A simple approach to mimic the effect of active vegetation in hydrological models to better estimate hydrological variables under climate change

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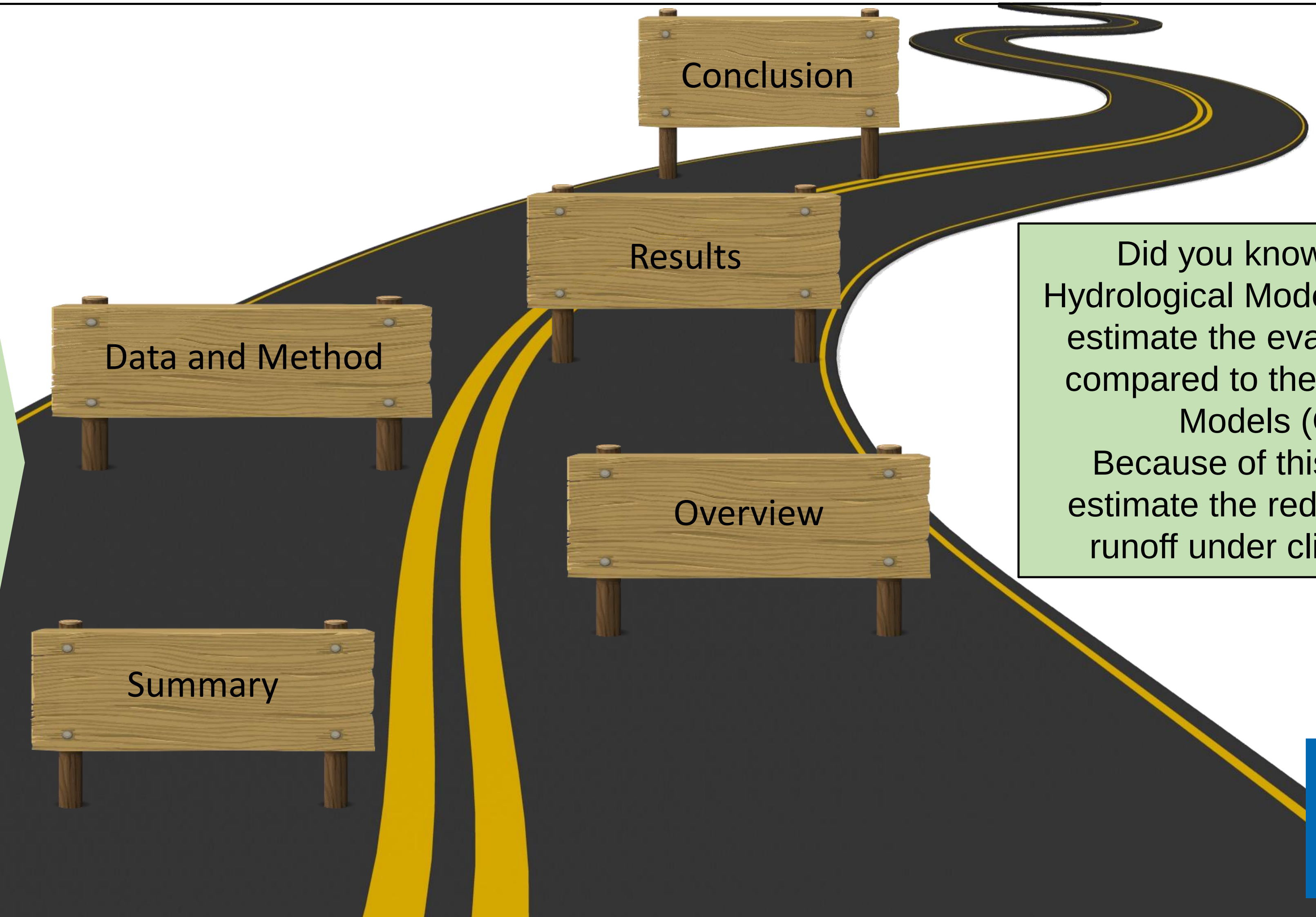
Navigation:

- Click on the icons and underlined text for more information
- With 'Home' icon you can always visit to the navigation page

Home



Did you know that Global Hydrological Models (GHMs) over-estimate the evapotranspiration compared to the Global Climate Models (GCMs)?
Because of this GHMs over-estimate the reduction of global runoff under climate change.

Federal Ministry of Education and Research
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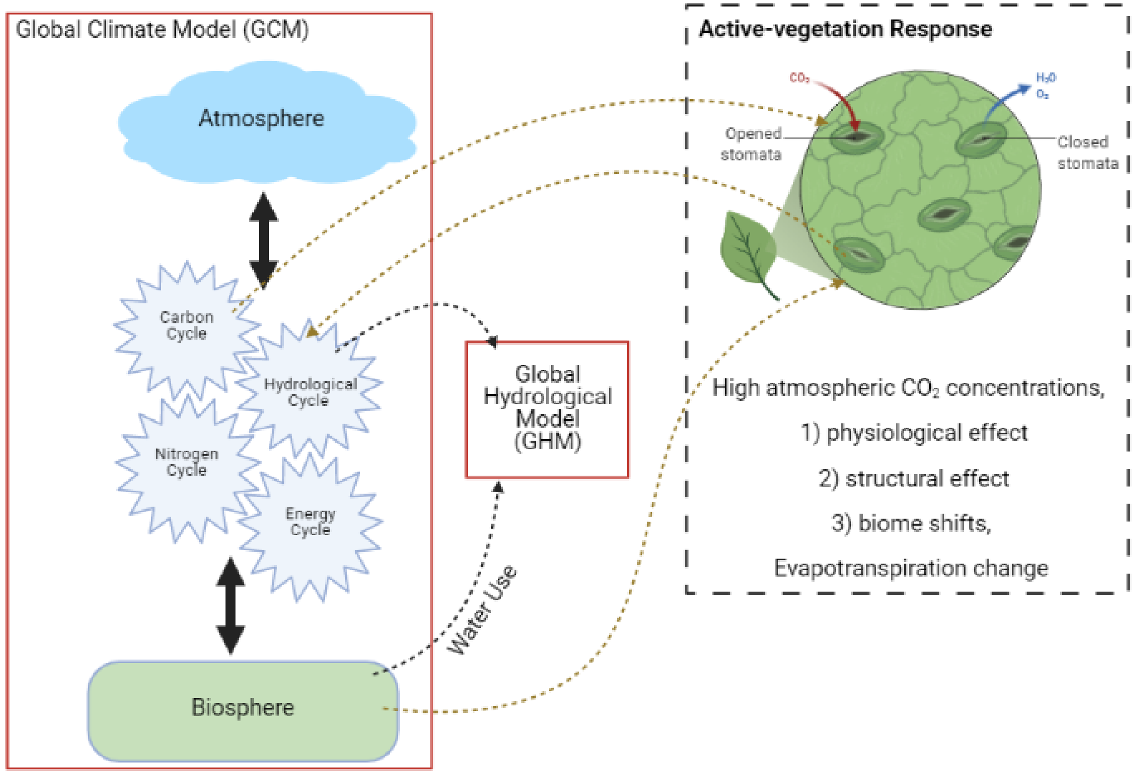
ERA4CS European Research Area for Climate Services
bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft

Summary

- Compared to GCMs, **GHMs over-estimate** the evapotranspiration **(ET)**, thus the reduction of runoff.

- This over-estimation is **partially** due to the **neglect** of **active vegetation** response (Milly and Dunne, 2016; Yang et al., 2019).



- Hydrological models **cannot simulate the feedbacks** among atmospheric processes, vegetation, water, and energy exchange at the land surface.

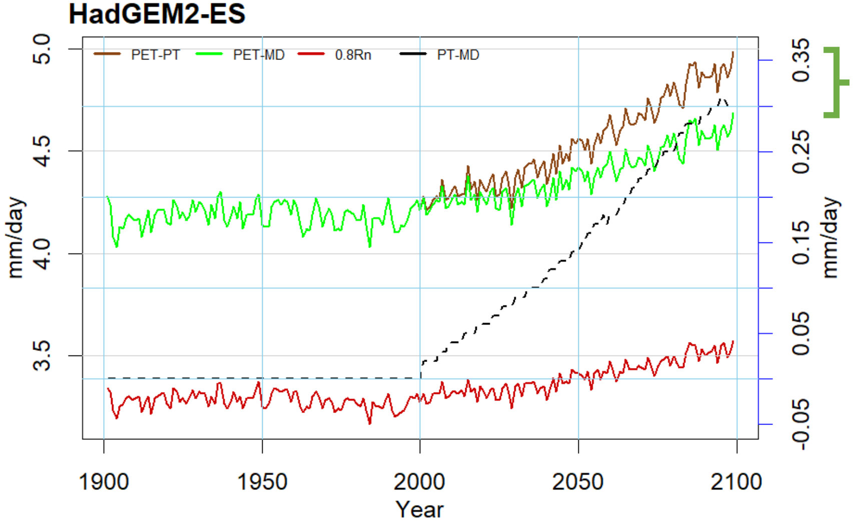
Objective:

- To present a **simple approach for hydrological models** that enables them to **mimic the effect of active vegetation**, on potential evapotranspiration under climate change.

Method:

- By **modifying** the potential evapotranspiration **(PET) scheme** in GHM. Allowing it to **mimic the ET** that is **computed by the GCM** for the **non-water-stressed grid cells**.

- **Projected PET,** averaged over the non-water-stressed cells under RCP8.5



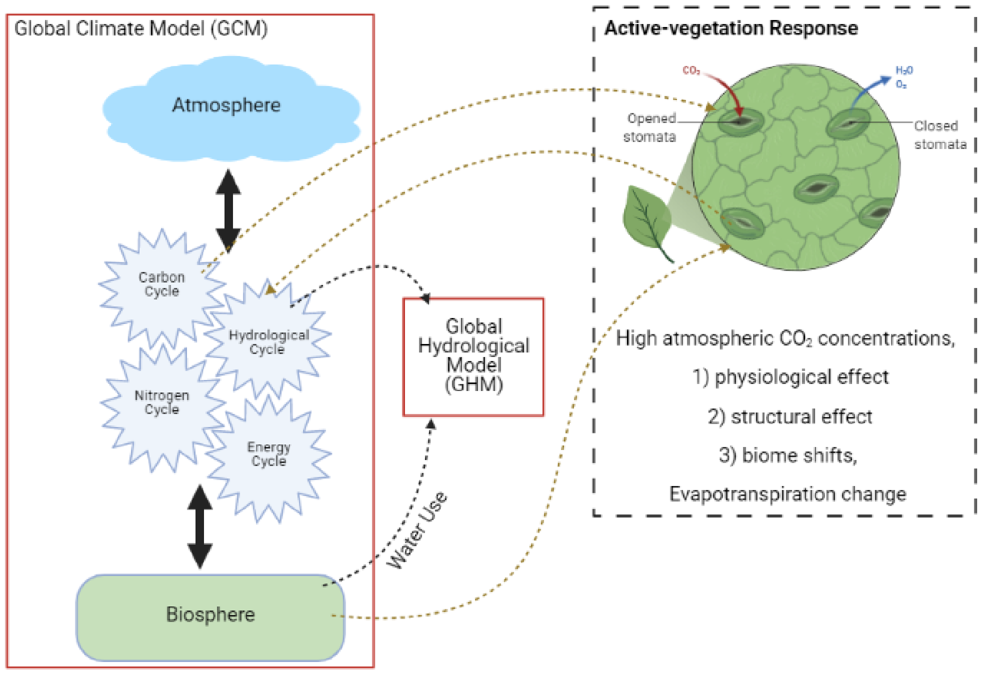
End of the century PET **reduced by 0.3 mm/day**

Brown: Default PET scheme,
Green: Modified PET scheme

- Ensemble of four GCM-GHM runs shows **11-22% PET increase** by the end of the century **with default PET** method, This is reduced to **6 – 15 %** with **modified method.**

Overview

- **Evapotranspiration (ET) →** rate of water; evaporate from the water surfaces + transpired from the plants.
- Under **non-water-stressed condition**, measurement of **ET =** potential evapotranspiration **(PET)**.
- ET → main driving force of global hydrological cycle, therefore in the context of global water availability assessment, **accurate estimates of ET is important** for **better estimate** the freshwater related **climate change hazards**.



- **GCMs** are coupled with a atmospheric and land surface models, this allows them to **simulate the feedbacks** among atmospheric processes, vegetation, water and energy exchange at the land surface.
- **GHMs calculate ET as a fraction of PET**, which is computed as a function of temperature and net radiation (sometimes: humidity and wind speed)
- **Active vegetation response** affect ET in 3 ways: with higher CO_2 concentrations;
  - Physiological effect: stomata closes and **reduce ET**
  - Structural effect: plant grow better and **increase ET**
  - Biome shift: **change ET**

Overview

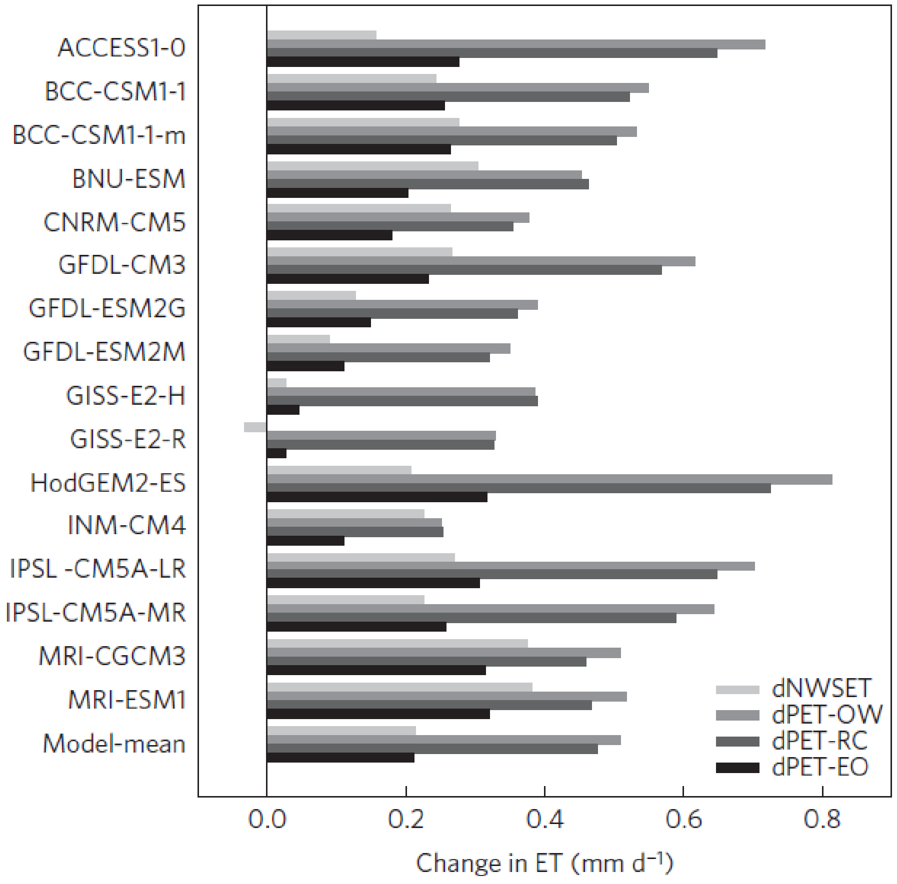


Figure 1 | Changes (future − historical; mm d^{-1}) of ET. Bars represent area-weighted averages over all non-water-stressed grid-cells/months, of climate-model non-water-stressed ET (dNWSET), reference-crop Penman–Monteith PET (dPET-RC), open-water Penman–Monteith PET (dPET-OW) and energy-only PET (dPET-EO) for each of 16 CMIP5 climate models and for the multi-model mean.

Ref: Milly & Dunne (2016)

- **Milly & Dunne (2016)** (Nature Climate Change) analyzed the changes in evapotranspiration of **16 climate models** for non-water-limited grid cells and months, only for grid cells/months with T <10 °C (NWSET), under RCP8.5 and the time period 2081-2100 as compared to 1981-2001.
- **Change of PET** computed **by state-of-the-art PET schemes (OW and RC)** are much **higher** than change of NWSET (**dNESET**).
- **Neglect of active vegetation** response is the main reason but also **combination of several factors** that can capture in complex simulation.
- **PET-EO** (PET energy only method) is Milly & Dunne (2016) ;
  - $\Delta PET = 0.8\, \Delta R_n$
  - **Alternative method** to approximately **reproduced** climate-model processes in **offline computations**.
  - In model-mean, change of PET-EO is as **same** as dNWSET
- **We developed an implementation** of this idea for hydrological models using the Priestley-Taylor equation (PET-PT) to estimate PET as a function of net radiation and temperature.

Data and Method

WaterGAP model

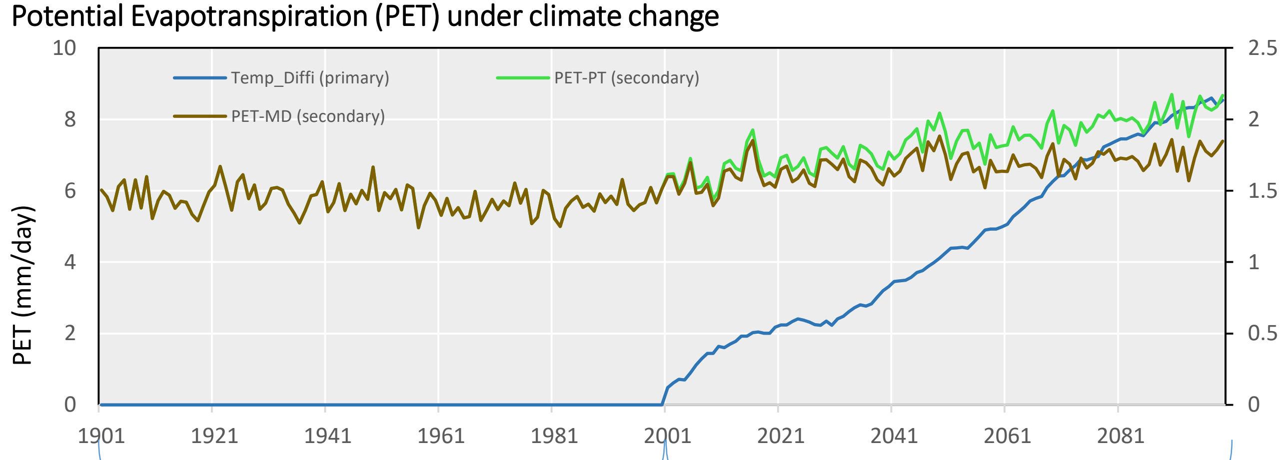
Input :
GCM derived climate data,
Water use data

Other processes

Calculation of PET

Output: fluxes and storages

PET-MD Method



Normal daily temperature used in Priestley-Taylor equation

Reduced daily temperature used in Priestley-Taylor equation

Verification

- Change of PET by the PET-MD computed for NWS cells and checked against the change of PET-EO of Milly & Dunne (2016) study results

Click on the underlined text to see more details

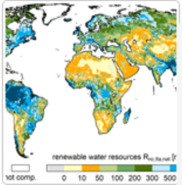
WaterGAP Model

WaterGAP2.2d

Ref: Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T. A., Popat, E., Portmann, F. T., Reinecke, R.,et al.: The global water resources and use model WaterGAP v2. 2d: Model description and evaluation, Geoscientific Model Development,14, 1037–1079, 2021.

Model description paper 23 Feb 2021

The global water resources and use model WaterGAP v2.2d: model description and evaluation



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Abstract

WaterGAP is a global hydrological model that quantifies human use of groundwater and surface water as well as water flows and water storage and thus water resources on all land areas of the Earth. Since 1996, it has served to assess water resources and water stress both historically and in the future, in particular under climate change. It has improved our understanding of continental water storage variations, with a focus on overexploitation and depletion of water resources. In this paper, we describe the most recent model version WaterGAP 2.2d, including the water use models, the linking model that computes net abstractions from groundwater and surface water and the WaterGAP Global Hydrology Model (WGHM). Standard model output variables that are freely available at a data repository are explained. In addition, the most requested model outputs, total water storage anomalies, streamflow and water use, are evaluated against observation data. Finally, we show examples of assessments of the global freshwater system that can be achieved with WaterGAP 2.2d model output.

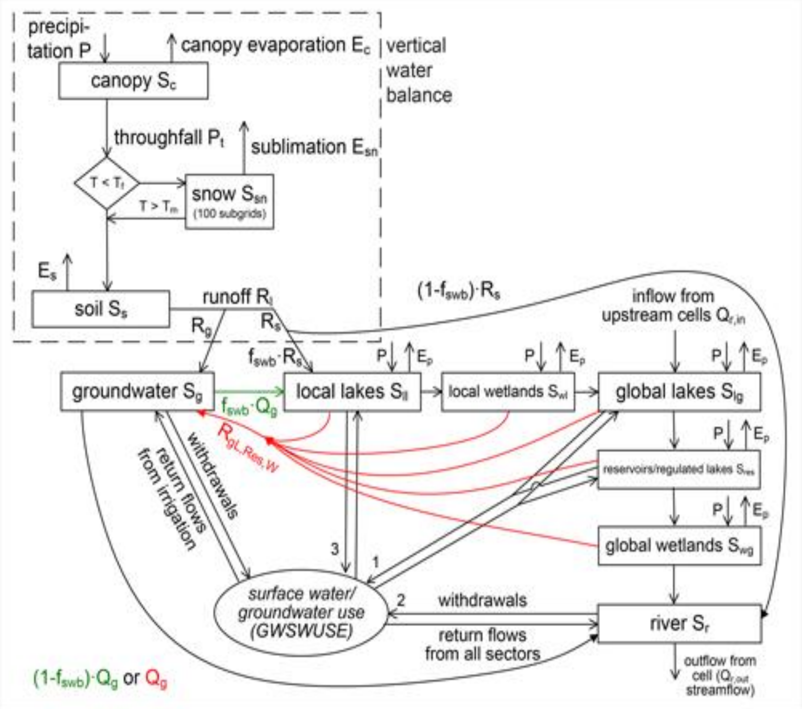


Figure 2 Schematic of WGHM in WaterGAP 2.2d. Boxes represent water storage compartments, and arrows represent water flows. Green (red) color indicates processes that occur only in grid cells with humid ((semi)arid) climate. For details the reader is referred to Sect. 4.2 to 4.8, in which the water balance equations of all 10 water storage compartments are presented.

Calculation of PET

PET calculation in WaterGAP

- In WaterGAP default PET calculation method is Priestley-Taylor (PET-PT):

$$PET = \alpha \; x \; \frac{\Delta \times Rn}{\Delta + \gamma} \quad \text{mm/day}$$

Where; α is An empirical constant accounting for the vapor pressure deficit and resistance values, Δ is slope of saturation vapor pressure (a function of daily temperature), Rn is net radiation, γ is psychrometric constant.

- Therefore, in climate change studies PET-PT is mainly driven by increasing daily temperature.

PET- MD Method

Modified PET scheme (PET-MD)

- We introduced a temperature reduction factor (temp_diffi) for each grid cell

temp_diffi= Ti(annual mean, (i-10)-(i+9) - T(annual mean, 1981-2000) ; for i = 2001-2090 → eq1

temp_diffi= Ti(annual mean, (i-10)-2099 - T(annual mean, 1981-2000) ; for i= 2091-2099 → eq2

Where Ti is the average temperature between i-10th year and i+9 (20-year window)

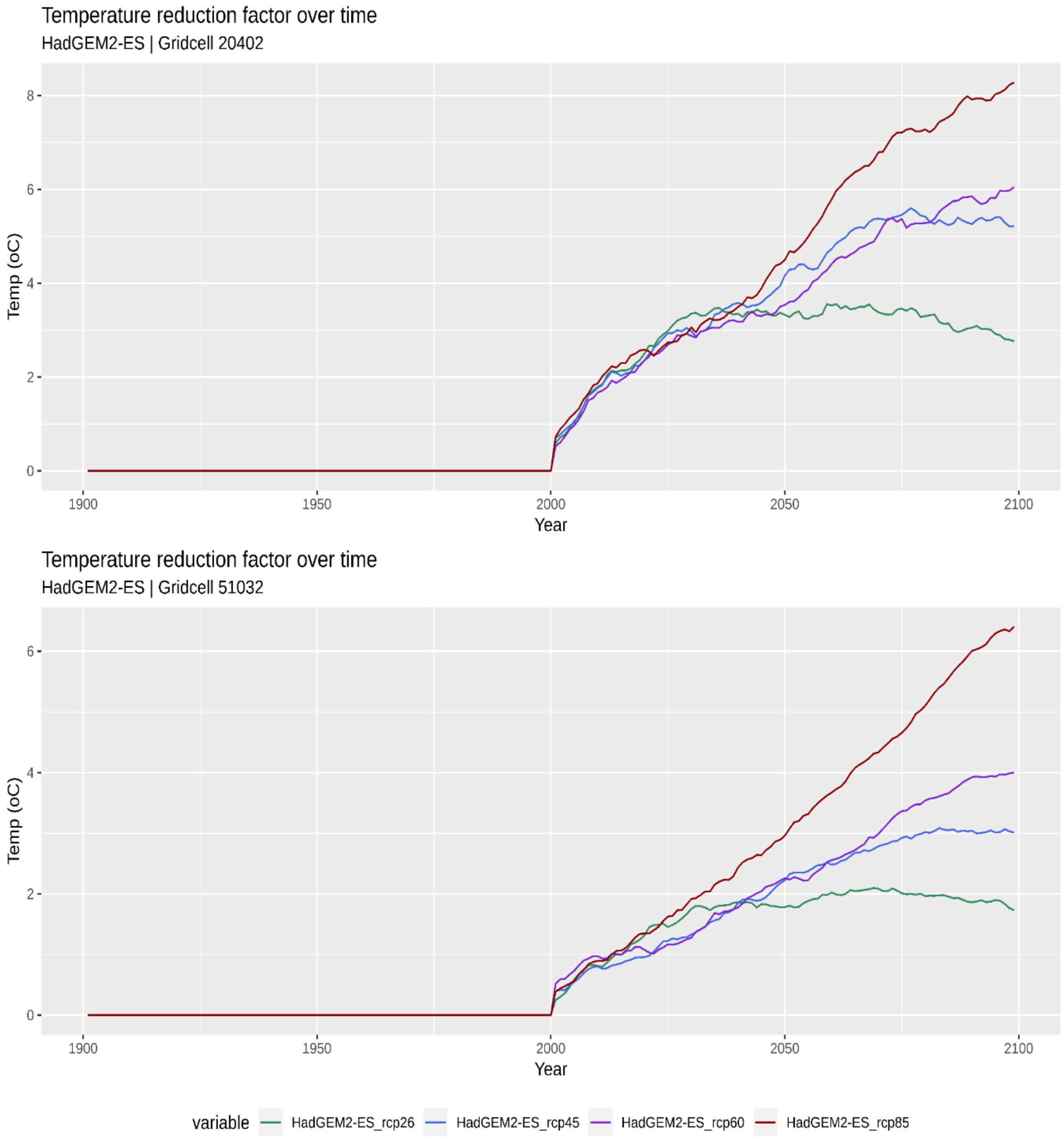
- Here you can find, temperature reduction factor for randomly chosen cell in Europe (grid cell 20402) and tropics (grid cell 51032).

- The computed temp_diffi used, to compute the reduced daily temperatures (dailyTemp_redu) for each grid cell;

dailyTemp_redu[d,i] = dailyTemp[d,i] - temp_diffi → eq3

- During the PET calculation, for a run which is going from 1901-2099;
  - Default PET-PT (PET- Presley Taylor) scheme is used until the year 2000 for both land and open water PET.
  - From year 2001 onwards for land cells: we used PET-PT scheme but with dailyTemp_redu and for open water cells PET-PT with daily temperature without the reduction factor.

Data and Method



- Time series of annual temperature reduction factor for two grid cells, for four RCPs of HadGEM2-ES climate model.
- Sudden increment of temp_diffi is observed at the year 2001 due to the methodological artifact.
- Higher reduction factors are observed for the areas with high temperature variability (top graph: a cell in Europe).

Verification

PET-MD Method verification

- GCM-GHM Simulation runs from 1901-2099 conducted using four bias-corrected CGM climate data for RCP8.5 scenarios (GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5)

- Two sets of runs:

  1) With defaults PET scheme of WaterGAP (PET-PT),

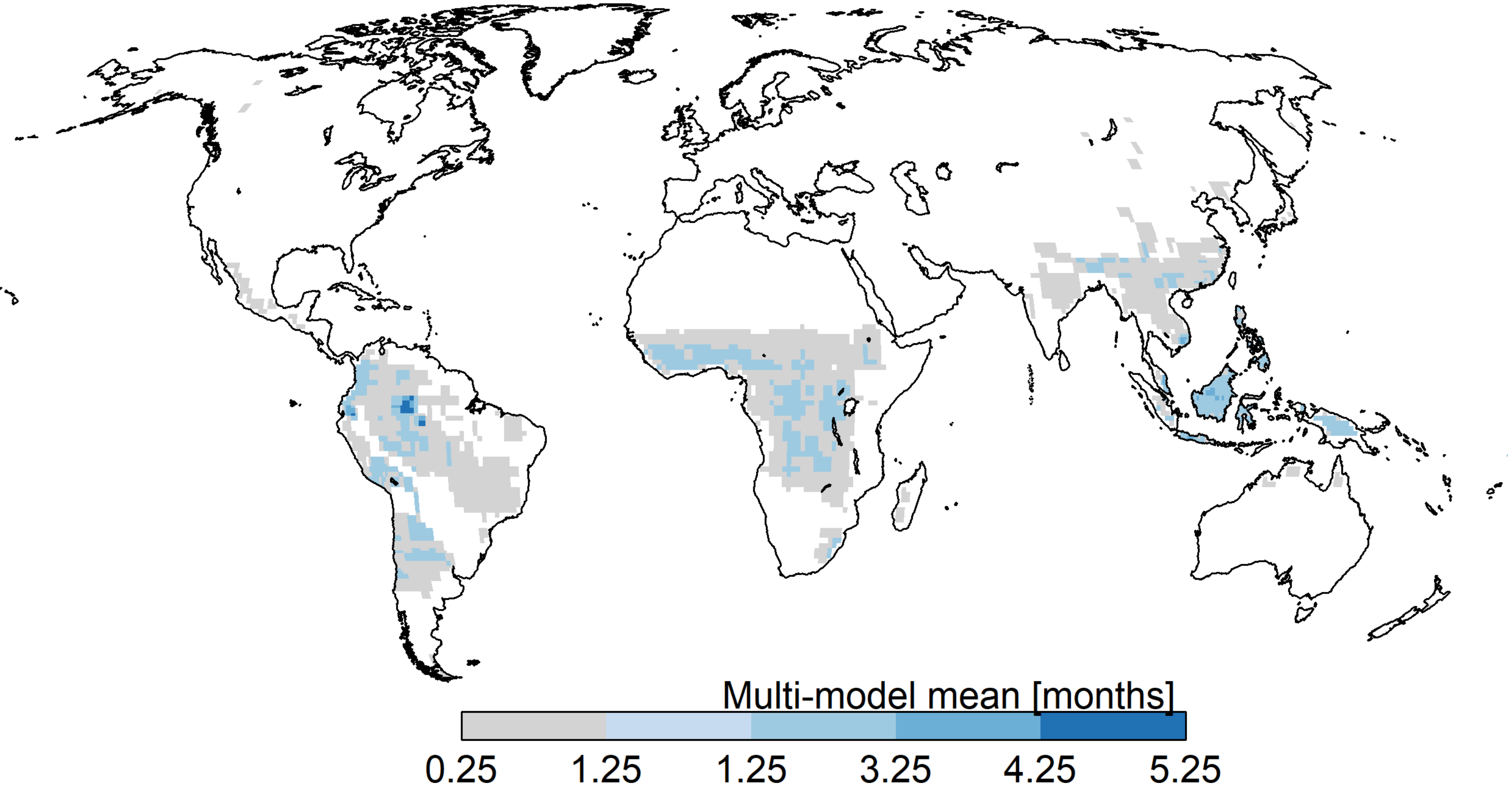
  2) Modified PET scheme (PET-MD)

- Change of PET is calculated between historical period (1981-2000) and future period (2081-2099) for all the NWS gird-cells/months (we used the same NWS gird-cells/months as Milly & Dunne (2016) study)

- Results compared against the Milly & Dunne (2016) study results

Non-water-stressed cells (NWS cells)

- Multi-model mean of number of months when evapotranspiration is non-water-stressed



- Theoretically, under NWS condition:

  ET computed by GCM = PET computed by GHM

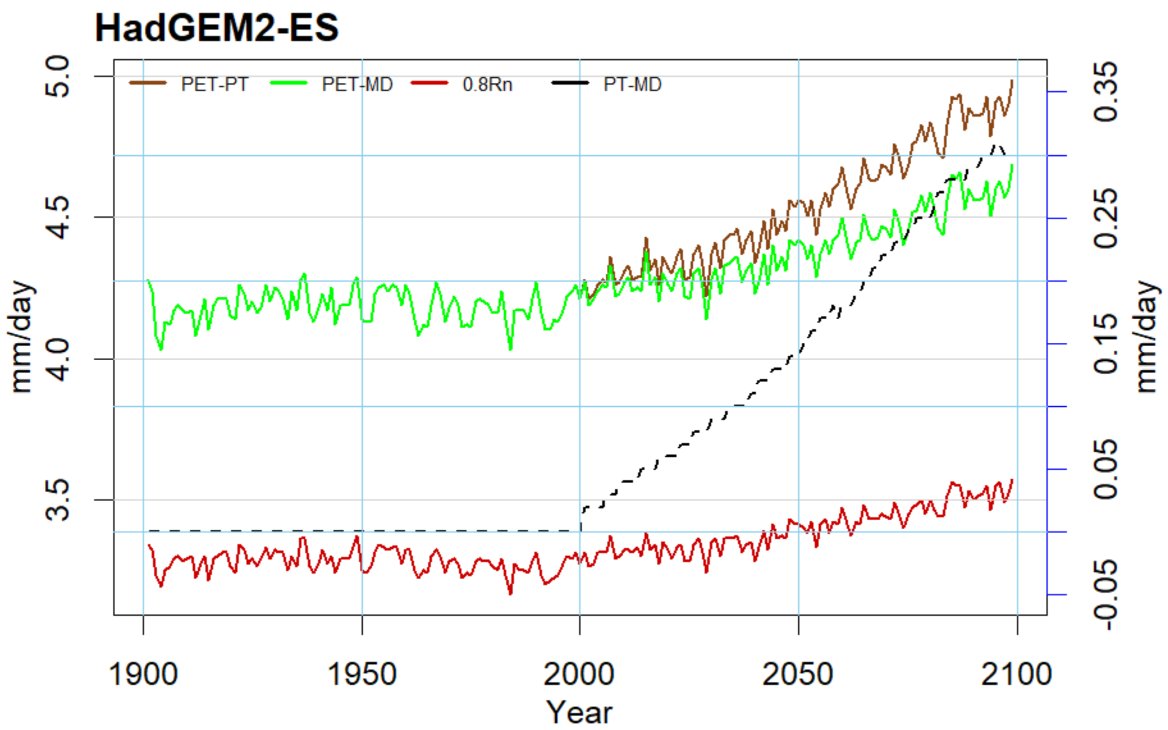
Results 1/3

- Area-weighted average over all NWS grid-cells/months, of PET computed by WGHM with PET-PT and PET-MD and net radiation (Rn). WGHM is forced with four different bias-corrected GCM climate data for RCP8.5 scenario. Historical period is 1981-2000 and change is computed as (Future – historical), where future is from 2081-2099. The last column shows the results from the Milly and Dunne (2016) study.

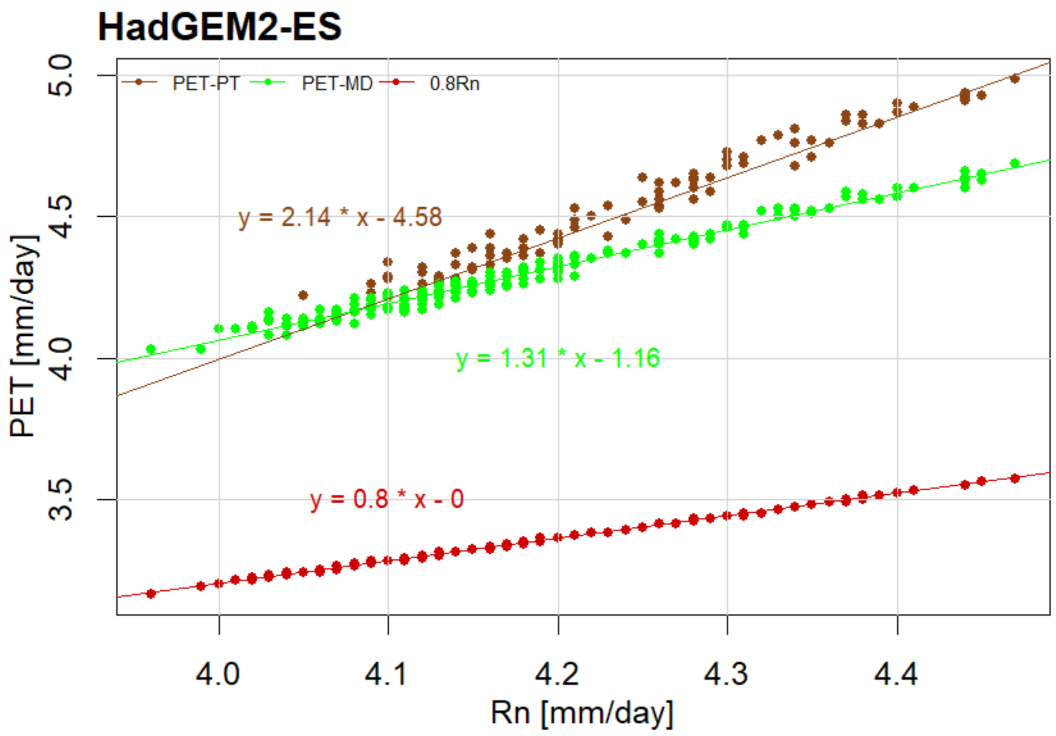
GCM	Variable	Historical (mm/day)	Change (mm/day)	% Change	dPET-EO from figure1 (Milly and Dunne, 2016) (mm/day)
GFDL-ESM2M	PET-PT	3.79	0.41	11%	0.1
	PET-MD	3.79	0.23	6%	
	Rn	3.82	0.2	5%	
HadGEM2-ES	PET-PT	4.17	0.70	17%	0.32
	PET-MD	4.17	0.41	10%	
	Rn	4.07	0.32	8%	
IPSL-CM5A-LR	PET-PT	4.44	0.98	22%	0.3
	PET-MD	4.44	0.68	15%	
	Rn	4.51	0.63	14%	
MIROC5	PET-PT	4.85	0.56	12%	Not included in the analysis
	PET-MD	4.85	0.33	7%	
	Rn	4.59	0.28	6%	

- Except for IPSL-CM5A-LR, change of PET-MD is quite similar to change of PET-EO
- With PET-PT, GHM projected 11% -22% increase of PET by the end of the century with respect to the historical period.
- With PET-MD, we could reduce this over prediction to 6% - 15%

Results 2/3



(a)

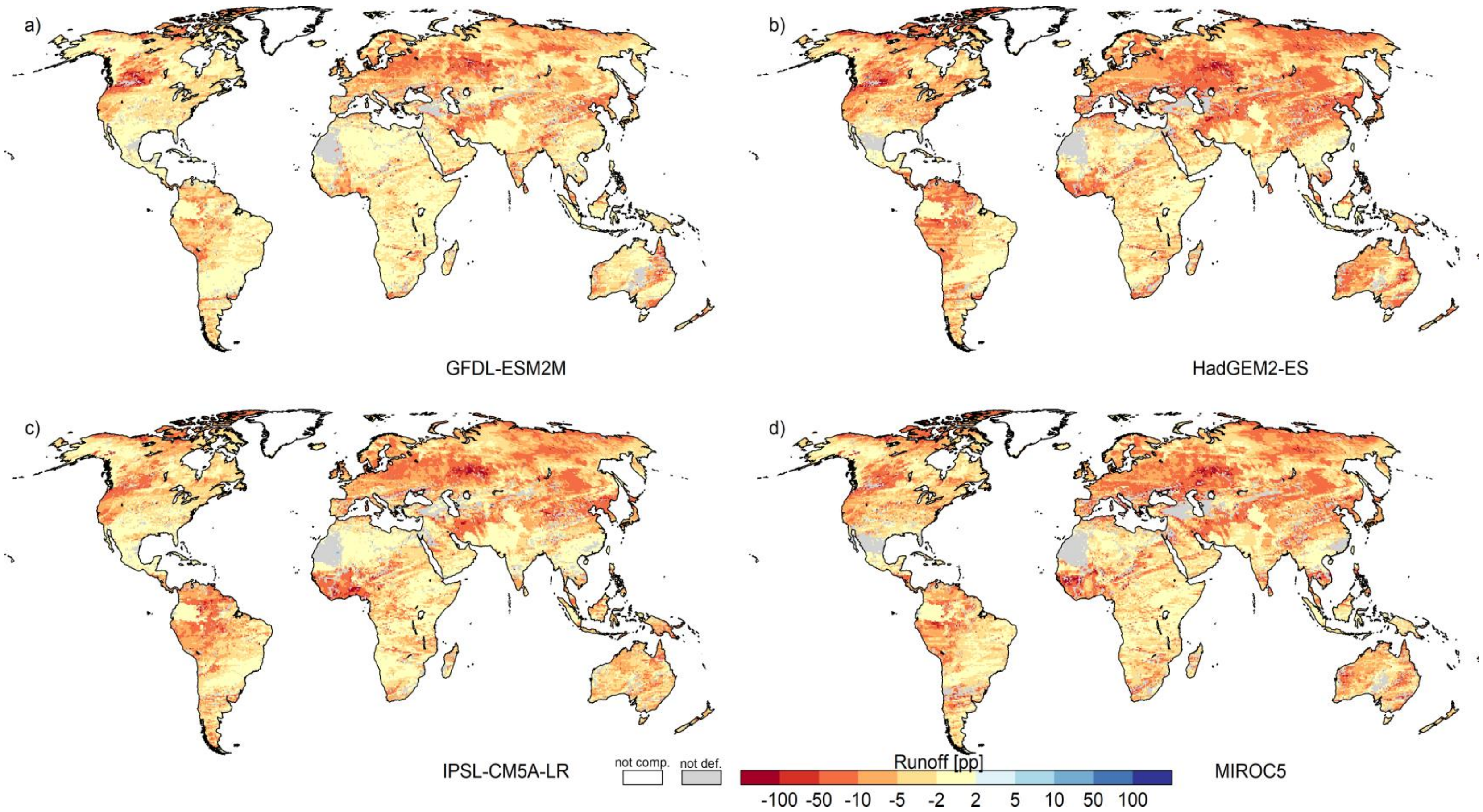


(b)

- Time-series of area-weighted average over all NWS grid-cells/months, of PET (computed by PET-PT and PET-MD), 80% of Net radiation (Rn) simulated by WaterGAP forced with HadGEM2-ES, RCP8.5 climate data.
- Black dotted line: Reduction of estimated PET, due to the modification (secondary y-axis)
- Rate of PET increase is reduced by PET-MD method.
- Regression analysis on the left shows PET calculated by PET-MD perform in the same way as 0.8Rn (i.e PET-EO)

Results 3/3

Impact on Runoff projection



- Four global maps shows the percentage point of change of runoff change by the end of the century (2081-2099) compared to historical period (1981-2000) for RCP8.5 scenario.
- Over-all change is negative, this implies that the PET-MD reducing the over estimation of runoff reduction.
- It is the percentage of runoff with respect to the historical period, that can be recover by including the effect of the active vegetation response.

$$Change\ of\ Runoff\ change[pp] = Change\ of\ runoff_{PET-PT}\% - Change\ of\ runoff_{PET-MD}\%$$

$$Change\ of\ Runoff\ \% = \frac{Runoff_{Future} - Runoff_{Historical}}{Runoff_{Historical}} \times 100$$

Conclusion

- Change PET-MD **shows promising results** when compared to the change of PET-EO, thus change of ET computed by GCMs.
- The PET-MD is successfully **reducing the over-prediction** of the PET in the future.
- PET-MD is **not driven by the daily temperature**, like in PET-PT.
- PET-MD method enables hydrological to **mimic the effect of active vegetation**, on potential evapotranspiration under climate change.

Thank you !!!

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