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Giovanni Selleri, Mattia Neri, Elena Toth
University of Bologna
giovanni.selleri4@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Which PET formulas for my rainfall-runoff modelling?

When rainfall-runoff modelling, there is usually the need to estimate PET (Potential Evapo-Transpiration) using a formula

Which formulas can I use?

Which formula for my study?

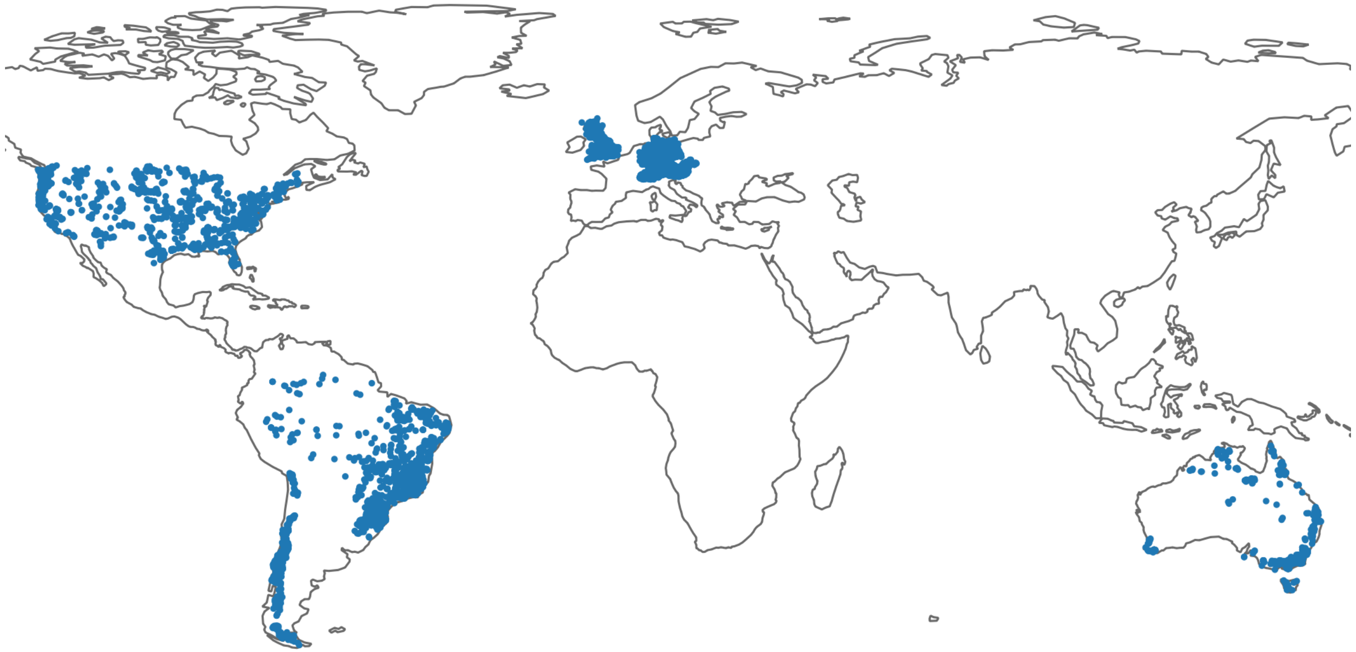
What could change?

Which data I have?

How the PET estimates vary when changing formula?

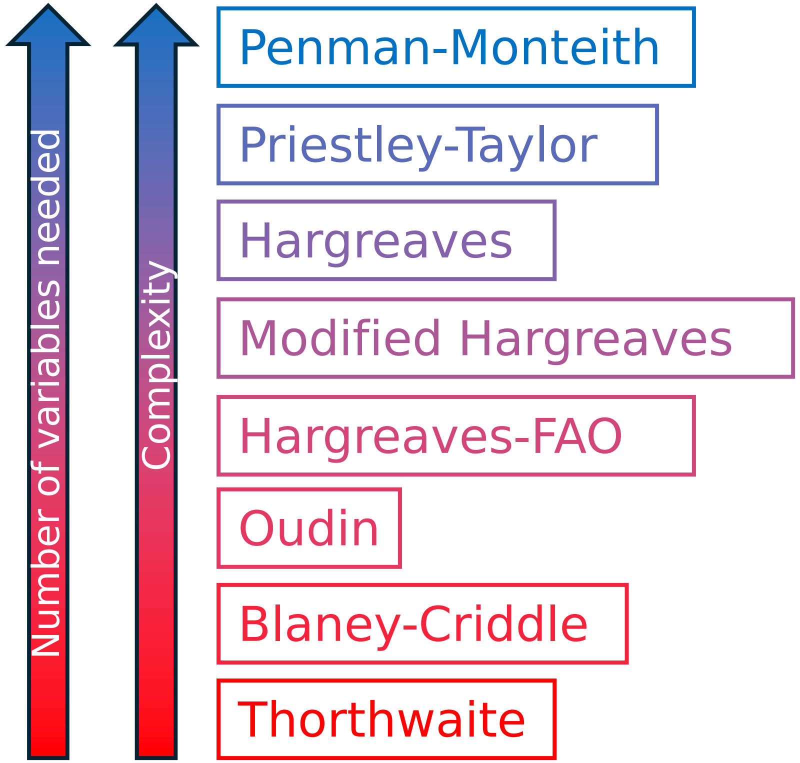
How the PET estimates vary when changing formula?

Caravan: an open source rainfall-runoff dataset



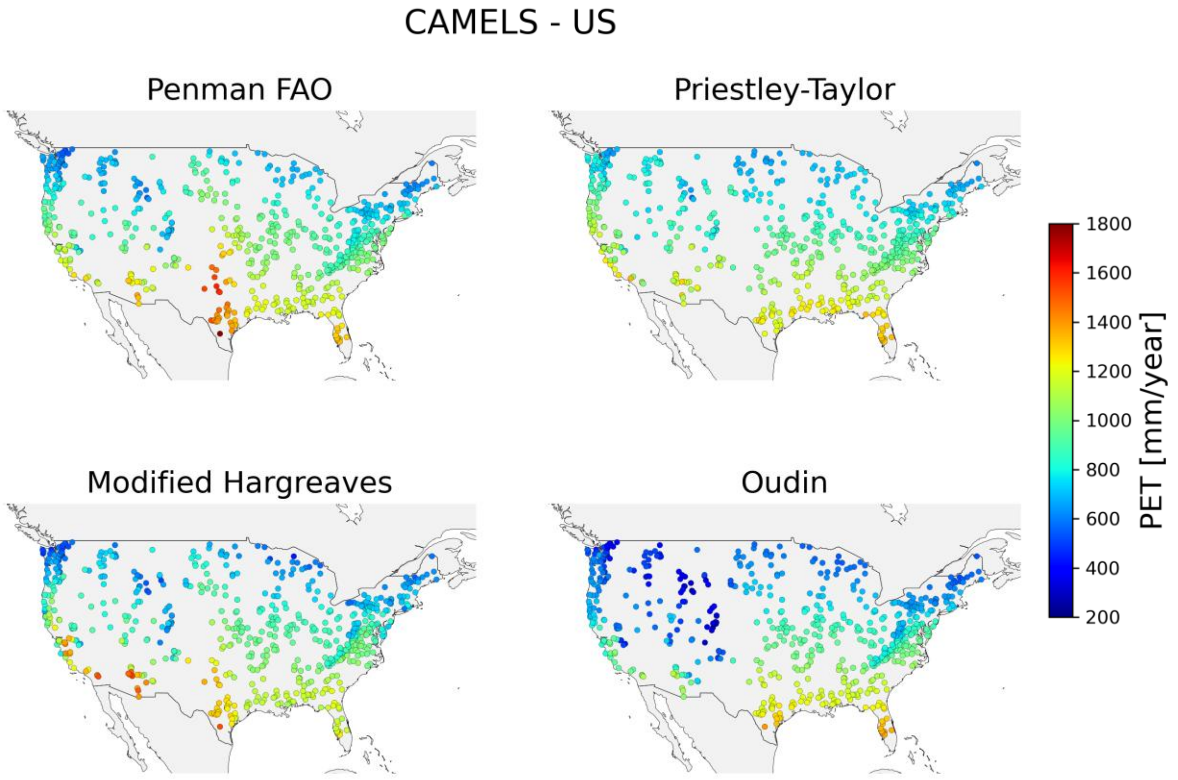
~5000 basins
Hydro-meteorological timeseries at catchment scale

PET formulas:

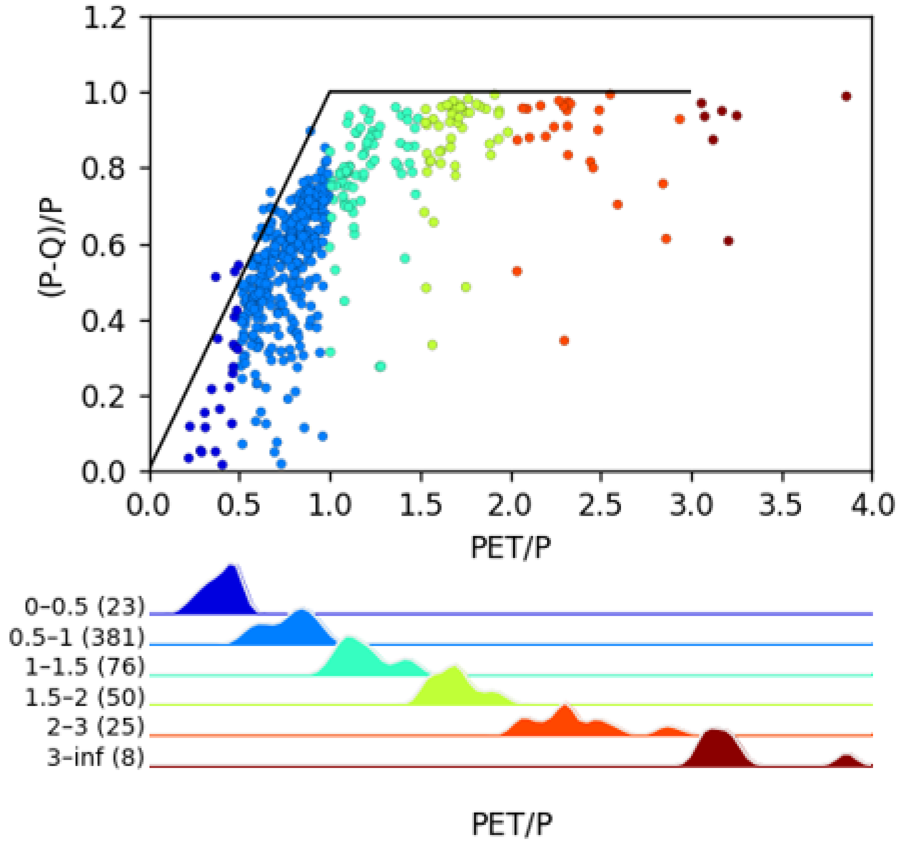


Analysis of PET estimates

Annual long-term average [mm/year]



Budyko framework for hydrological consistency



Sharing is encouraged

Which PET formulas for my rainfall-runoff modelling?

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PICO4.4

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Summary

Objectives

PET formulas & Data

Analysis of PET estimates

Hydrological consistency in Budyko

Conclusions

Supplementary

Which PET formulas for my rainfall-runoff modelling?

Several PET formulas have been proposed to estimate PET at catchment scale

Choosing the formula is usually up to the single researcher, that each time must decide based on the input data available and their personal preferences

Our objectives are:

- Comparing the PET estimates at catchment scale
- Checking their hydrological consistency in the Budyko framework

PET formulas & Data

Formulas use meteorological data to estimate PET

The choice of the formula depends on data availability

We chose the data necessary for the Penman-Monteith formula (FAO version), which combines energy and mass balance (used as benchmark)

We selected other seven PET formulas among the most used in literature, which are less data-demanding, down to a simple temperature-based equation

PET formulas: description

Penman FAO	Combines the energy balance and the mass transfer	(R_{solar}, R_{th}, T_{avg}, T_{max}, T_{min}, T_{dew}, Wind, Pressure)
Priestley Taylor	Radiation based	(R_{solar}, R_{th}, T_{avg})
Hargreaves	Radiation is estimated with latitude, and the difference Tmax-Tmin is used as proxy for the atmospheric turbidity	(T_{avg}, T_{max}, T_{min}, Latitude)
Modified Hargreaves	The contribution of monthly precipitation is added to the calculation of turbidity	(T_{avg}, T_{max}, T_{min}, Precipitation, Latitude)
Hargreaves-FAO*	The atmospheric turbidity term range is limited	(T_{avg}, T_{max}, T_{min}, Latitude)
Oudin	Empirical based on temperature	(T_{avg}, Latitude)
Blaney-Criddle*	Empirical based on temperature, elevation and daily light hours	(T_{avg}, Latitude, Elevation)
Thorthwaite	Empirical based on temperature	(T_{avg})

* Results not showed here for sake of brevity

PET formulas: necessary variables

Penman FAO	Net solar radiation	Net thermal radiation	Tmean	Tmax	Tmin	Tdew	Wind speed	Pressure		
Priestley Taylor	Net solar radiation	Net thermal radiation	Tmean							
Hargreaves			Tmean	Tmax	Tmin					Latitude
Modified Hargreaves			Tmean	Tmax	Tmin				Precipitation	Latitude
Hargreaves-FAO*			Tmean	Tmax	Tmin					Latitude
Oudin			Tmean							Latitude
Blaney-Criddle*			Tmean							Latitude
Thorthwaite			Tmean							

* Results not showed here for sake of brevity

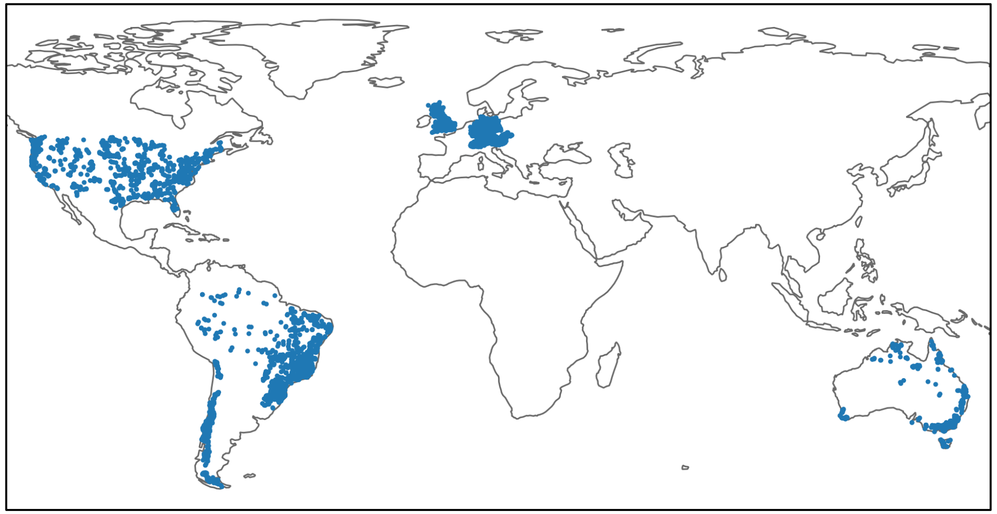
PET formulas & Data

Caravan: an open source rainfall-runoff dataset (Kratzert et al., 2023)

https://github.com/kratzert/Caravan

Caravan contains hydro-meteorological daily timeseries at catchment scale:

- Streamflow observations from other large-sample datasets (CAMELS initiative)
- Meteorological timeseries derived from ERA5-Land reanalisys



PET formulas & Data

The time period of daily meteorological variables is 1951-2023

The interval of daily streamflow observations depends on the source dataset, most of the data are in the period 1981-2014

We selected ~5000 basins in Caravan:

Caravan region	Number of basins
US	671
Brazil	870
Chile	505
UK	671
Australia	222
Germany	1887
Switzerland	269

Analysis PET estimates

Distribution of PET annual average by formulas

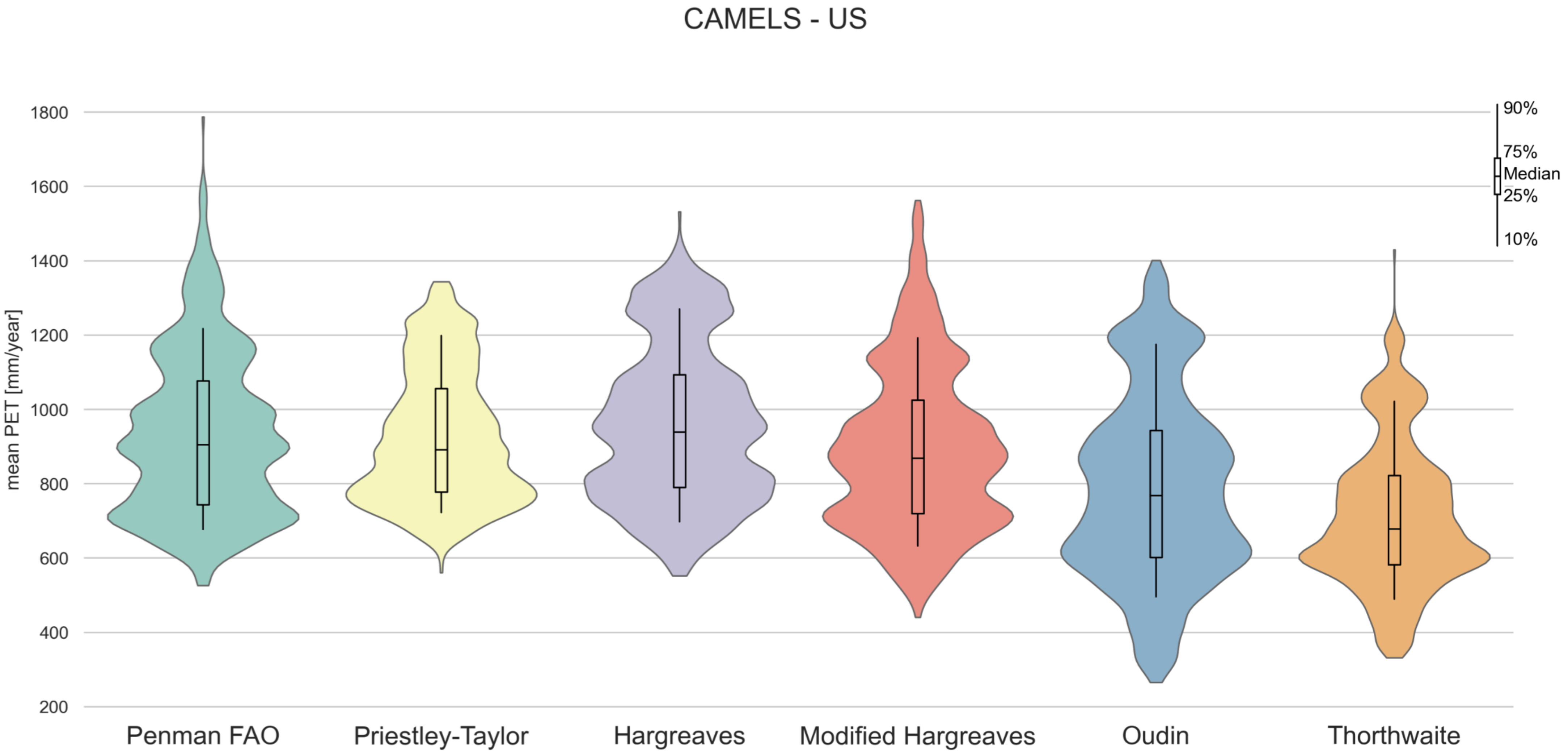
Map of PET annual average

Map of the PET relative annual average (w.r.t. Penman FAO benchmark formula)

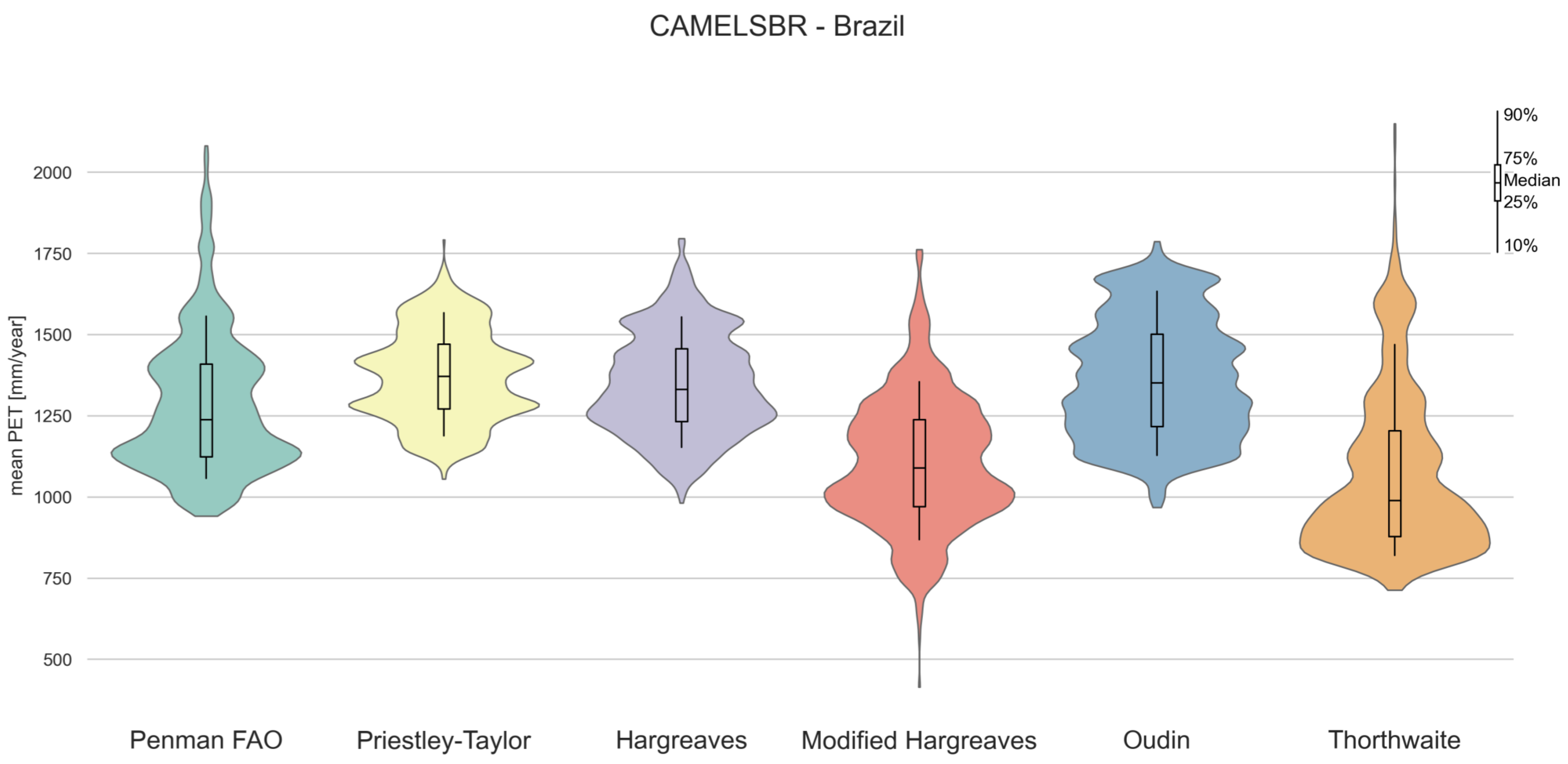
Map of PET long term variability throughout the year

Map of Aridity Index

PET annual average [mm/year] distribution



PET annual average [mm/year] distribution



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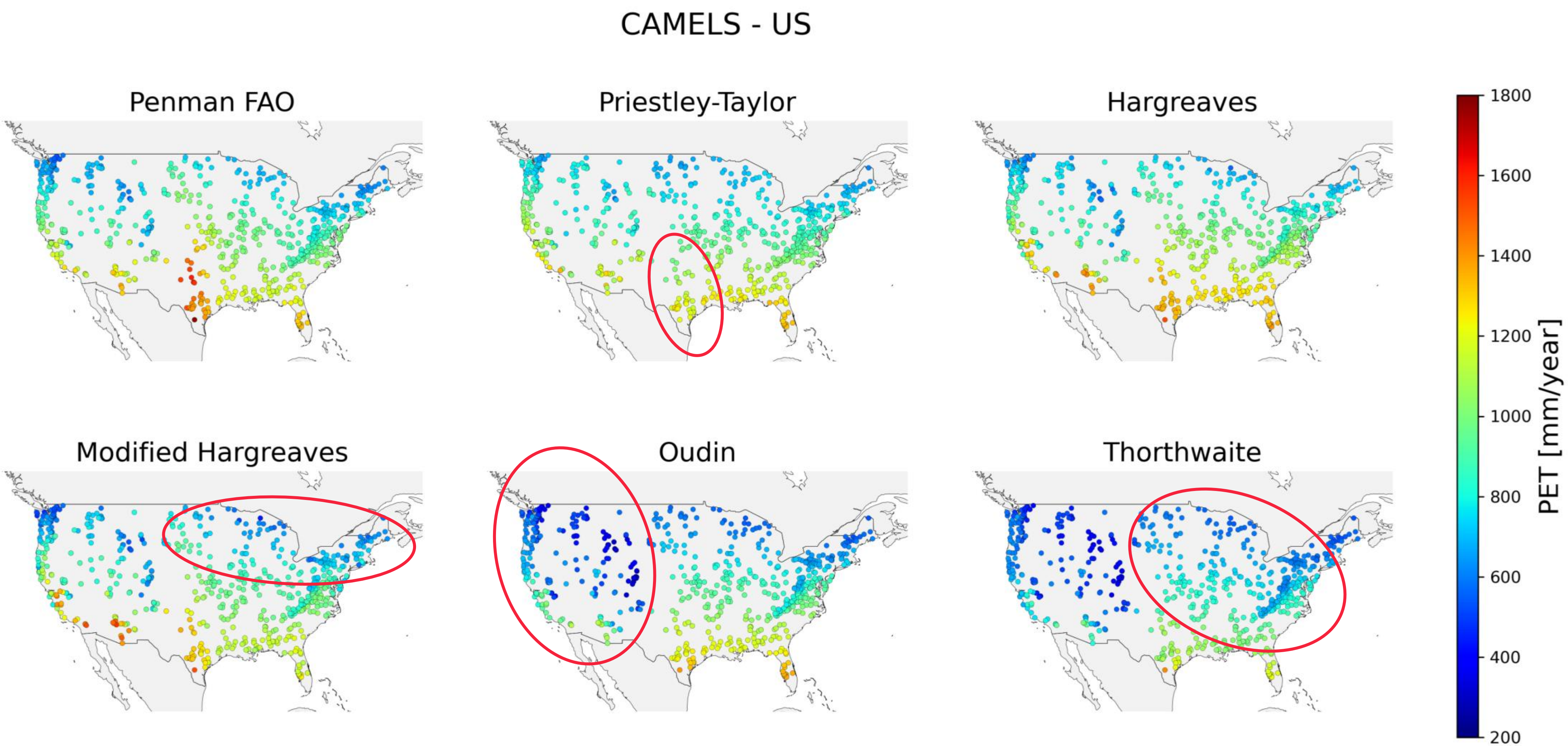
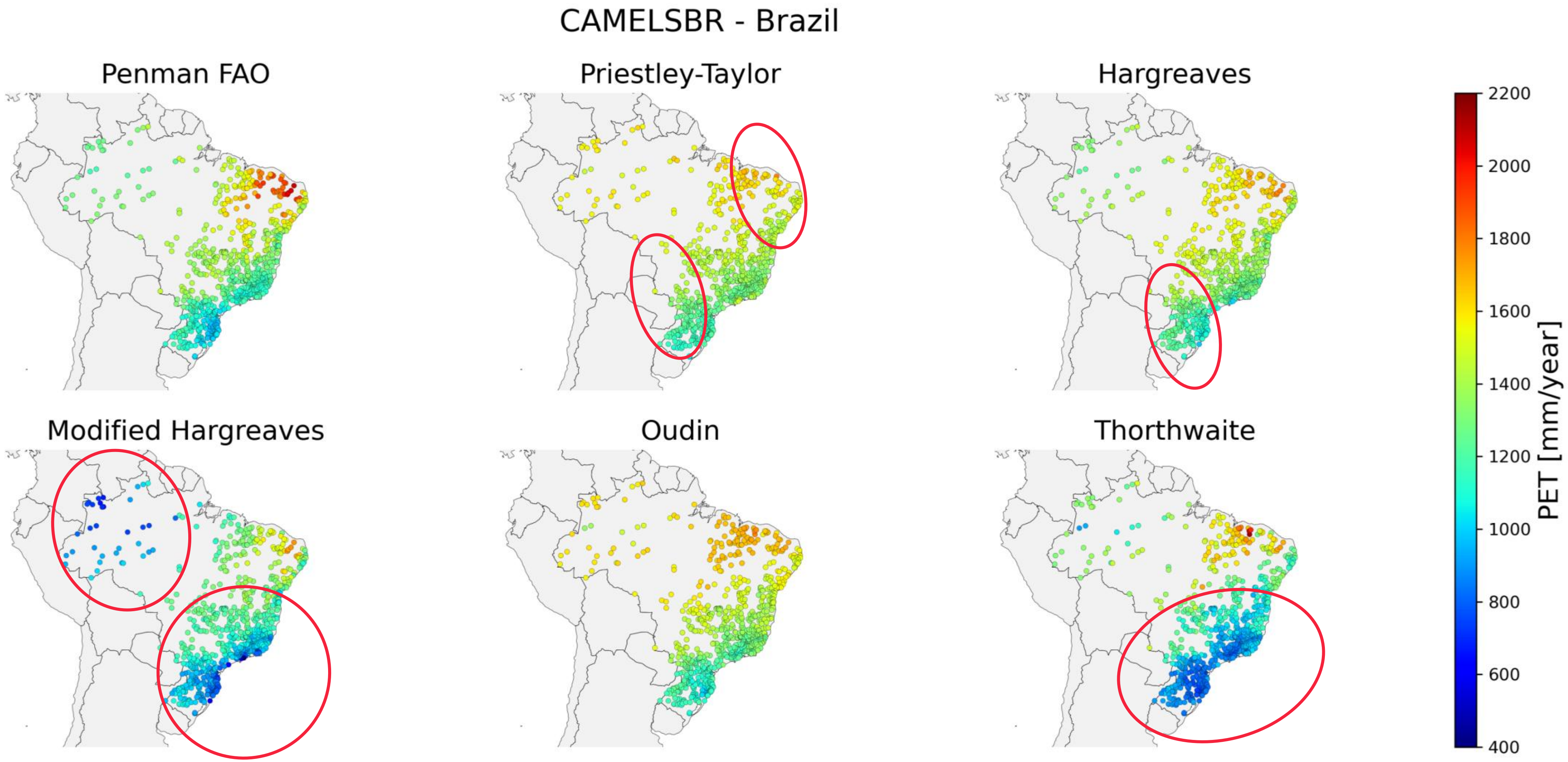


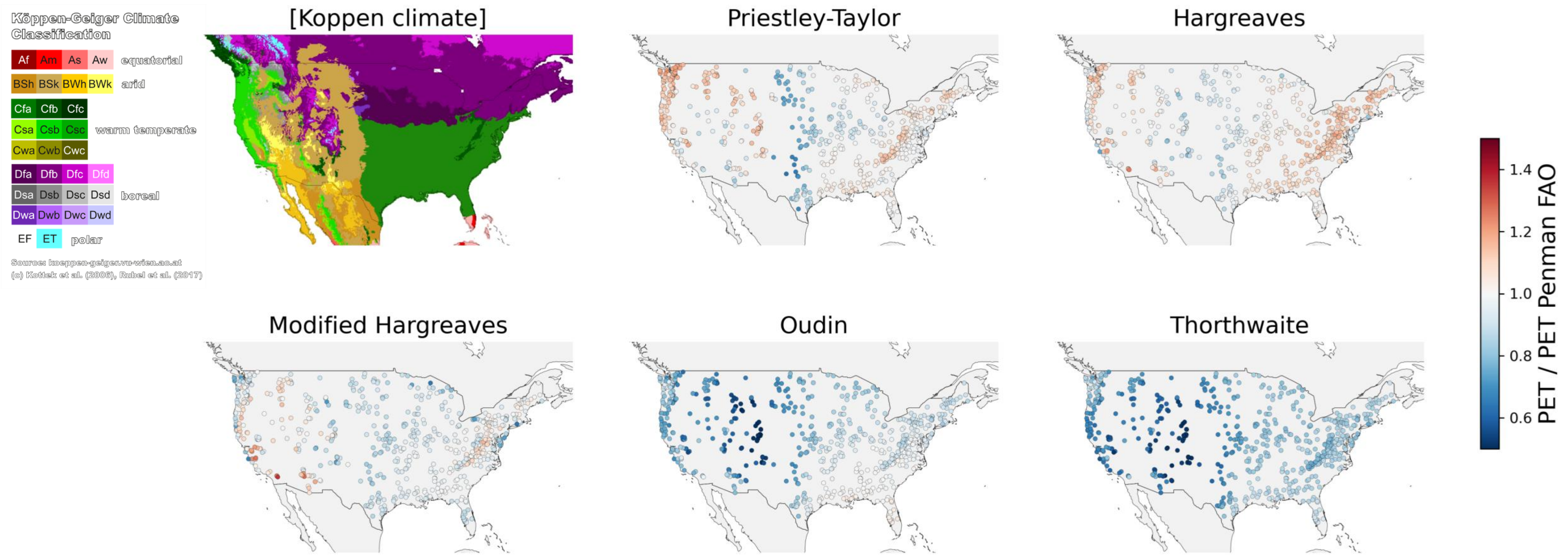
PET annual average [mm/year]



PET relative annual average

$$\frac{PET\ formula\ i}{PET\ Penman\ FAO}$$

CAMELS - US



PET relative annual average

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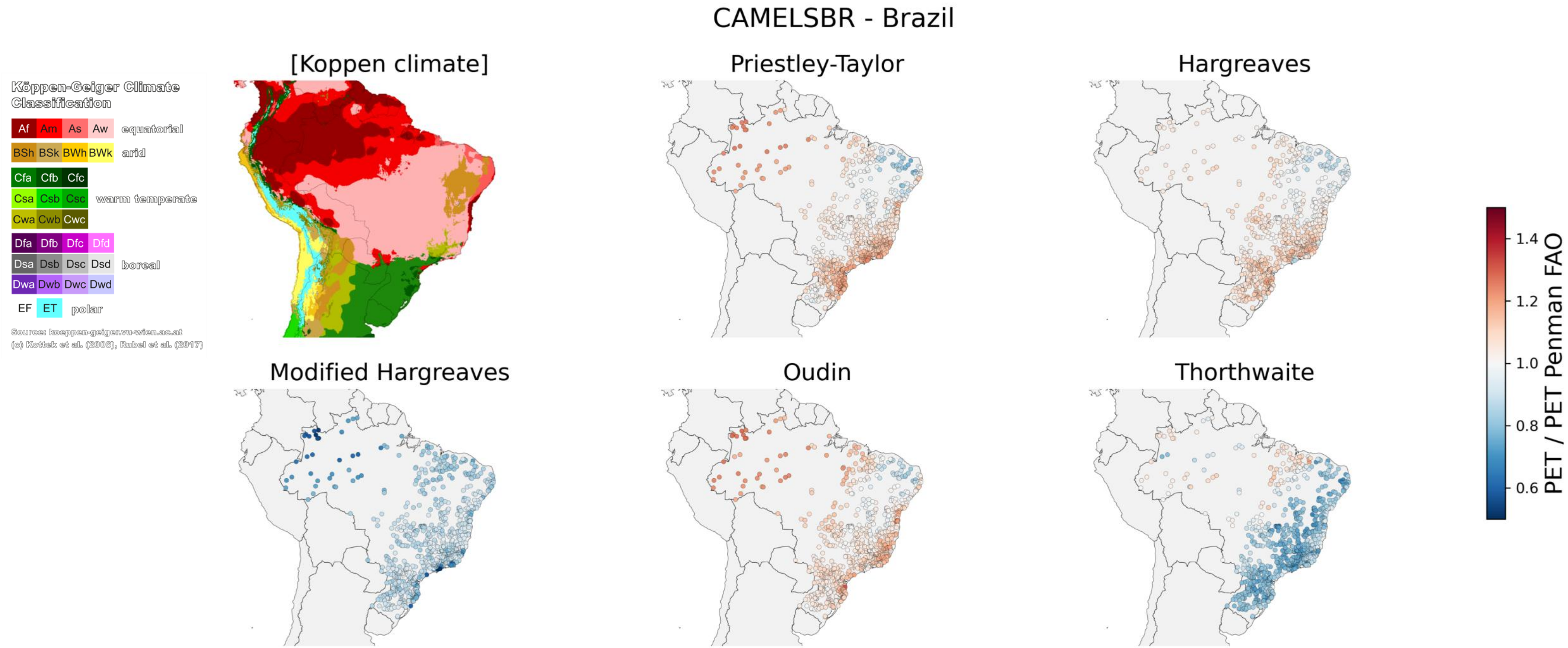
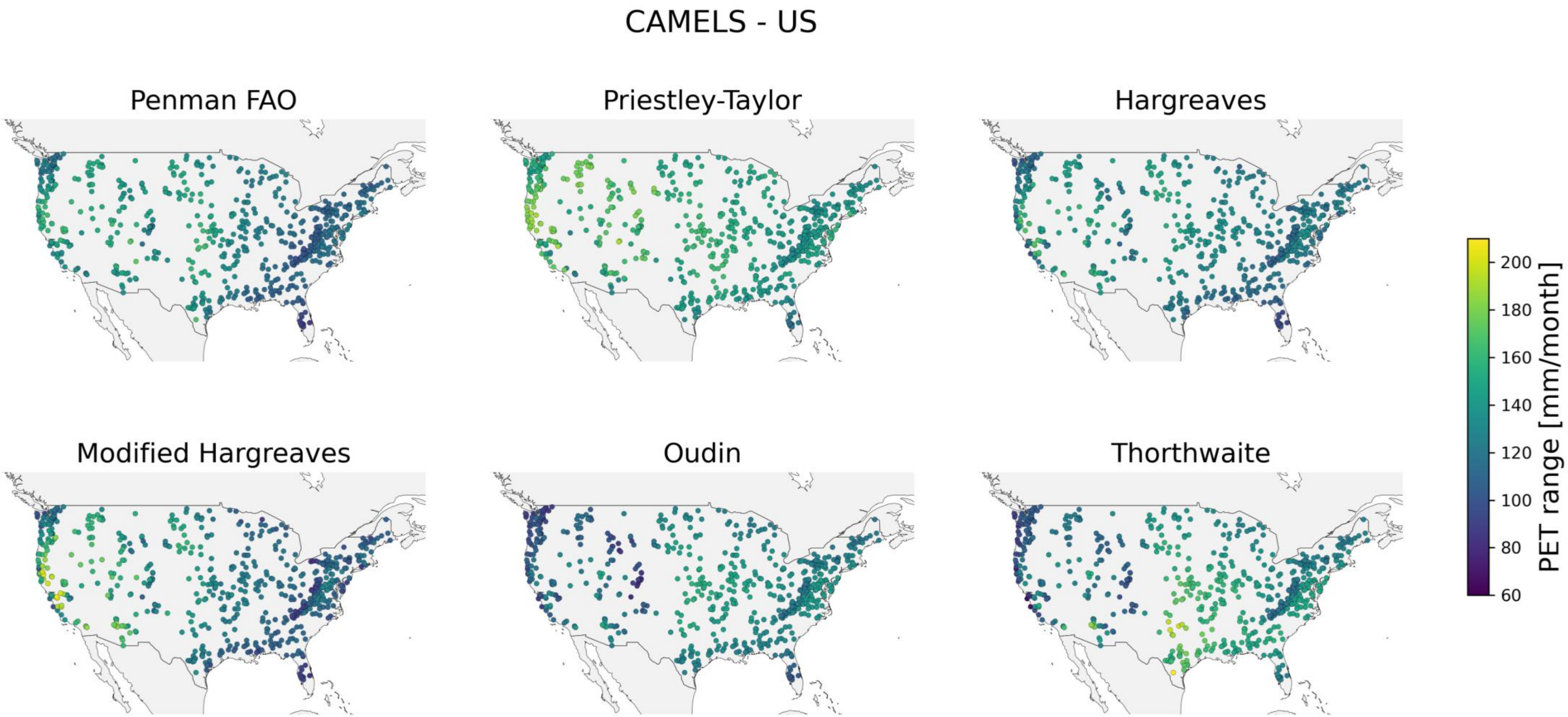


PET long term variability throughout the year

$$\max\left(PET_{monthly\ long\ term\ average} \right) - \min\left(PET_{monthly\ long\ term\ average} \right) \left[\frac{mm}{month}\right]$$



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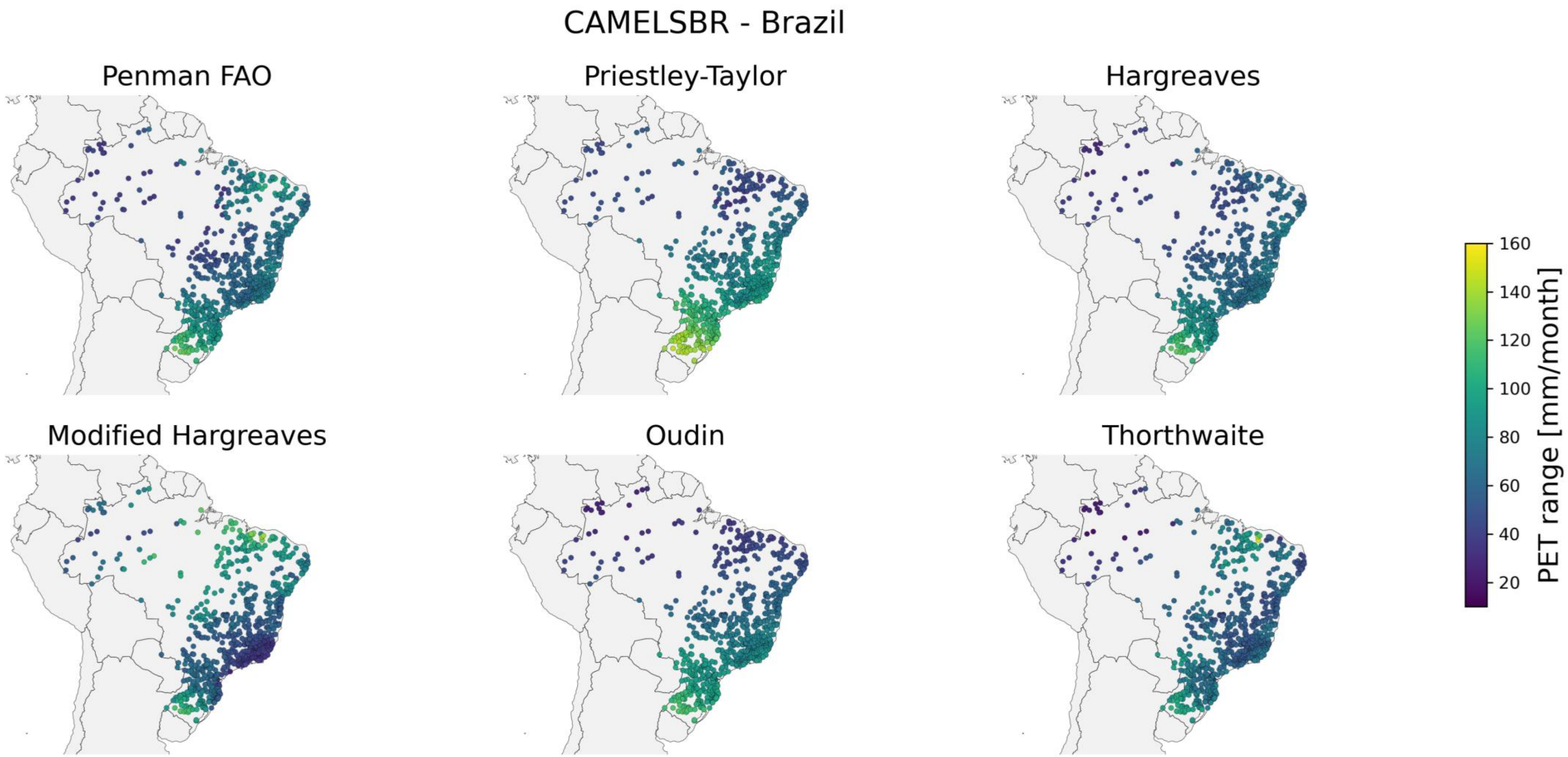
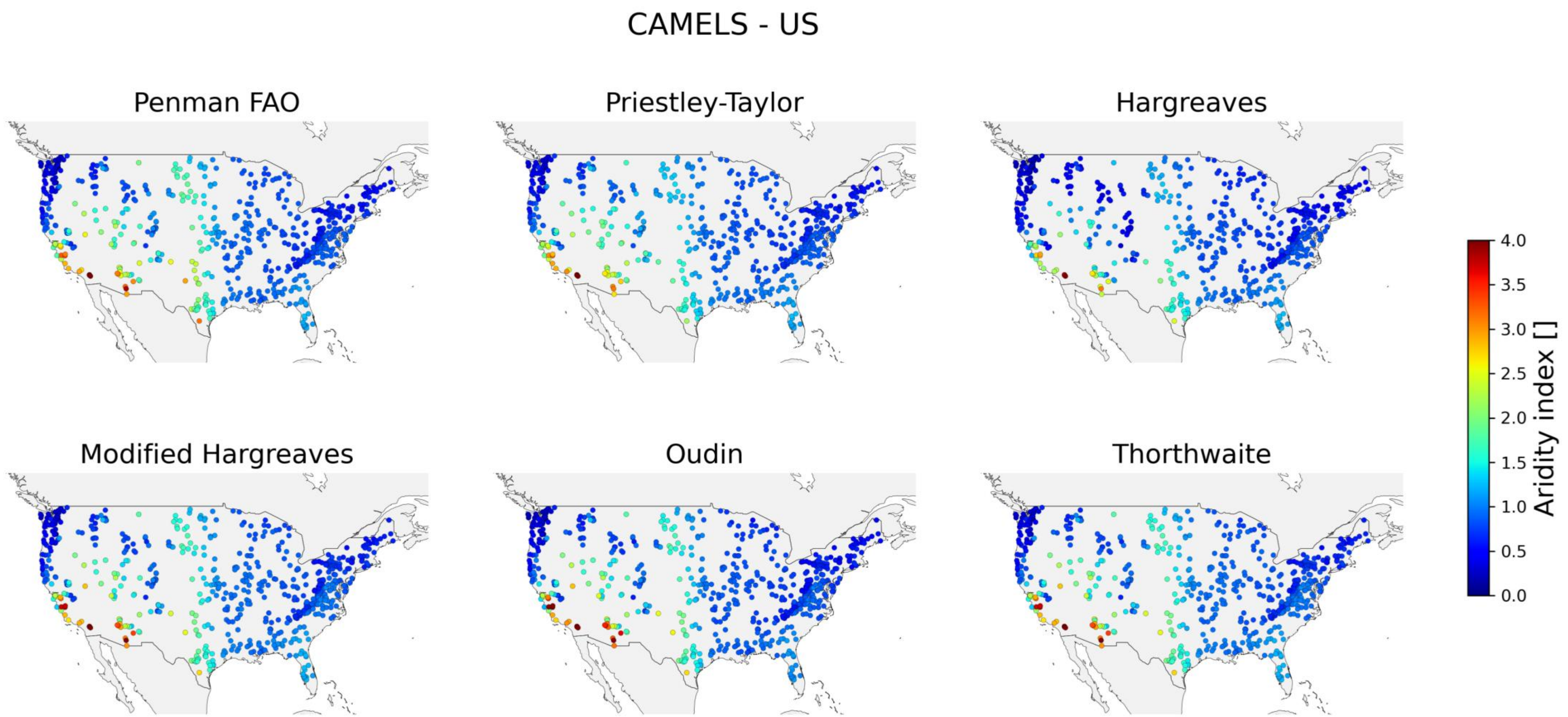


Aridity index $\frac{PET}{P}$



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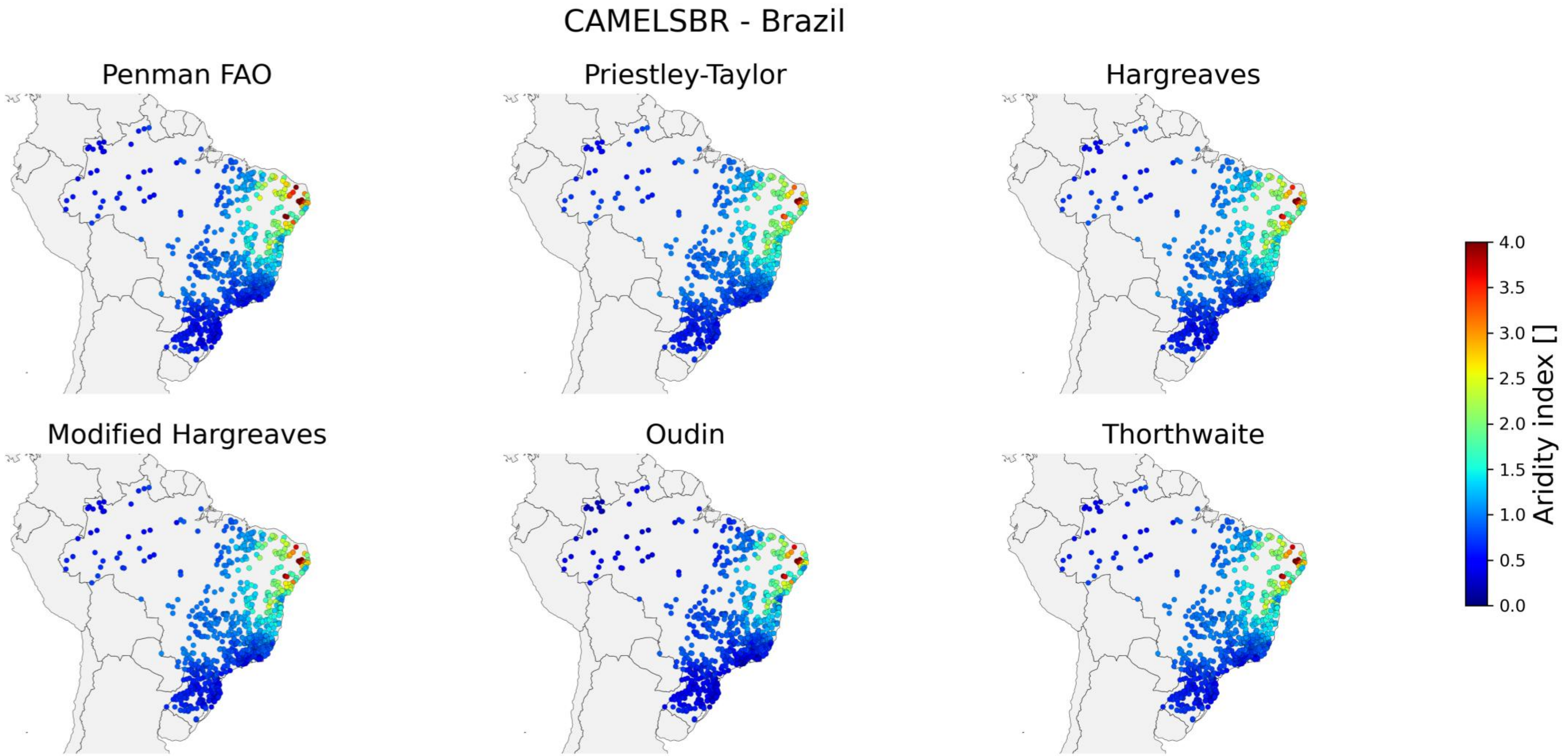


Hydrological consistency of PET

The Budyko space conceptually represents the coupled long-term water and energy balance (Budyko, 1974)

Catchment are scattered in a diagram using two dimensionless ratios:

- PET/Precipitation
- (Precipitation-Streamflow)/Precipitation

The assumption is no changes in water storages, therefore requiring multiyear averages

In the Budyko diagram we show also the distribution of aridity index (PET/Precipitation) and how it changes for different formulas

Hydrological consistency of PET

Data for Budyko:

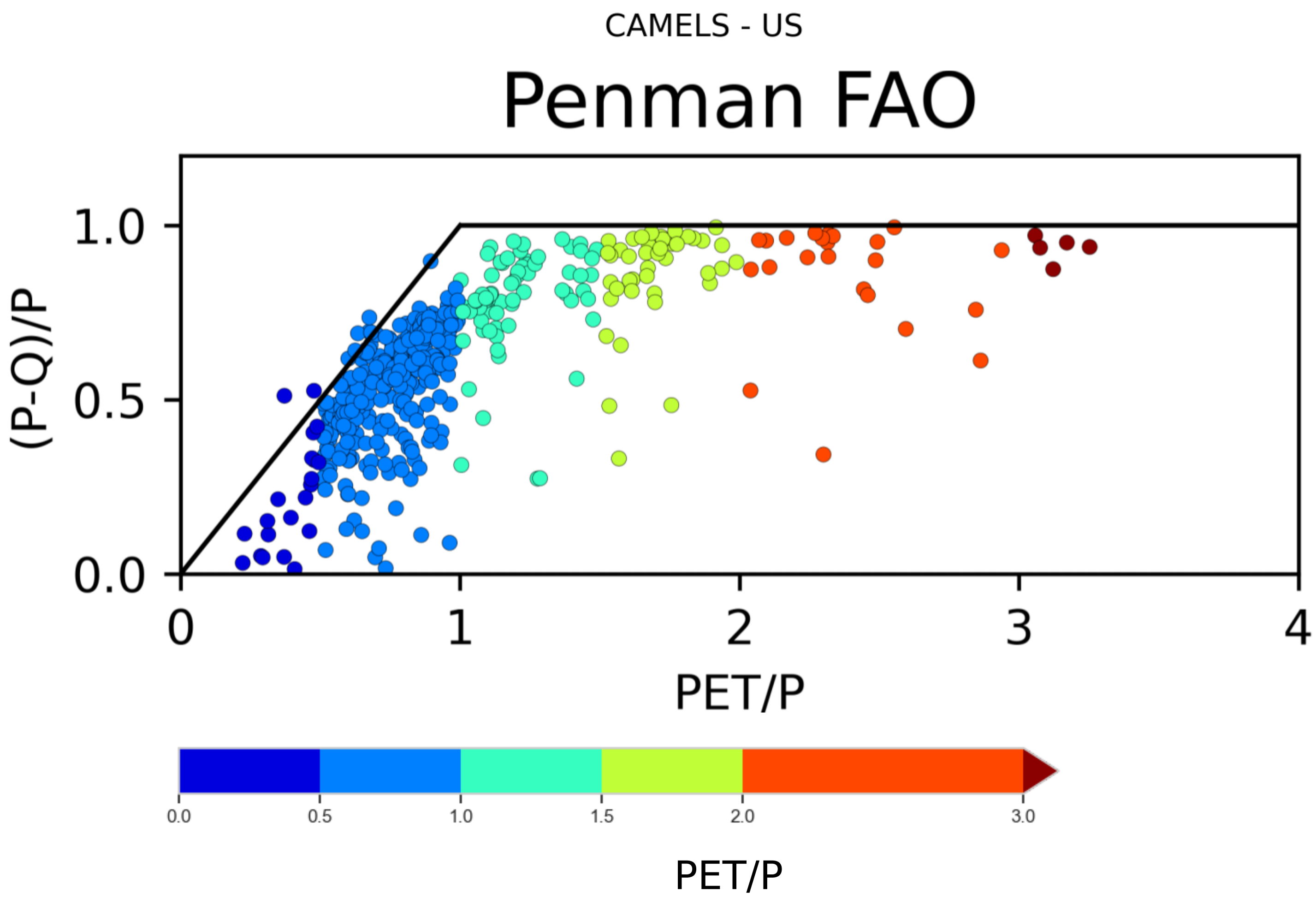
Caravan provides daily observations of streamflow

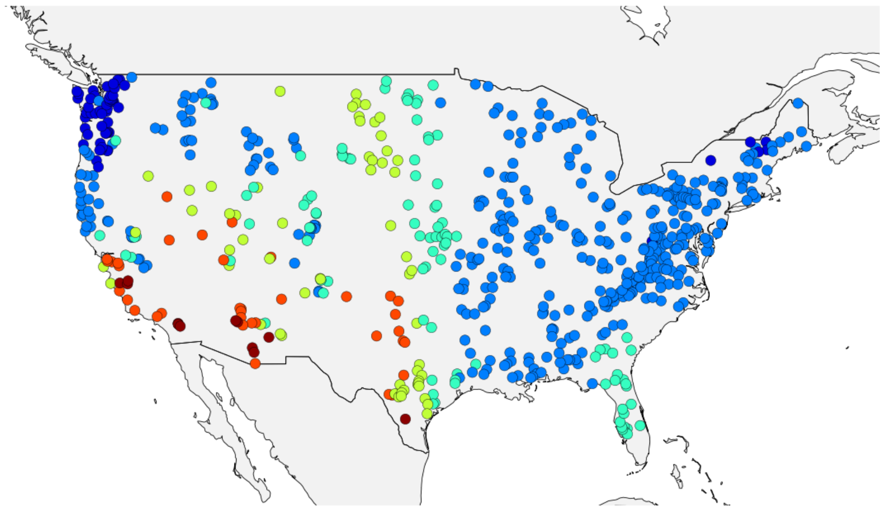
For some catchments the timeseries is not continuous

We filtered again the basins in Caravan, keeping only the ones with at least 30 full years of daily streamflow data available (~3500 basins)

Budyko space

Colors of catchments in the plot are defined by the aridity index from Penman FAO





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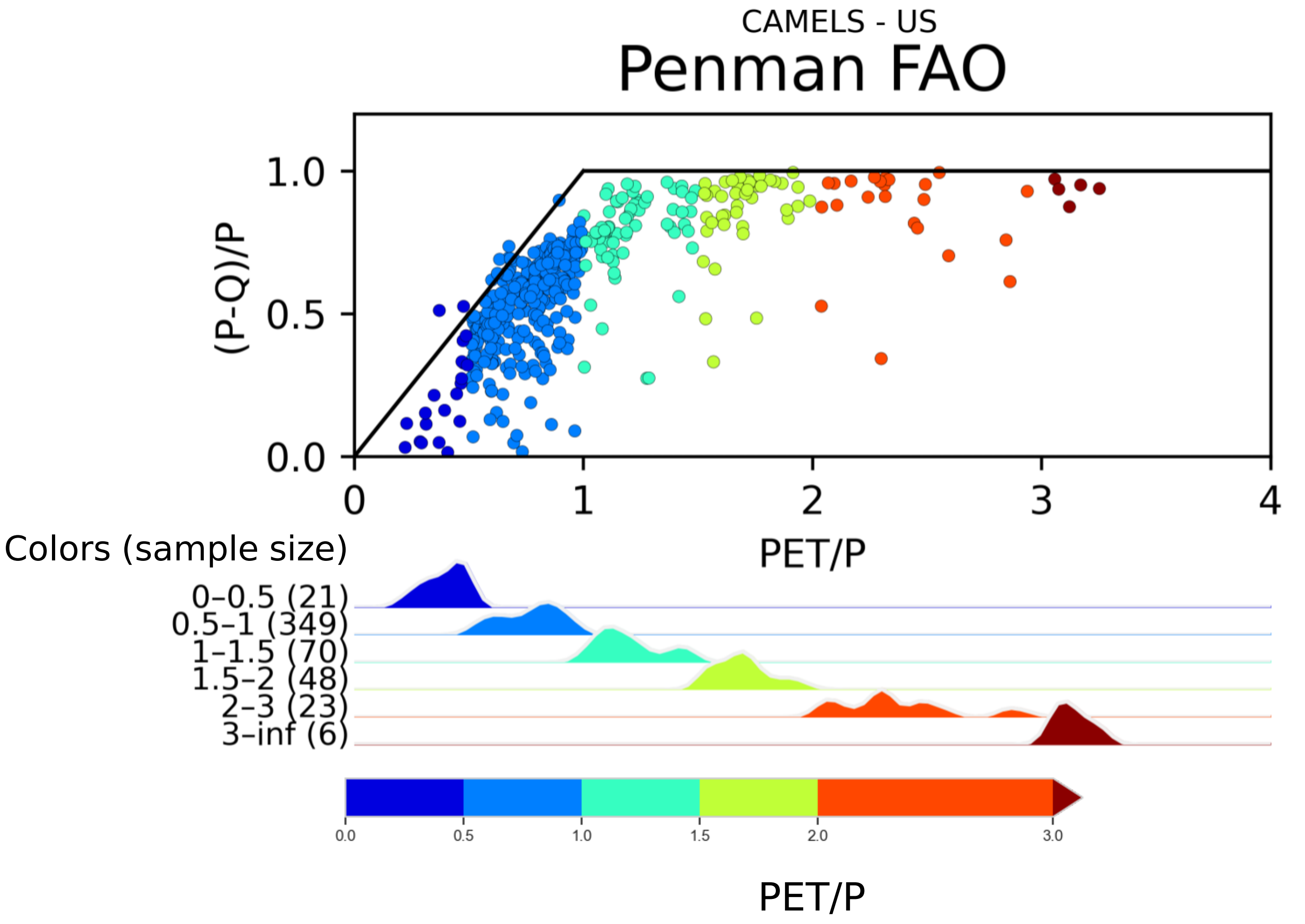

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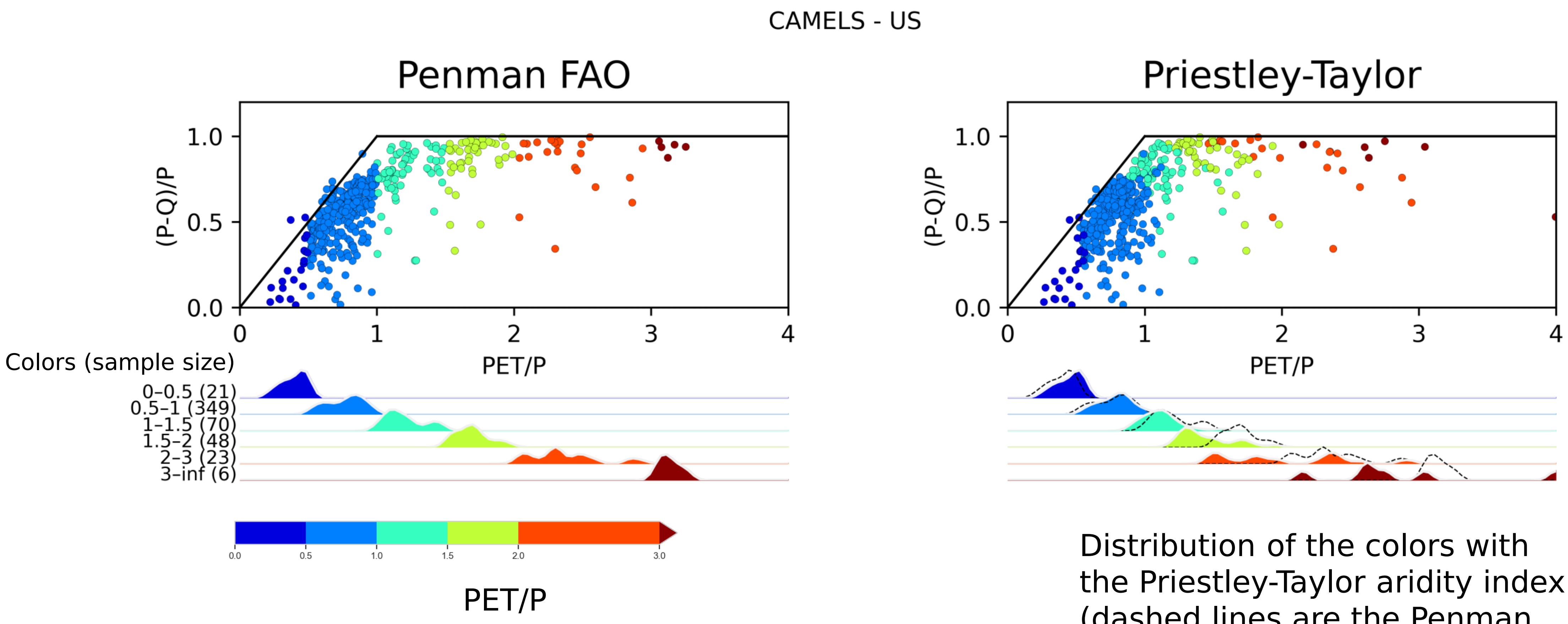
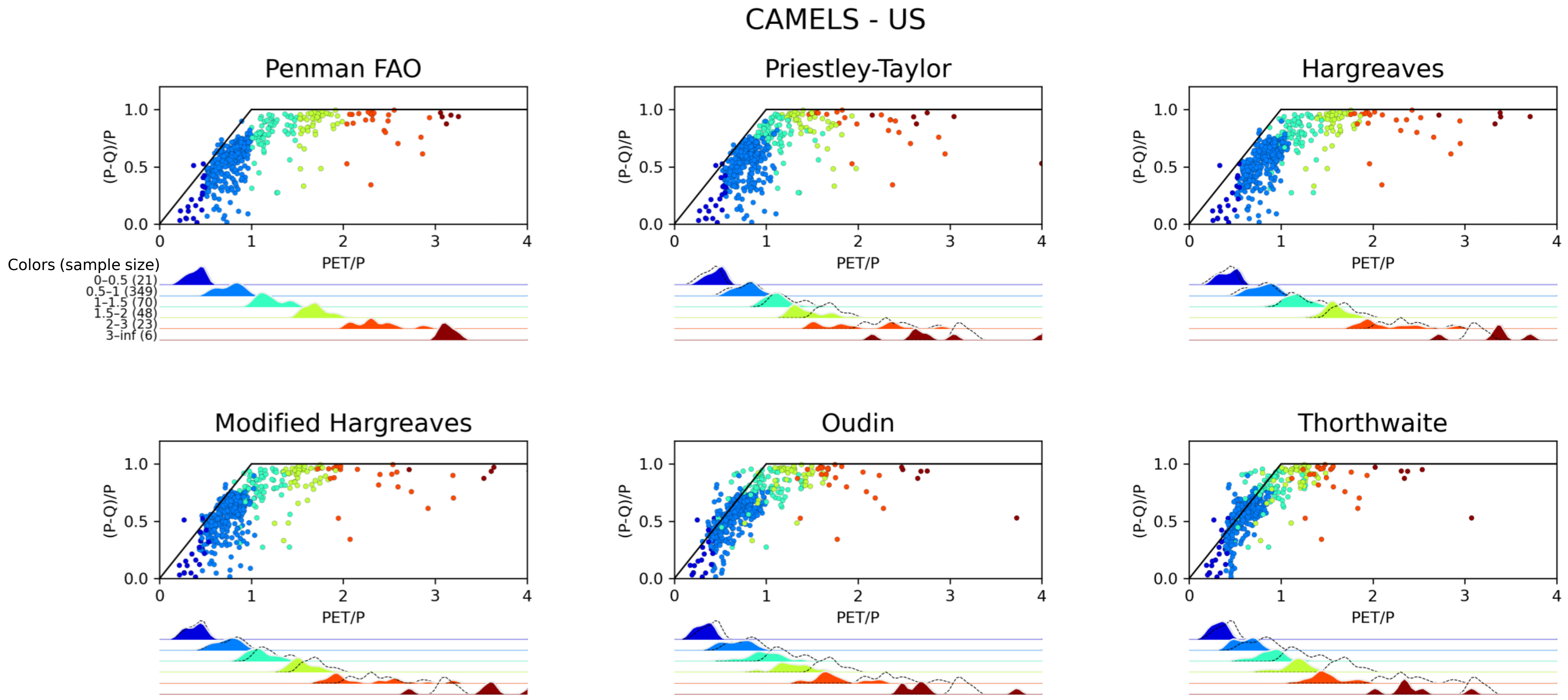


Distribution of the colors with the Priestley-Taylor aridity index (dashed lines are the Penman FAO distribution)

Budyko space

Colors of catchments in the plot are defined by the aridity index from Penman FAO

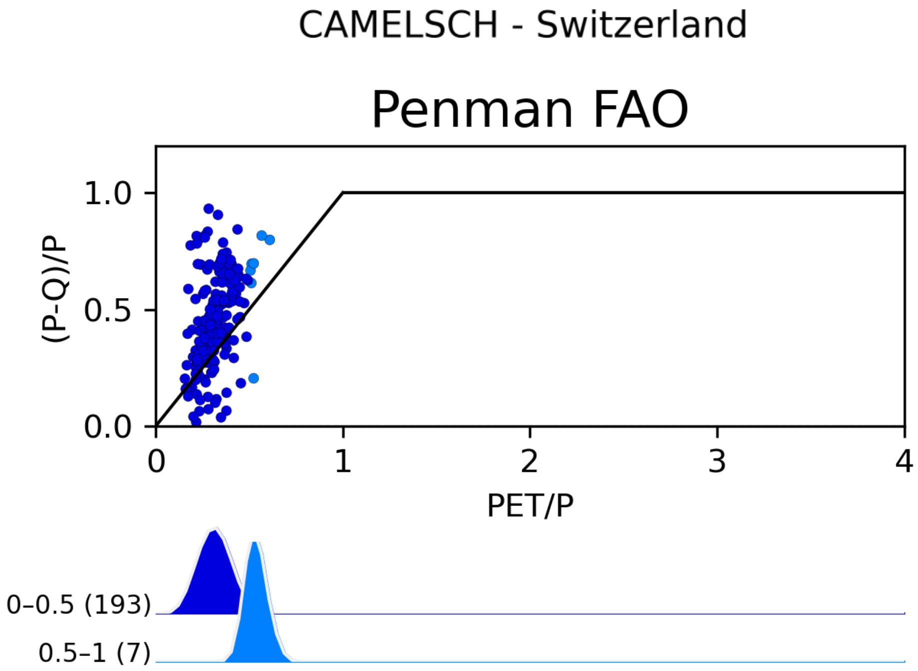


Limits of ERA5-Land data?

The ERA5-Land precipitation provided in Caravan differ from observation-based products, resulting in significantly lower efficiency in hydrological modelling (Clerc-Schwarzenbach et al., 2024)

Difference in precipitation can affect the positioning of catchments in the Budyko space

Budyko plots of European catchments (UK, Germany and Switzerland) show potential effects of this precipitation bias



Conclusions

PET estimates have significant variations changing formulas: such variation is not uniform among the same regions and across different countries.

Considering as benchmark the Penman-Monteith FAO, different formula are the best performing in different regions.

Aridity index estimation - and consequently the Budyko plot position - is strongly affected by the formula choice, especially for water-limited catchments.

Caravan precipitation (ERA5-Land data) are known to have issues (Clerc-Schwarzenbach et al., 2024) and this affects the Budyko analysis.

Supplementary

PET annual average distribution

PET annual average

PET relative annual average

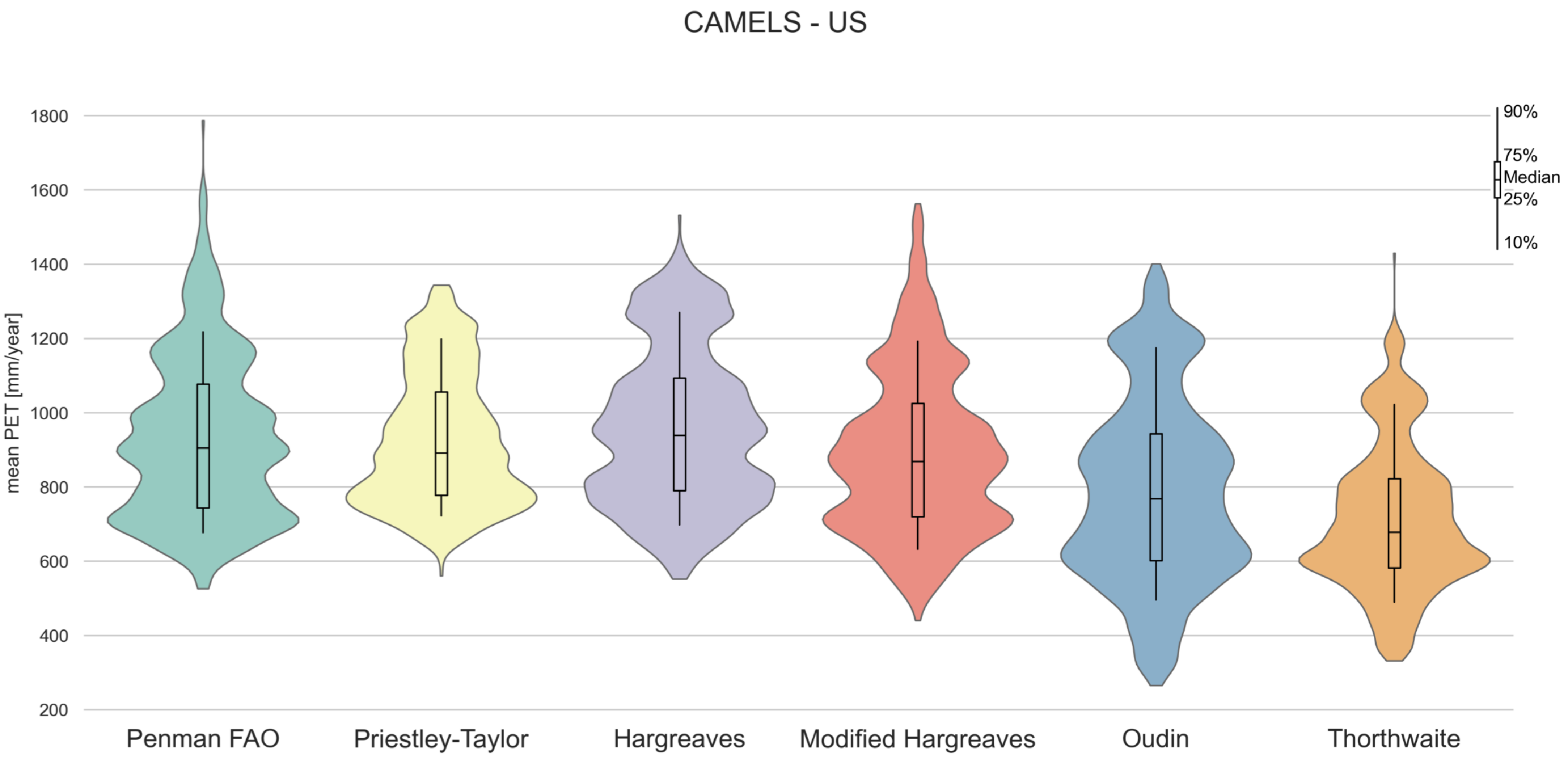
PET long term variability throughout the year

Aridity index

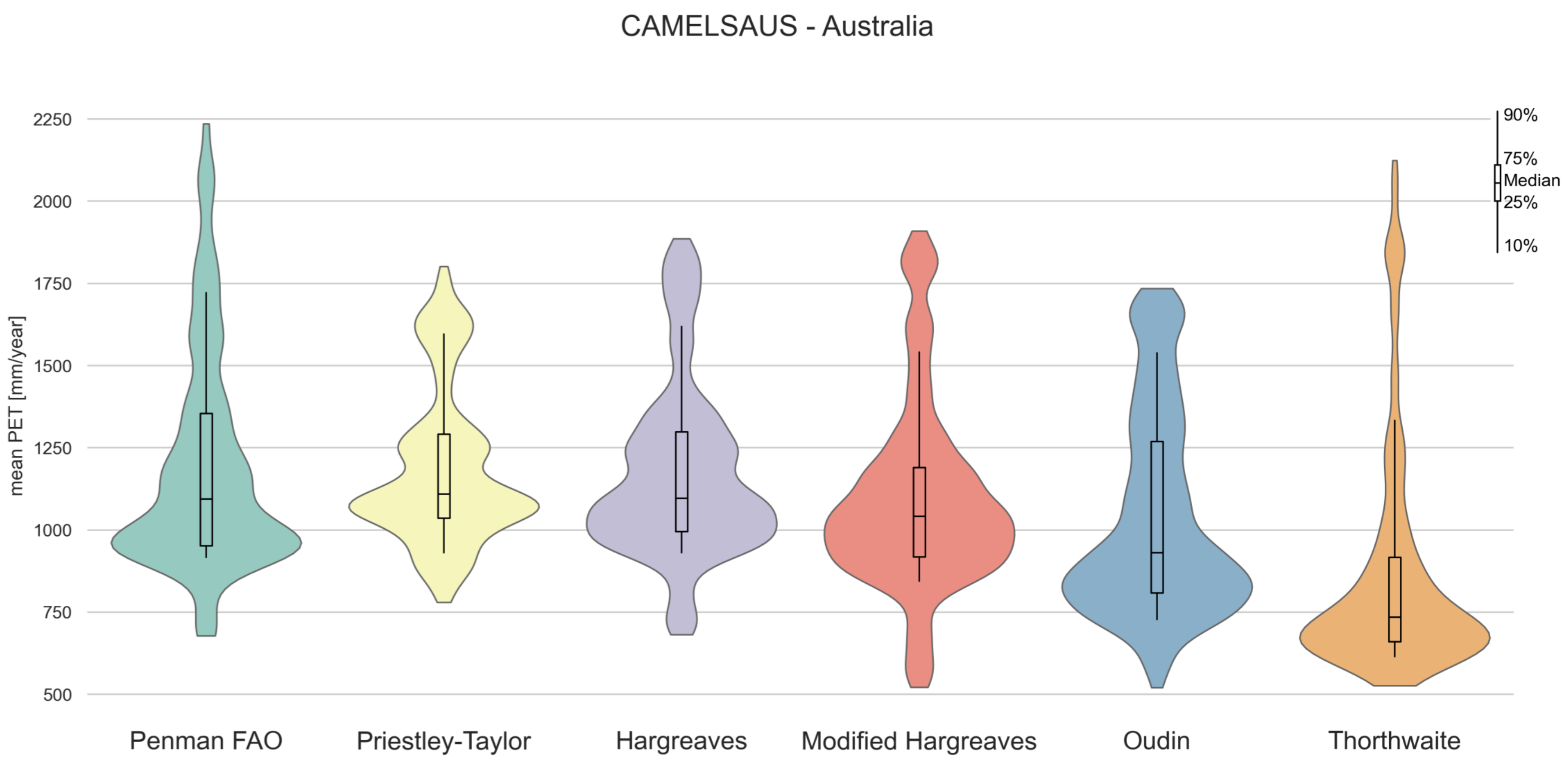
Budyko space

PET formulas

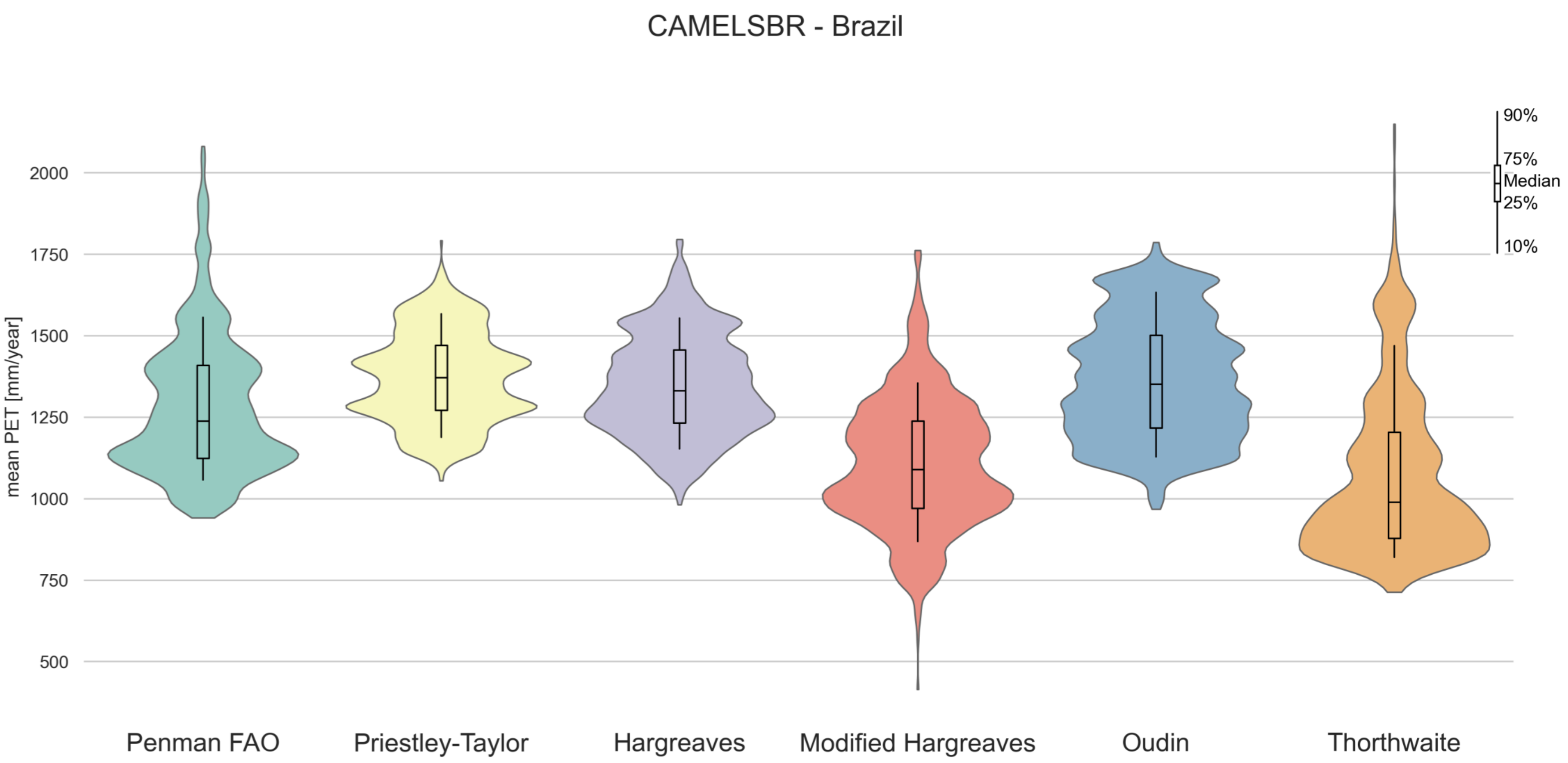
PET annual average distribution



PET annual average distribution



PET annual average distribution



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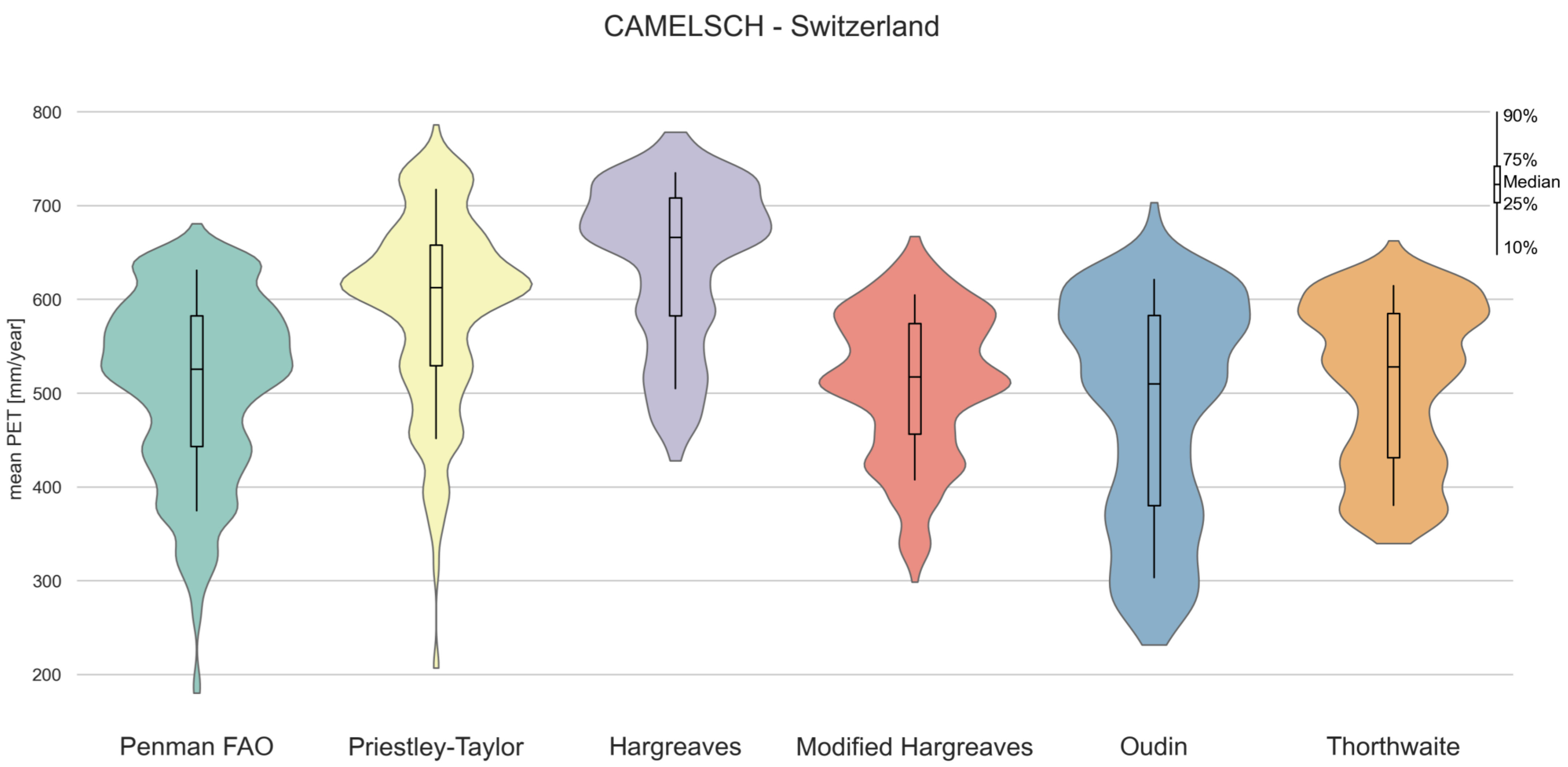

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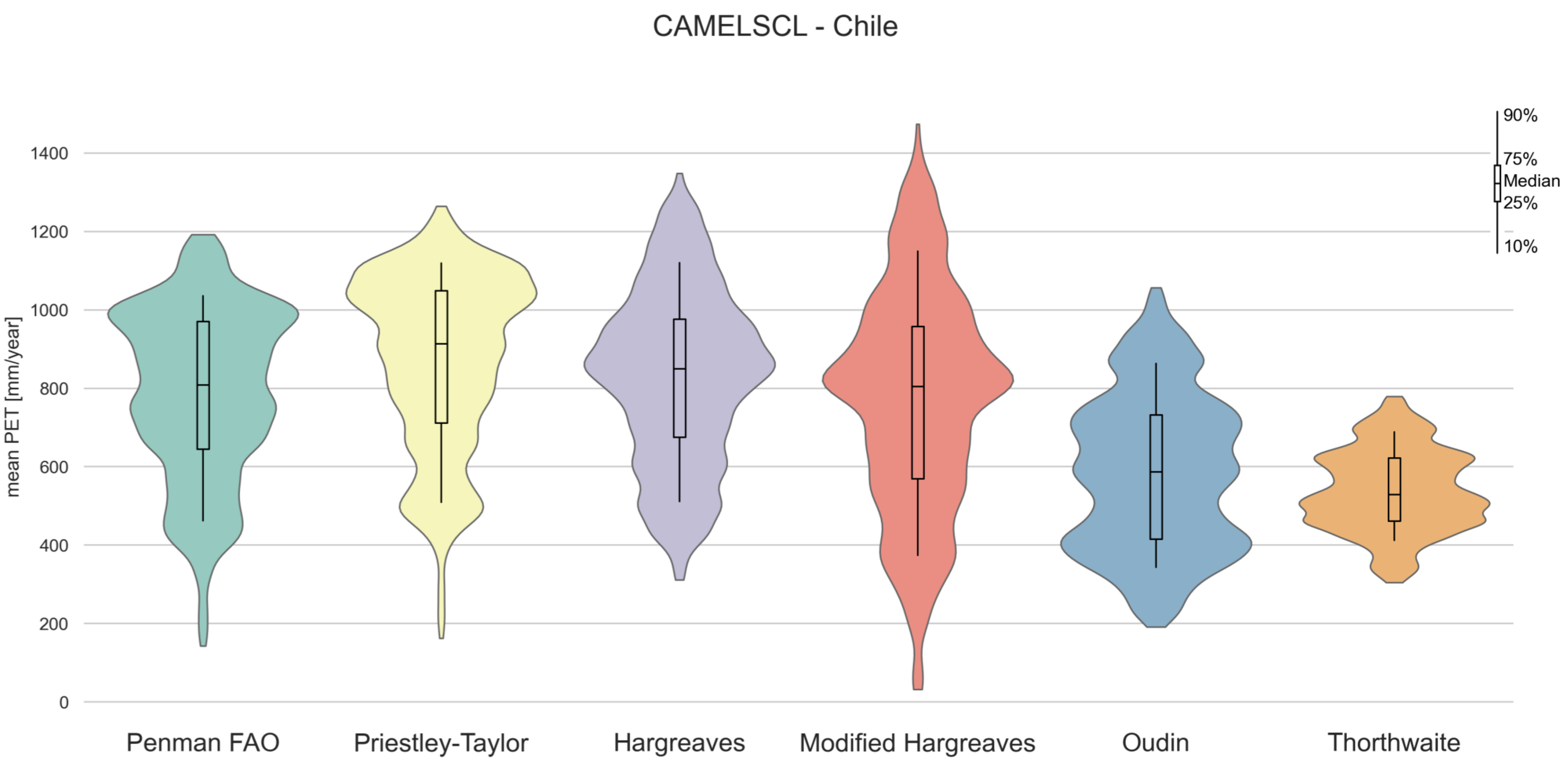

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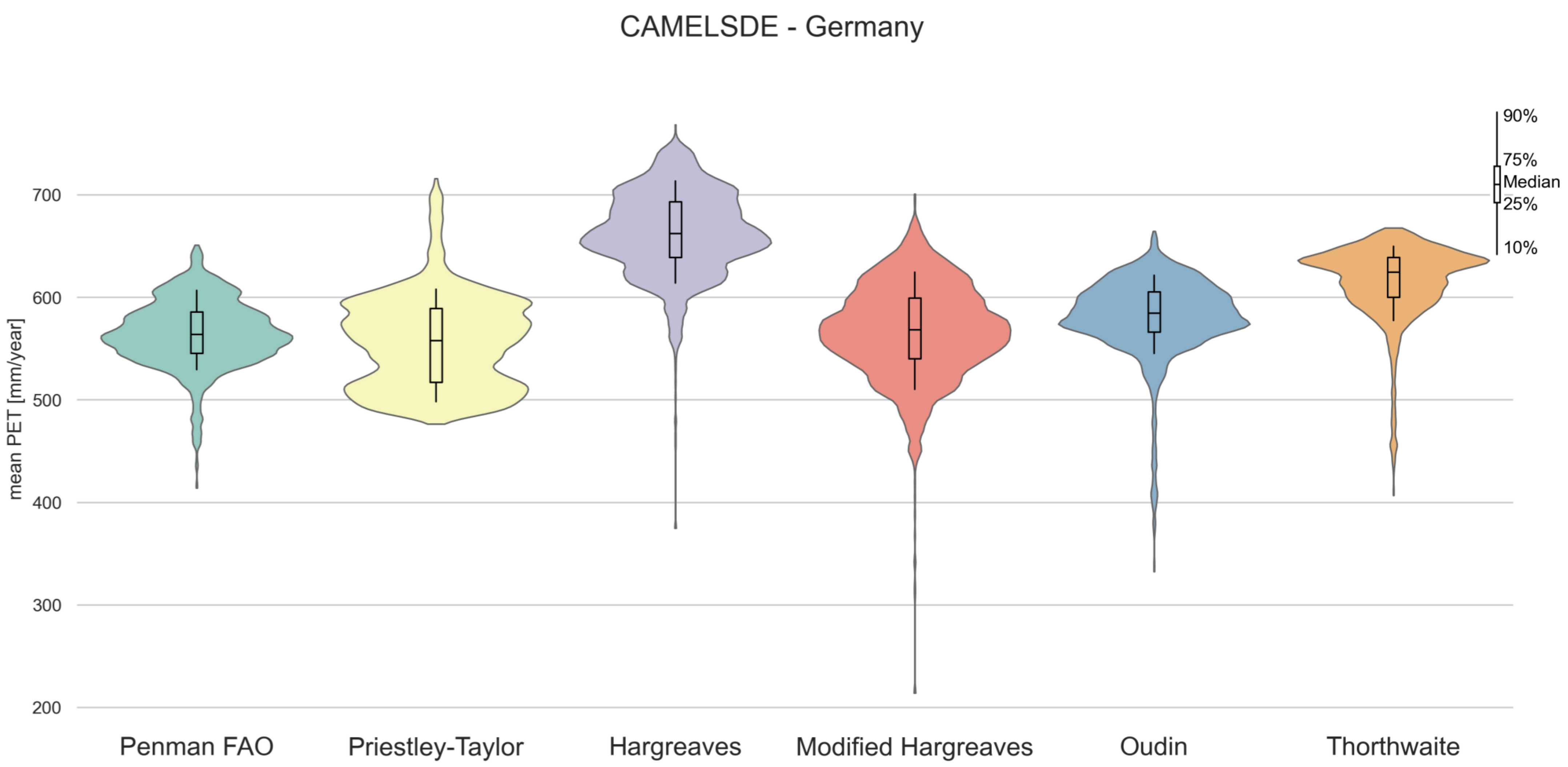

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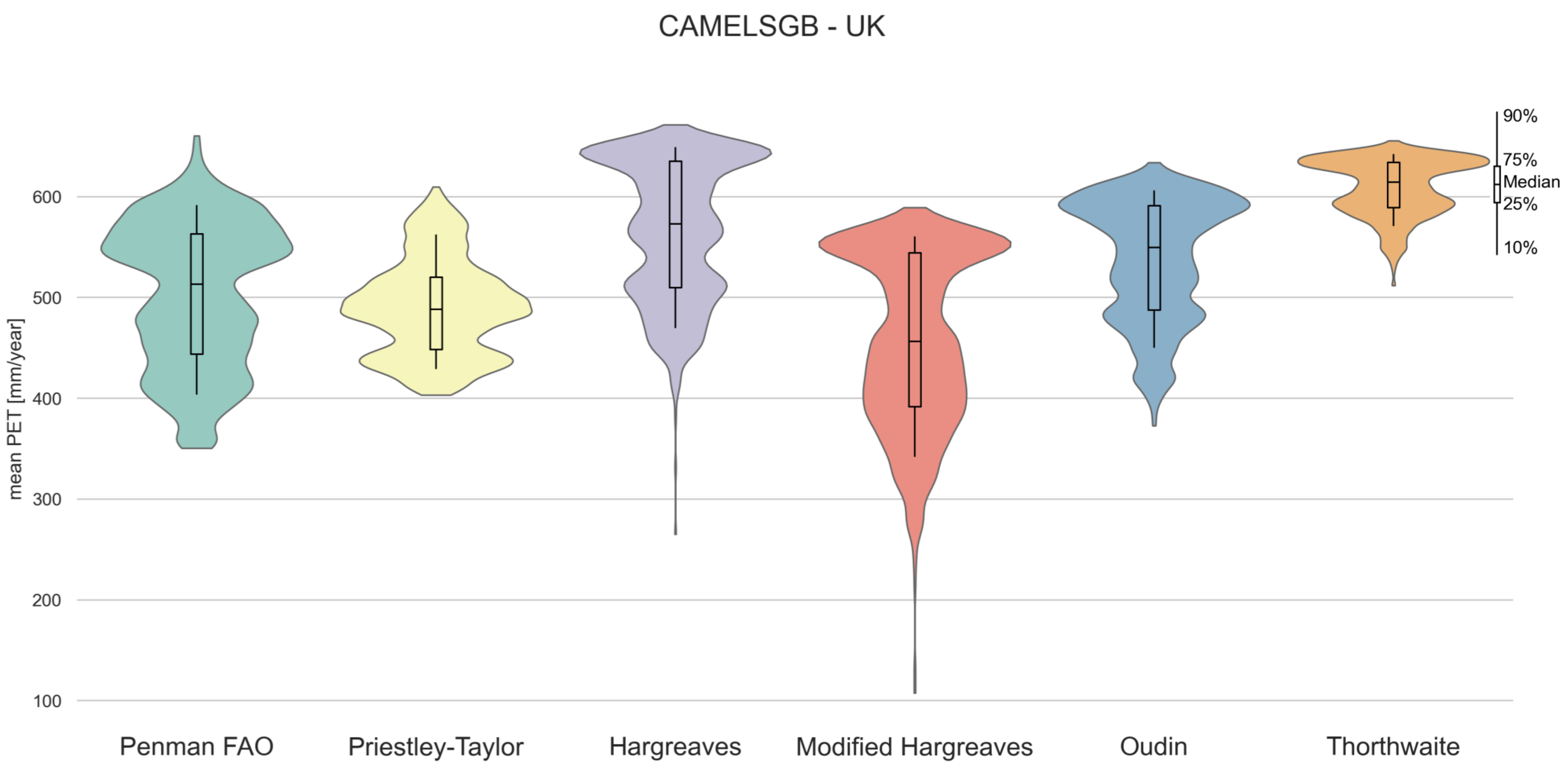
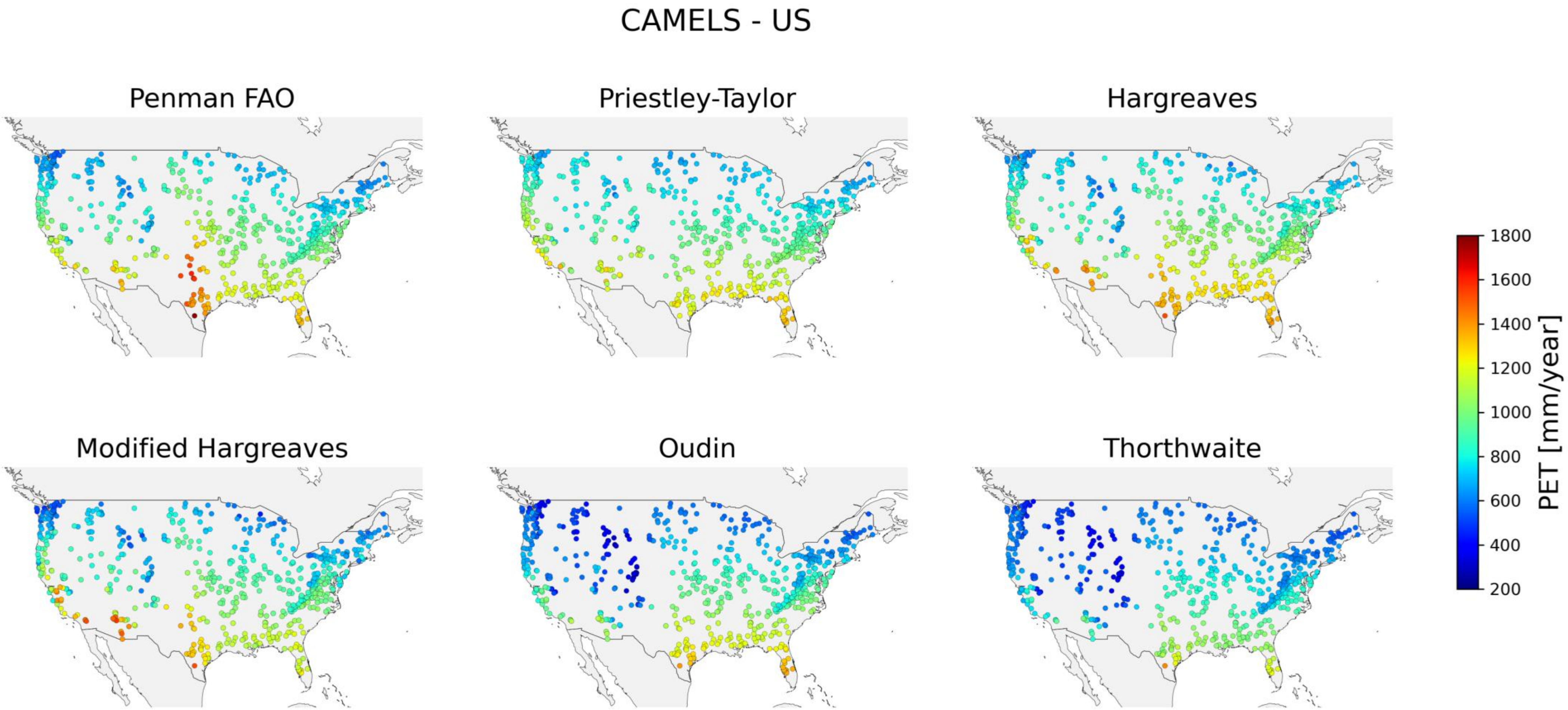


PET annual average



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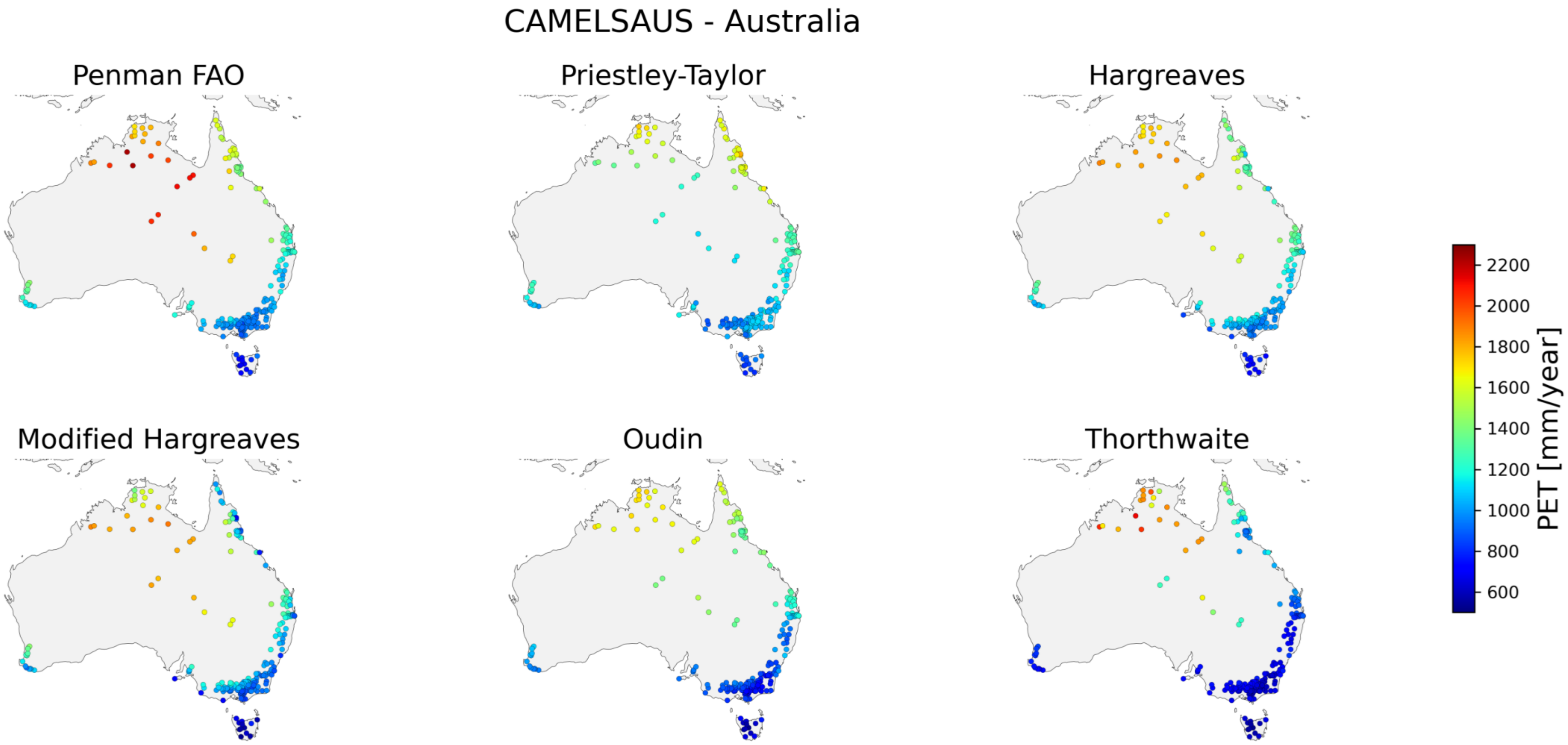

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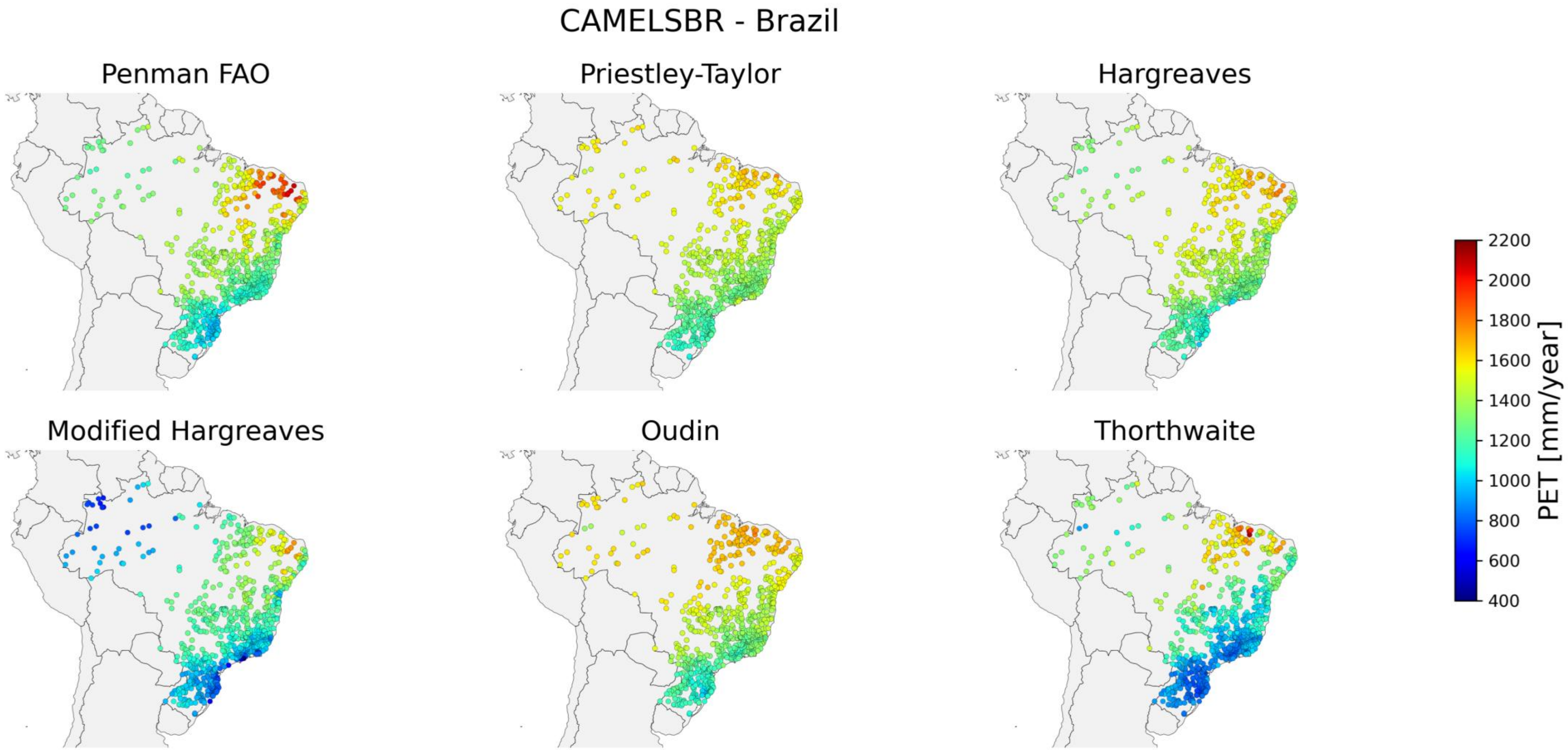

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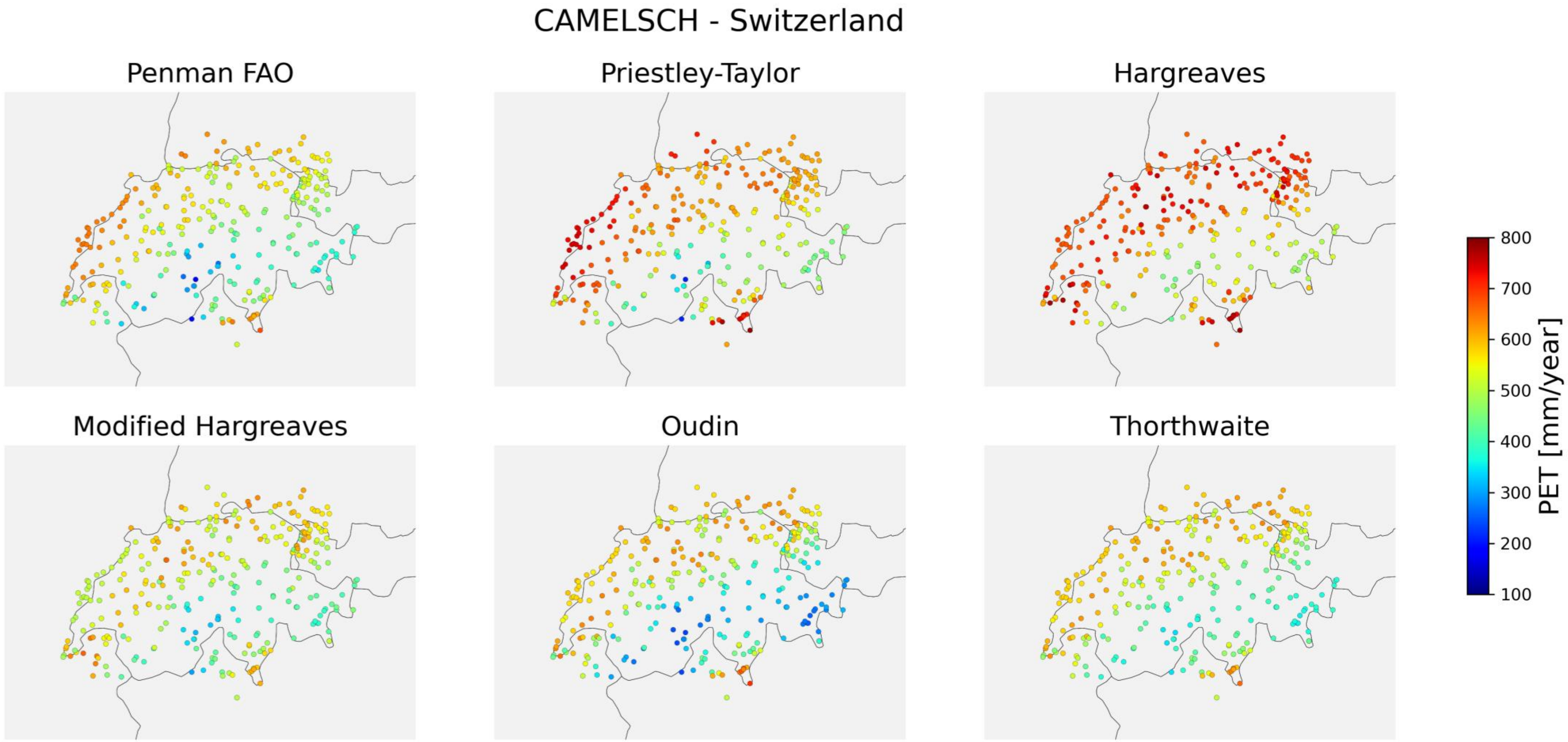

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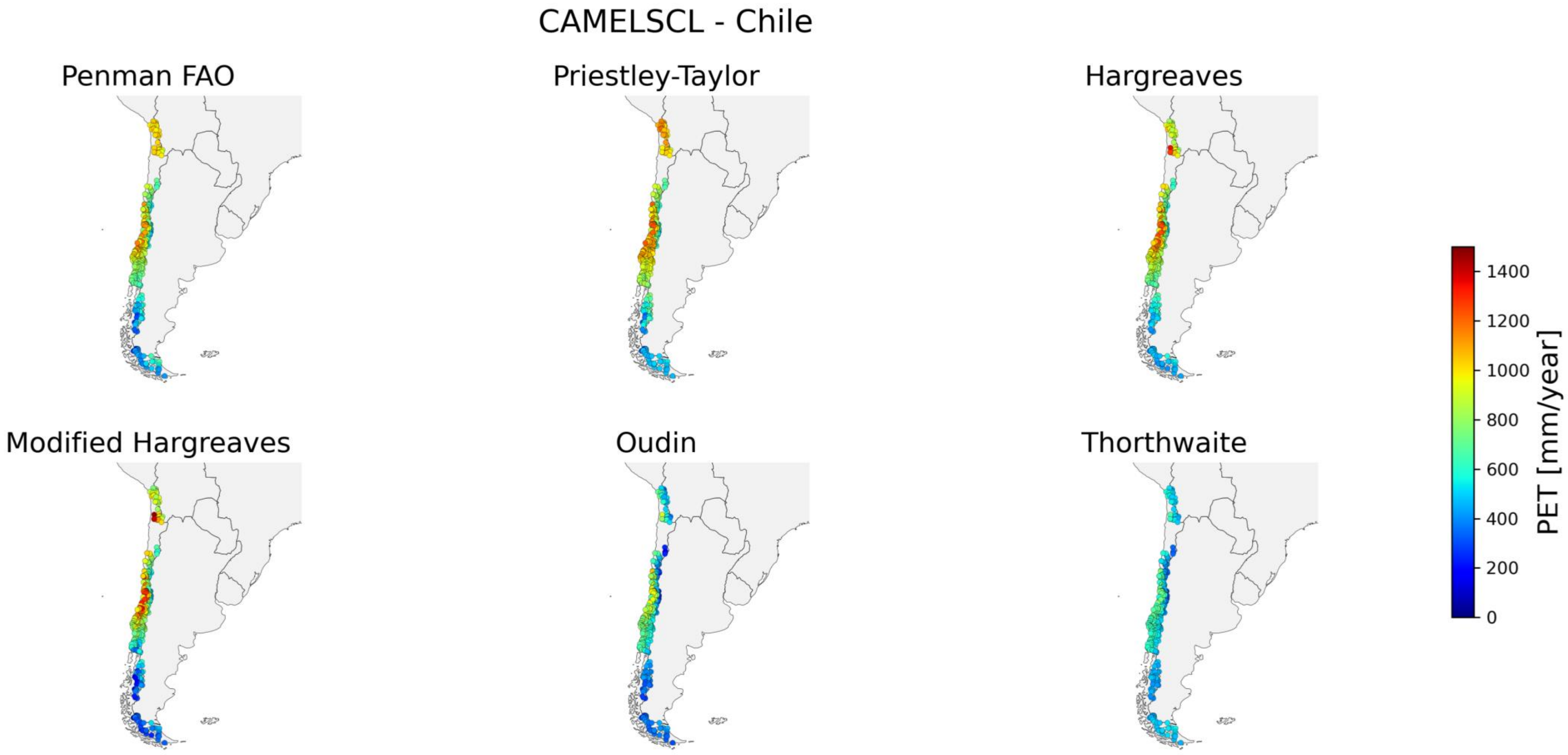

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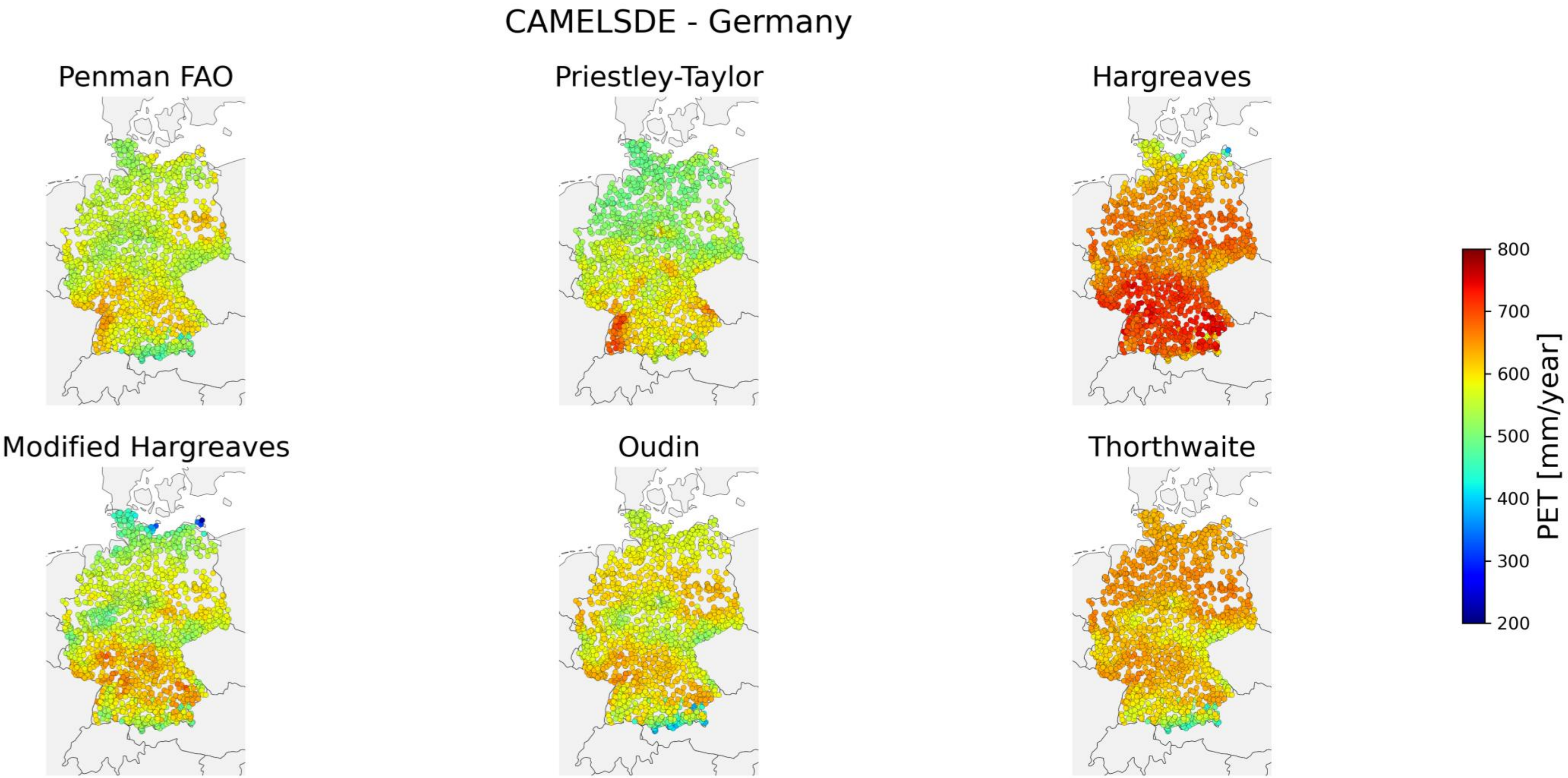

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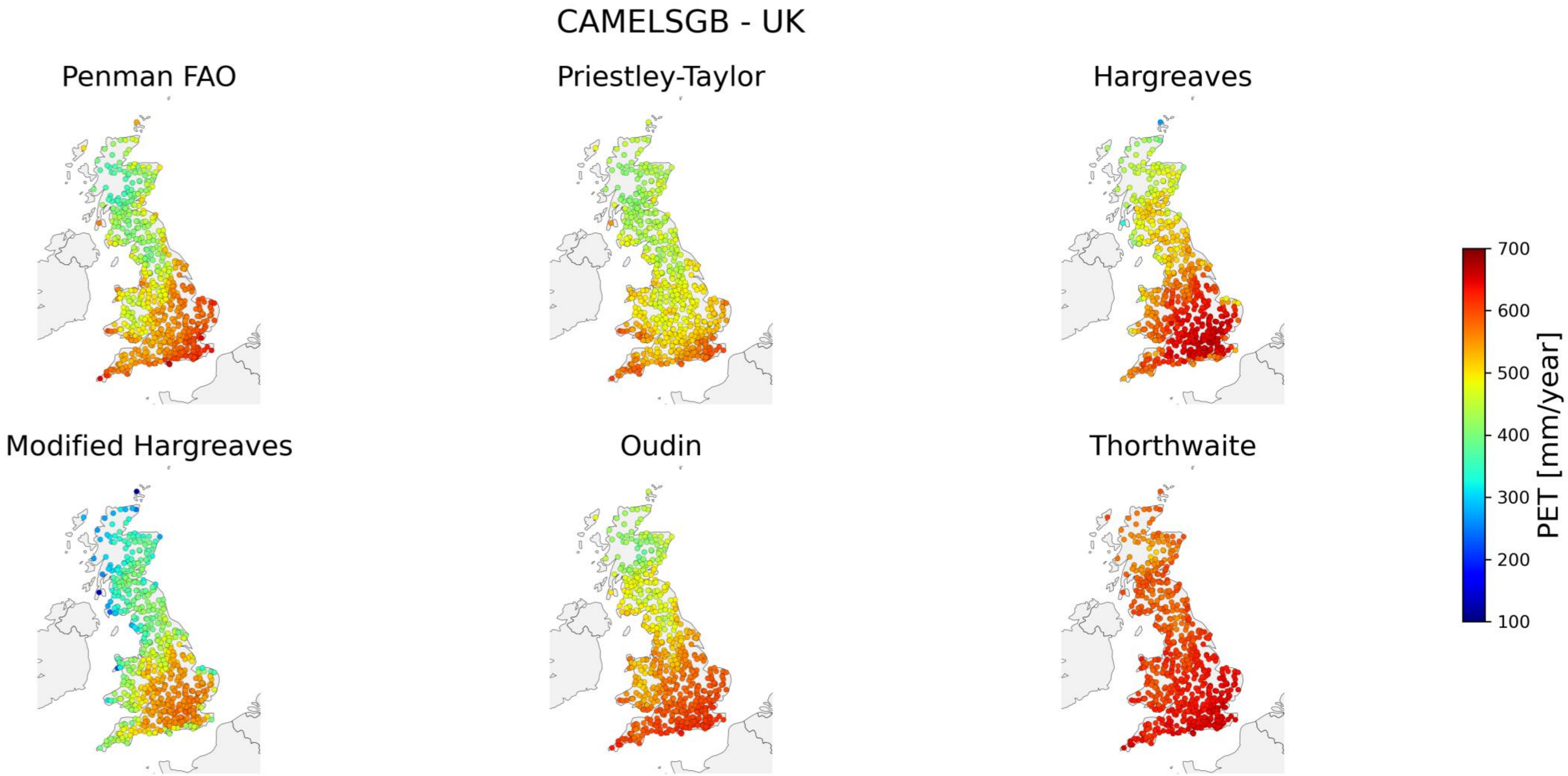
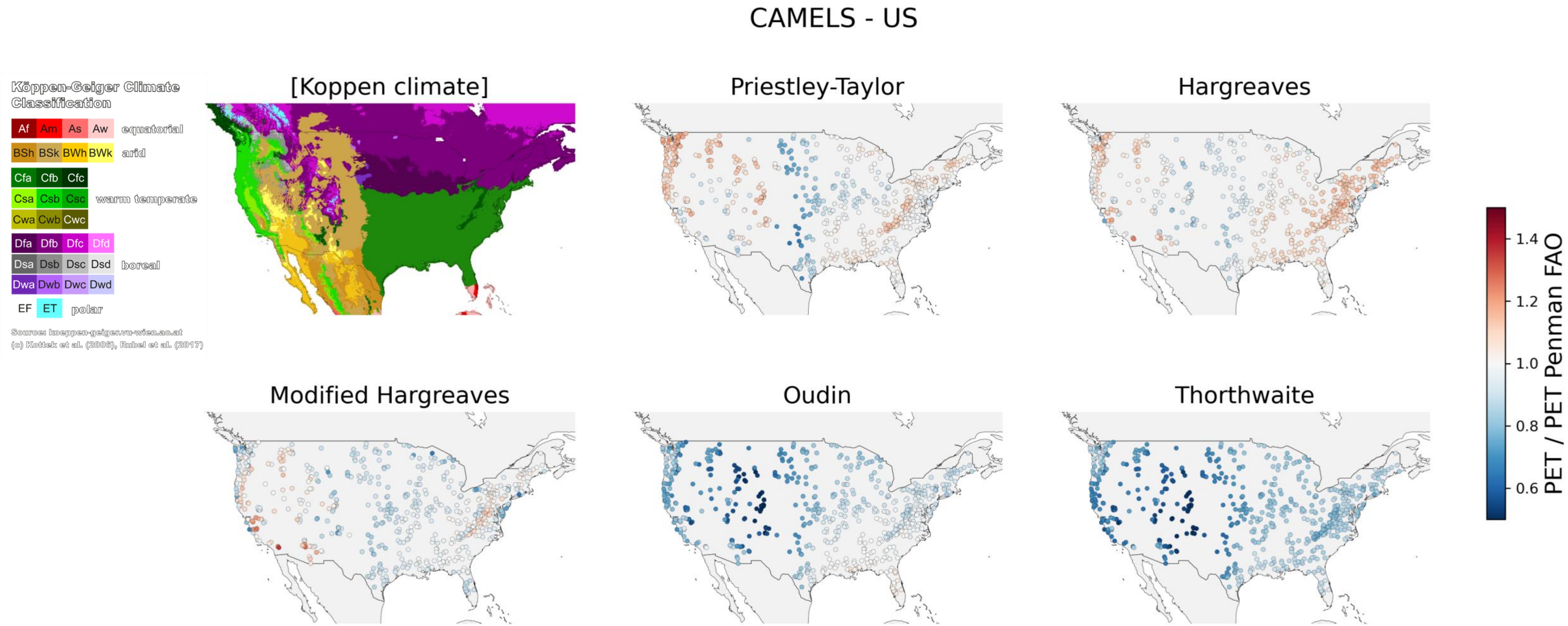


PET relative annual average



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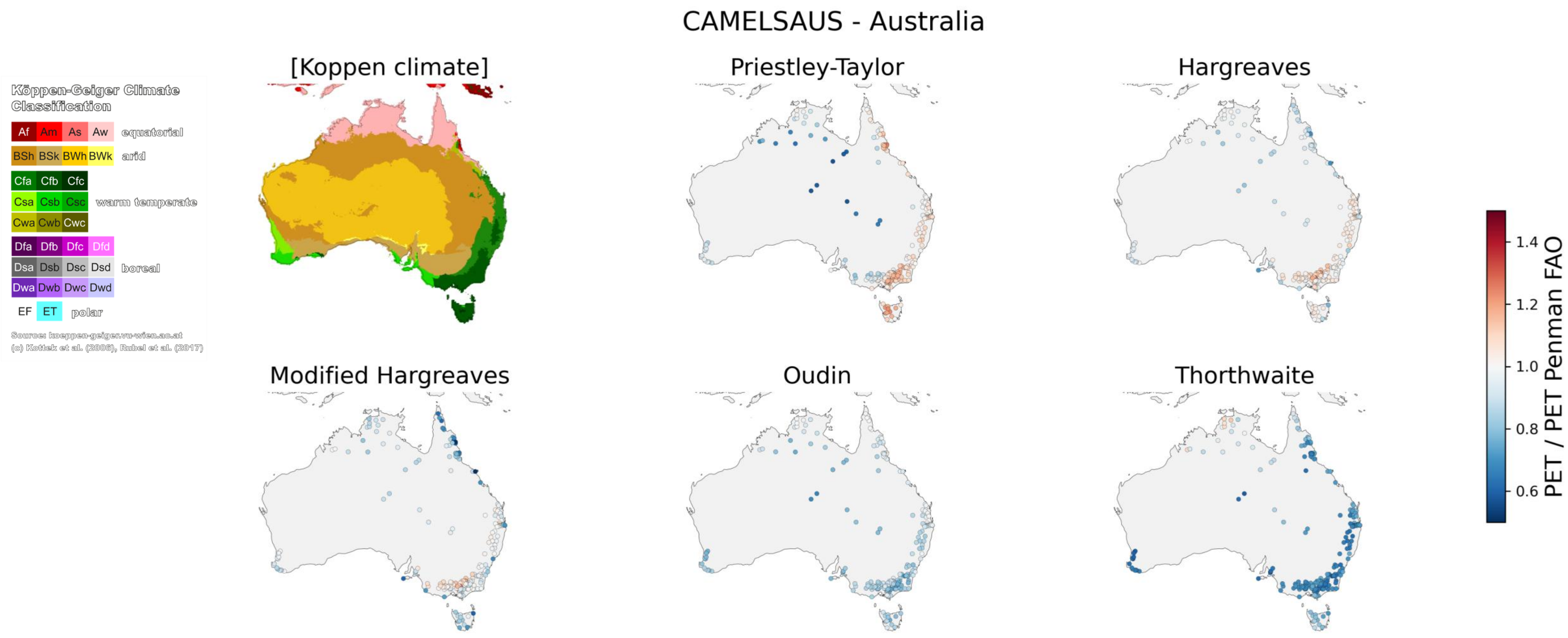

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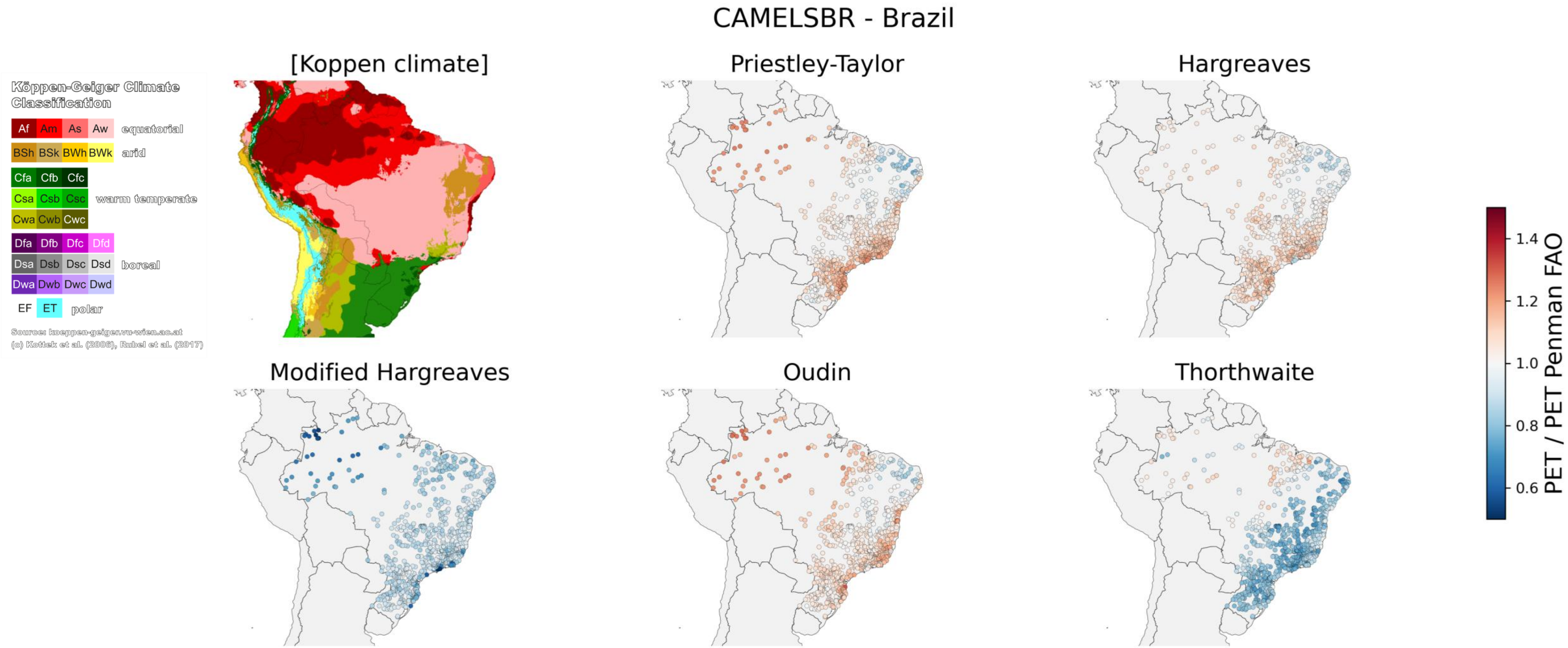

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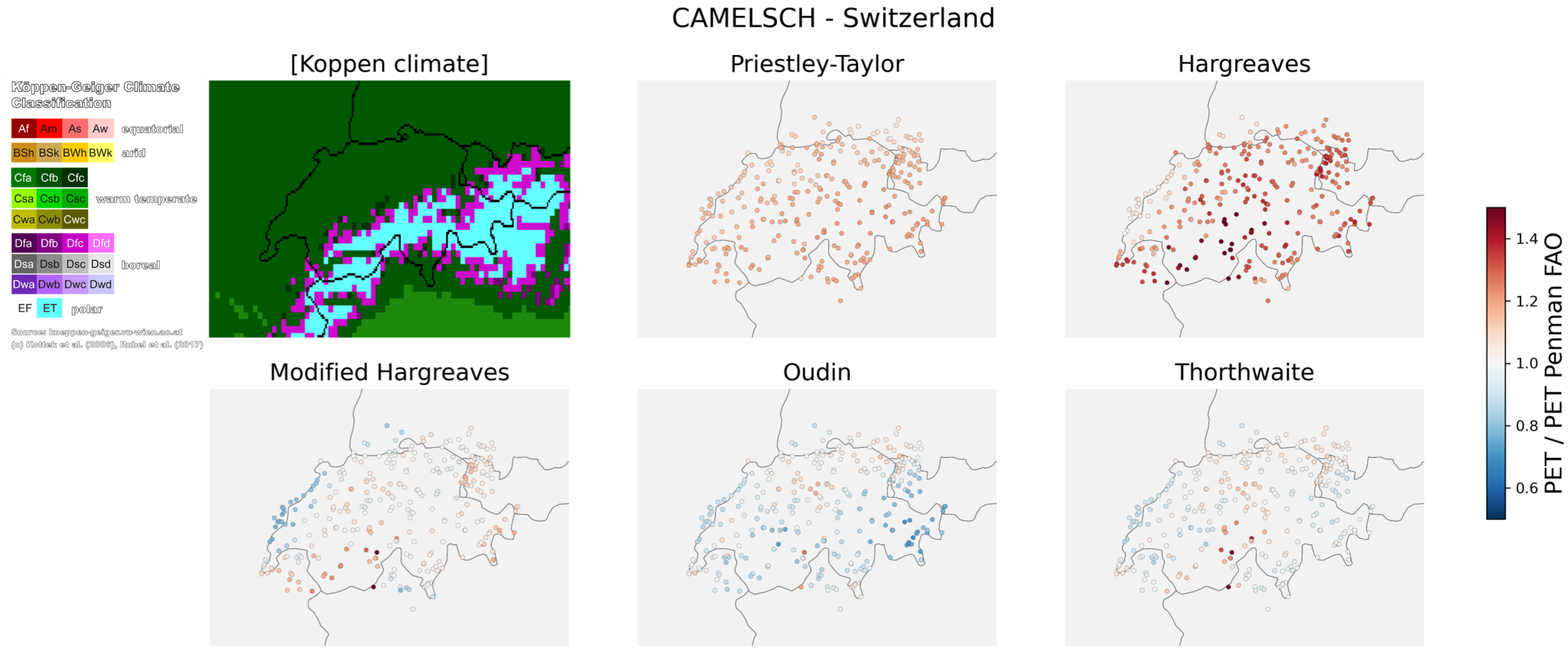

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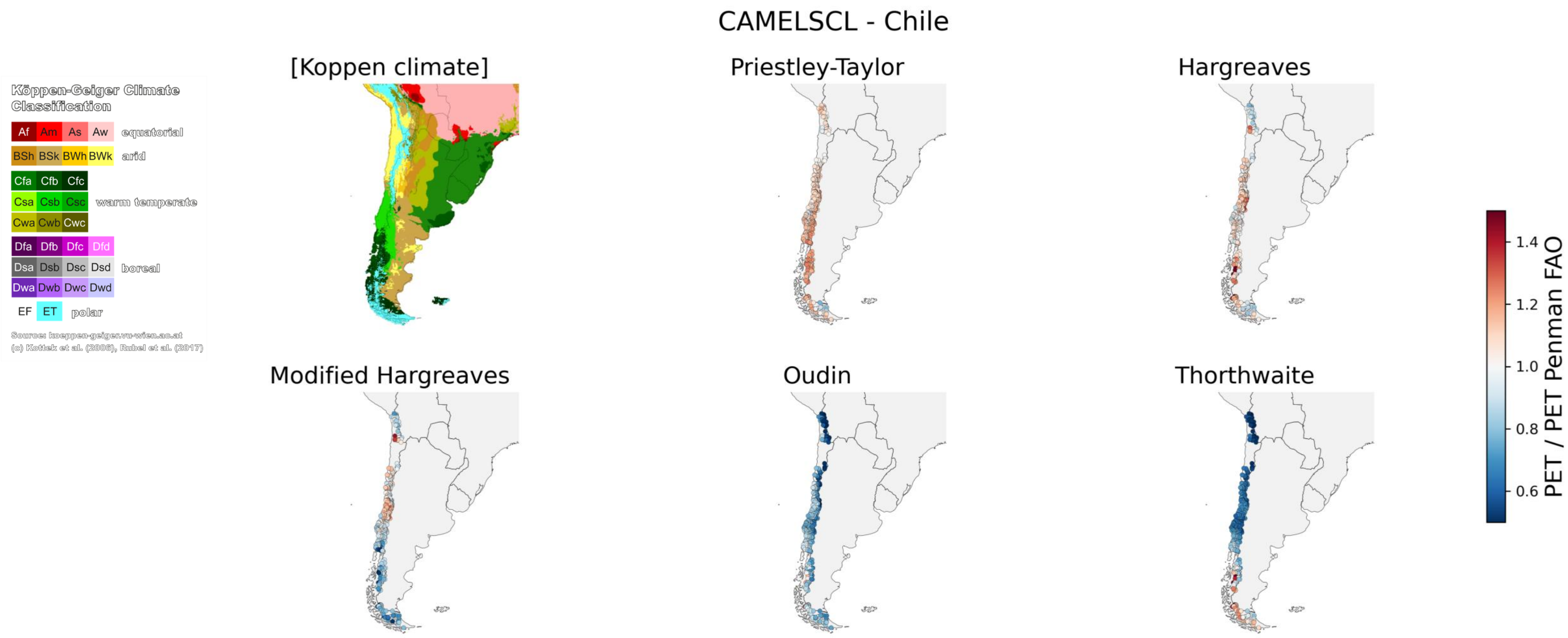

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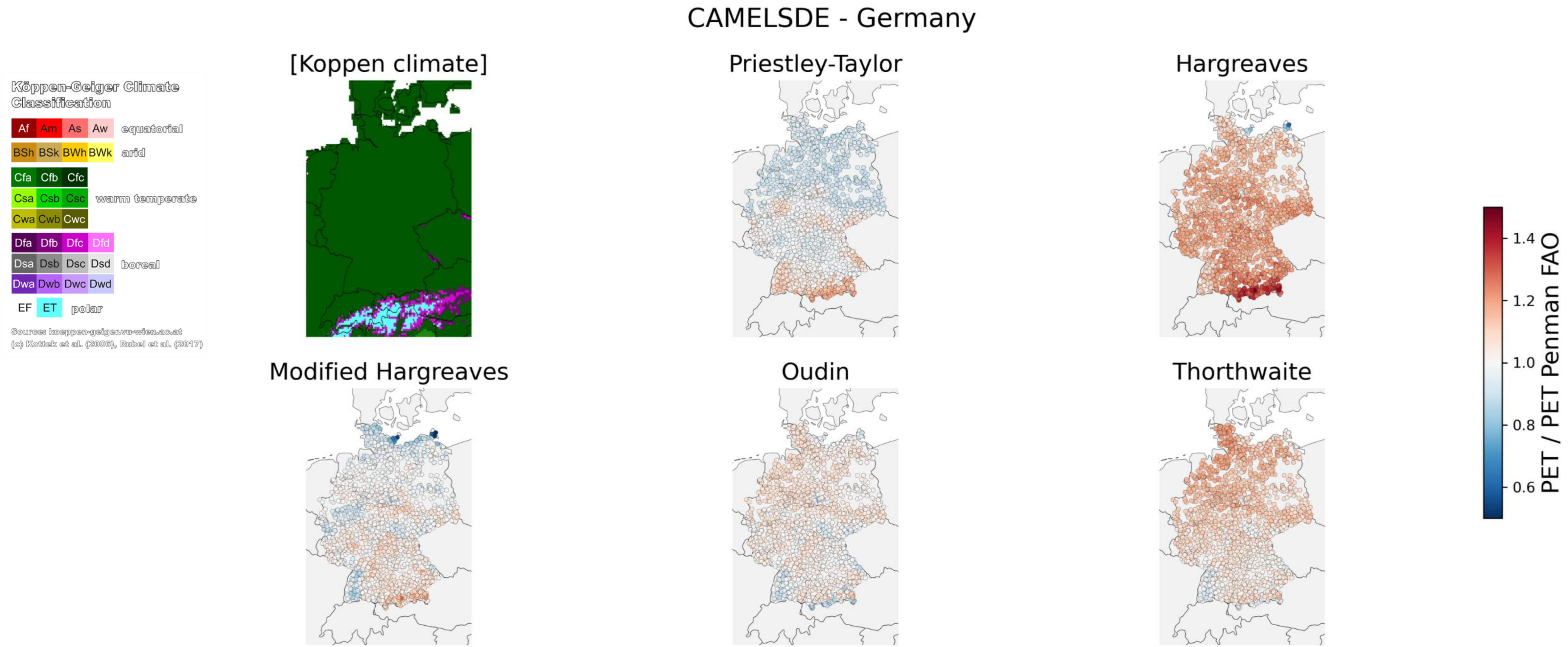

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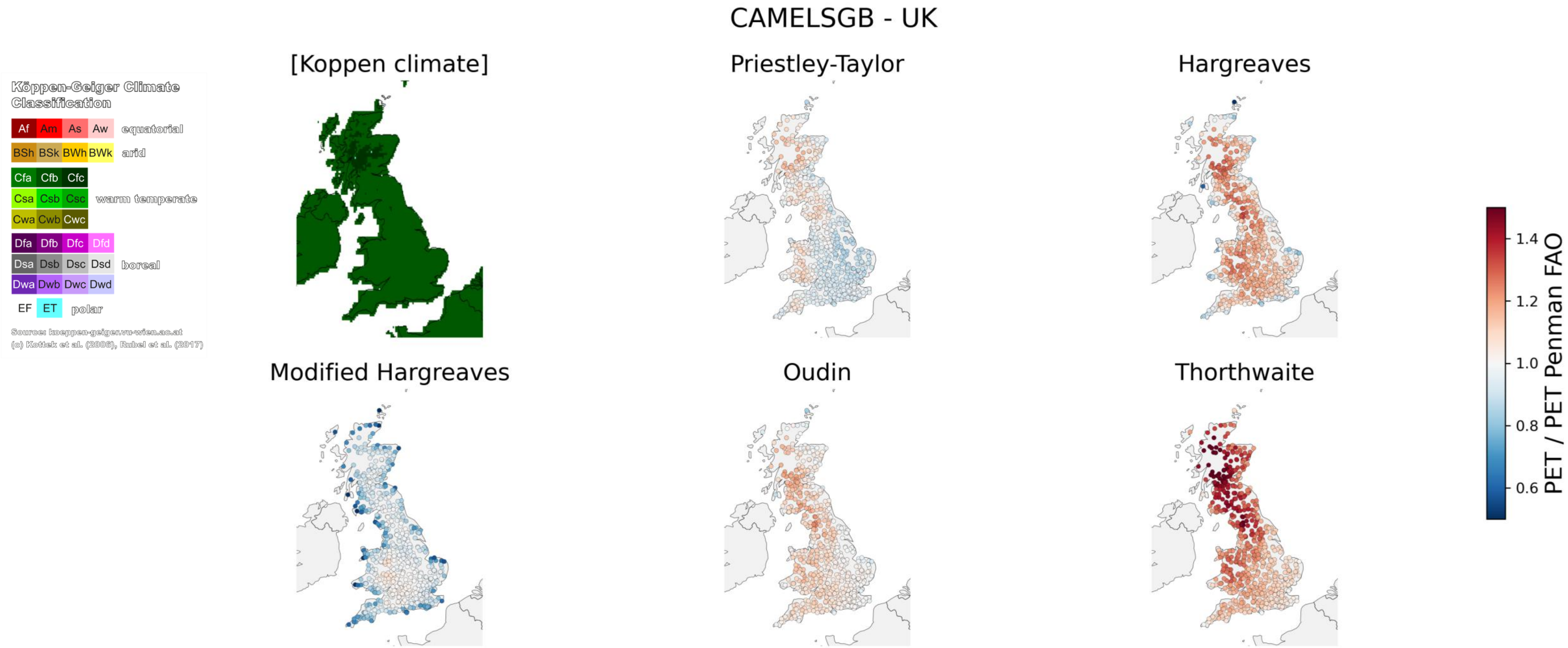
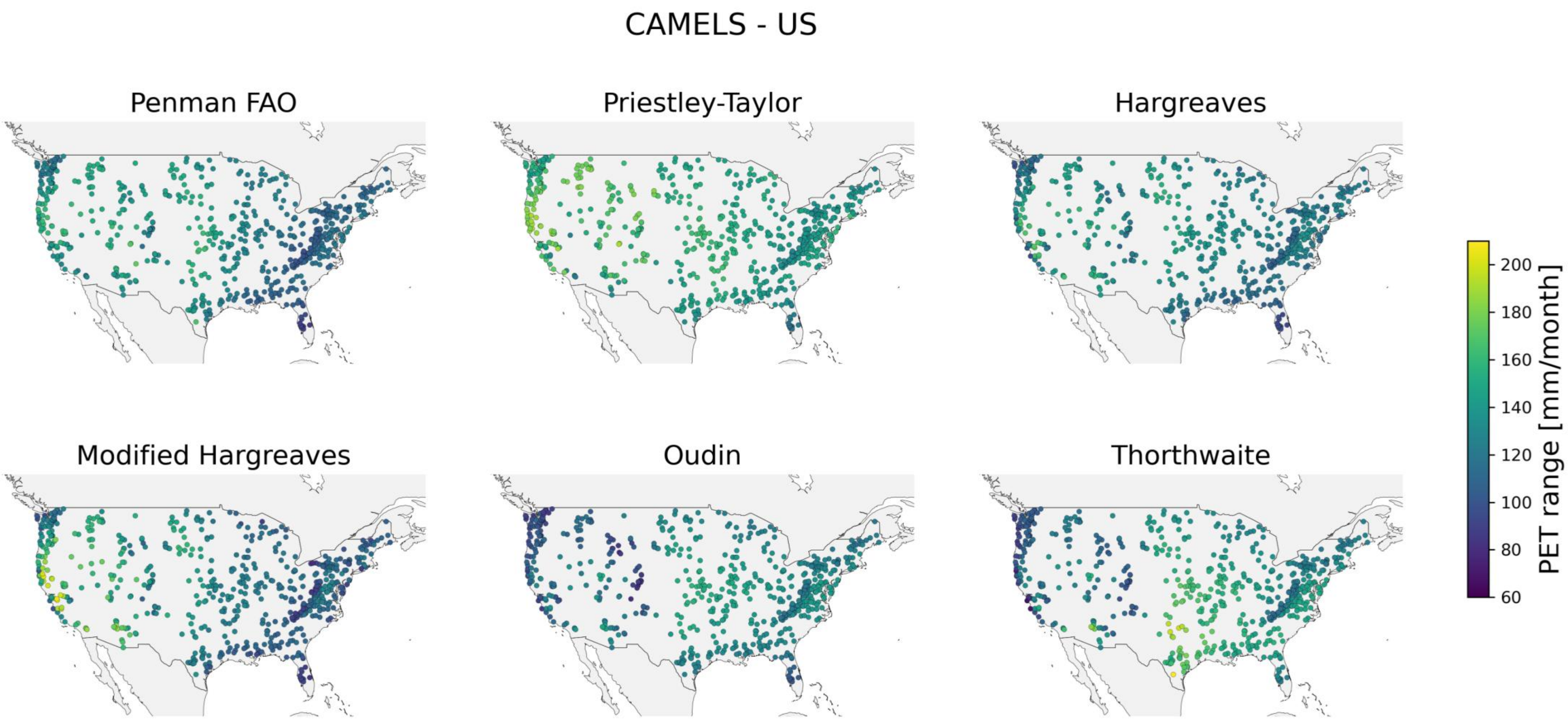


PET long term variability throughout the year



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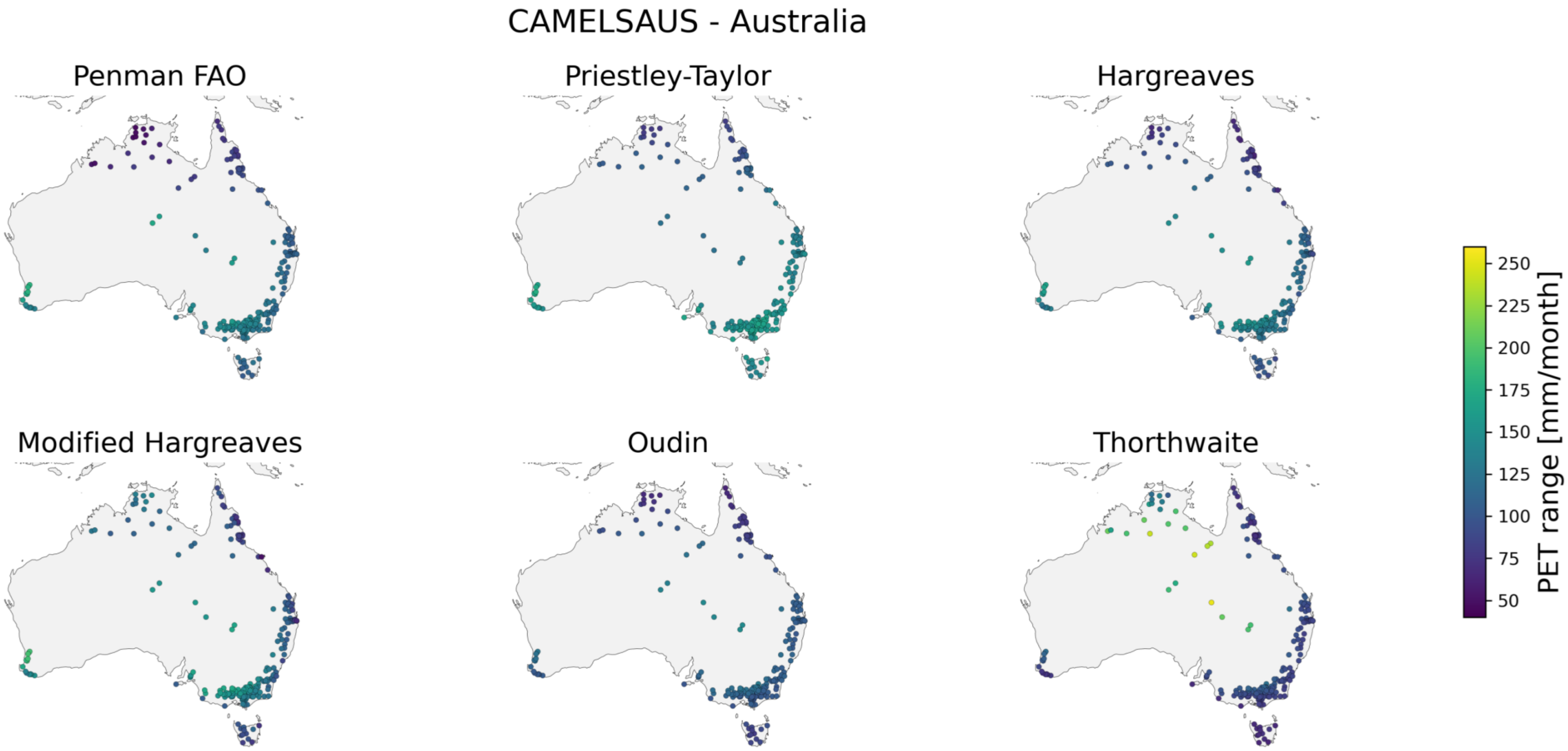

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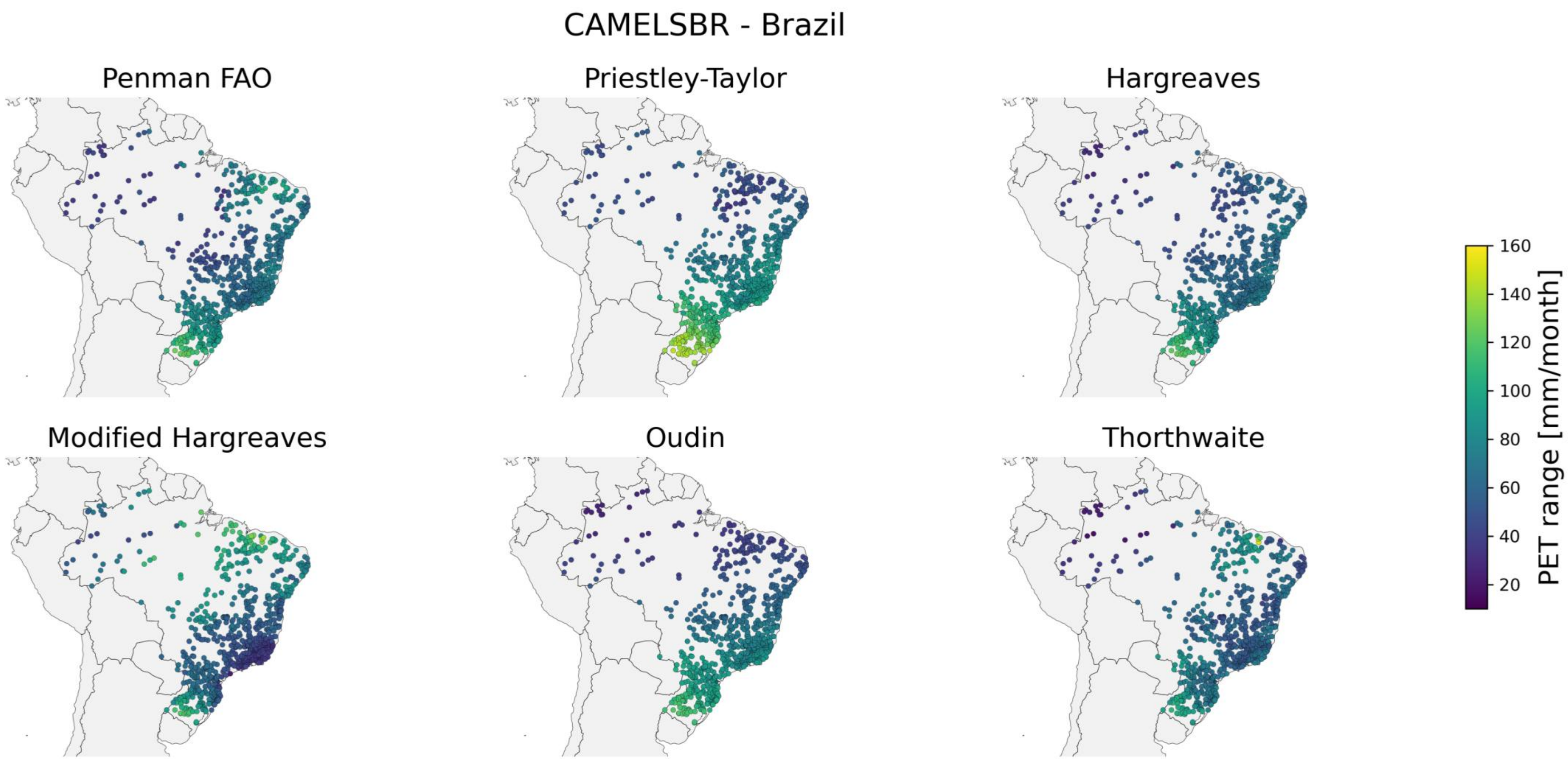

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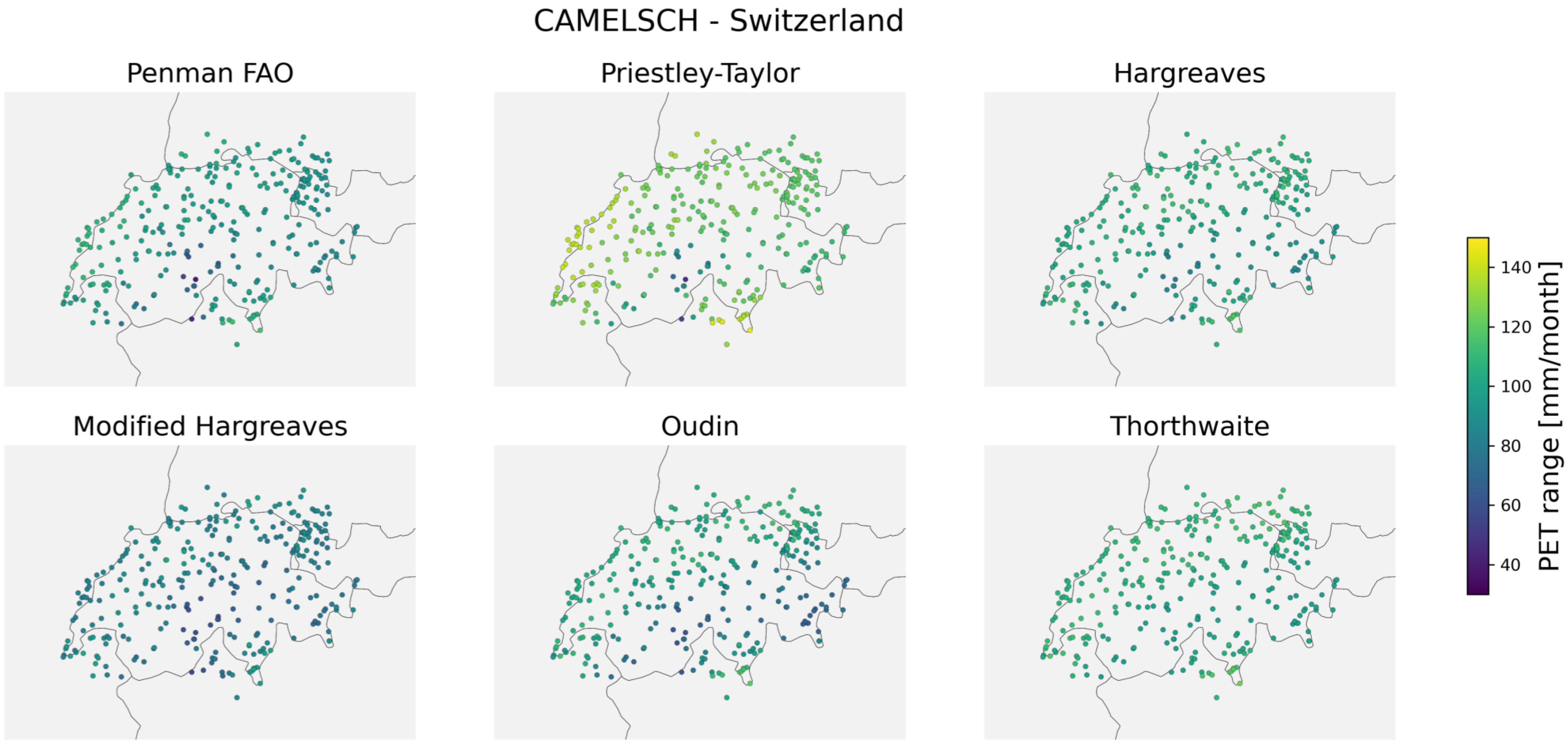

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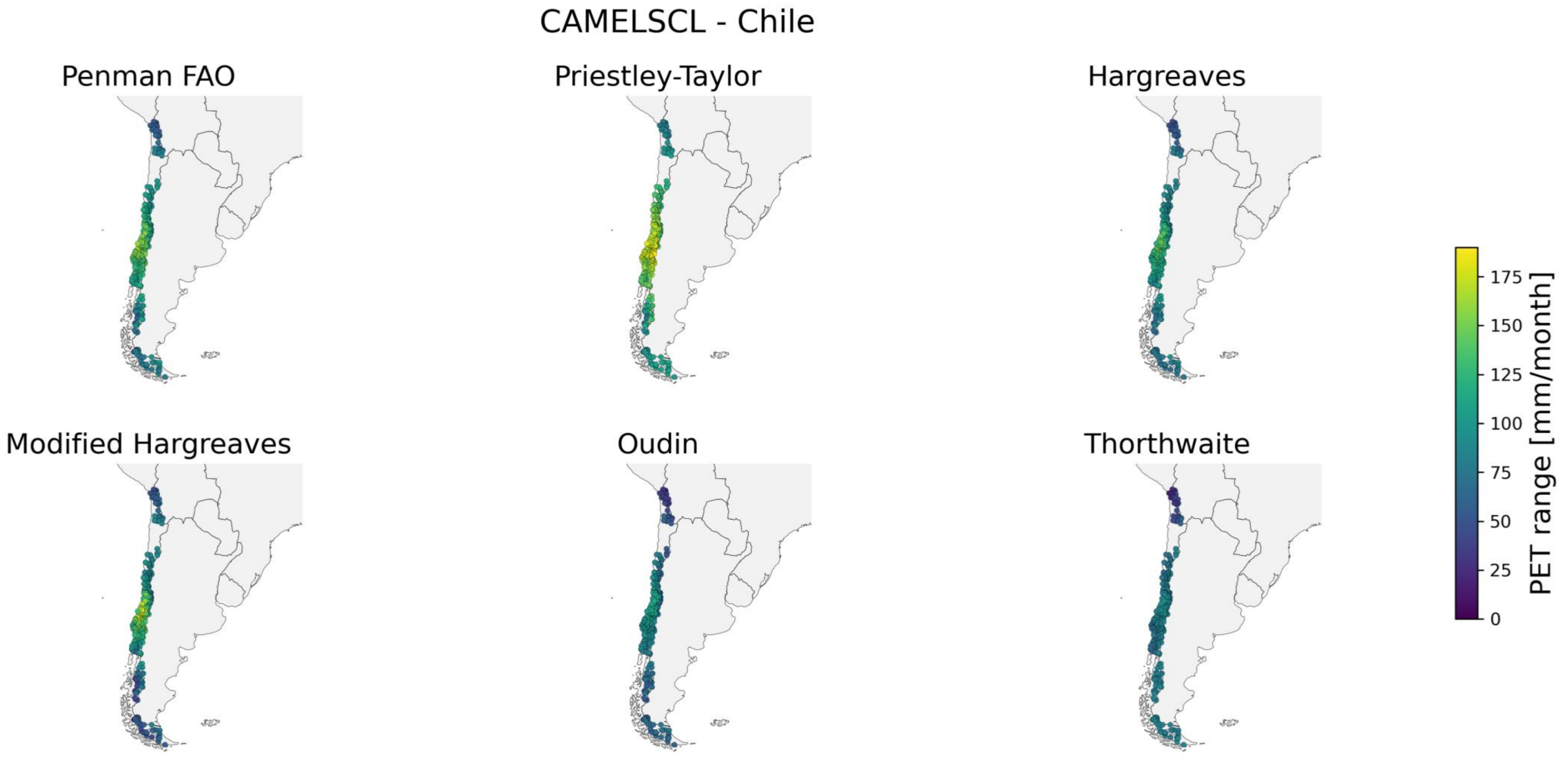

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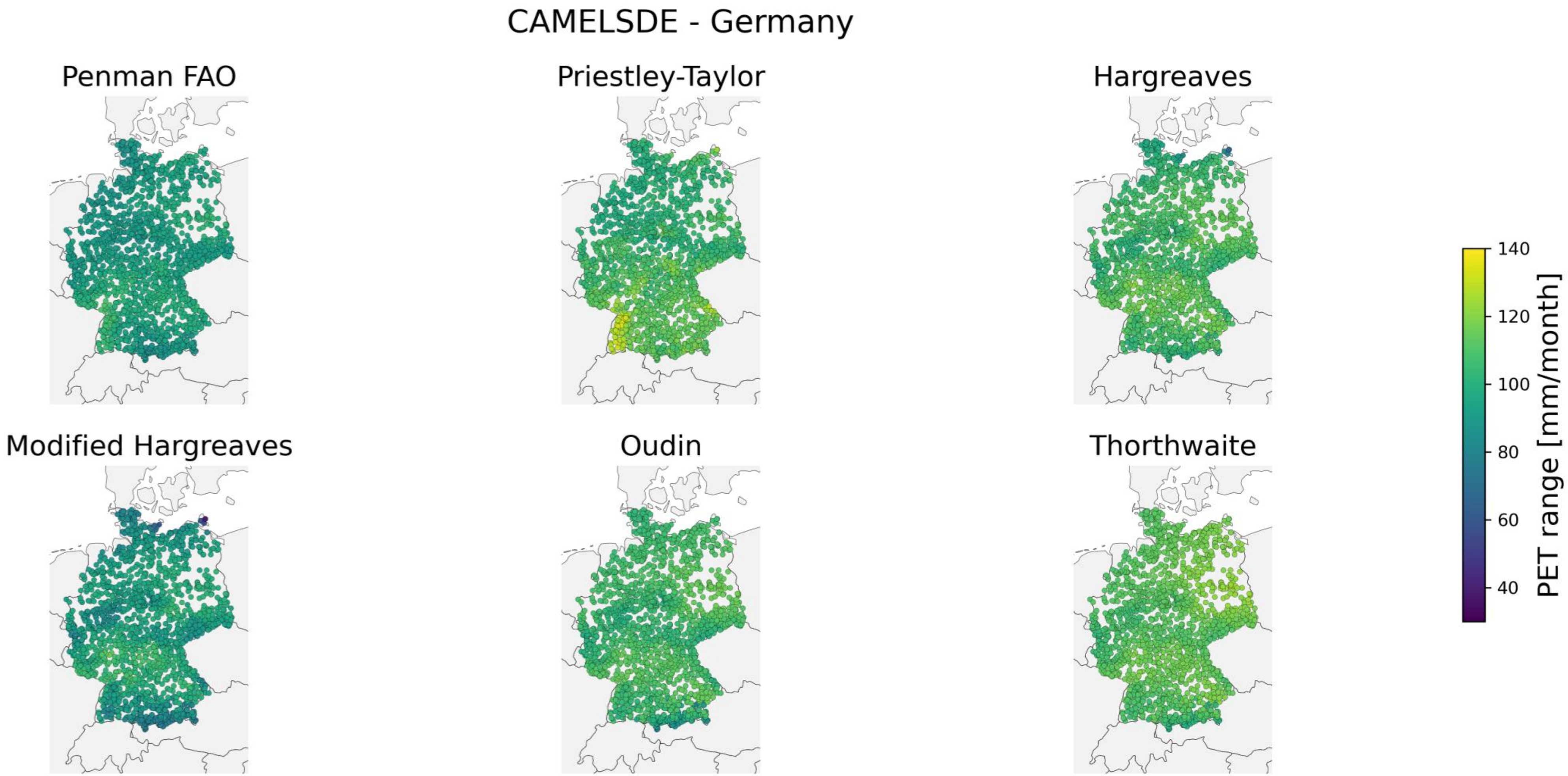

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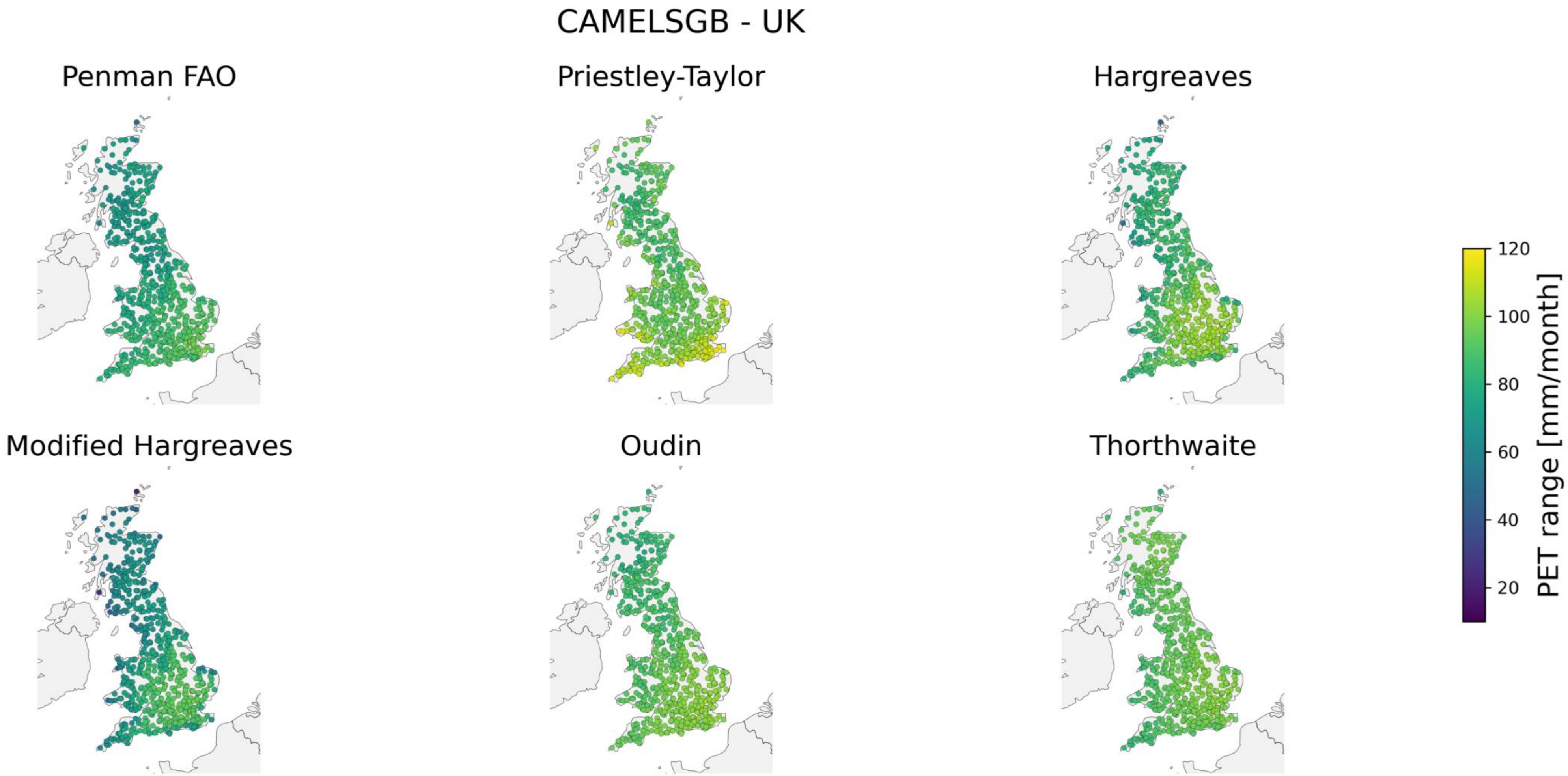
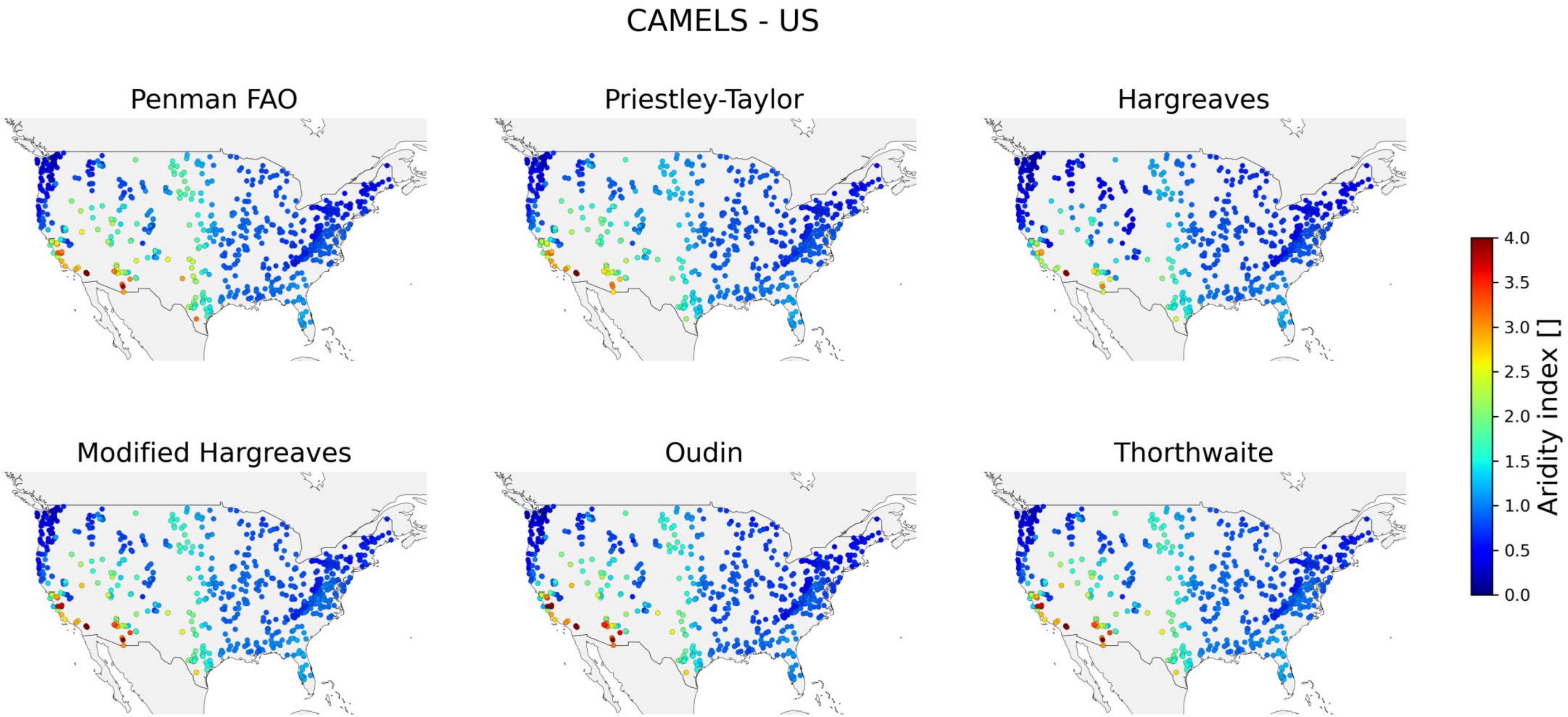


Aridity index



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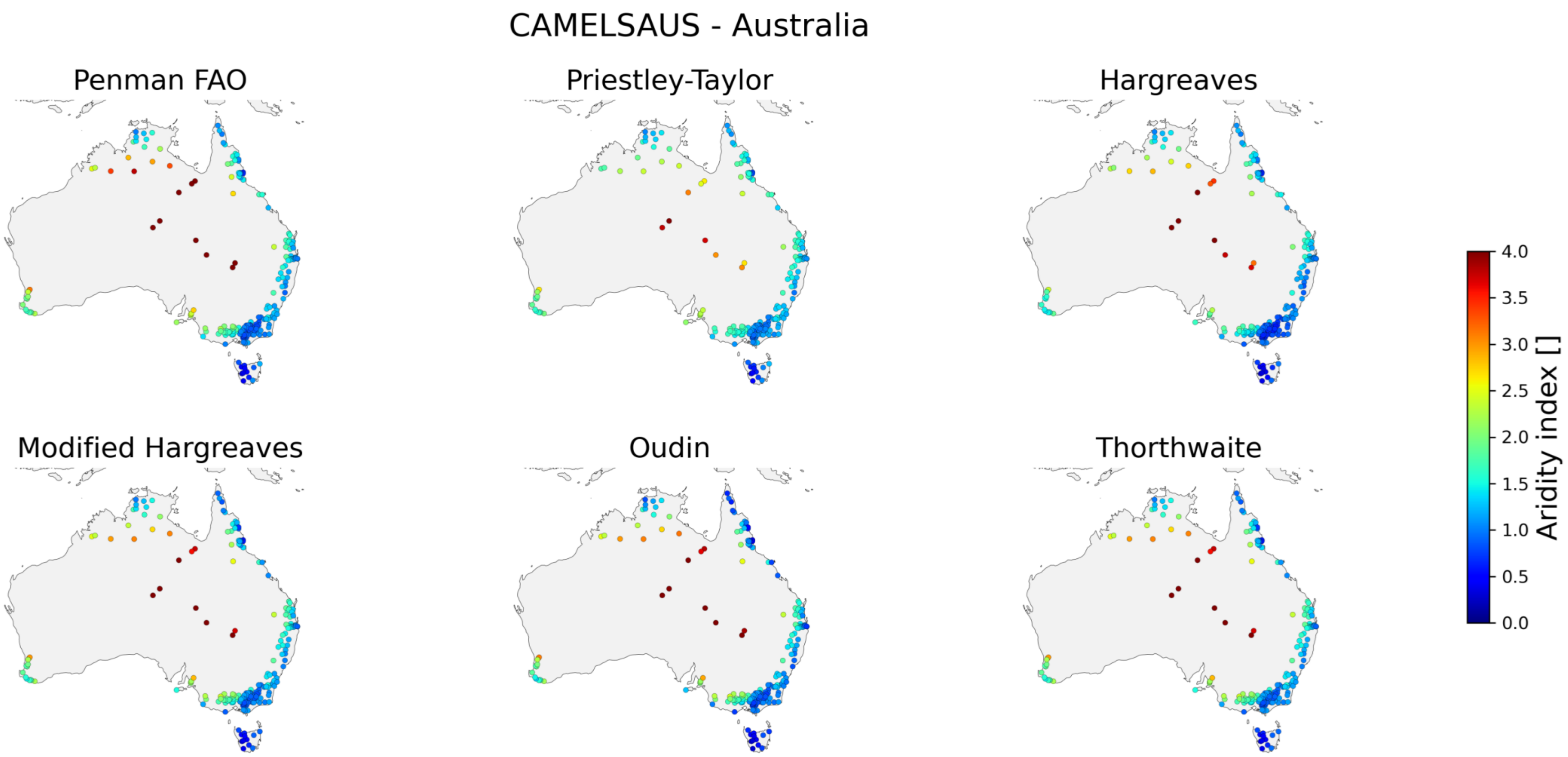

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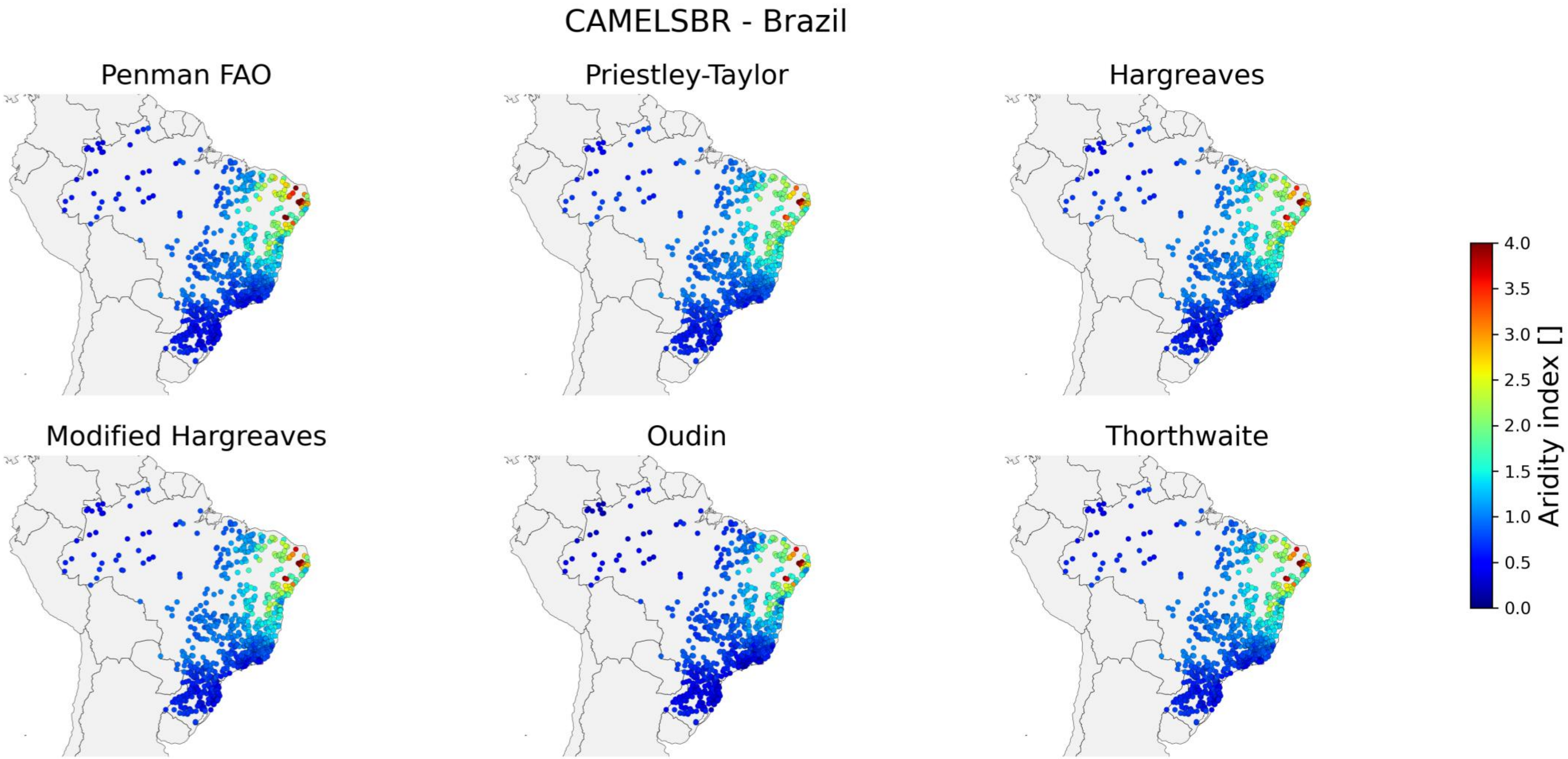

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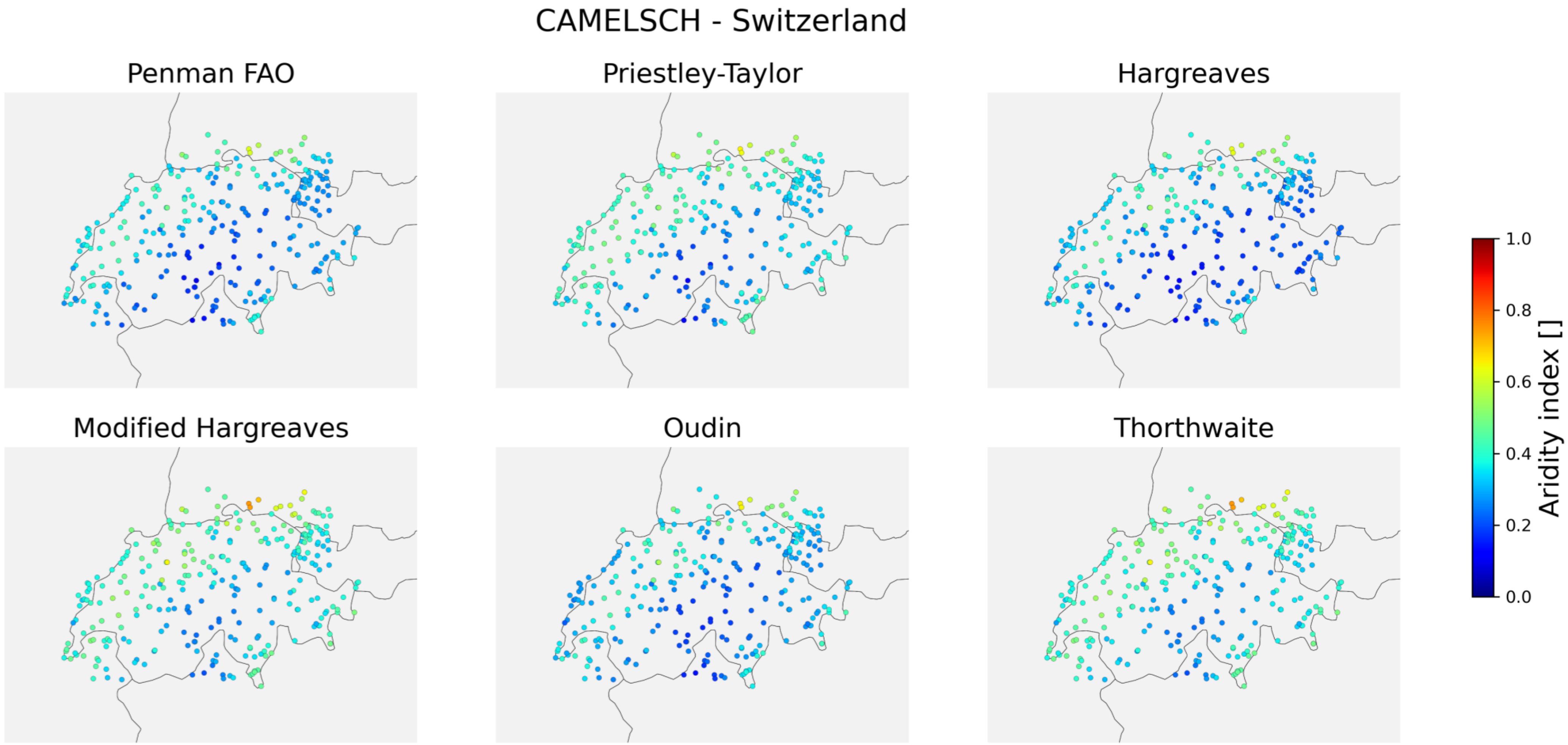

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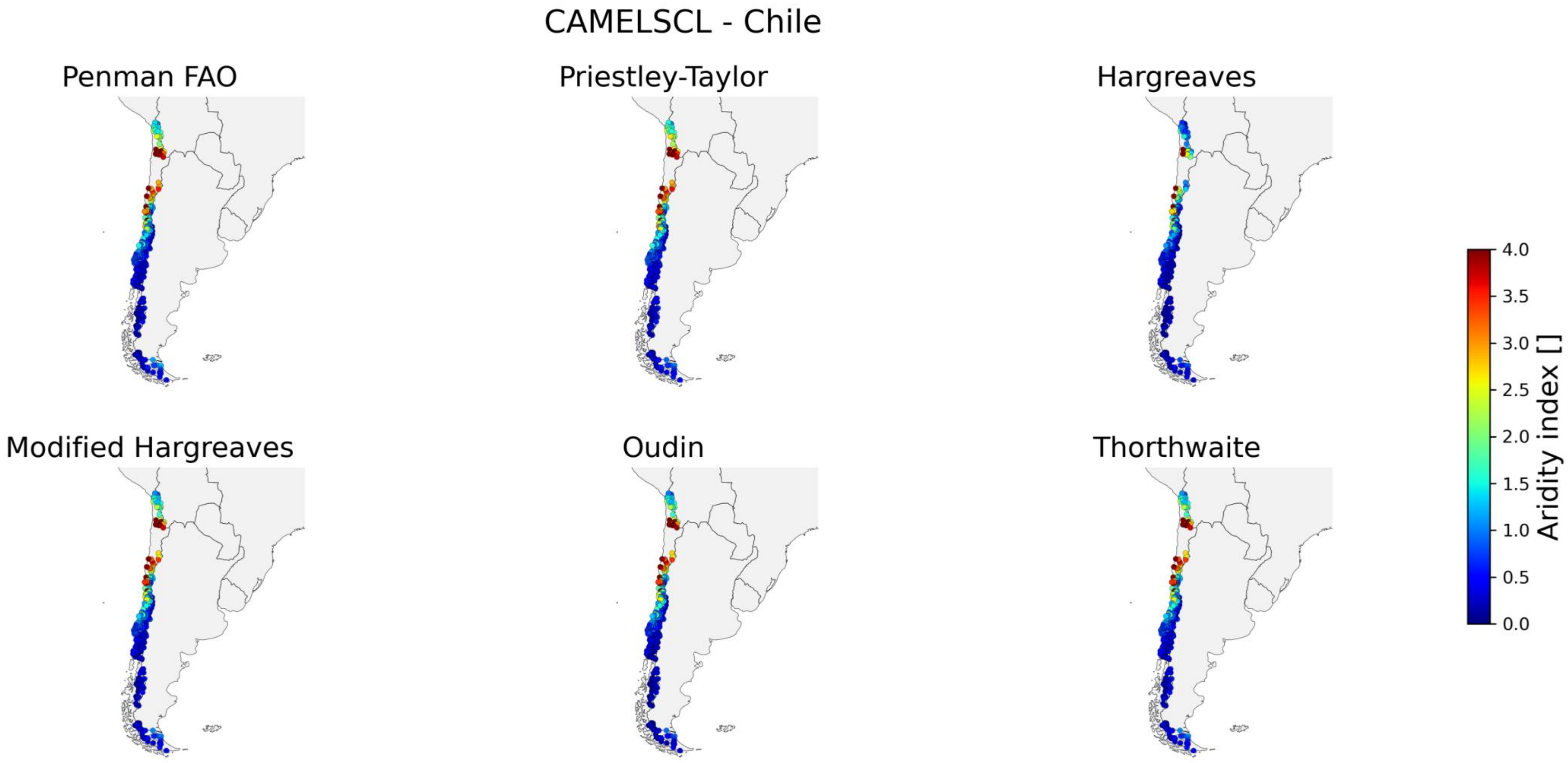

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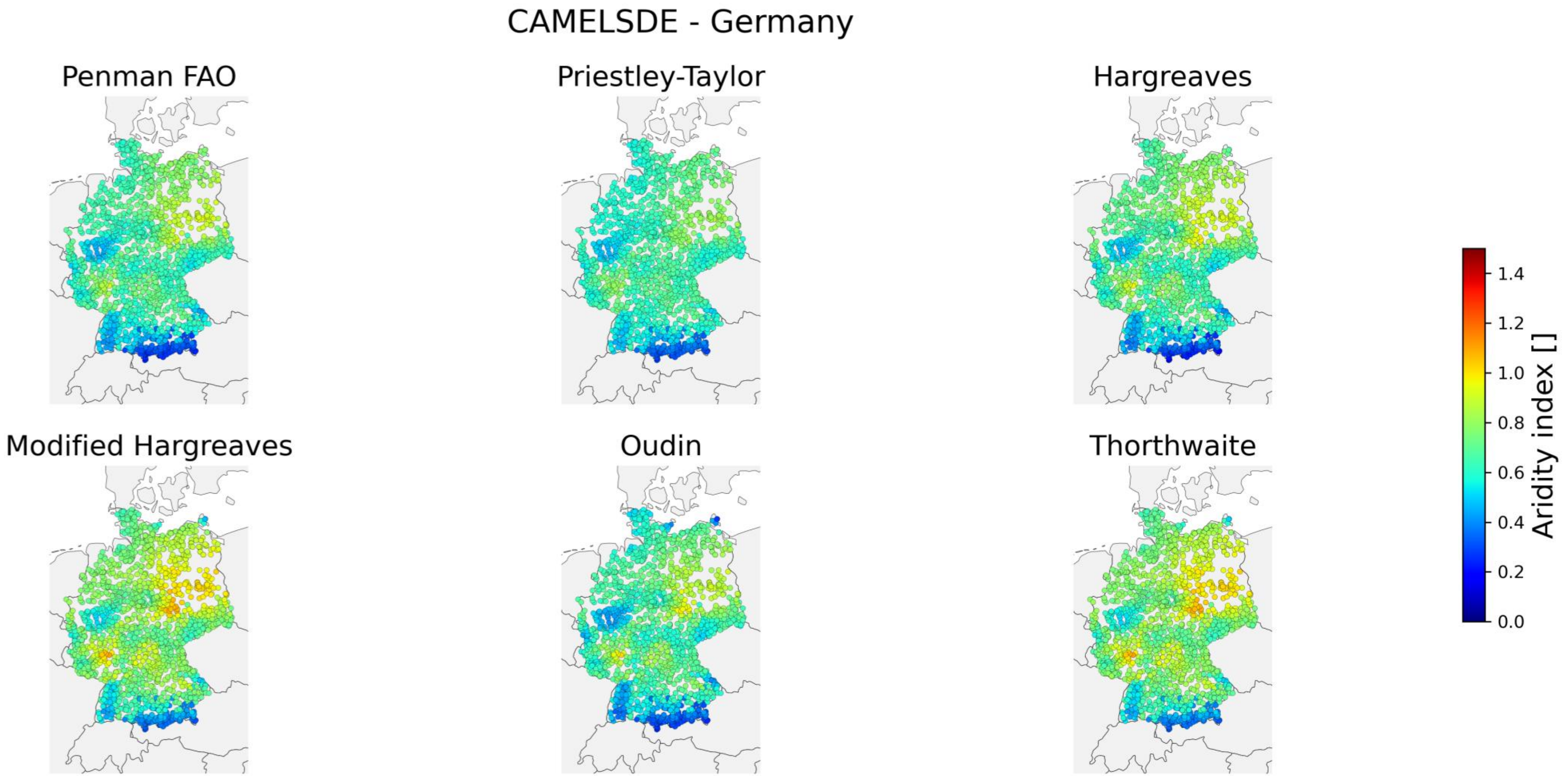
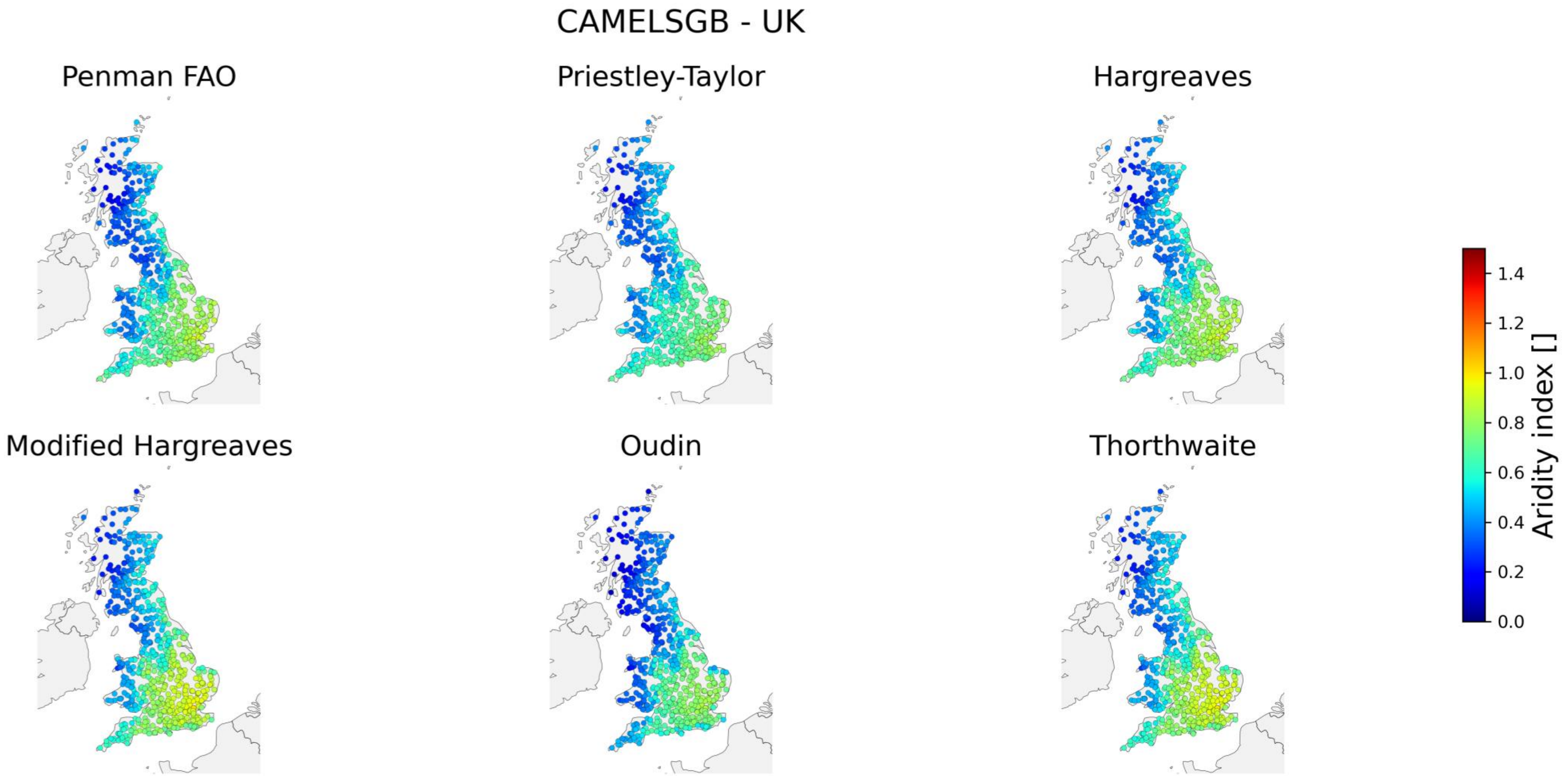
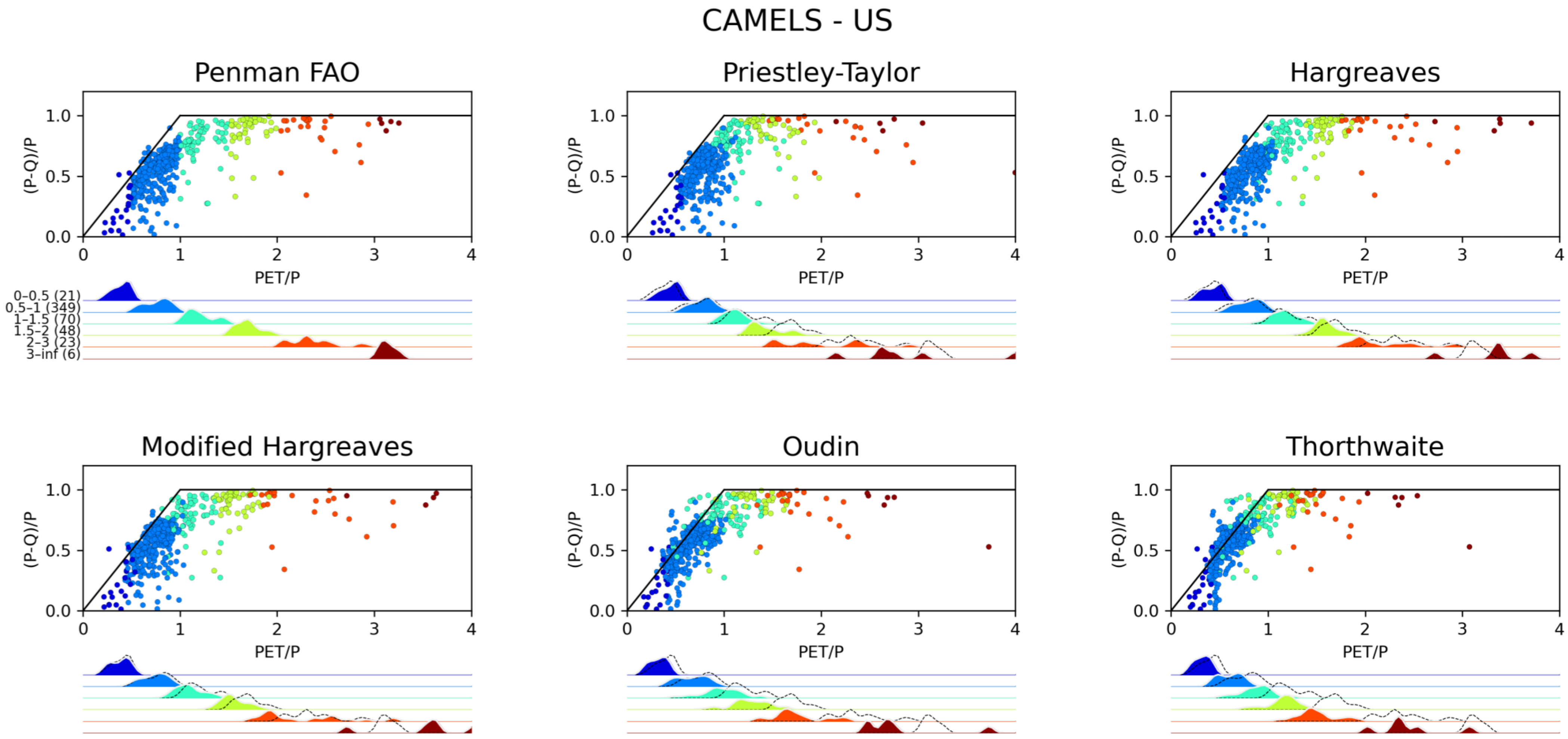


Aridity index



Budyko space



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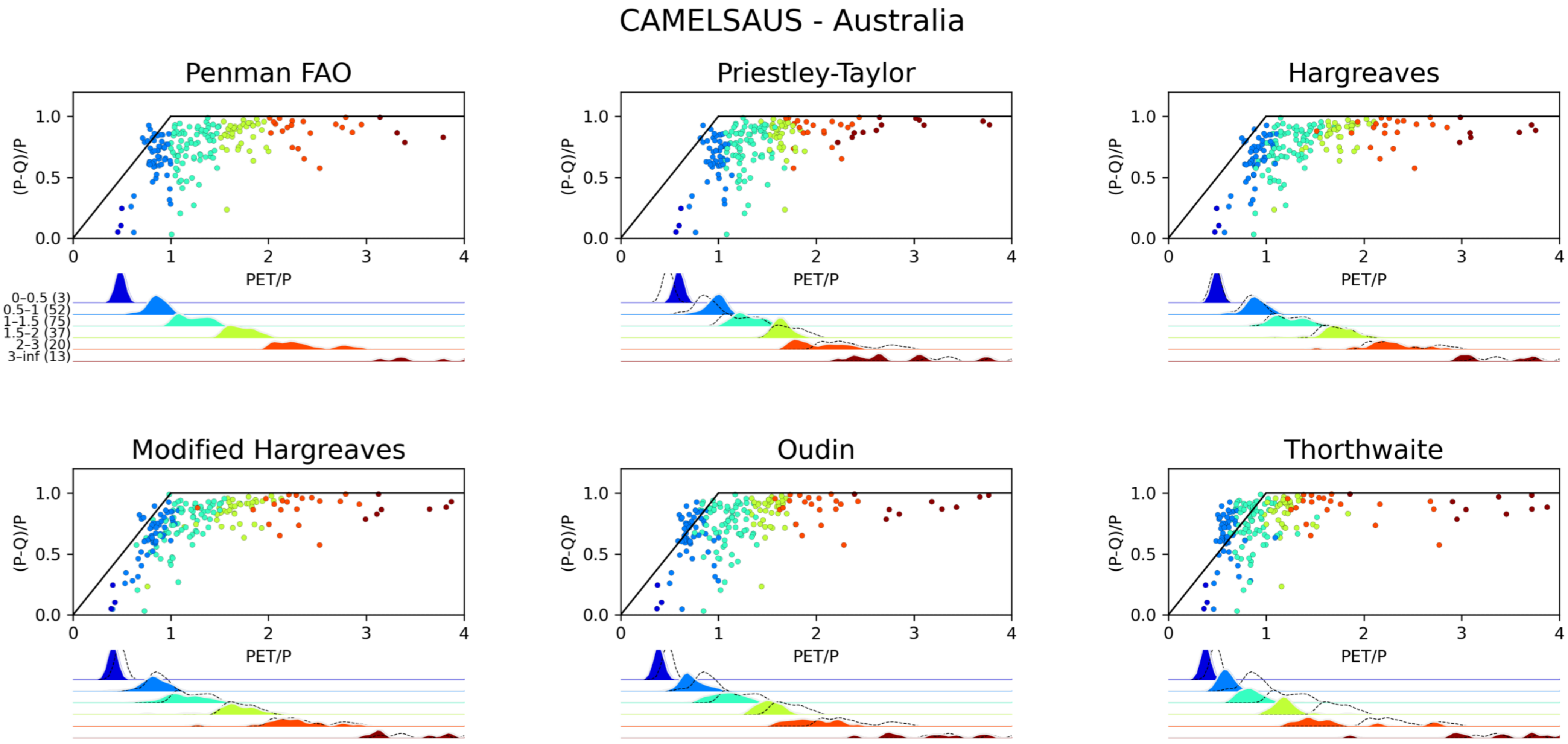

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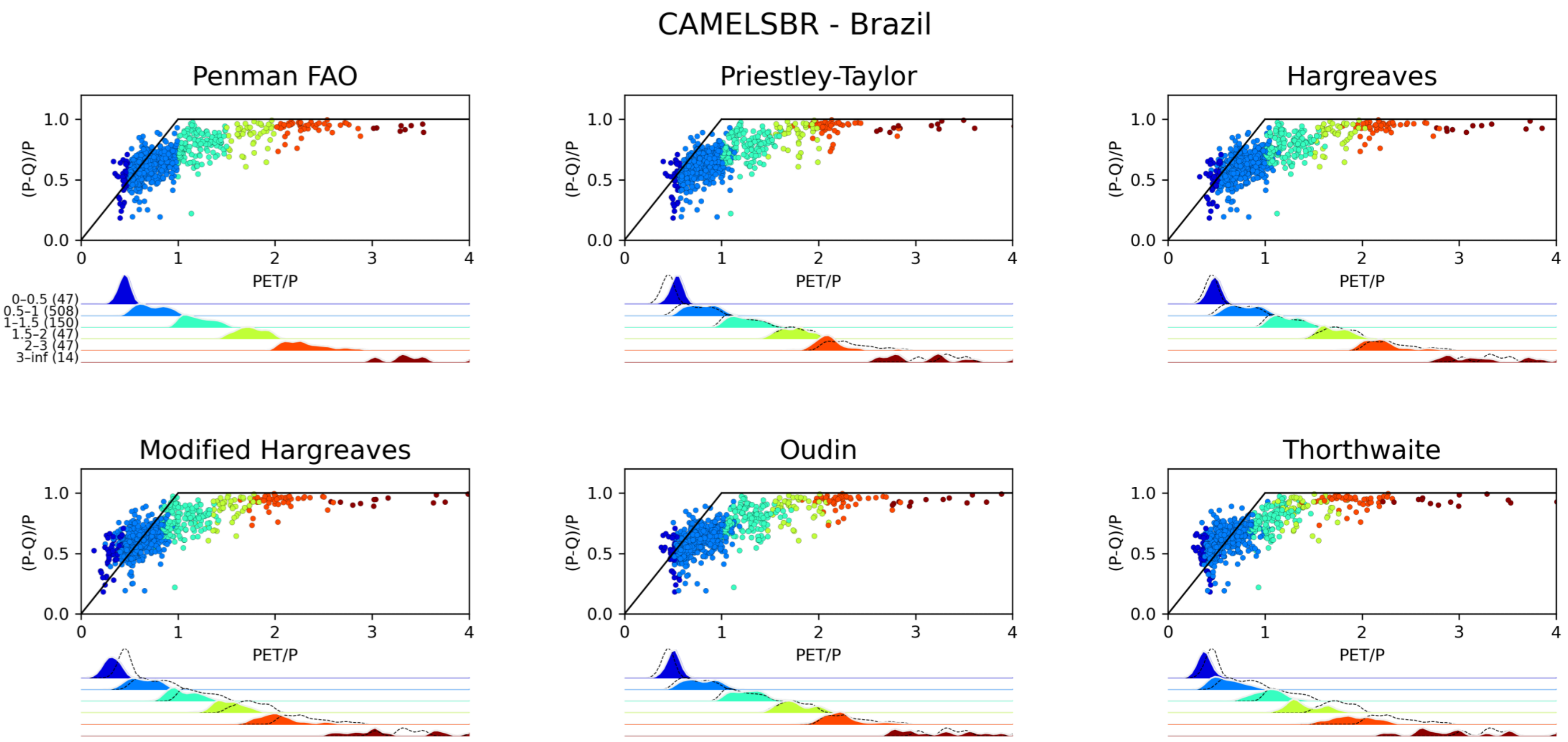

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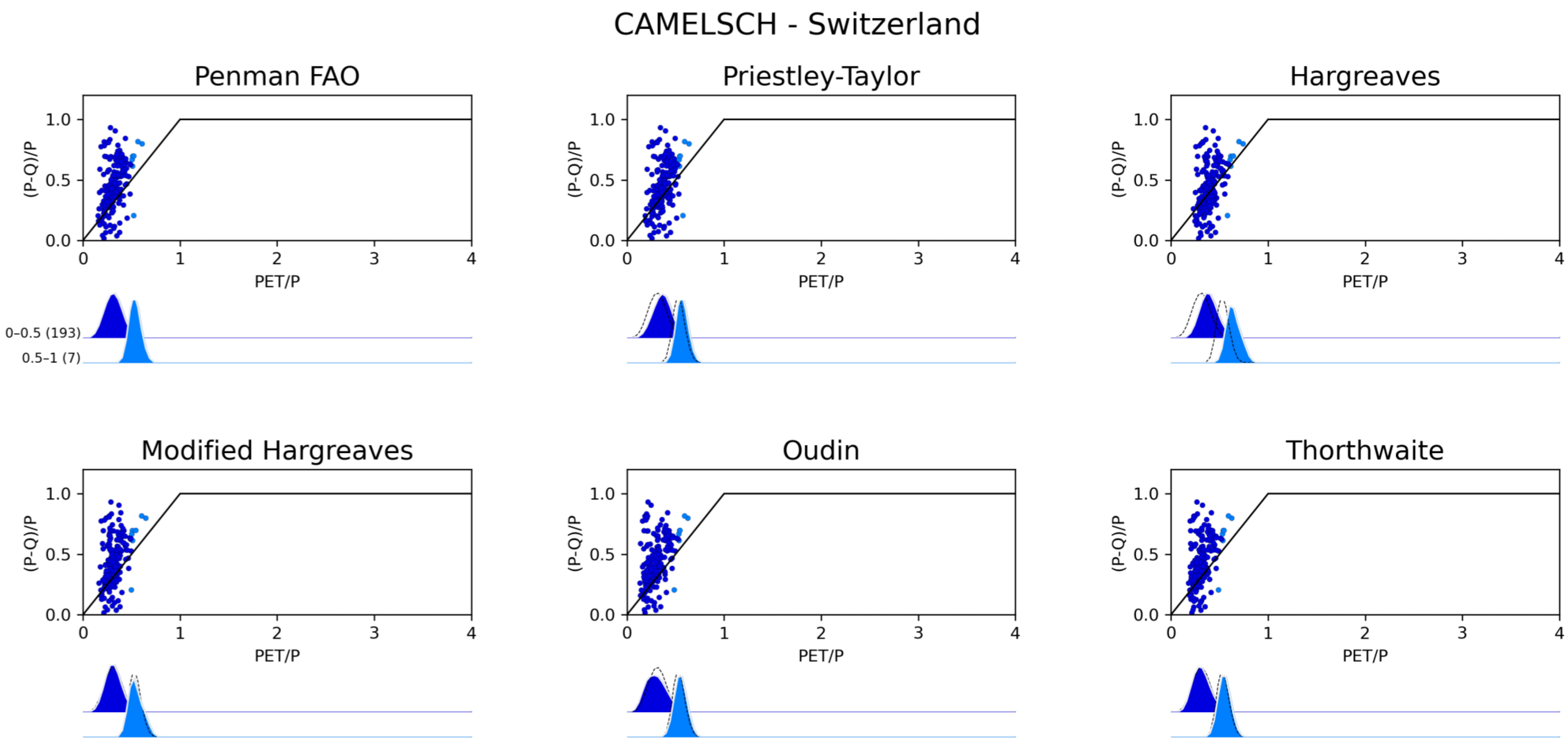

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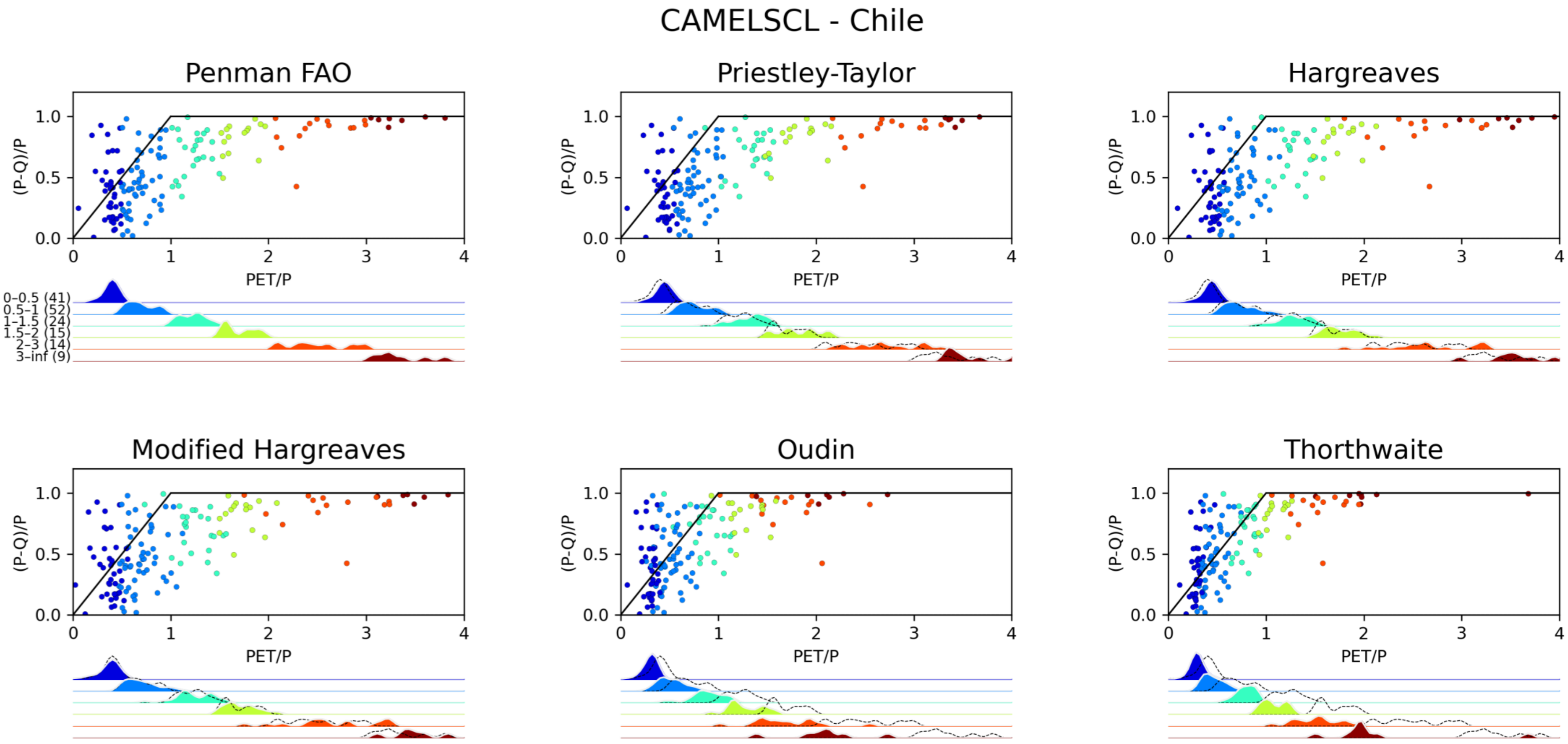

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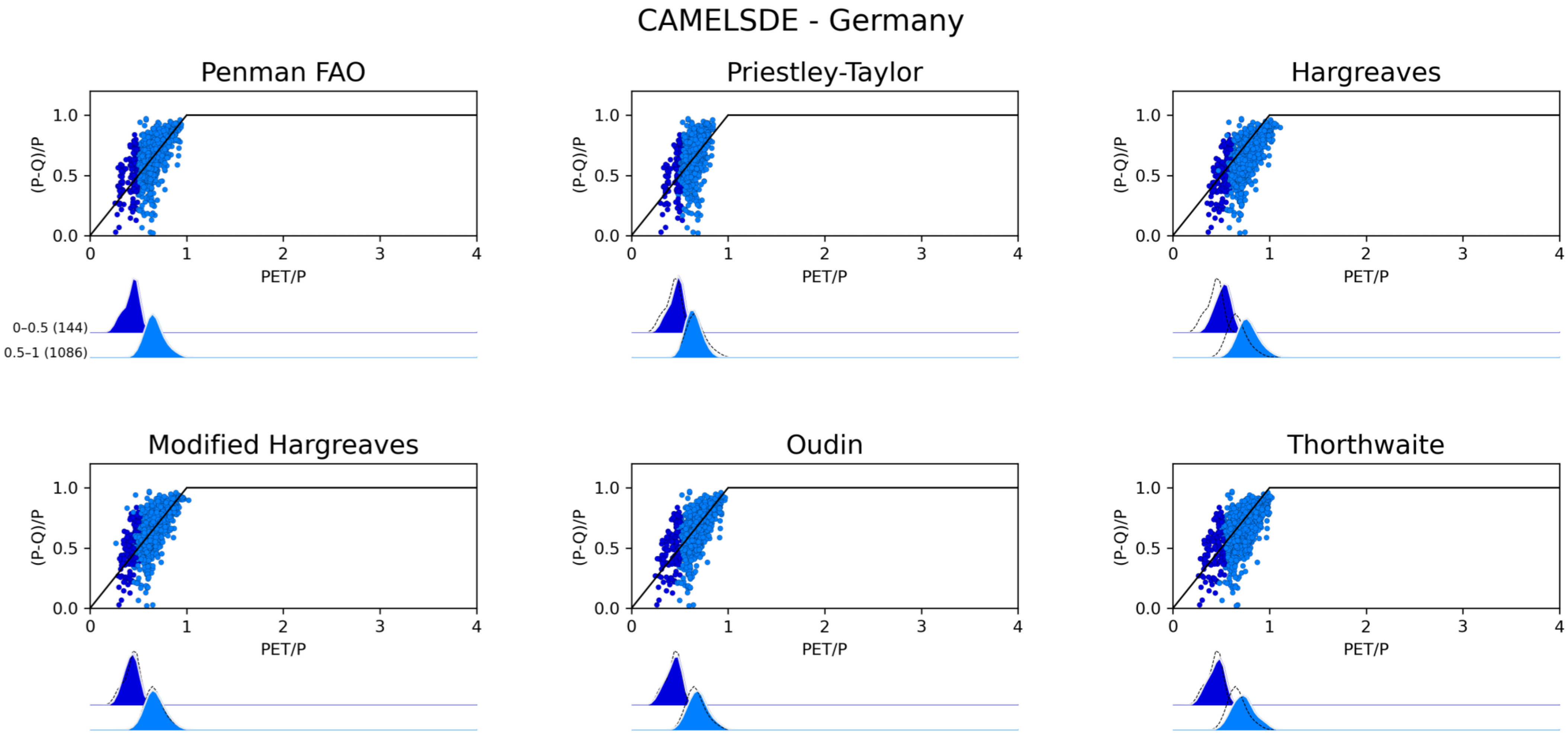

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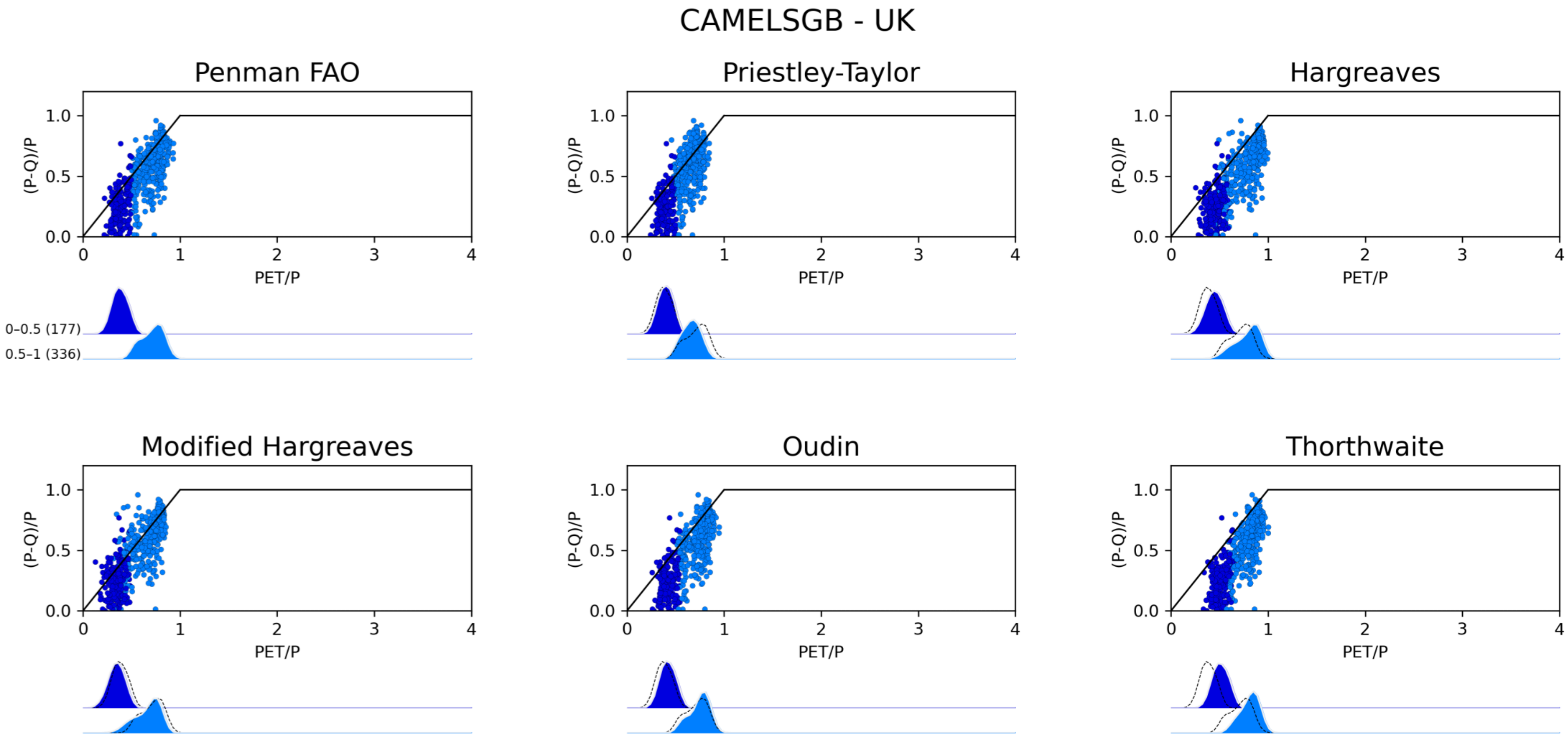

PET formulas:

FAO Penman-Monteith

Priestley-Taylor

Hargreaves

Modified Hargreaves

Oudin

Thorthwaite

FAO Penman-Monteith (Allen & Pereira, 1998)

$$\mathrm{PET} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \text{ [mm/day]}$$

- Δ: Slope of the saturation vapor pressure curve (kPa/°C)
- R_n: Net radiation at the crop surface (MJ/m²/day)
- G: Soil heat flux density (MJ/m²/day)
- γ: Psychrometric constant (kPa/°C)
- T: Mean daily air temperature at 2m height (°C)
- u_2: Wind speed at 2m height (m/s)
- e_s: Saturation vapor pressure (kPa)
- e_a: Actual vapor pressure (kPa)

Priestley-Taylor (Priestley & Taylor, 1972)

$$\mathrm{PET} = \alpha \cdot \frac{\Delta \cdot (\mathrm{R_n} - \mathrm{G})}{\lambda_v \cdot (\Delta + \gamma)} \cdot 1000\ [mm/day]$$

- α: Empirical constant = 1.26
- Δ: Slope of saturation vapor pressure curve (kPa/°C)
- R_n: Net radiation (MJ/m²/day)
- G: Soil heat flux (MJ/m²/day)
- λ: Latent heat of vaporization (MJ/kg)
- γ: Psychrometric constant (kPa/°C)

Hargreaves (Hargreaves & Samani, 1985)

$$PET = 0.0023 \cdot R_a \cdot \left(T_{avg} + 17.8\right) \cdot \sqrt{T_{max} - T_{min}}\ [mm/day]$$

- R_a: Extraterrestrial radiation (MJ/m²/day)
- T_{avg}: Average daily temperature (°C)
- T_{max}: Maximum daily temperature (°C)
- T_{min}: Minimum daily temperature (°C)

Modified Hargreaves (Adam et al., 2006)

$$\mathrm{PET} = 0.0013 \cdot \mathrm{R_a} \cdot \left(\mathrm{T_{avg}} + 17\right) \cdot \left(\mathrm{T_{max}} - \mathrm{T_{min}} - 0.0123\mathrm{P}\right)^{0.76} \ [mm/day]$$

- R_a: Extraterrestrial radiation (mm/day)
- T_{avg}: Average daily temperature (°C)
- T_{max}: mean maximum daily temperature for a given month (°C)
- T_{min}: mean minimum daily temperature for a given month (°C)
- P is the precipitation for a given month (mm)

Oudin (Oudin et al., 2005)

$$\mathrm{PET} = \frac{\mathrm{R_a} \cdot (\mathrm{T_{avg}} + 5)}{\lambda \cdot 100}\ [mm/day]$$

- R_a: Extraterrestrial radiation (MJ/m²/day)
- T_{avg}: Average daily temperature (°C)
- λ: Latent heat of vaporization (2.45 MJ/kg)

Thornthwaite (Thornthwaite, 1948)

$$PET = 16 \cdot \left(\frac{10 \cdot T_{avg}}{I}\right)^{a} \cdot \frac{N}{12} \cdot \frac{d_m}{30}$$

- T_{avg}: Average daily temperature (°C)
- N: Hours of light of the day
- d_m: Days in the month
- I: Annual heat index

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514}$$

- T_i: average long-term temperature of month i
- a: Empirical exponent

$$a = 0.492 + 1.792e^{-5}\, I - 771e^{-7}\, I^2 + 675e^{-9}\, I^3$$

Other references

Earth maps: Made with Natural Earth. Free vector and raster map data @ naturalearthdata.com