Estimation of stomatal resistance and total evapotranspiration

in the exceptional warm summer 2013 over Germany

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Why is important?

- Current climatic trends and projections highlight consistent tendencies of rising temperature and increasing climatic variability (Easterling *et al*., 2000)

- Accordingly, extreme events are likely to become globally more frequent and intense in the near future (IPCC, 2007).

- Plants influence extreme heat events by regulating land-atmosphere water and energy exchanges. The contribution of plants to changes in future heat extremes will depend on the responses of vegetation growth and physiology to the direct and indirect effects of elevated CO_2. (Skinner et al., 2018)

- Nevertheless, vegetation algorithm of COSMO-CLM v5.16 does not consider the stomatal regulation and vegetation growth depending on atmospheric CO_2 concentrations.

Figure: Süddeutsches Klimabüro

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Purposes of the research

Figure: PIXELSQUID

Verify the new vegetation algorithms implemented into the regional climate model COSMO-CLM v5.16 on the example of exceptional warm summer 2013

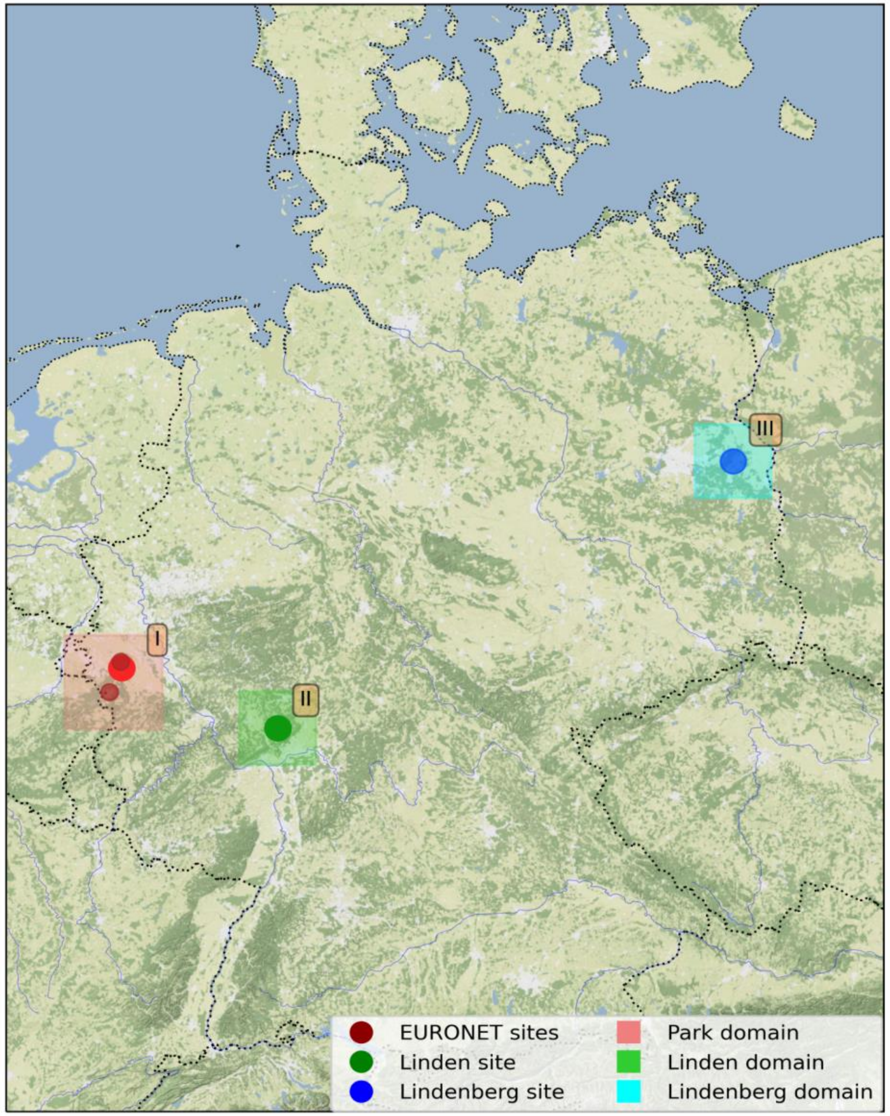
- Taking into account: processes of leaf photosynthesis, CO_2 partial and vapor pressure, maximum stomatal resistance, available soil water
- Calculating separately for sunlit and shaded leaves
- Applying three different vegetation algorithms adapted from the Community Land Model (v3.5 and v4.5)

Figure: iStock

Identify the most perspective vegetation algorithm implemented in COSMO-CLMv5.16

- Results made on the basis of the one-dimensional version of COSMO-CLMv5.16.
- Results are combined and presented in the vertical soil-vegetation-atmosphere column
- Results are calculated over three research domains over Germany with C_3 grass presented by *Lolium perenne*, *Festuca rubra* and *Poa pratensis*

Research domains



COSMO-CLM parameters:

- Time increment: 25 s
- Spatial resolution: 0.0275° ~ 3 km
- Grid size: 25 * 25
- Numbers of vertical atmospheric layers: 50
- Numbers of soil layers: 9

Verification parameters:

- AEVAP, $ALHFL_{PL}$, $ALHFL_S$, $ASHFL_S$, QV_{2M}, QV_S, T_{2m}, T_S, T_{max}
- T_{min}, PS, $RELHUM_{2M}$, ZTRALEAV, ZVERBO, RSTOM

Data for comparisons:

- HYRAS, GLEAM datasets (T_{2m}, T_S, T_{max}, T_{min}, AEVAP, ZVERBO)
- EURONET, FLUXNET, TRY
- TERENO, Linden and Lindenberg sites information

Model experiments

COSMO-CLM v5.16 – Regional climate model of the Consortium for Small-Scale Modelling

CLM 3.5, CLM 4.5 – Community Land Model

CCLMref

- ***Jarvis-Stewart*** approach with BATS model parameterization scheme
- Does not consider stomatal regulation and vegetation growth depending on atmospheric CO_2 concentrations
- Uses simplified Jarvis approach based on empirical dependencies between canopy and environmental variables.

CCLMv3.5

- ***Ball-Berry*** approach coupled with leaf photosynthesis and calculating separately for sunlit and shaded leaves. (**CLMv3.5**)
- Night-time values of stomatal resistance is equal to 20.000 s m^{-1}

CCLMv4.5

- ***Ball-Berry*** approach coupled with leaf photosynthesis and calculating separately for sunlit and shaded leaves. (**CLMv4.5**)
- Night-time values of stomatal resistance is controlling by available soil water

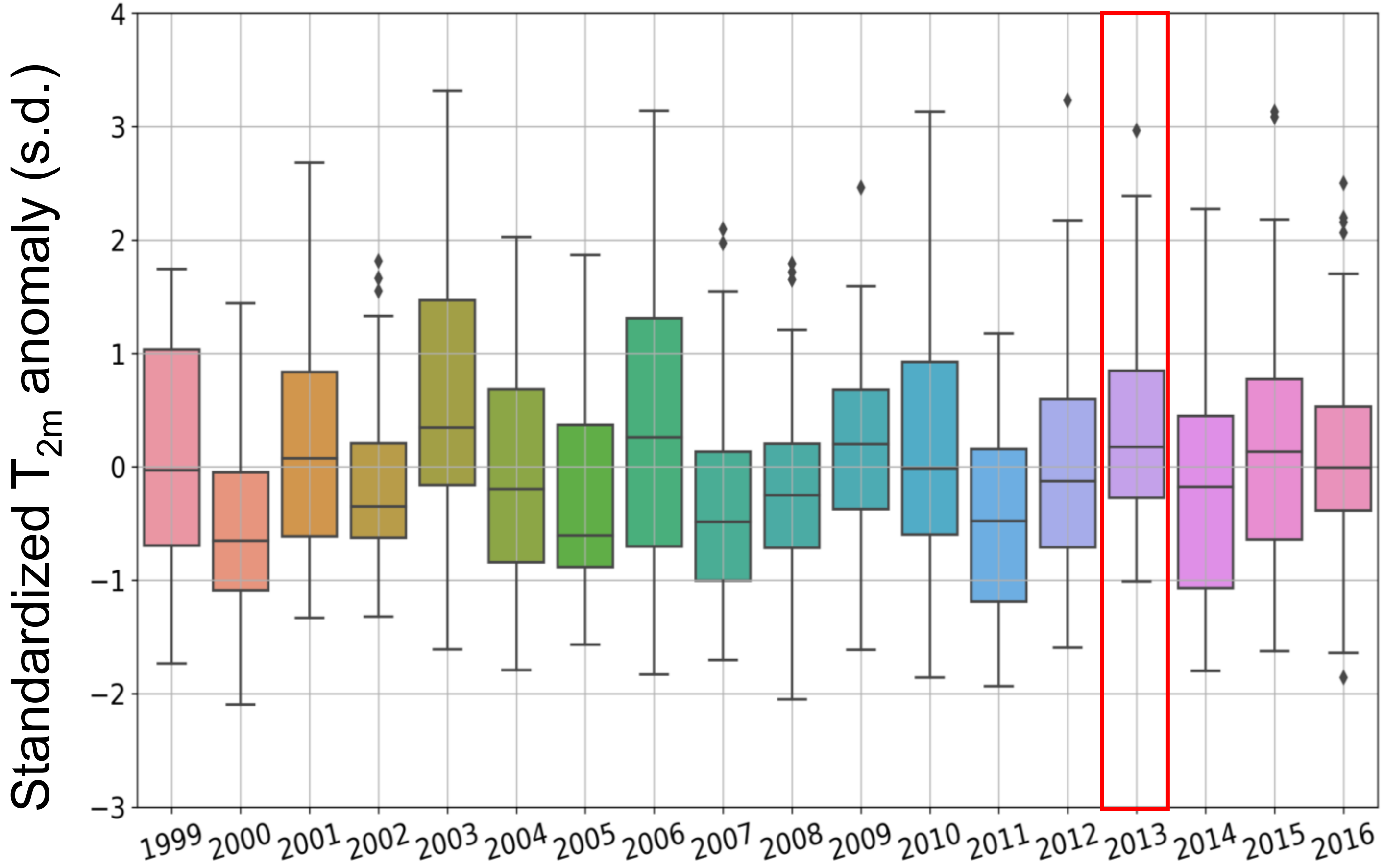
CCLMv4.5e

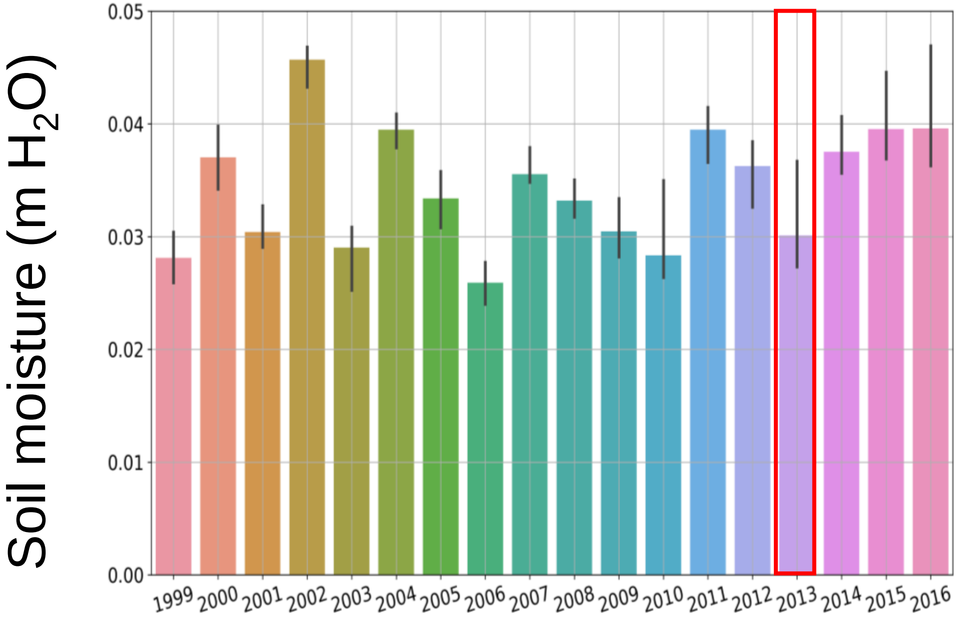
- ***Ball-Berry*** approach coupled with leaf photosynthesis and calculating separately for sunlit and shaded leaves. (**CLMv4.5**)
- Night-time values of stomatal resistance is controlling by available soil water
- Additional changes in calculations of transpiration from dry leaf surfaces

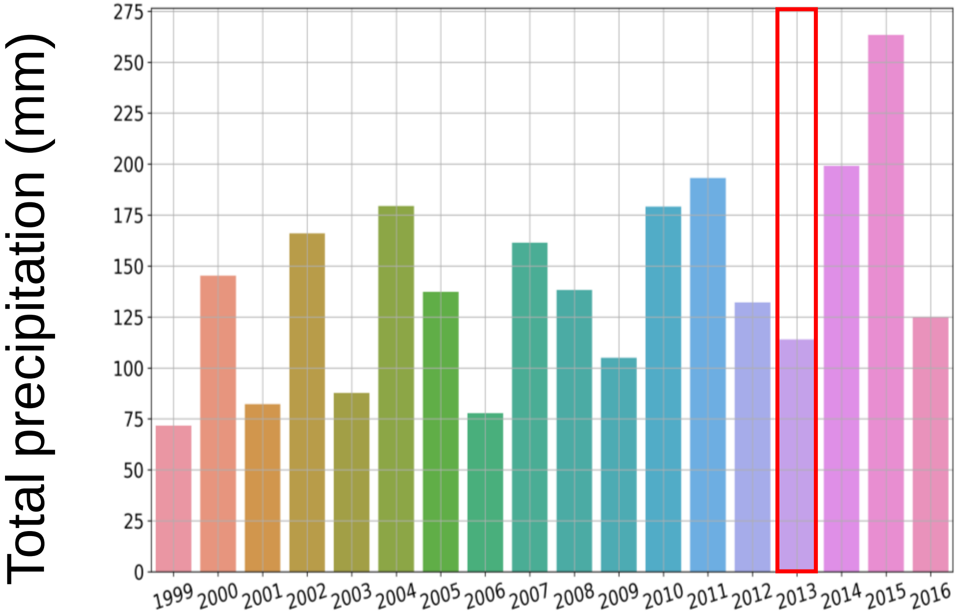
Research period

Summer months (July – August) of 2013

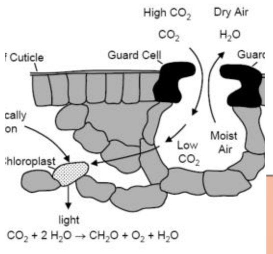
$$\boldsymbol{T_{2m,\,stand}} = \frac{T_{2m} - T_{2m,mean}}{T_{2m,std}}$$





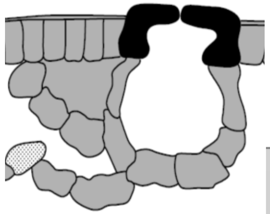


Plant stomata behavior



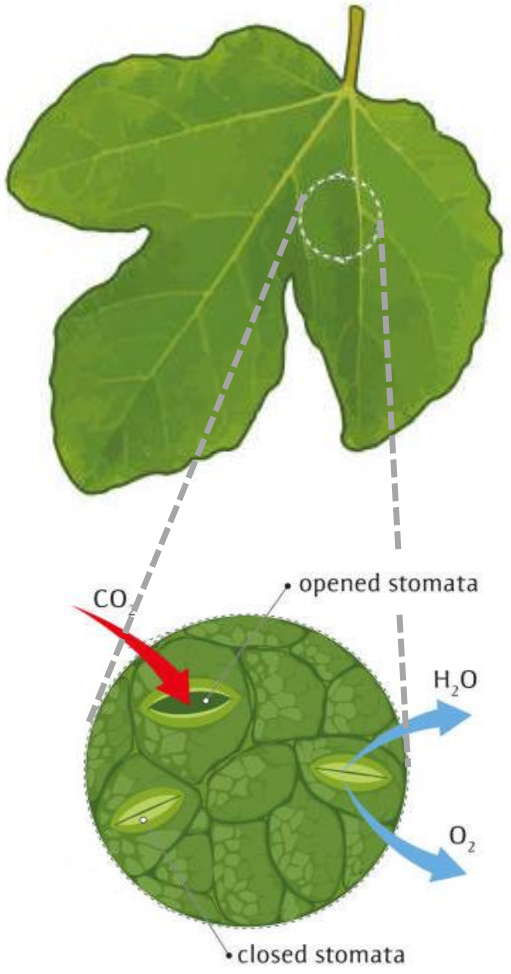
Stomata open

- High light level
- High leaf nitrogen
- Moderate CO_2
- Moist leaf
- Moist air
- Warm temperature



Stomata close

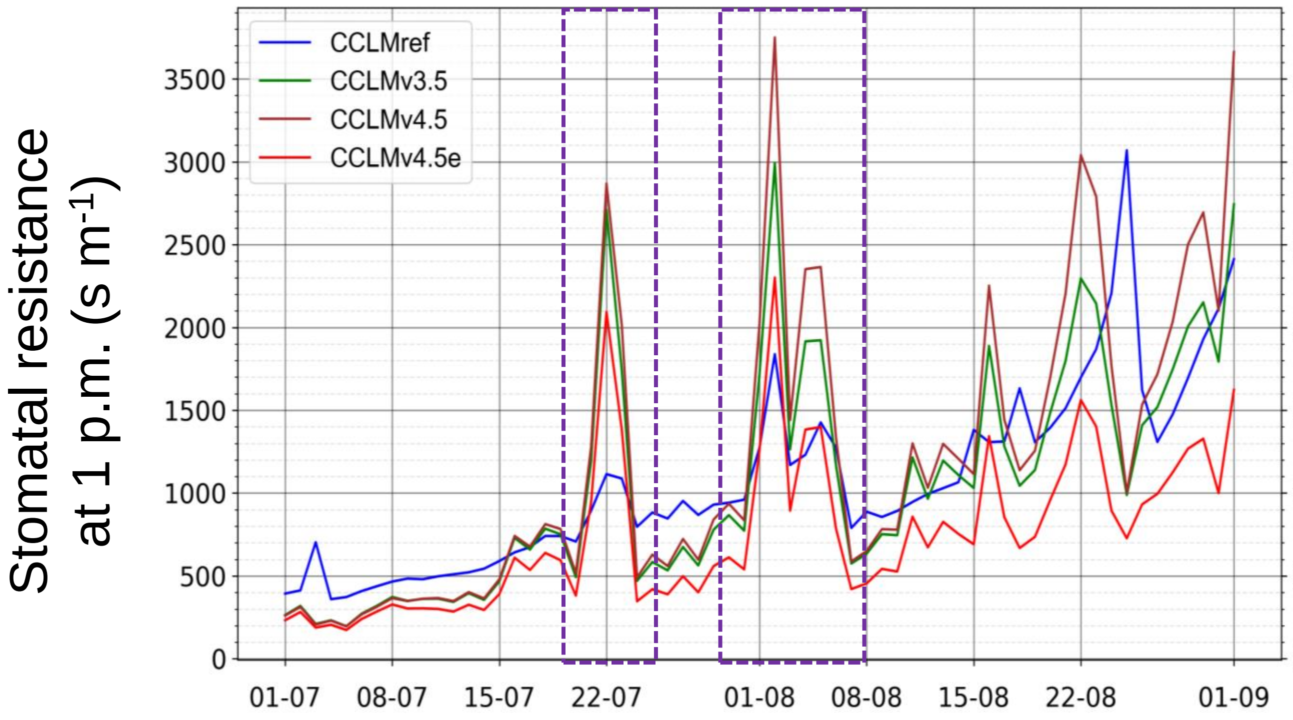
- Low light level
- Low leaf nitrogen
- High CO2
- Dry leaf
- Dry air
- Cold temperature



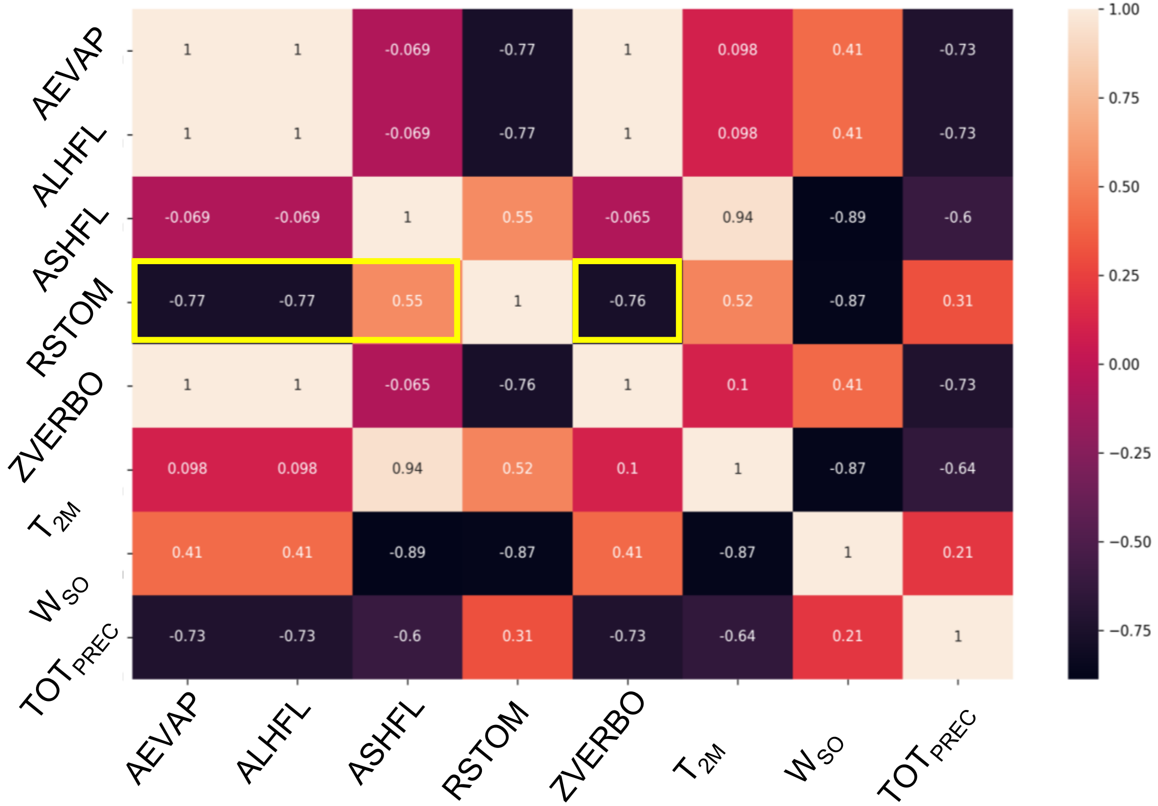
↓ Stomatal resistance ↑ Plant transpiration ↑ Amount of water evaporation ↑ Latent heat flux ↓ Sensible heat flux ↓ Air temperatures ↑ Surface moisture (1st level)

Validating experiment results

Summer months (July – August) of 2013



COSMO-CLM correlation heatmap



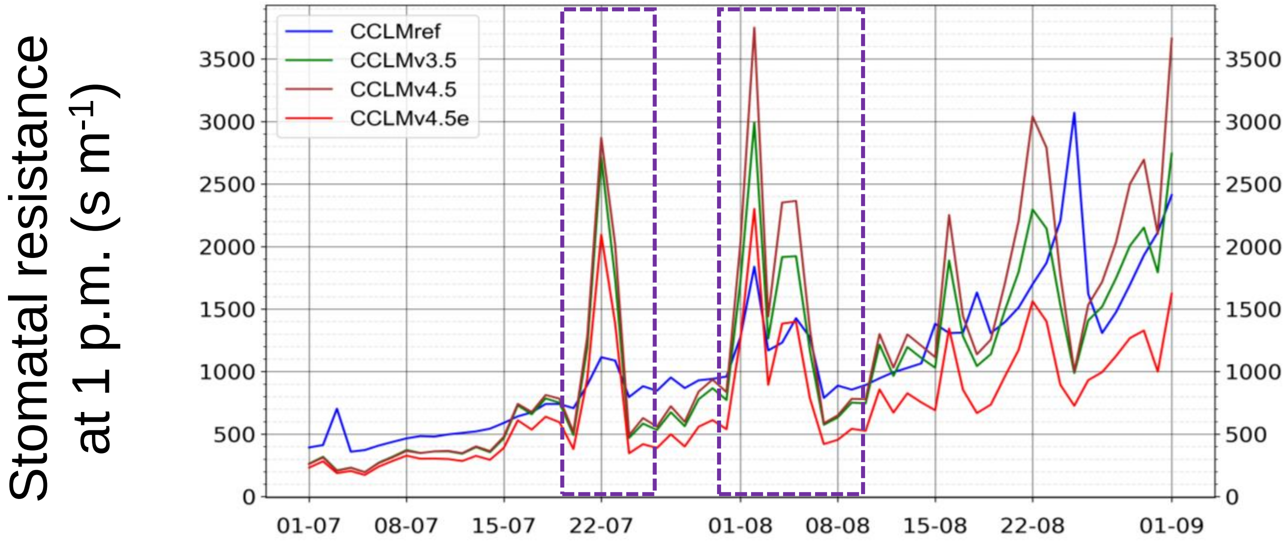
CCLMref CCLMv3.5

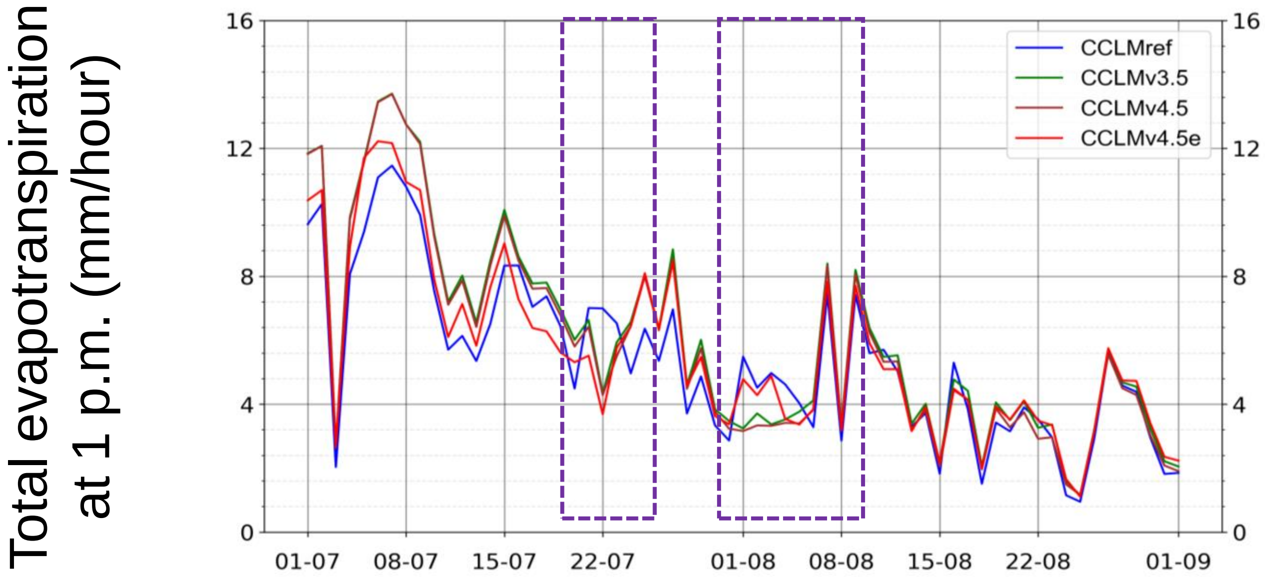
CCLMv4.5 CCLMv4.5e

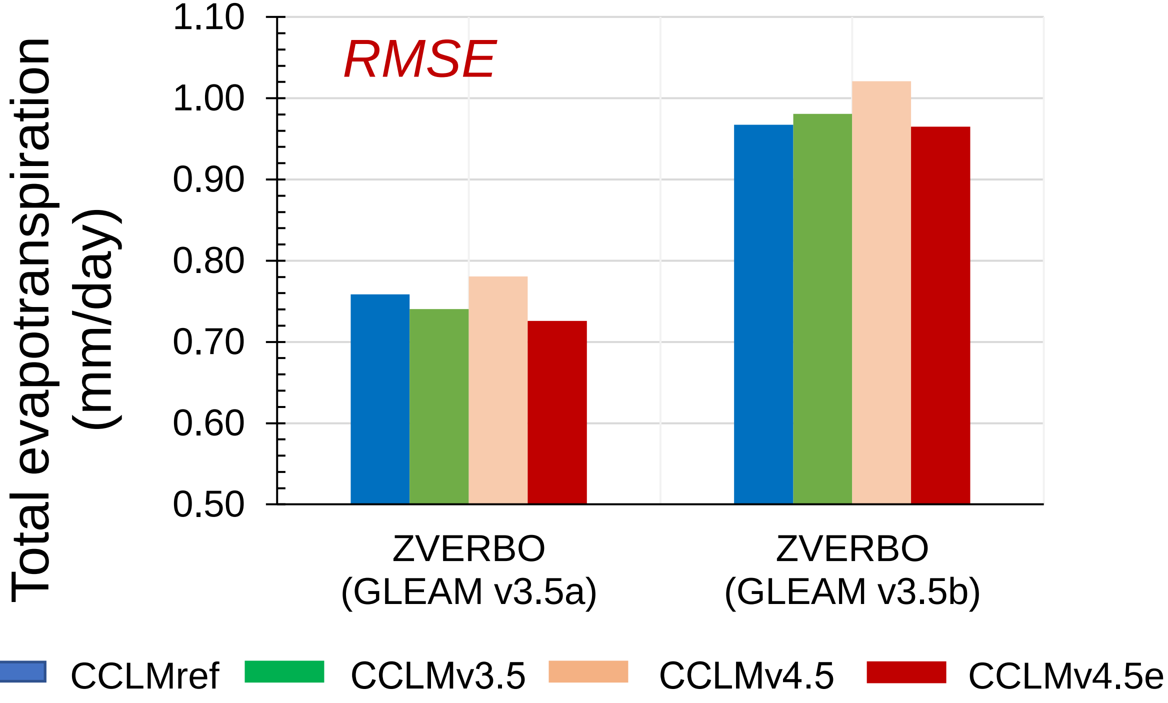
Results: Experiments based on physically Ball-Berry stomatal resistance approach coupled with processes of leaf photosynthesis show more reaction on the stressful environmental conditions that can be clearly seen in the figure

Validating experiment results

Summer months (July – August) of 2013



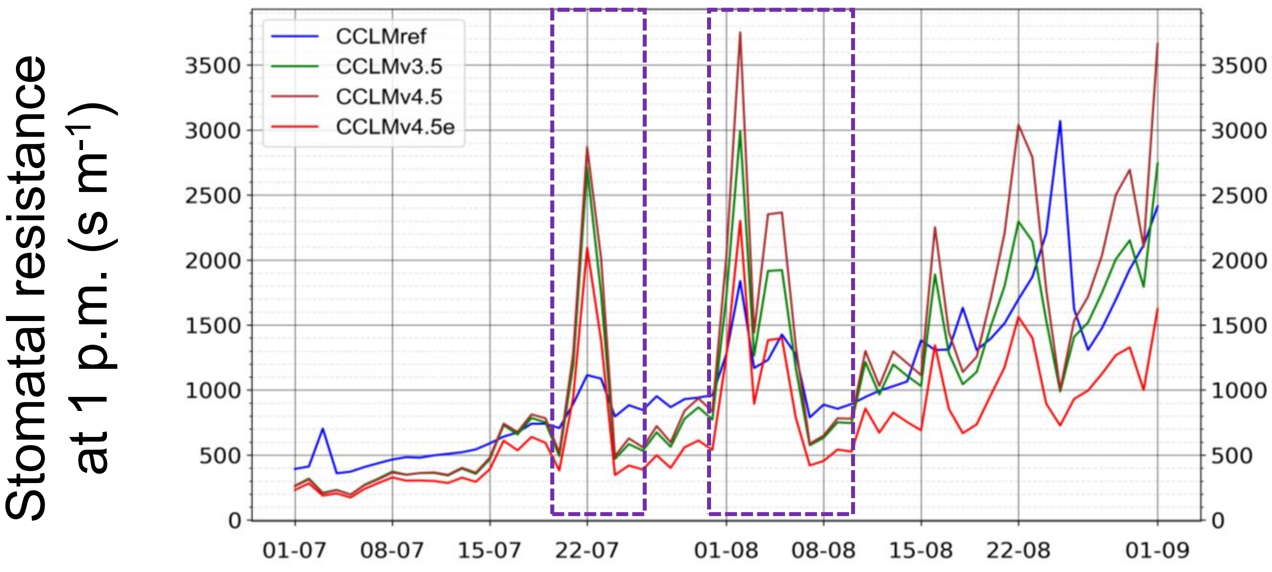


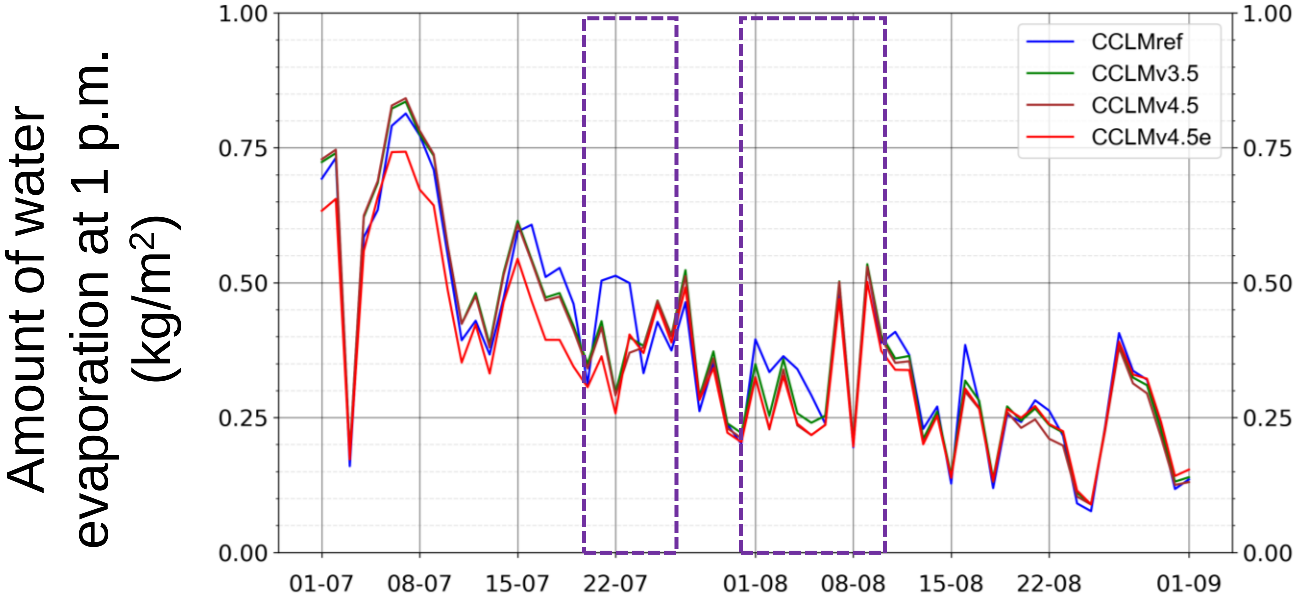


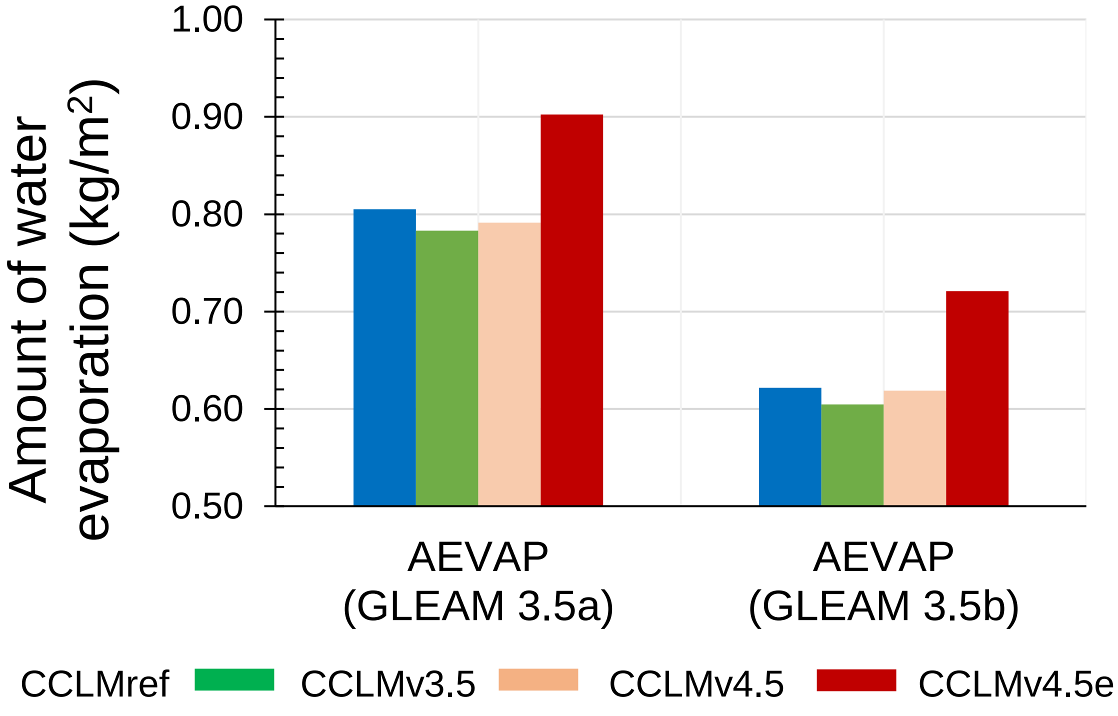
Results: ***CCLMv4.5e*** has the slightly better daily scores for **ZVERBO** at the meteorological stations in Parc domain (*RMSE = 0.812, r = 0.825*) in comparison with GLEAM data set averaged to the point.

Validating experiment results

Summer months (July – August) of 2013

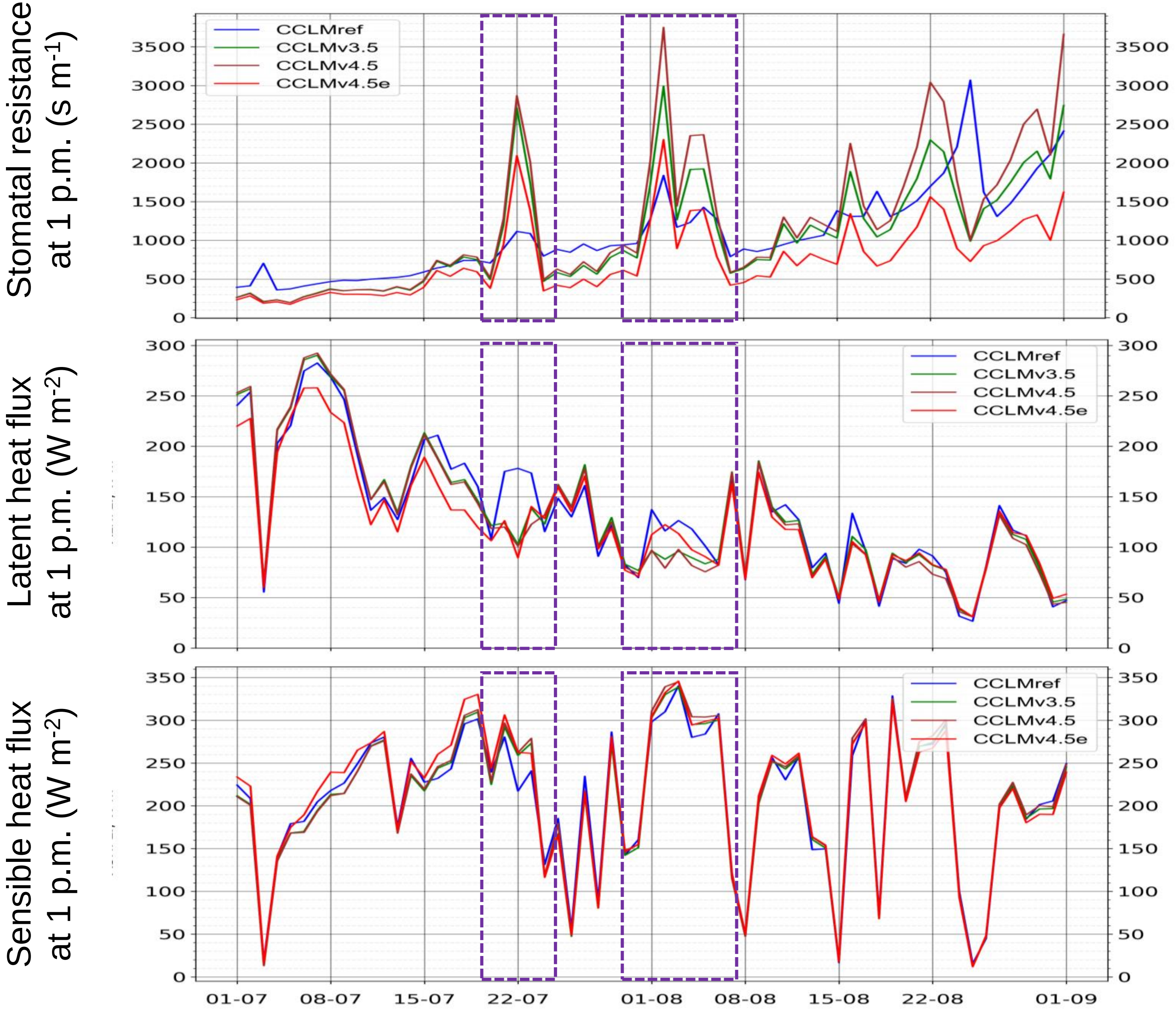






Results: ***CCLMv3.5*** has the better scores for **AEVAP** at the meteorological stations in Parc domain (*RMSE = 0.694, r = 0.848*) in comparison with GLEAM data set averaged to the point.

Validating experiment results



Results: Experiments show that for validation of sensible and latent heat fluxes will be better to use observational gridded datasets. Nevertheless, experiment ***CCLMref*** demonstrates slightly more accurate results.

CCLMref | CCLMv3.5
CCLMv4.5 | CCLMv4.5e

Conclusions

In COSMO-CLM v5.16, the new vegetation algorithms have been implemented	Validation of the new algorithms have been done	The documentation for the updates have been written
❖ Stomatal resistance ❖ Leaf photosynthesis ❖ Two-big leaf	❖ in the exceptional warm summer 2013	❖ Code (*https://github.com/EvgenyChur/PT-VAINT*); ❖ Documentation (https://github.com/EvgenyChur/Doc_version1);

The experiment CCLMv4.5 shows the results, representing changes in stomatal resistance better than the reference experiment. At the same time, the estimation results for total evapotranspiration demonstrates a slight decrease in accuracy in comparison with the other experiment in the exceptionally warm summer 2013. Nevertheless, results of the experiment CCLMv4.5 seems to be relevant, and all the new implementations will be worked on the CCLMv4.5 basis.

Implementation the CCLMv4.5 algorithm into COSMO-CLM v6.0

Our contacts:

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Stomatal resistance algorithm

CCLMref

The Jarvis-Stewart approach with BATS model parameterization scheme:

$$g_{st}^{can} = \frac{1}{r_{max}} + \left(\frac{1}{\mathrm{r_{min}}} - \frac{1}{\mathrm{r_{max}}}\right)[\mathrm{F_{rad}F_{wat}F_{tem}F_{hum}}]$$

$\mathrm{F_{rad}}, \mathrm{F_{wat}}, \mathrm{F_{tem}}, \mathrm{F_{hum}}$ – environmental stress functions (photosynthetic active radiation, soil water content, ambient temperature and specific humidity)

r_{max}, r_{min} – maximal and minimal stomatal resistance

CCLMv3.5; CCLMv4.5; CCLMv4.5e

The Ball-Berry approach coupled with processes of leaf photosynthesis

$$g_{st}^{can} = g_{st}^{sun}\mathrm{L^{sun}} + g_{st}^{sha}\mathrm{L^{sha}}$$

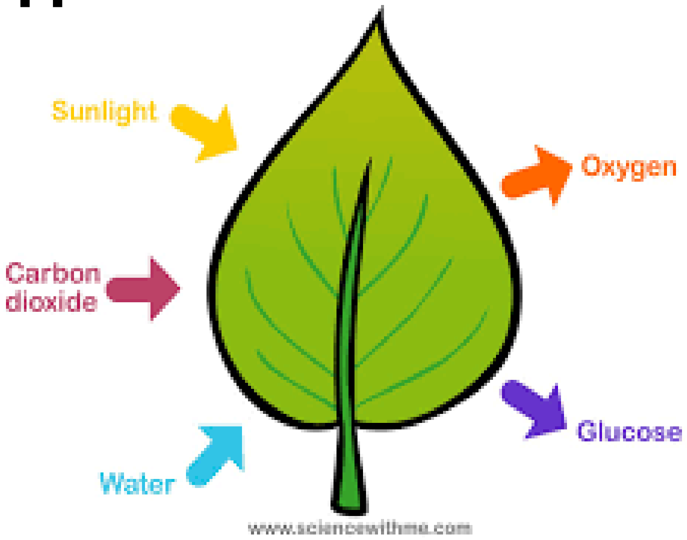
$$g_{st}^{sun,sha} = \frac{1}{r_s^{sun,sha}} = m\frac{A^{sun,sha}e_s}{c_s e_i}P_{atm} + \boldsymbol{bF_{wat}}$$

$\mathrm{r_s^{sun,\,sha}}$, $\mathrm{g_{st}^{sun,\,sha}}$ – stomatal resistance and conductance for sunlit and *shaded* leaves, A – leaf photosynthesis, $\mathrm{e_s}$, $\mathrm{e_i}$ – vapor pressure at leaf surface and inside the leaf; $\mathrm{c_s}$ – CO_2 partial pressure; m, b – empirical coefficients;

Leaf photosynthesis algorithm

$$A = A^{sun} L^{sun} + A^{sha} L^{sha}$$

$$A^{sun,\,sha} = min(w_c, w_j, w_e)$$



Leaf photosynthesis algorithm is based on the *Farquhar** and *Collatz** models for C_3 and C_4 plants and uses sunlit and shaded leaves parameters

$$w_c = \begin{cases} \dfrac{V_{cmax}\,(c_i - \Gamma_*)}{c_i + K_c\,(1 + \dfrac{O_i}{K_0})} \; * \\ \mathbf{V_{cmax}} \; * \end{cases} \qquad w_j = \begin{cases} \dfrac{(c_i - \Gamma_*)\, 4.6\,\alpha\,\phi}{c_i + 2\,\Gamma_*} \; * \\ \mathbf{4.6\,\alpha\,\phi} \; * \end{cases} \qquad w_e = \begin{cases} 0.5\, V_{cmax} \; * \\ \mathbf{4000\, V_{cmax} \dfrac{c_i}{P_{atm}}} \; * \end{cases}$$

V_{cmax} – the maximum rate of carboxylation, K_c; K_o – the Michaelis−Menten constants for CO_2 and O_2, Γ_* – the CO_2 compensation point, c_i – the internal leaf CO_2 partial pressure, O_i – the O_2 partial pressure, α – the quantum efficiency coefficient, ϕ – the absorbed PAR

Two-big leaves algorithm

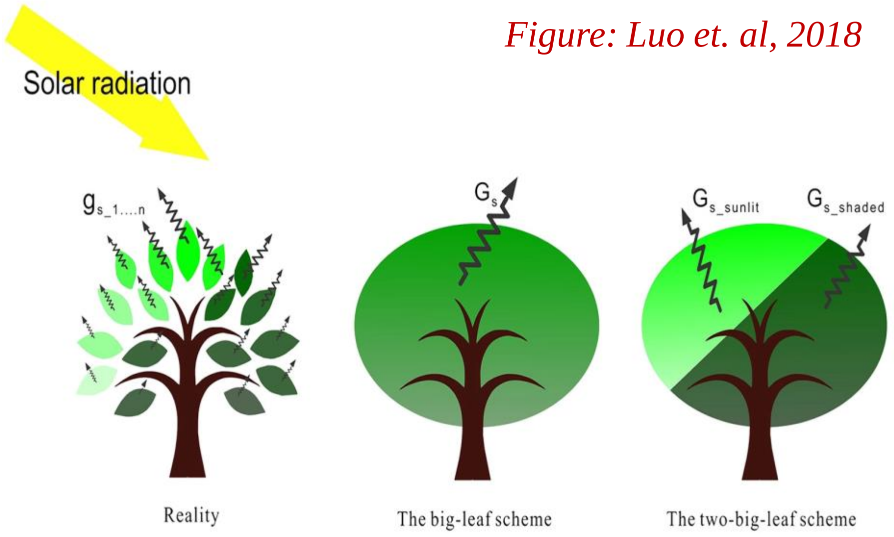


Figure: Luo et. al, 2018

- Sunlit (f_{sun}) and shaded (f_{sha}) fraction of canopy:

$$f_{sun} = 1 - \frac{e^{-KL}}{KL} \qquad f_{sha} = 1 - f_{sun}$$

- Sunlit (L^{sun}) and shaded (L^{sha}) leaf area indices:

$$L^{sun} = f_{sun}L \qquad L^{sha} = f_{sha}L$$

- Sunlit (ϕ^{sun}) and shaded (ϕ^{sha}) absorbed photosynthetically active radiation (PAR):

$$\phi^{sun} = \frac{\left(\phi^{\mu}_{dir} + \phi^{\mu}_{dif} f_{sun} + \phi_{dif} f_{sun}\right)\left(\frac{L}{L+S}\right)}{L^{sun}}$$

$$\phi^{sha} = \frac{\left(\phi^{\mu}_{dif} f_{sha} + \phi_{dif} f_{sha}\right)\left(\frac{L}{L+S}\right)}{L^{sha}}$$

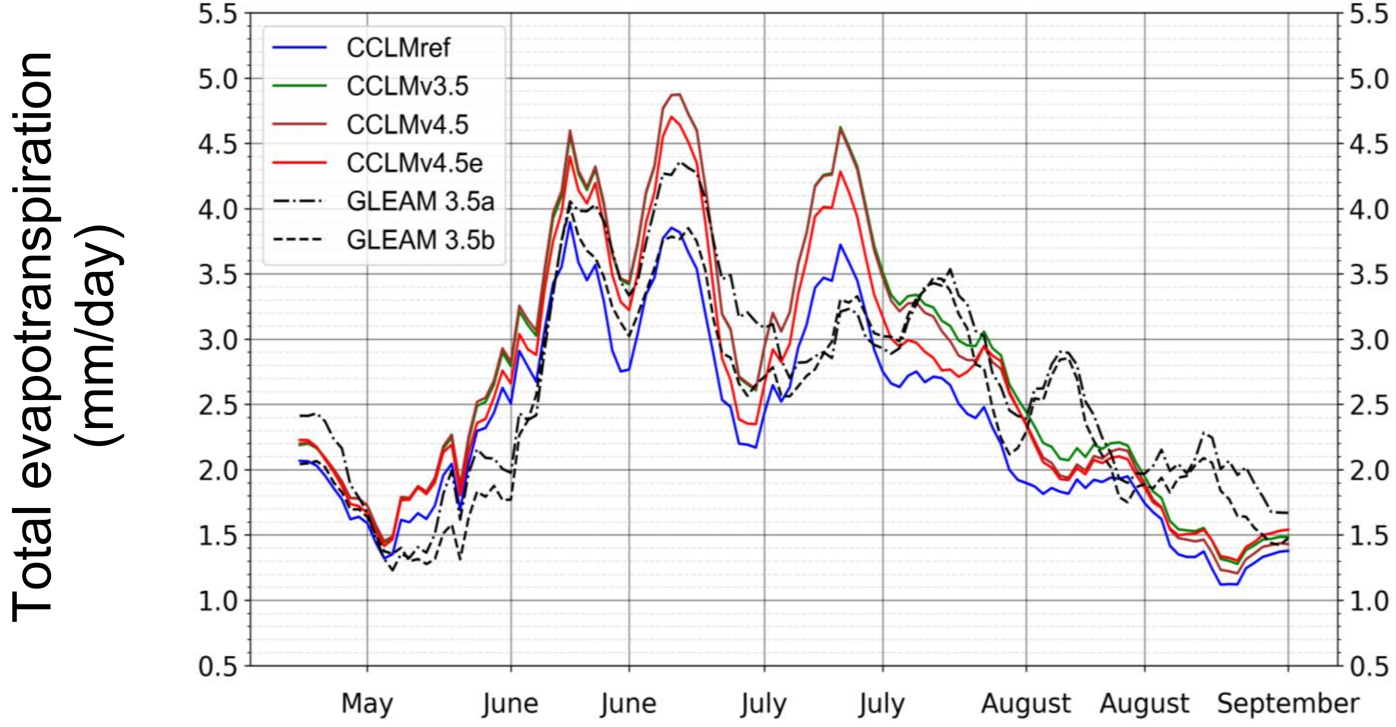
ϕ^{μ}_{dir} – the portion of the incoming visible waveband direct beam radiation

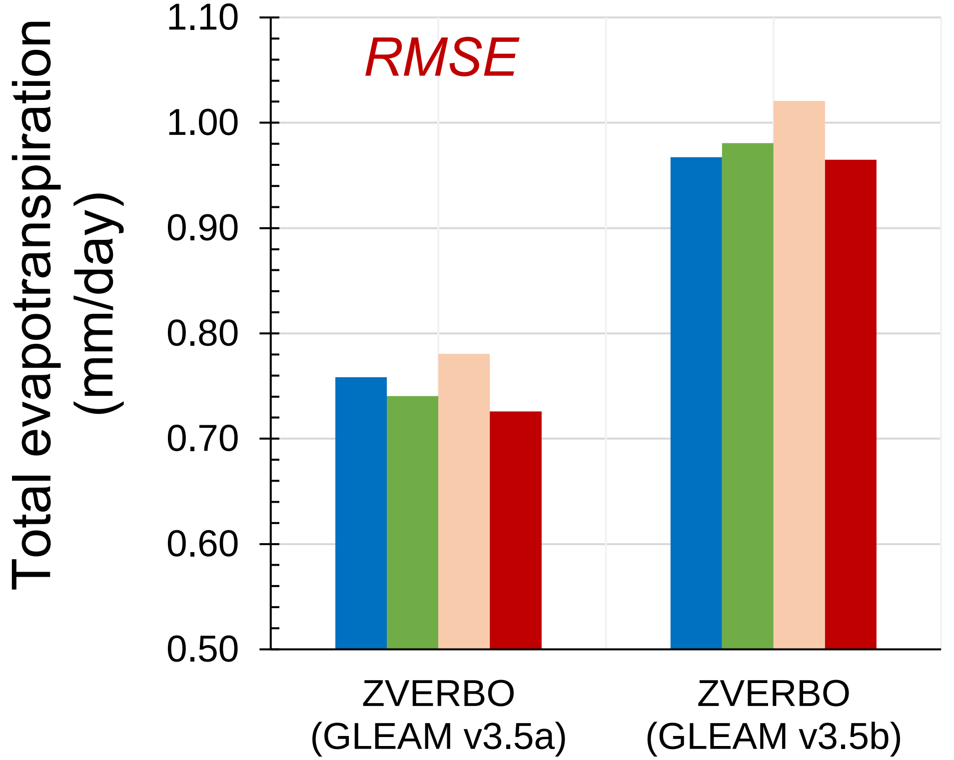
ϕ^{μ}_{dif} – the absorbed visible waveband direct beam radiation

ϕ_{dif} – is the incoming visible waveband diffuse radiation

Validating experiment results

Total evapotranspiration (*ZVERBO*)





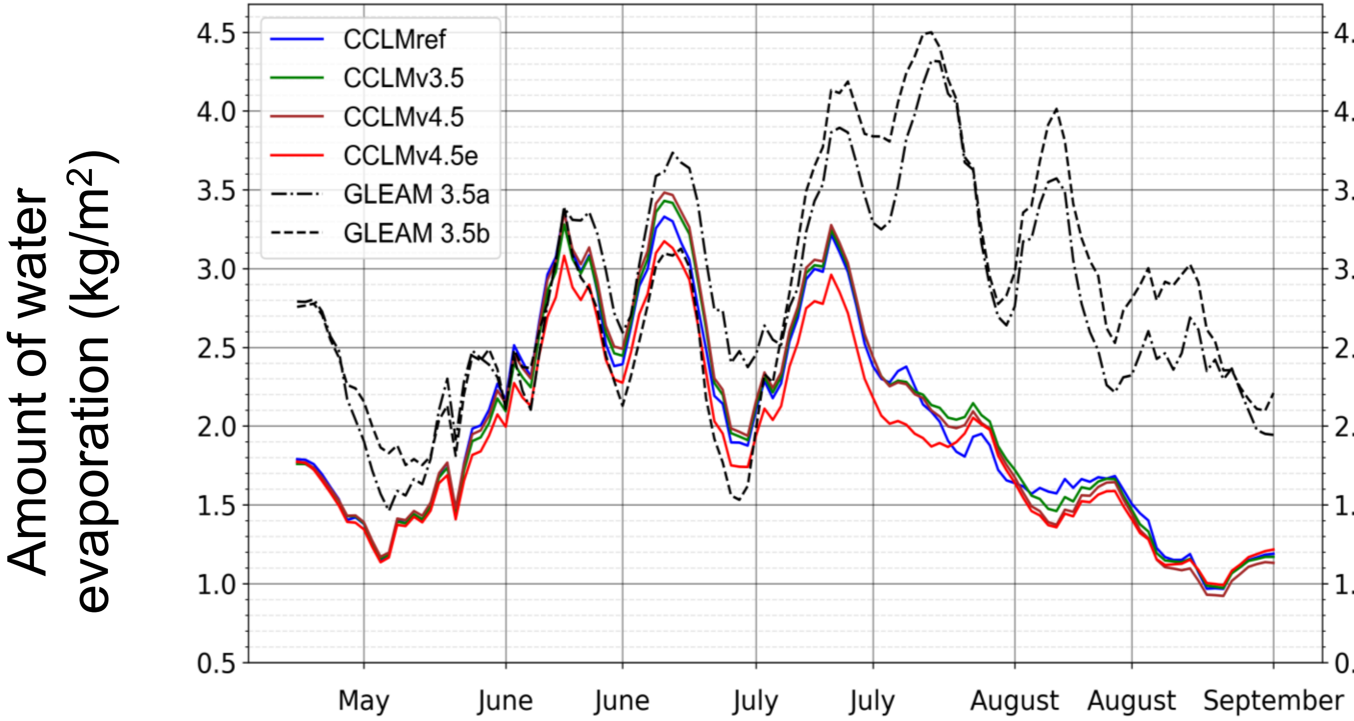
CCLMref CCLMv3.5

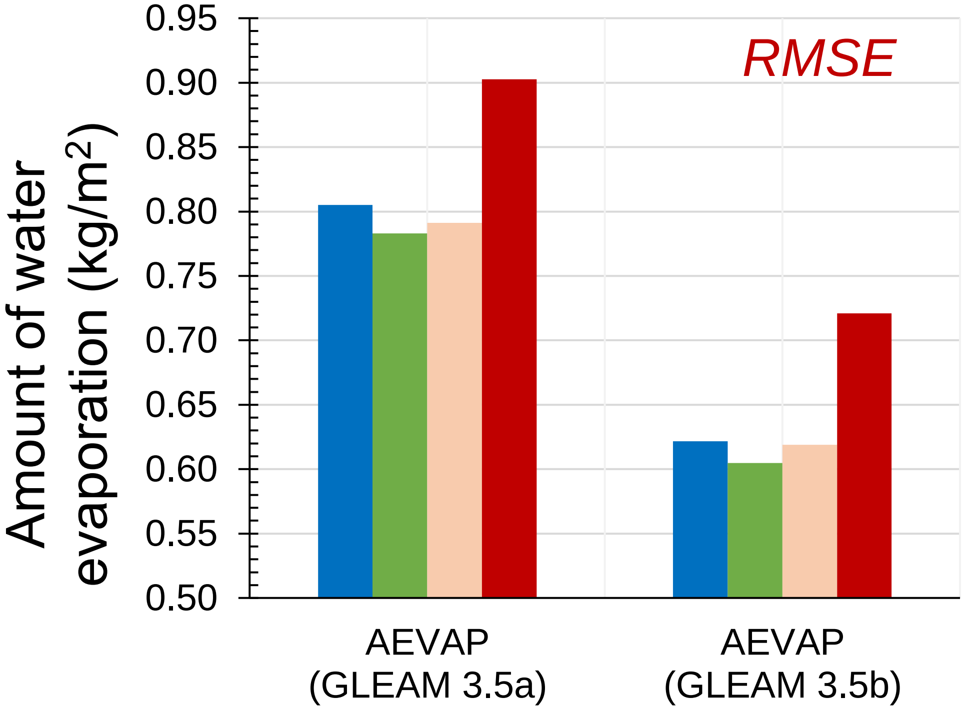
CCLMv4.5 CCLMv4.5e

Results: ***CCLMv4.5e*** has the slightly better scores for **ZVERBO** at the meteorological stations in Parc domain (*RMSE = 0.812, r = 0.825*) in comparison with GLEAM data set averaged to the point.

Validating experiment results

Amount of evaporation (*AEVAP*)





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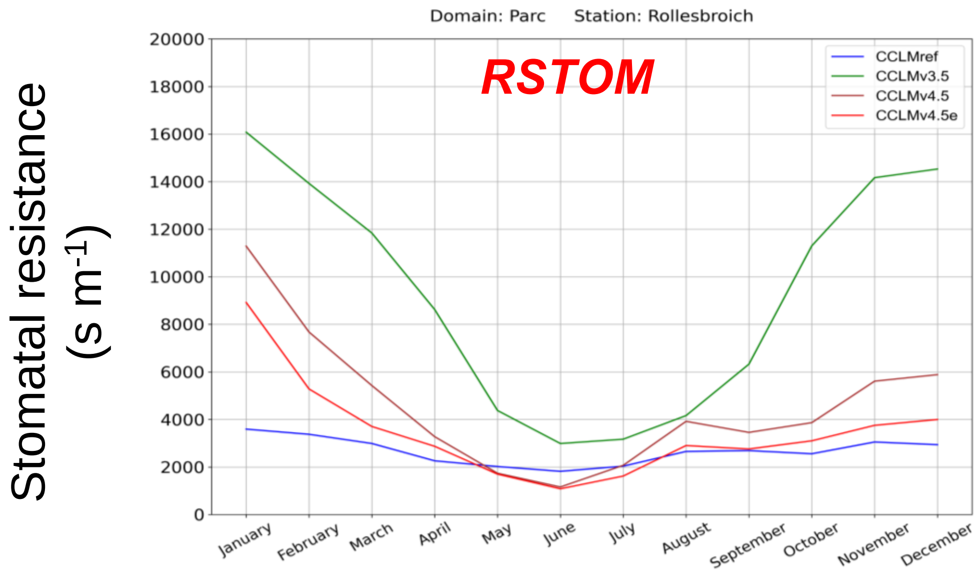
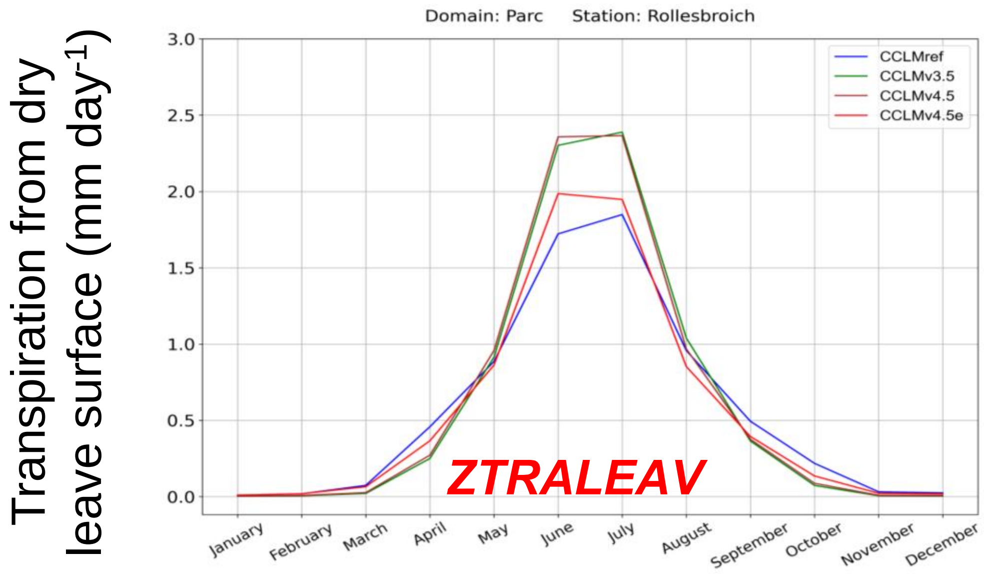
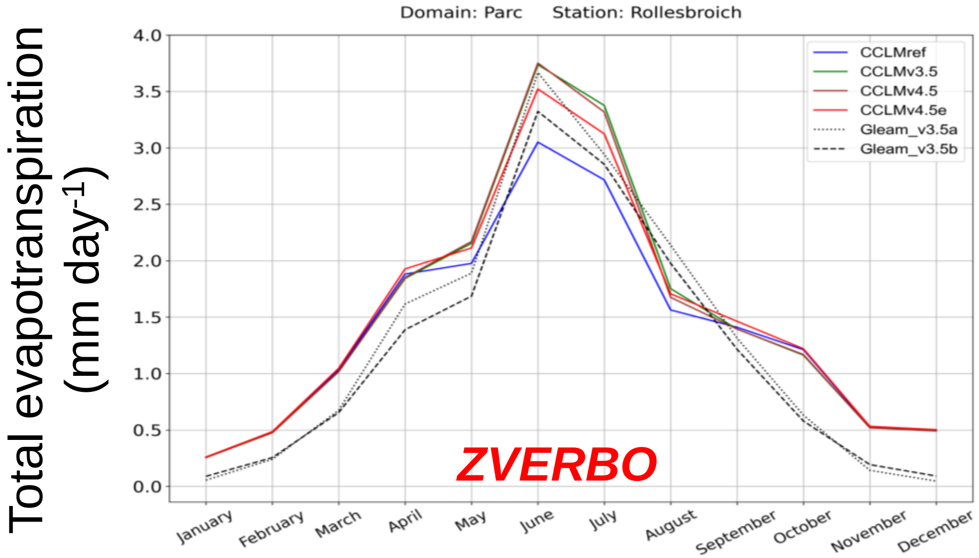
Results: ***CCLMv3.5*** has the better scores for **AEVAP** at the meteorological stations in Parc domain (*RMSE = 0.694, r = 0.848*) in comparison with GLEAM data set averaged to the point.

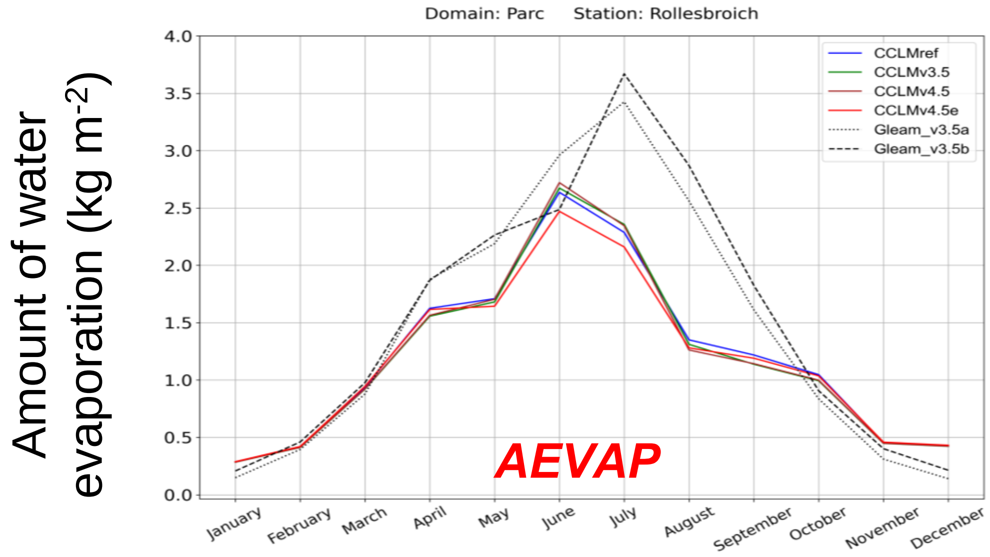
Additional materials:

Annual cycles of COSMO-CLM parameters





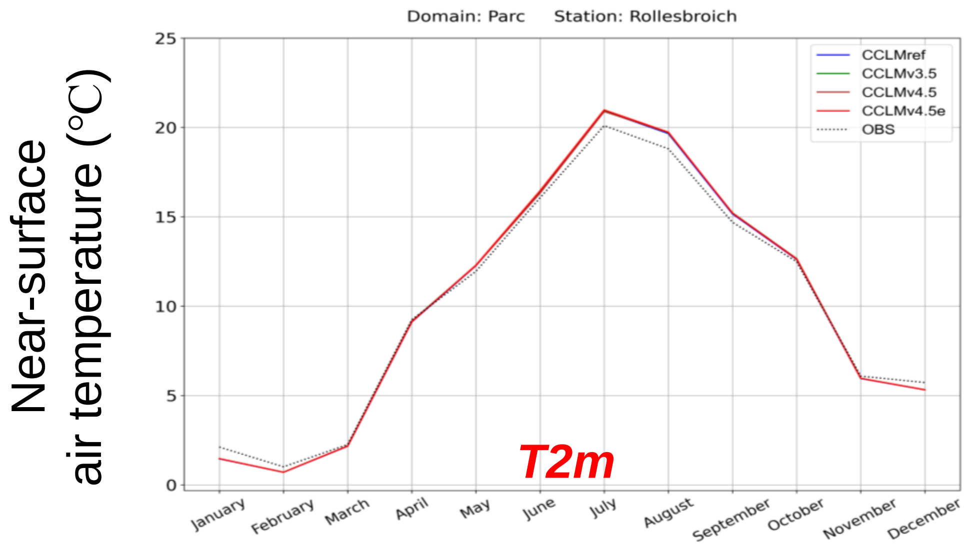


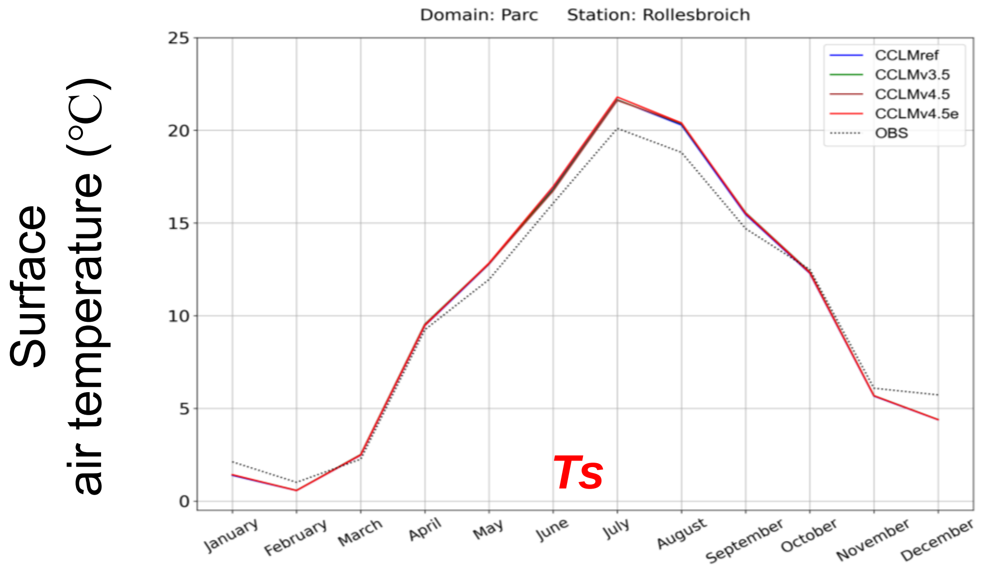


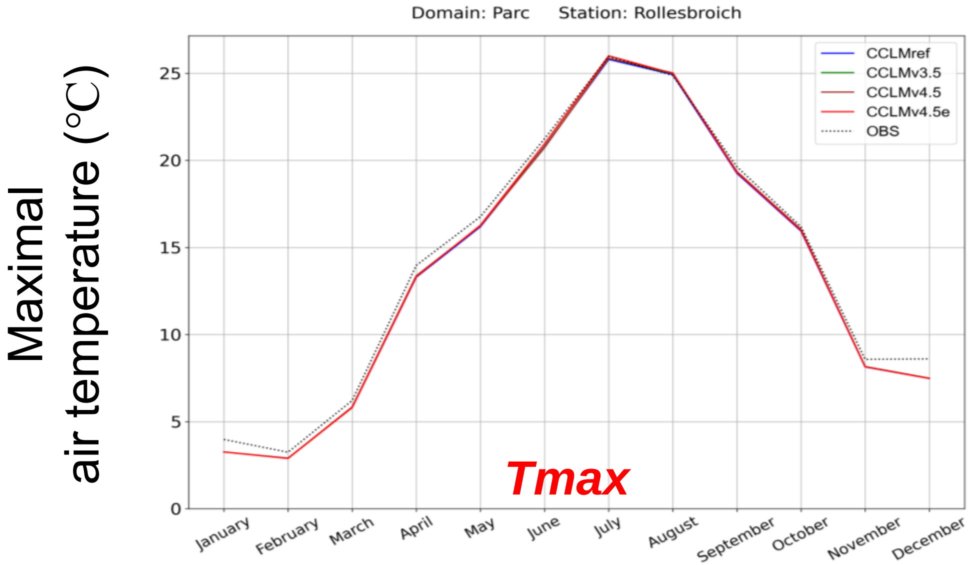
 CCLMref CCLMv3.5 CCLMv4.5 CCLMv4.5e GLEAM v3.5a GLEAM v3.5b

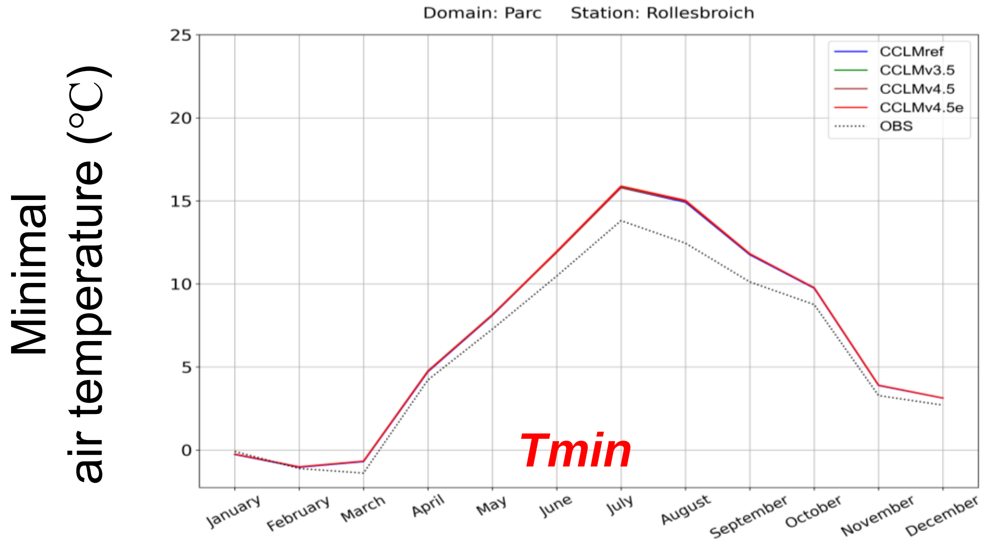
Annual cycles of COSMO-CLM parameters

Additional materials:





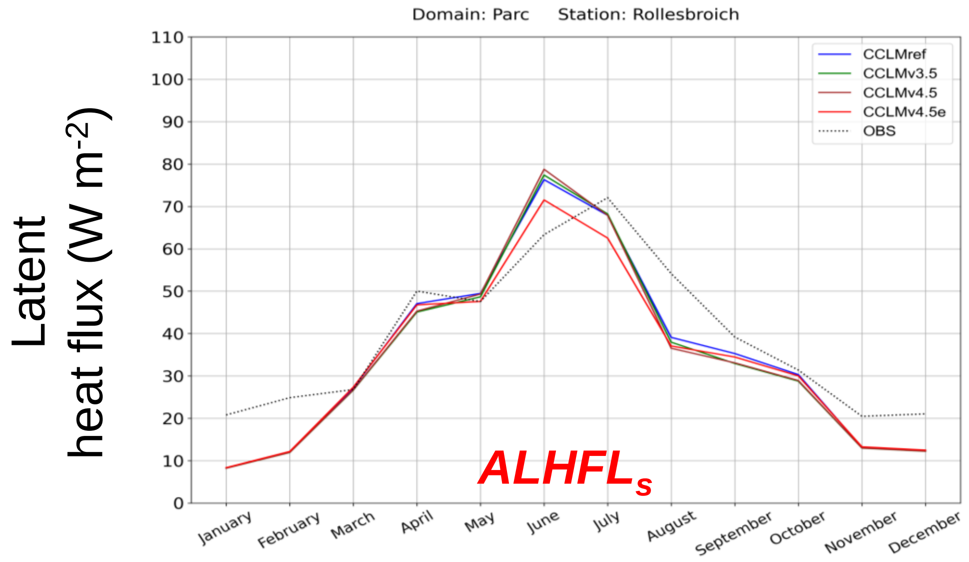


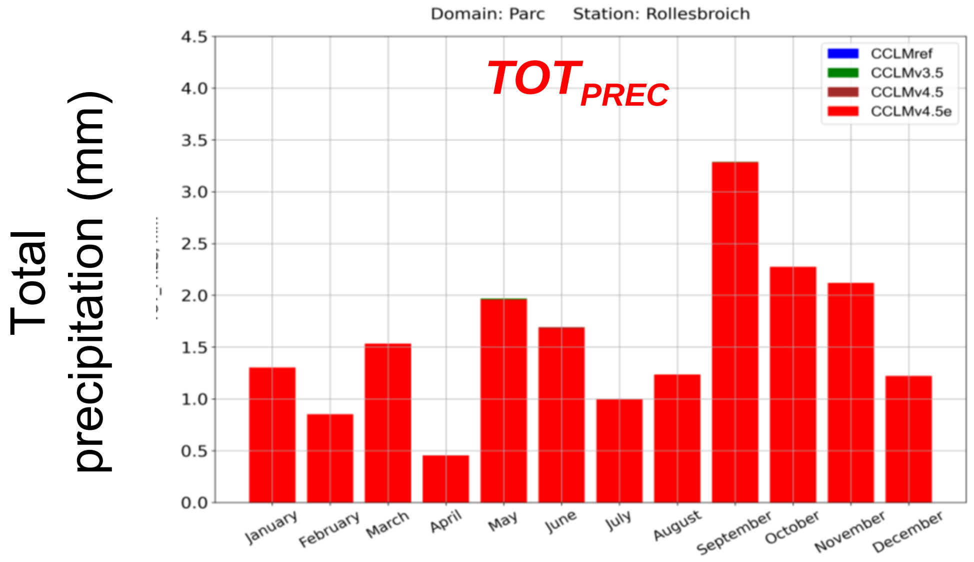


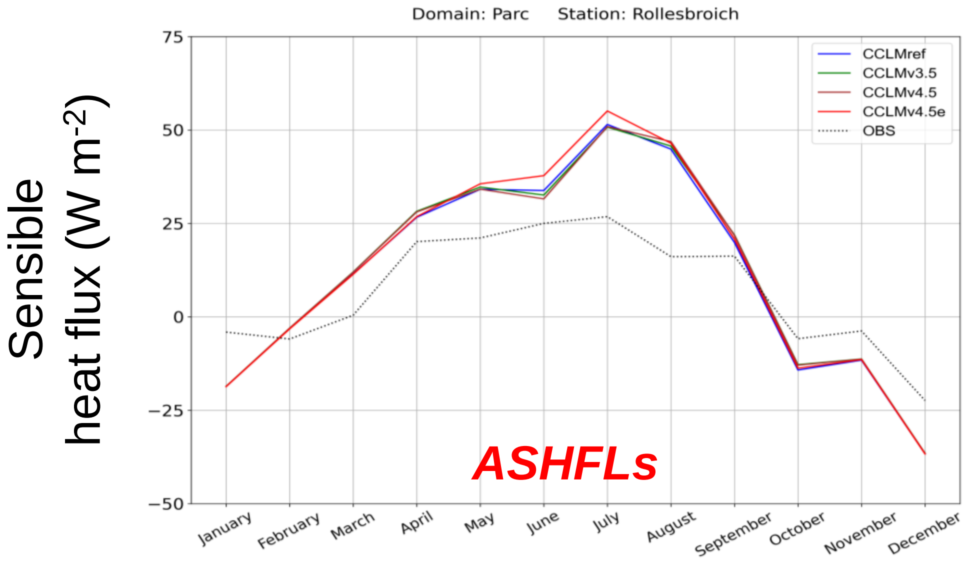
CCLMref CCLMv3.5 CCLMv4.5 CCLMv4.5e HYRAS

Additional materials:

Annual cycles of COSMO-CLM parameters







CCLMref CCLMv3.5 CCLMv4.5 CCLMv4.5e OBS