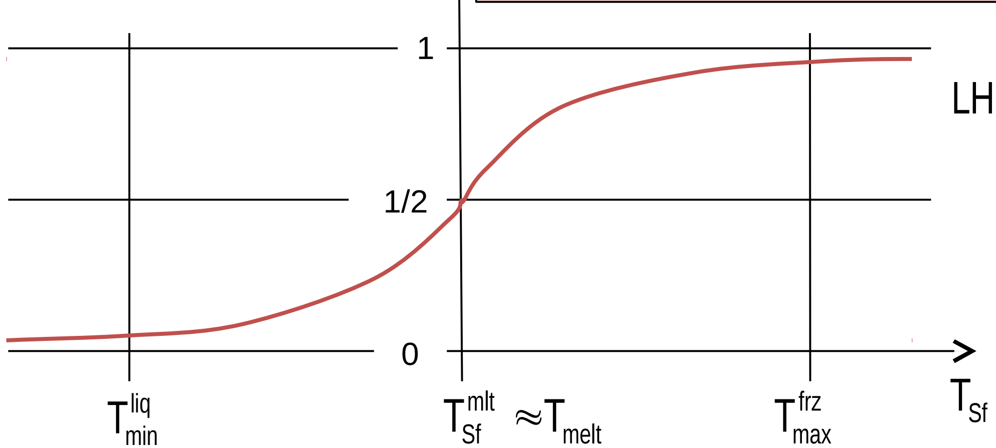
- Quadratic equation for $\mathbf{0} \le w_{Sf} \le w_{Sf}^{max}$; automatically positive-definite and limited
- Simultaneous consideration of all sources and sinks
- VWF_{Sx}^{pot} still depends on previous surface temperature T_{Sf}^{0}
  - No implicit coupling between hydrological and thermal equations 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 $T^{liq}_{min} \le T_{Sf} \le T^{frz}_{max}$ **liquid and frozen** interception-water **coexists** with a **smooth transition**.

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

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



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

$$\partial_{T_{Sf}}[LHF]^0_{Sf} = -\left[\rho_s u^H_s \cdot f^{red}_{Sf} \cdot d_T q^{sat}_v \cdot L_{ev}\right](T^0_{Sf})$$

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

generalized latent heat of vaporization

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

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

$$PHF^0_{Sf} = L_{fl} \cdot \left[RWF_{Sf} - (RWF_{Sf} + SWF_{Sf}) \cdot f^{liq}_{Sf}(T^0_{Sf})\right]$$

: related explicit part

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

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

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

Next steps:

- **Completion** of running implementations related to interception water
- **Running** chain of test-cases
- **Performing** some code-optimizations in terms of vectorization
  → ❖ **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 α_B^C and the additional heat capacity c_C :

$$THF_C - GHF_C = \left[\rho_c c_c\right]^0 \frac{T_{Cm} - T_{Cm}^0}{\Delta t} \qquad T_{Cm} = \frac{1}{2} \cdot (T_C + T_B)$$

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 mass of R-elements and interception water

α_B^C due to 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!**

- **n cover layers** including the **surface of the dense soil** (n=0) are connected by long-wave radiation interaction and sensible heat exchange

  ⇨ **thermally decoupled roughness elements (shading)**

- Only **a part of the inner surfaces is connected to A** by the resistance chain, the **other part is for the inter- surface exchange**

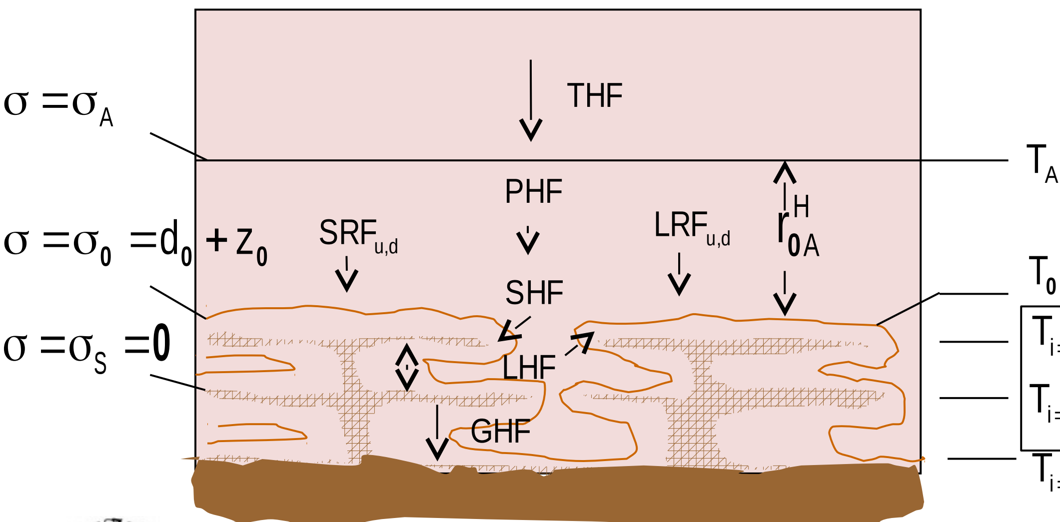
  ⇨ strongly effects the **LAI-impact of transpiration**!

$$r_{SA}^H = r_{S0}^H + r_{0A}^H$$

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

$$SAI = 2n + 1 = 2 \cdot LAI + c\_lnd$$

$$S_0 = \frac{(SAI-1)\cdot(SAI_\infty - 1)}{(SAI-1)+(SAI_\infty - 1)} + 1 \quad \begin{cases} = 1 & , SAI = 1 \\ \rightarrow SAI_\infty & , SAI \rightarrow \infty \end{cases}$$



$$a_B + a_C = 1 = a_B^R + a_C^R$$

functions of SAI only

$$T_{i=n} = T_R = a_B^R T_B + a_B^R T_C$$

$$T_{i\geq 1} = T_B + \frac{i}{n} \cdot (T_R - T_B)$$

$$T_{i=0} = T_B$$

T_C, T_B

$$T_S = a_B T_B + a_C T_C$$

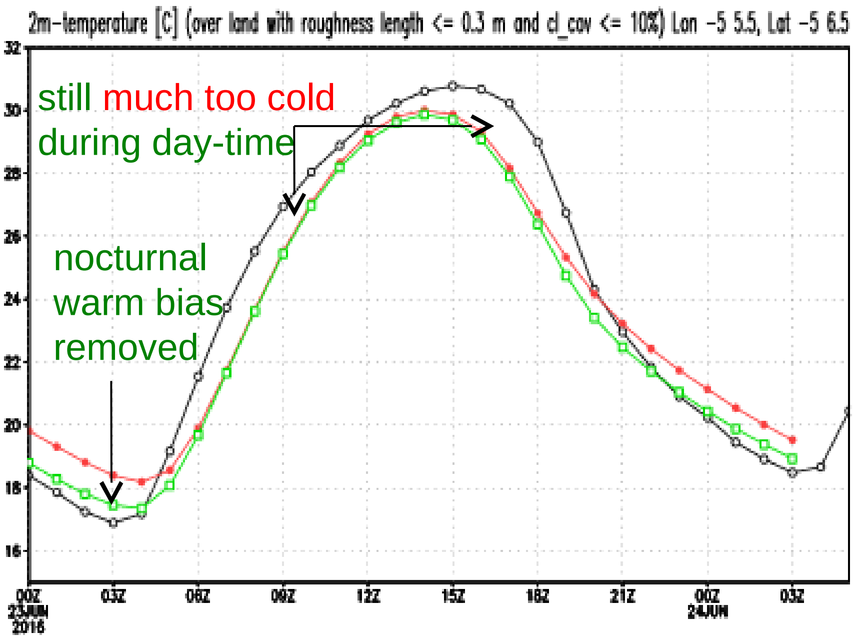
Case study: 23.06.2016

COSMO-DE with lateral boundaries from ICON-EU

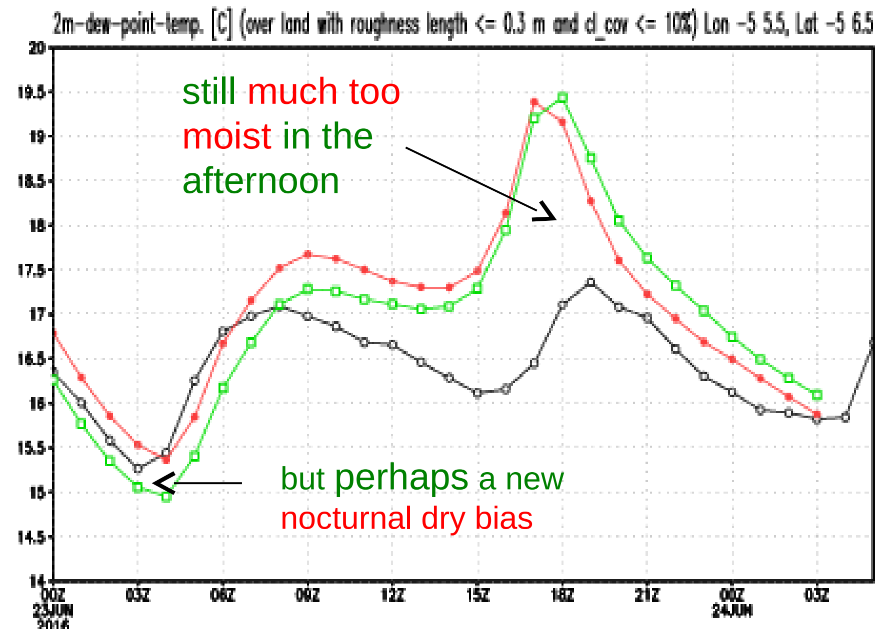
- ✓ only for rather smooth surfaces; applied filter
- ✓ almost saturated soil due to long standing rain period before
- ✓ almost no clouds due to high pressure situation; + applied filter

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

Case study: 23.06.2016

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

COSMO-DE with lateral boundaries from ICON-EU

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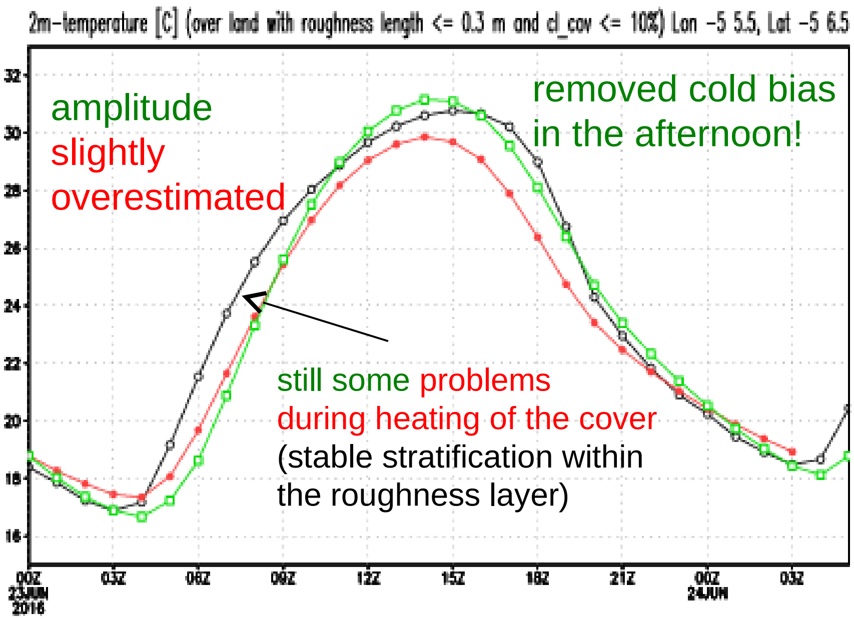
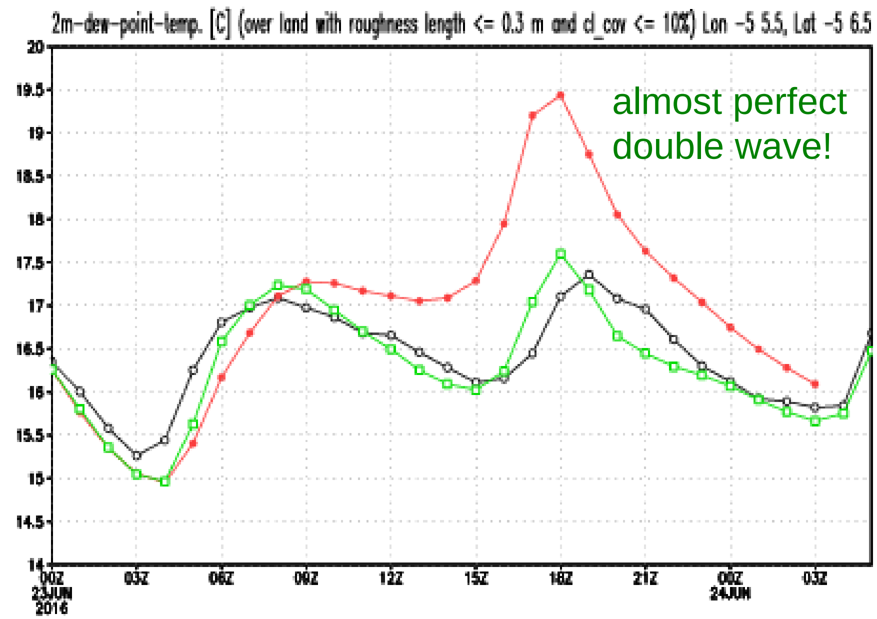
T_2m



TD_2m



— ana_lm3_exp_10279 — out_lm3_exp_10279 — out_lm3_rlmk_new_surf–icon–icon–itype_surf=1–lsfluse=T–e_surf=10–c_soil=2–itype_vdif=1

direct analysis of T_2m and TD_2m

revised TURBDIFF imported from ICON

revised TURBDIFF imported from ICON + new decoupled surface cover: SAI_{∞} =10

Curing the interpolation problem:

- Changing linear u^{ϕ}-profile above roughness layer **by a hyperbolic function in case of stable stratification (which is in accordance with solution from turbulence model)**

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

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

new branch

Curing the vertical-discretization and neutral RL problem:

- **Resistance formulation based on revised profile functions**
  - without the interpolation node at level z_P
  - down through the RL
  - using the assumed constant profile properties u_*, θ_* and Γ

Iterative solution for TKE and the stability-functions:

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

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

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

$$\rightarrow \quad G_T^M := \frac{\ell^2}{q^2}\cdot F_T^M \geq 0 \qquad G^H := \frac{\ell^2}{q^2}\cdot F^H$$

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

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

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

SAI **LCF** **DAI**

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

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

Positive definite solution of prognostic TKE-equation:

VDif and optionally also HDif

optional vertical smoothing controlled by 'frcsmot'

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

$$S_0^{M,H} = S^{M,H}$$

$$\frac{1}{\tau} := \frac{1}{2\Delta t} + \frac{q_0}{\alpha^{MM}\ell} \qquad q_1 := \frac{\tau}{2}\cdot\left[Adv(q_0) + Dif(q_0) + \ell\cdot\underbrace{\left(S_0^M F_T^M - S_0^H F^H\right)}_{>'frcsecu'\, R_f^c\,\cdot F_T^M}\right] \qquad q_2^2 := \tau\frac{q_0^2}{2\Delta t} \geq 0$$

$q_0 = q$ — $t = t_0 + \Delta t$ — $S^{M,H} = 'stbsmot'\, S_0^{M,H} + (1 - 'stbsmot')\cdot S^{M,H}$

$$q = q_1 + \sqrt{q_1^2 + q_2^2} > 0$$

→ always a positive solution of TKE equation

→ $'frcsecu' \rightarrow -\infty$
~~$'tkesecu' \rightarrow 0$~~

$$\frac{\ell^2}{q_c^2}\left(S^M F_T^M - S^H F^H\right) = \gamma^c_{|R_i=0} = \frac{\alpha^H(1 - 3c^M)}{f^H(1)}$$

$$q = MAX\{'tkesecu'\cdot'vel\_min',\ 'tkesecu'\, q_c,\ 'tkesmot'\, q_0 + (1 - 'tkesmot')\cdot q\}$$

→ Calculation of stability functions: S^M, S^H

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

$$r_M \cdot \left(F^M + F_C^M\right)$$

partly substituting artificial security limits and related stratification damping

STIC-impact:

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

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

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

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

Current realization:

- We usually apply parameterizations of effects on 1-st order budgets due to different processes (turbulence, convection, SSO wakes) without using a clear separation procedure
  - ➢ Each scheme for a specific SGS process would only be valid, if all the other sub grid scale processes were in accordance with the specific closure assumptions, what is in CONTRADICTION to the need of DIFFERENT SGS models!!
  - ➢ Problems with incomplete description: double-counting, non-realizability

- Some SGS contributions of source terms in 1-st order budgets as well as in the budgets for SGS motions are only considered partly or inconsistently
  - ➢ Some direct and indirect SGS effects are missing or are poorly described

- Some coupling between local parameterizations is missing
  - ➢ Partly unrealistic or contradicting model results

Conditional-Domain (CD) budgets for description of sub-grid circulations:

$$\overline{\zeta}_{|G}(\mathbf{r},t) := \frac{1}{|G(\mathbf{r},t)|} \int_{\mathbf{s}\in G(\mathbf{r},t)} \zeta(\mathbf{s},t)\, d^3s$$

conditional average (representing e.g. the convective updraft or downdraft
G_+ G_-

- budget for a conditional averaged property:

$$\partial_t\left(a\overline{\rho}\hat{\phi}\right) + \overline{\nabla} \cdot \left[a\overline{\rho\phi\underline{\mathbf{v}}^{\phi}} \right] = a \cdot \left(Q^{\phi}_{sur} + \overline{Q^{\phi}}\right) \qquad Q^{\phi}_{sur} := -\frac{1}{|G|} \int_{\mathbf{s}\in B} \rho\phi \cdot \left(\mathbf{v}^{\phi} - \partial_t \mathbf{s}\right) \cdot \mathbf{n}\, d^2s$$

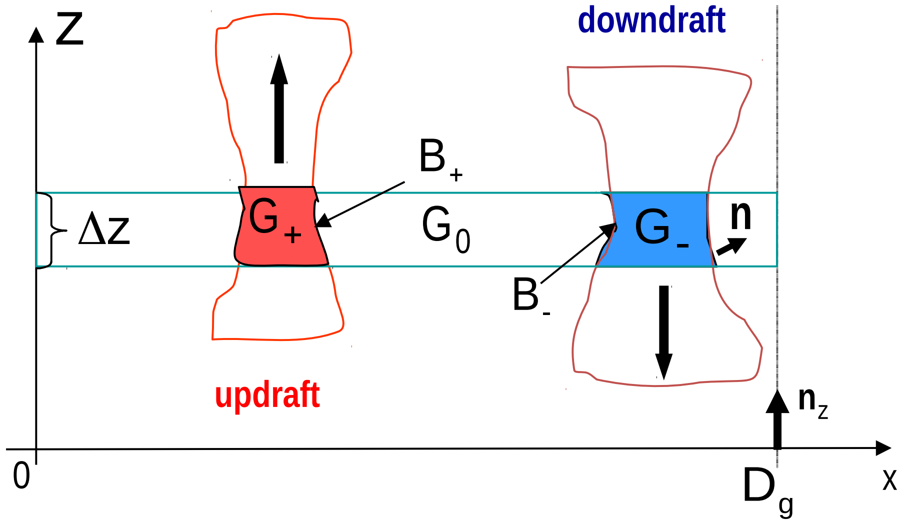
inflow via the inner boundary surface

volume fraction of the related subdomain

- continuity equation:

$$\partial_t \ln a = \frac{1}{|G|} \int_{\mathbf{s}\in B} \partial_t \mathbf{s} \cdot \mathbf{n}\, d^2s = \frac{|B|}{|G|} \overline{\partial_t s_n}_{|B}$$

Inner boundary surface of the subdomain



Equations to be solved under simplifying assumptions

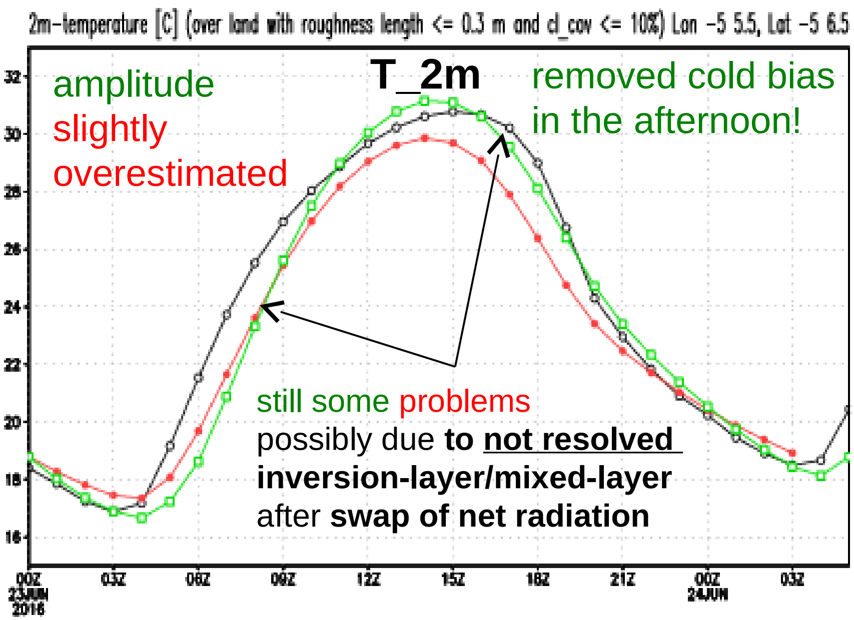
– stationarity, same horizontal advection for each subdomain, ...

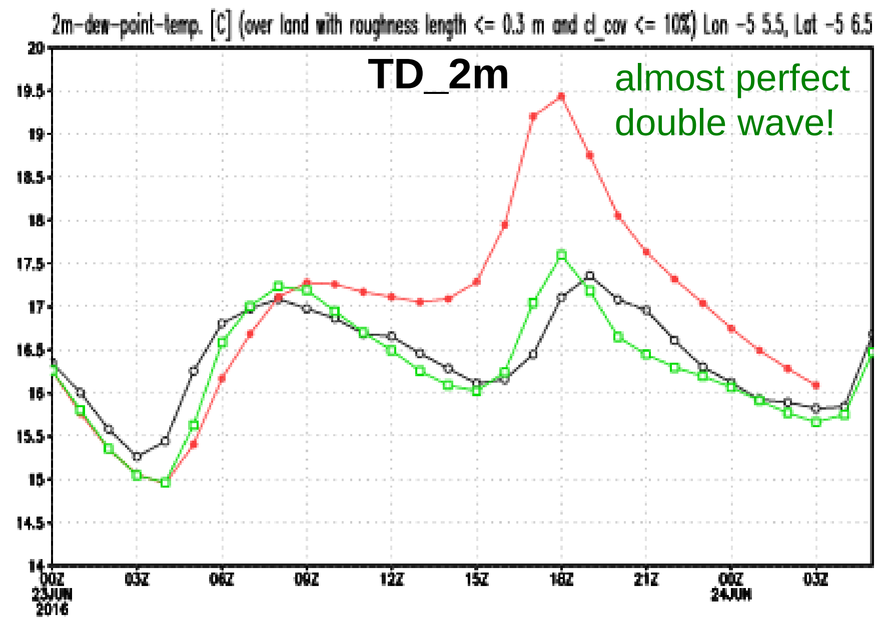
- A more advanced **semi-transparent C-layer extension** (by M. Raschendorfer) with **parameterized heat-conduction** and **heat storage** of the **full roughness cover** (e.g. plant canopy) is **being adapted** from an existing test-version prepared last year within COSMO.
  - The **final combination**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





— ana_lm3_exp_10279 — out_lm3_exp_10279 — out_lm3_rlmk_new_surf-icon-icon-itype_surf=1-lsfluse=T-e_surf=10-c_soil=2-itype_vdif=1

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

➢ effect of single-precision radiation calculations on results

Testing & Tuning of (Revised Cloud Radiation Coupling) $T^2(RC)^2$:

Harel Muskatel (HM)

Uli Blahak (UB), Pavel Khain (PK),, Alon Shtivelman (AS),
Matthias Raschendorfer (MR), Daniel Rieger (DR),
Simon Gruber (SG), Martin Koehler (MK),
Xavier Lapillonne (XL), Oliver Fuhrer (OF), Gdaly Rivin (GR),
Natalia Chubarova (NC), Marina Shatunova (MS),
Alexey Poliukov (AP), Alexander Kirsanov (AK).

- **New Optical Properties (OP) of ice & cloud droplets after Fu et al. / Hu & Stamnes:**

✓ **OP as function of wave length and Effective Arguments (EA): R_{eff}, particl. Length (L) and Depth (D)**

✓ **EAs deduced from particle size distribution N(L) and mass-size relation m((L)**

✓ **Theoretical relation between OPs as function of EAs fitted in terms of rational functions for 8 distinctive spectral bands**

UB, HM

↓

✓ **Implementation into ICON radiation-code**

SG

✓ **test runs with ICON-global performed**

SG, MK

➢ **Tests with ICON-LAM at IMS / Russia**

- **ICON-ART dust as input for COSMO radiation:**

✓ Successfully implemented

✓ Few clear-sky comparisons against CLIRAD-model and Nes-Tziona AERONET station with positive results

➢ Further testing

DR, HM

DR, NC

- **CAMS prognostic aerosols in water in scheme for water-droplet nucleation :**

✓ Derivation of cloud NC as function of aerosol NC according Segal & Khain

✓ Expression vertical Reff-profile dependent on cloud NC including sub-grid effects through turbulence and convection

UB

✓ Successfully implemented in COSMO (1-mom. microph. and radiation)

✓ Few-days case study performed:

- o Calculated Cloud NC available in microph. effects LWC and CLC
- o Reff has large impact on radiation heating rates
- ➢ T2m, precip. and integr. cloud-cover are strongly effected

➢ Further testing and verification with mixed aerosol types

HM

- <u>Tuning 4 sub-versions for cloud-radiation interaction in COSMO :</u>

i. Standard scheme with constant Reff

ii. Parameterized Reff based on Tegen-climatology

iii. Parameterized Reff based on CAMS-aerosols

iv. Parameterized Reff based on Tegen-climatology

+ special extension for shallow cumulus clouds

PK

- ✓ **Comparison of global radiation-simulation with local measurements and CM-SAF for a 4-month period in 2016**
- ✓ **Improvement of RMSE for global radiation by several %**

PK

- <u>Reviewing current shallow-cumulus parameterization :</u>

- ➢ **Comparison of LWC through shallow-convection with Pavel's approach of pure adiabatic lifting**
- ➢ **Employing LWC from shallow convection for Pavel's extended parameterization of R_{eff} for convective clouds.**