What do models get right about changes in evapotranspiration?

Attribution of mechanisms of ET change

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Evapotranspiration: The Key Link

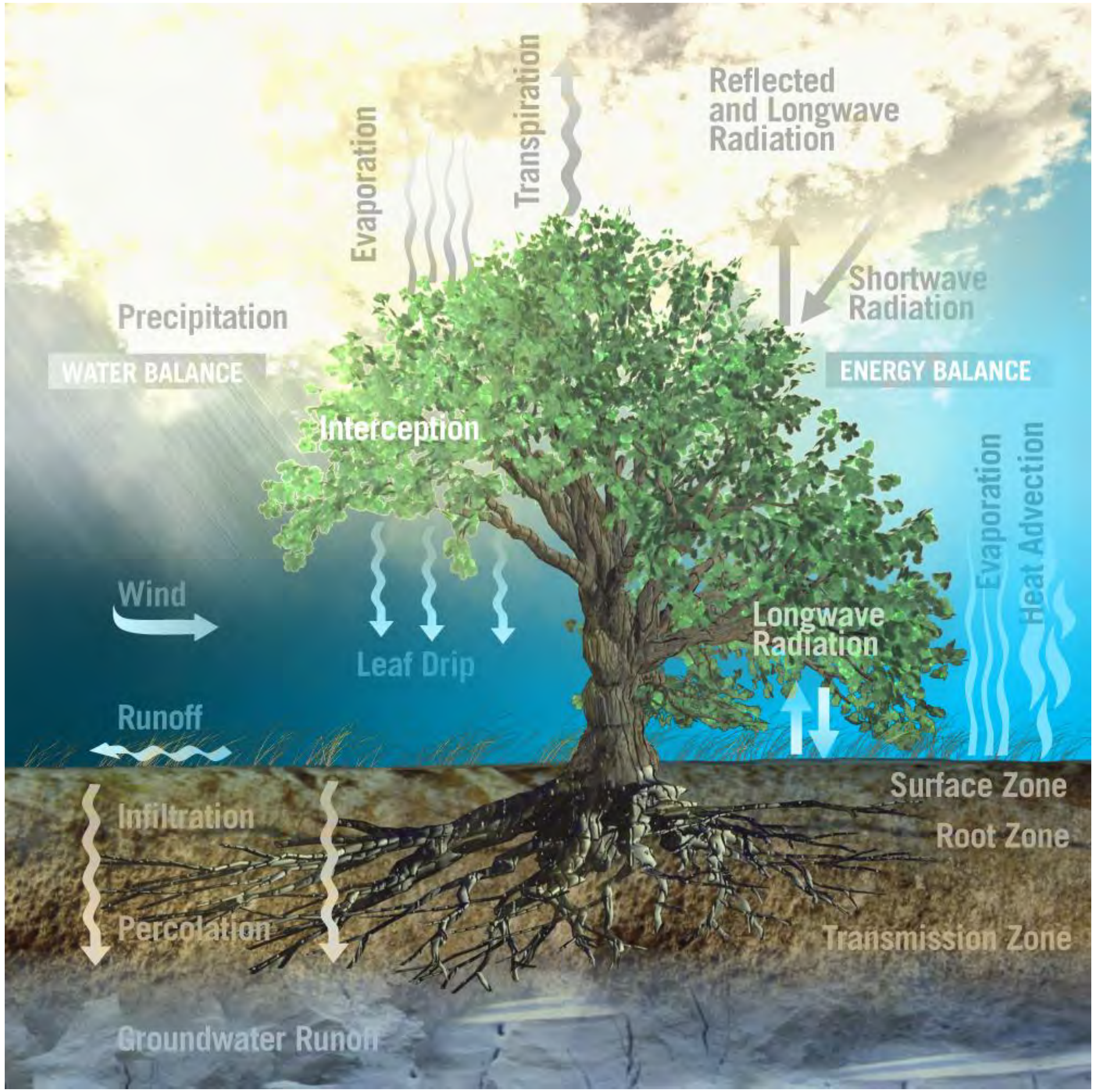
Evapotranspiration:

connects the land and the atmosphere,

connects the energy and water cycles

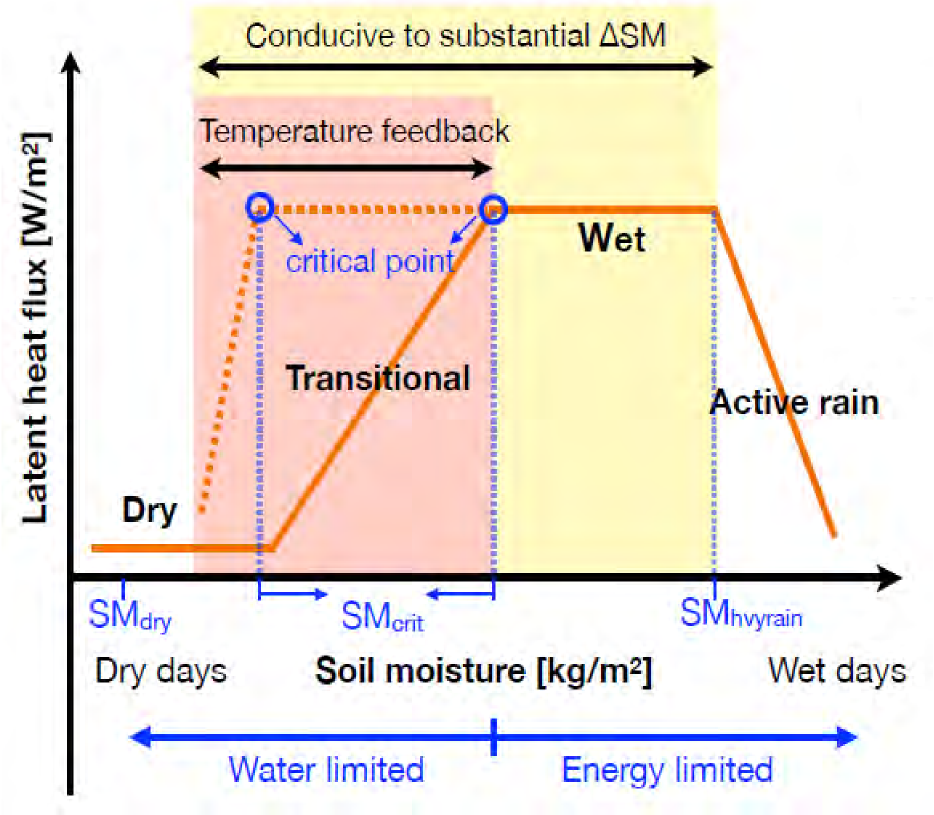
ET is sometimes limited by water availability, sometimes limited by energy availability

Driven by sub-daily processes… high-temporal frequency data are required (Findell et al., 2024)

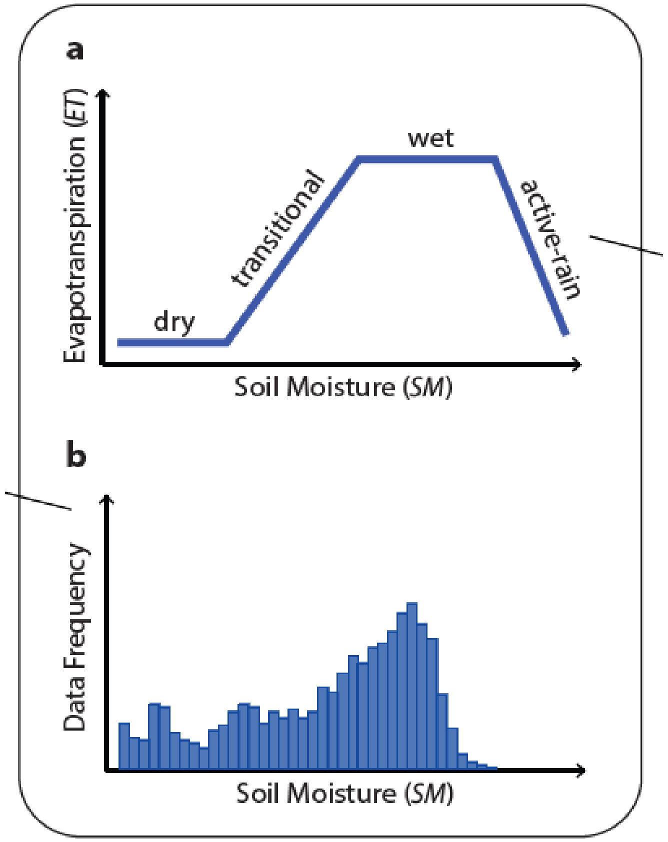


ESA–AOES Medialab

The non-linear relationship between Soil Moisture and ET



Duan, Findell and Fueglistaler, 2023, GRL



Hsu, Findell, et al., subm.

It's not just the local SM-ET relationship that matters,

It's also the PDF of SM: *how SM availability aligns with that SM-ET relationship*

Calculating ET change

Mean ET:

sum across all individual observations

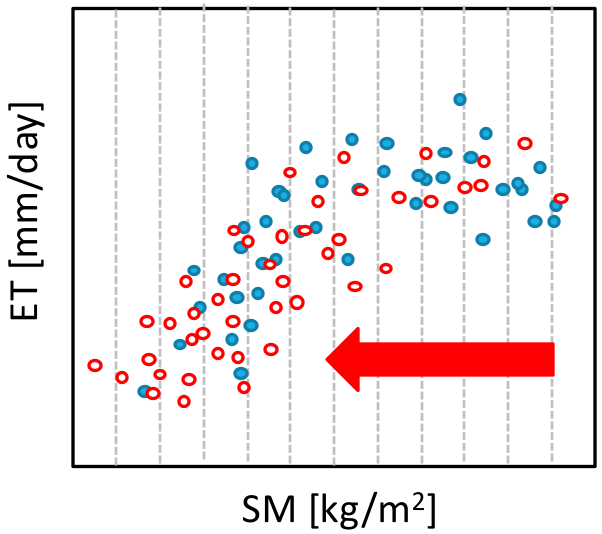
$$\overline{ET} = \frac{1}{n_{obs}} \sum_{i=1}^{n_{obs}} ET_i$$

OR:

bin the data,
sum across (number in bin*mean ET in bin)

$$\overline{ET} = \frac{1}{n_{obs}} \sum_{i=1}^{k_{bins}} (n_i \times \overline{ET_i})$$

Using a simple frequency-intensity decomposition

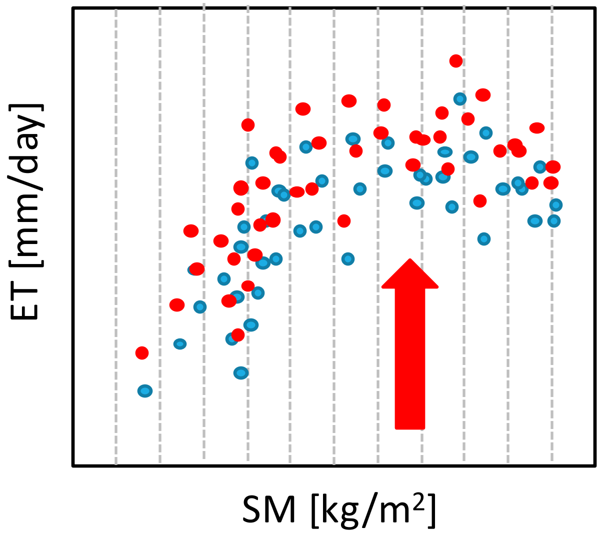


Change in ET between times 1 and 0:

$$\Delta\overline{ET} = \overline{ET_1} - \overline{ET_0}$$

Could come from a change in number of obs in each bin

Change in Soil Moisture availability



OR

Could come from a change in mean ET in each bin

Change in the SM—ET relationship

Could reflect aerosol-radiative effects, LULCC, vegetation dynamics, etc.

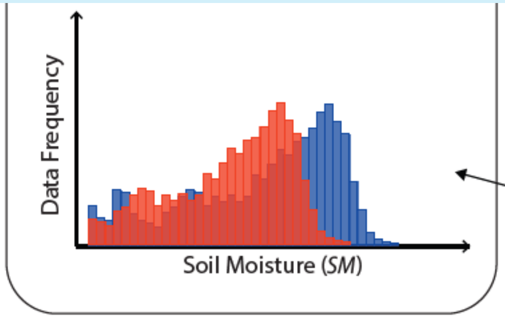
Pathways of ET change

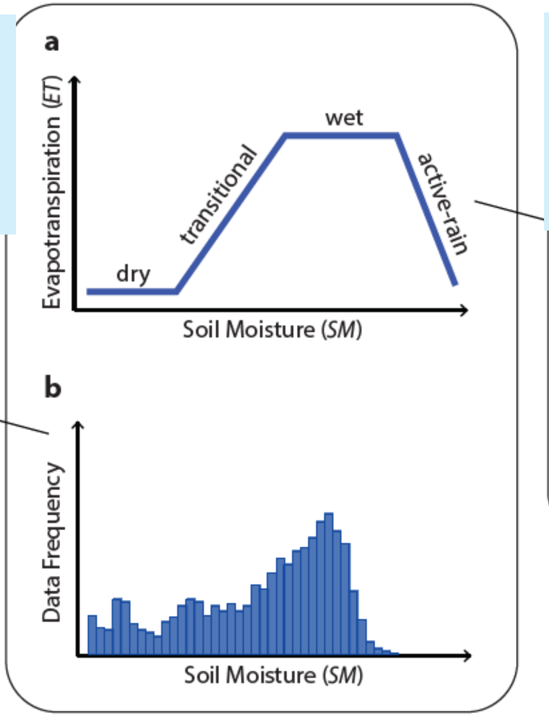
$$\Delta\overline{ET} = ET_M + ET_N + ET_C$$

$$\Delta\overline{ET} = \overline{ET}_1 - \overline{ET}_0 = \frac{1}{n_{obs}} \sum_{i=1}^{k_{bins}} \left((\Delta n_i \times \overline{ET}_{0i}) + (n_{0i} \times \Delta\overline{ET}_i) + (\Delta n_i \times \Delta\overline{ET}_i) \right)$$

Moisture pathway

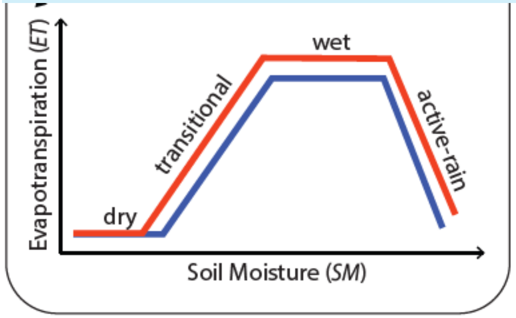
$$ET_M = \sum(\Delta n \times \overline{ET}_0)$$





Non-moisture pathway

$$ET_N = \sum(n_0 \times \Delta\overline{ET})$$



Combined pathway (Nonlinear term)

$$ET_C = \sum(\Delta n \times \Delta\overline{ET})$$

Datasets considered

GLEAM4 as the observationally-based reference (Miralles et al., 2025)

- GLEAM4 provides data of the different components of evapotranspiration by maximizing the recovery of information on ET contained in current satellite observations of climatic and environmental variables
- Soil moisture constraints on evaporation; Detailed treatment of forest interception; Extensive use of microwave observations
- Long-term continuous records

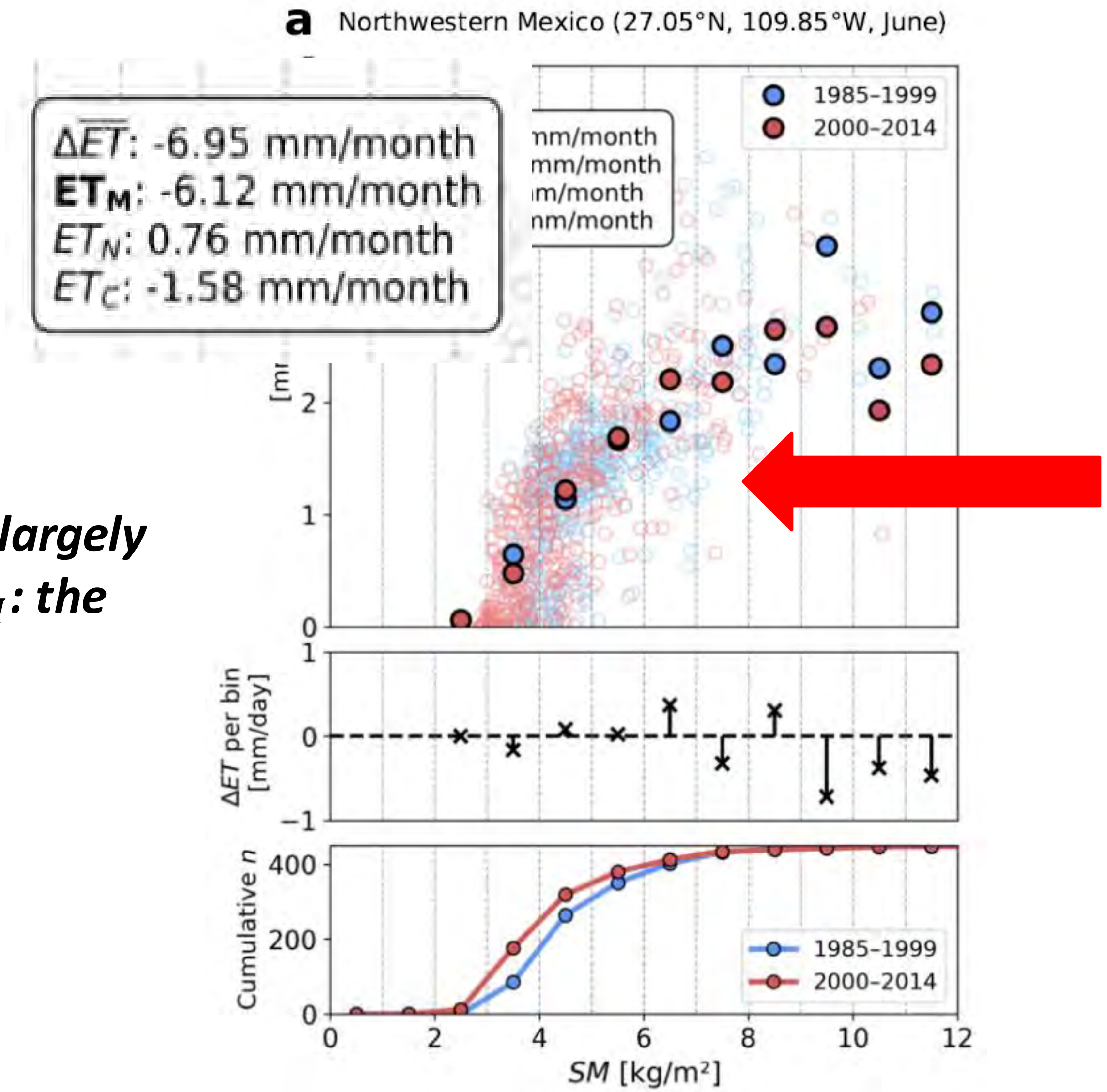
CMIP6 historical simulations with ***daily*** soil moisture (SM) and evapotranspiration (ET) available

- 14 models

30 years of overlap: consider differences between two 15-year time blocks

- 2000-2014 compared to 1985-1999

Examples using GLEAM4 data



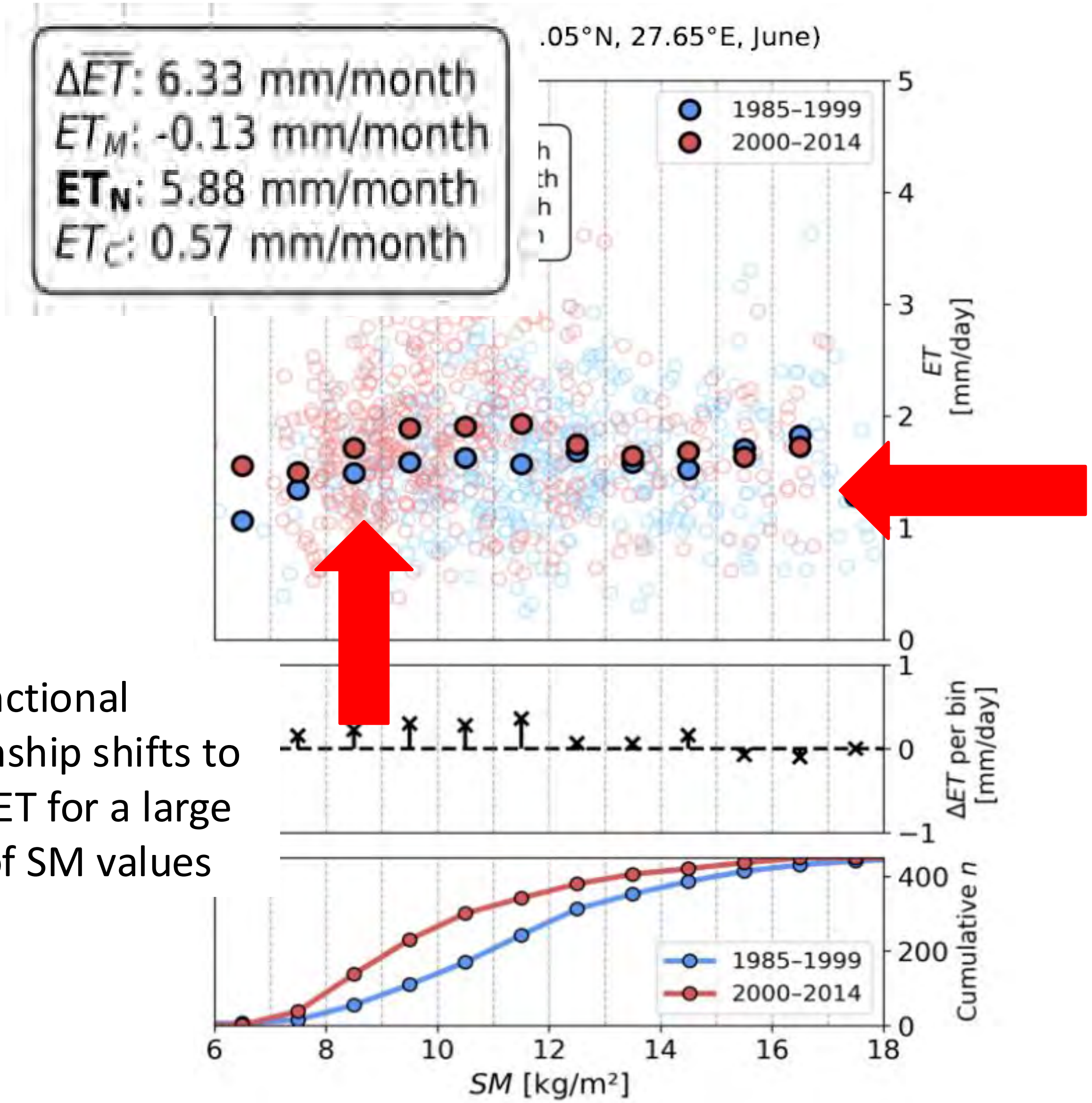
The change in ET is largely attributable to ET_M: the moisture pathway

The PDF shifts left, towards drier conditions

In the transitional regime: strong sensitivity of ET to SM

Examples using GLEAM4 data

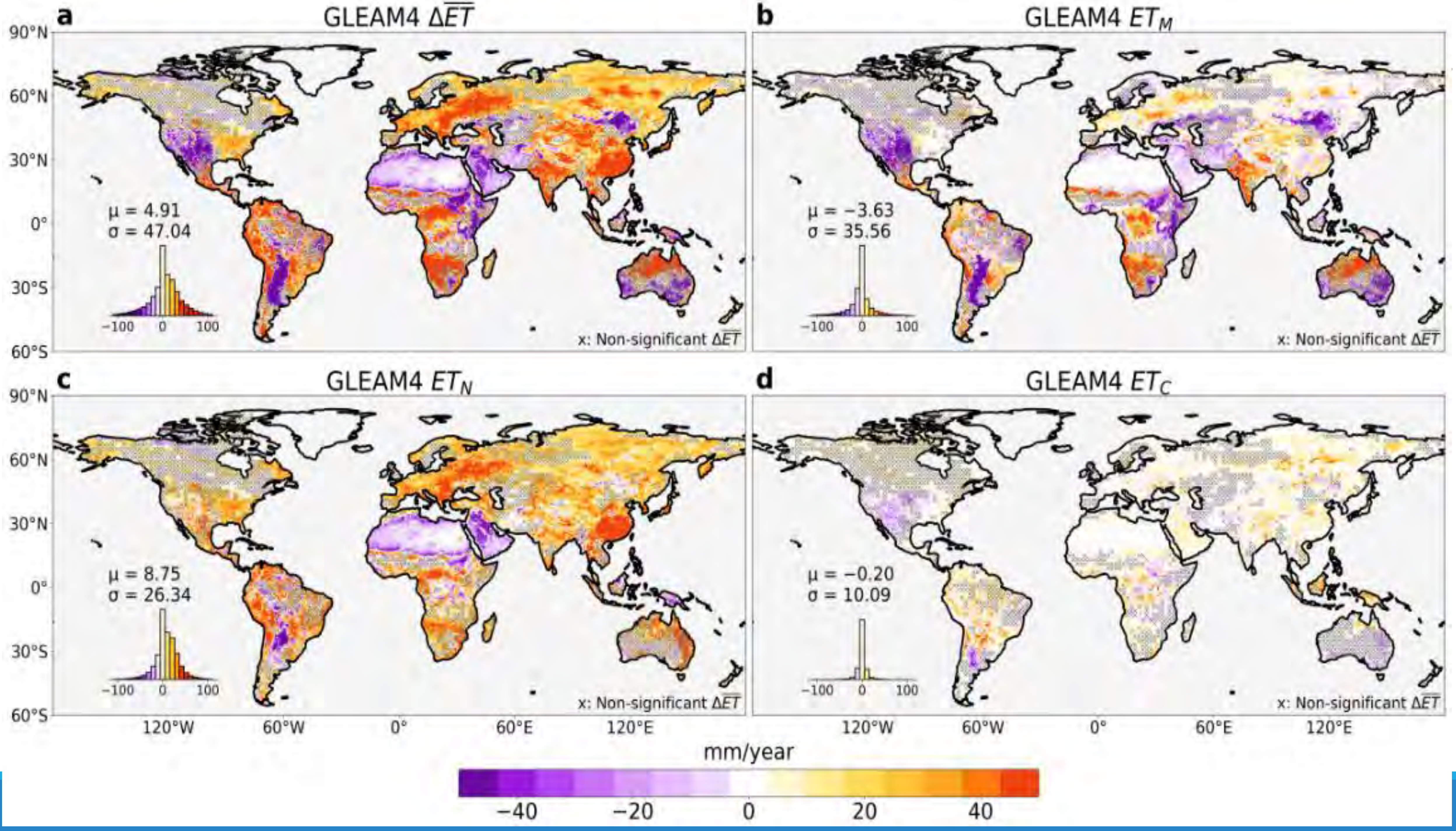
The change in ET is largely attributable to ET_N: the non-moisture pathway



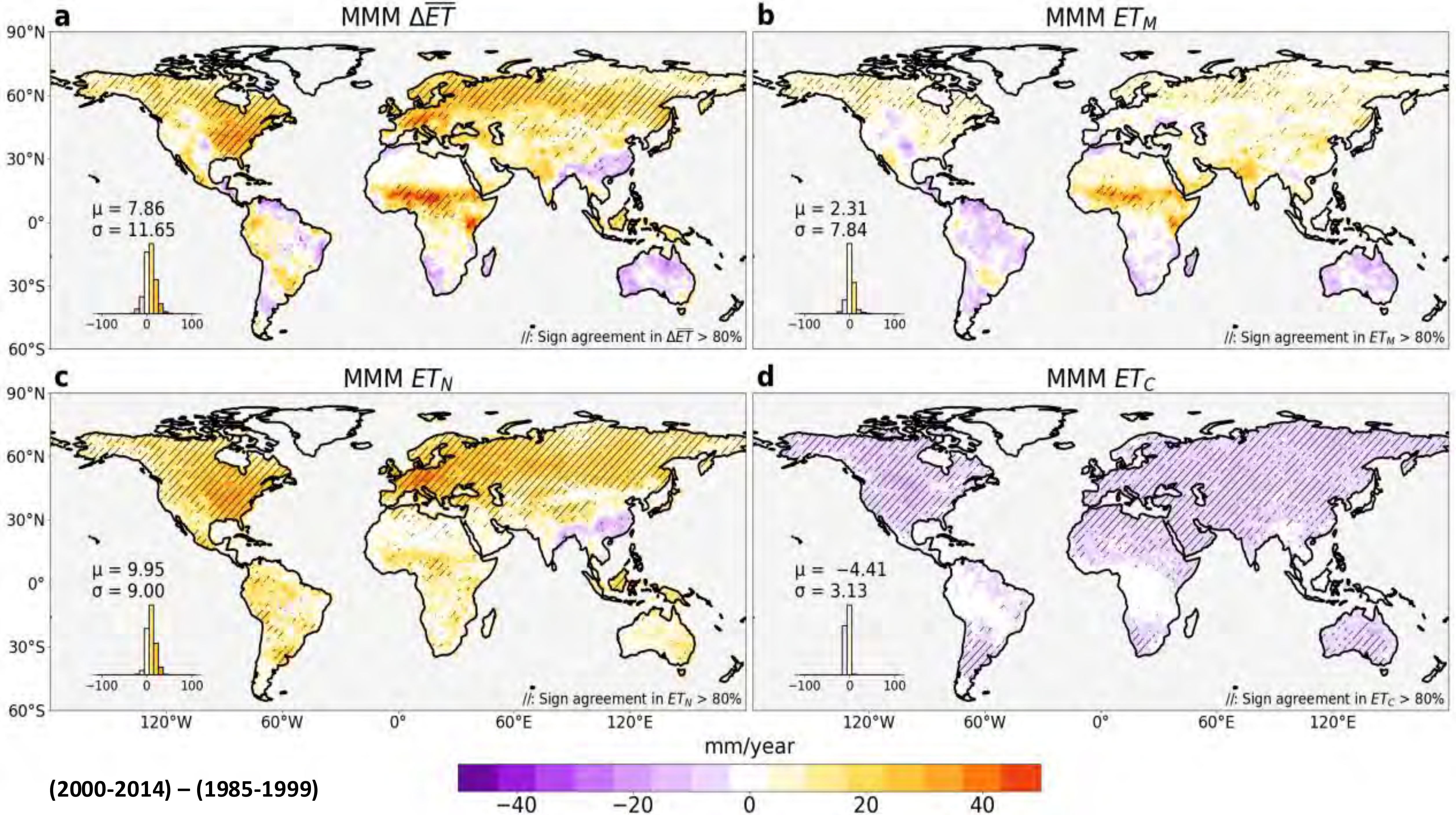
The functional relationship shifts to higher ET for a large range of SM values

The PDF shifts left, towards drier conditions

In the wet regime: little sensitivity of ET to SM

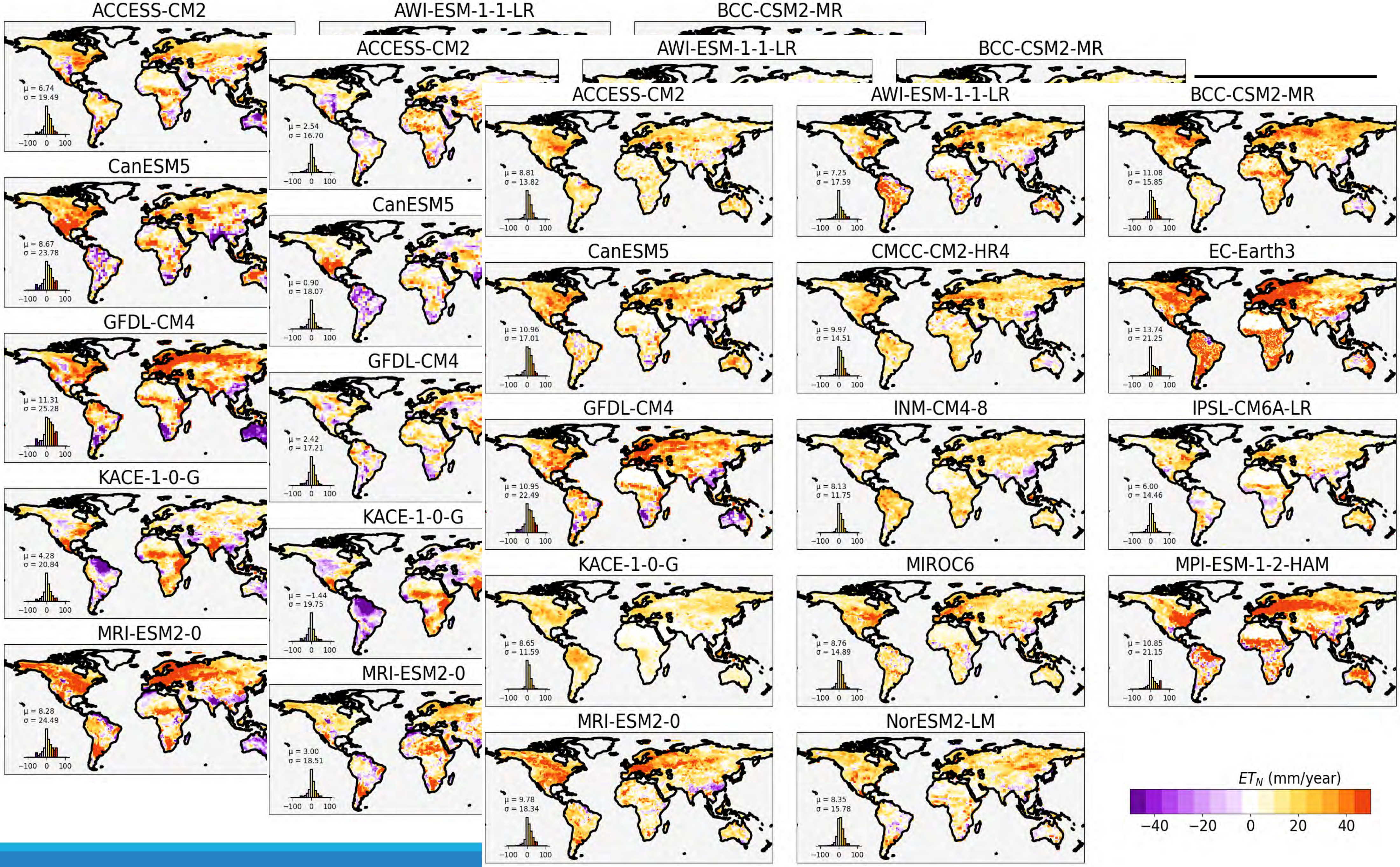


a
GLEAM4 $\Delta\overline{ET}$
b
GLEAM4 ET_M
c
GLEAM4 ET_N
d
GLEAM4 ET_C
90°N
60°N
30°N
0°
30°S
60°S
120°W
60°W
0°
60°E
120°E
μ = 4.91
σ = 47.04
μ = −3.63
σ = 35.56
μ = 8.75
σ = 26.34
μ = −0.20
σ = 10.09
−100
0
100
x: Non-significant $\Delta\overline{ET}$
mm/year
−40
−20
0
20
40



(2000-2014) – (1985-1999)

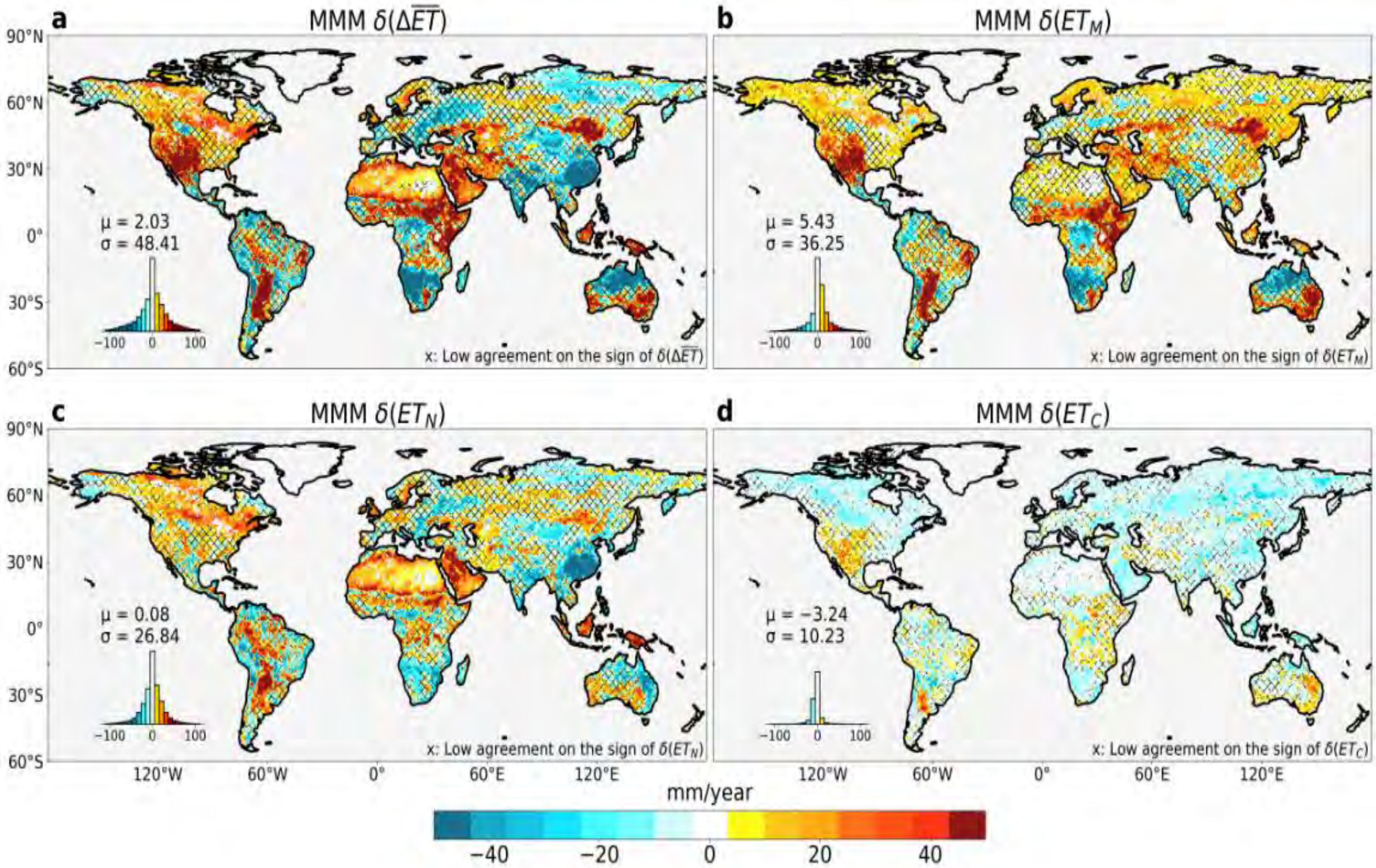
ΔET, *ET_M*, *ET_N* in different models



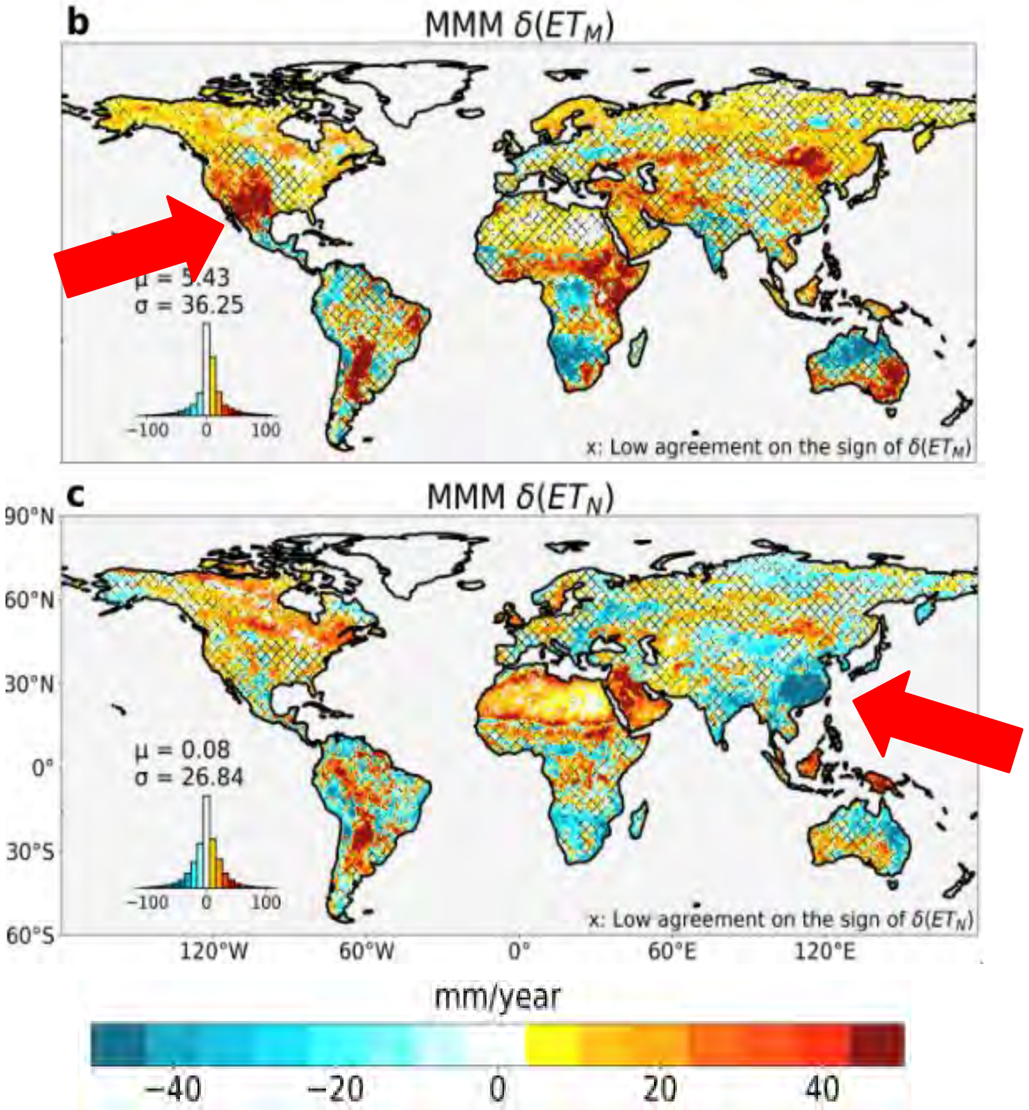
δ: individual model minus GLEAM

Deviation from GLEAM.

Where MMM=0, sign of δ will be opposite of GLEAM signal.



δ: individual model minus GLEAM



US SW: Model deviations from GLEAM attributable to the moisture pathway $\boldsymbol{ET_M}$

- GLEAM shows substantial ET decline, consistent with Simpson et al (2024) and others
- ET in most models changes very little, *largely because the SM PDF does not dry out enough*

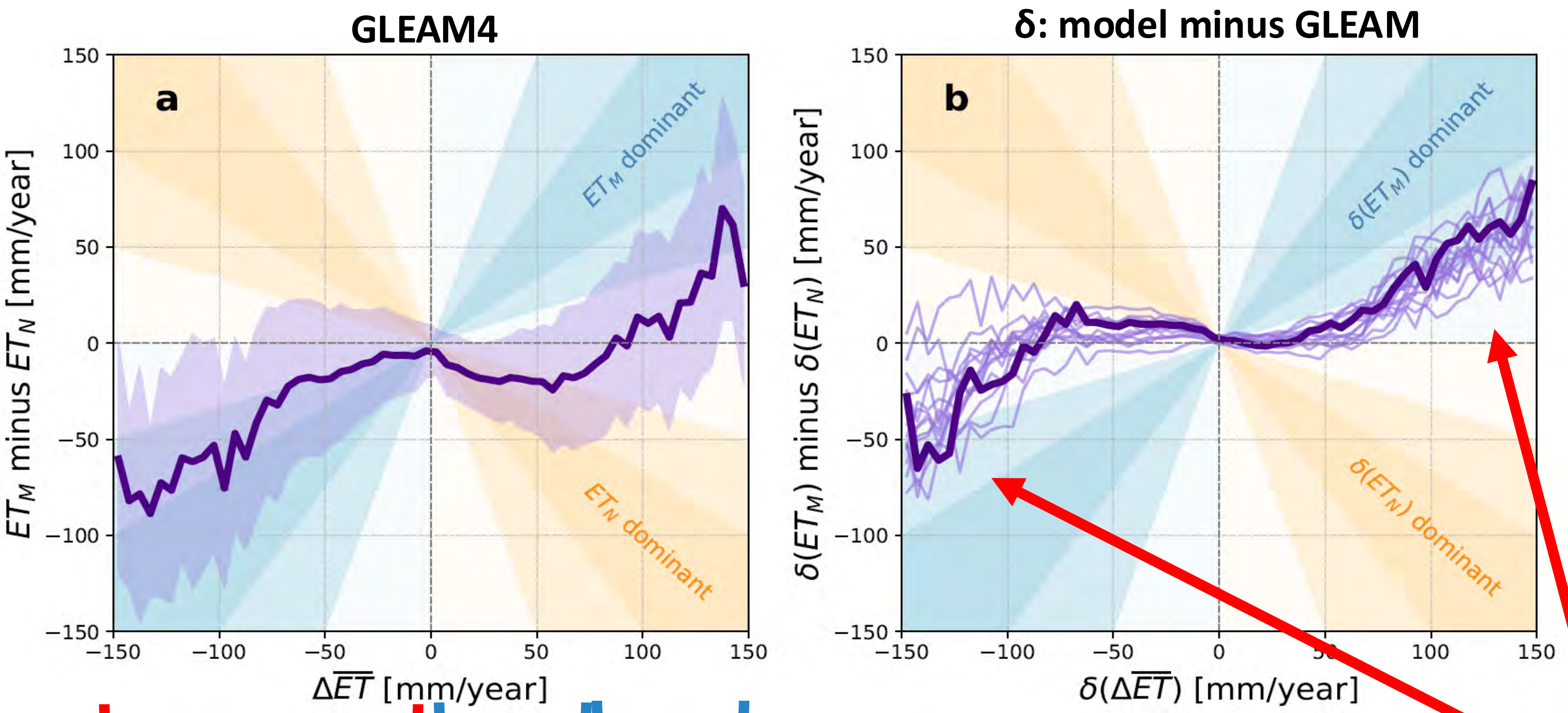
SE China: Model deviations from GLEAM attributable to the non-moisture pathway $\boldsymbol{ET_N}$

- GLEAM shows ET increases in this region
- While the models capture most $\boldsymbol{ET_N}$-forced signals, this area is entirely missed
- Wang et al (2021): *"Incorrect Asian aerosols affecting the attribution and projection of regional climate change in CMIP6 models"*

What do the models fail to capture?

- Vegetation representation? Soil physics of arid regions?
- Aerosol forcing? SST biases?
- *Analyses of LESFMIP simulations could help sort this out*

Attributable responses



Models do a better job of capturing the non-moisture pathway

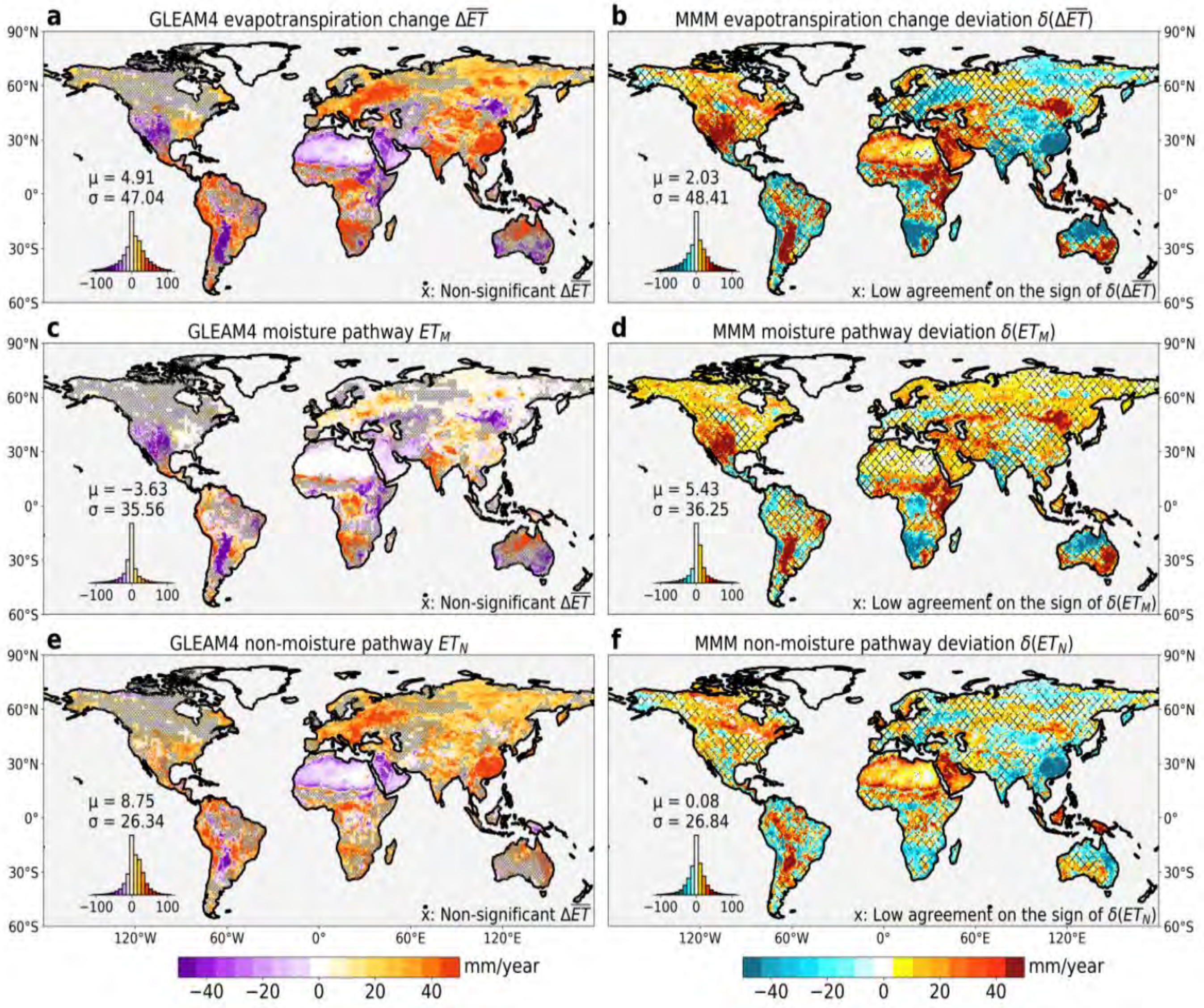
For declining ET, moisture pathway is dominant

For moderate ET increases, non-moisture pathway is dominant

For large ET increases, moisture pathway is dominant

Large model deviations: models are not capturing the moisture pathway

Summary



- An empirical approach separates ET changes into pathways related to
  (1) **Soil Moisture availability** and
  (2) **Other factors** *(e.g., radiation, aerosols, vegetation dynamics, etc.)*

- Observationally-based data show complicated regional changes in ET

- The biggest changes are attributable to Soil Moisture availability
  → ***models fail to capture this pathway***

- Models do a better job capturing moderate increases in ET attributable to the non-moisture pathway

Thank you!

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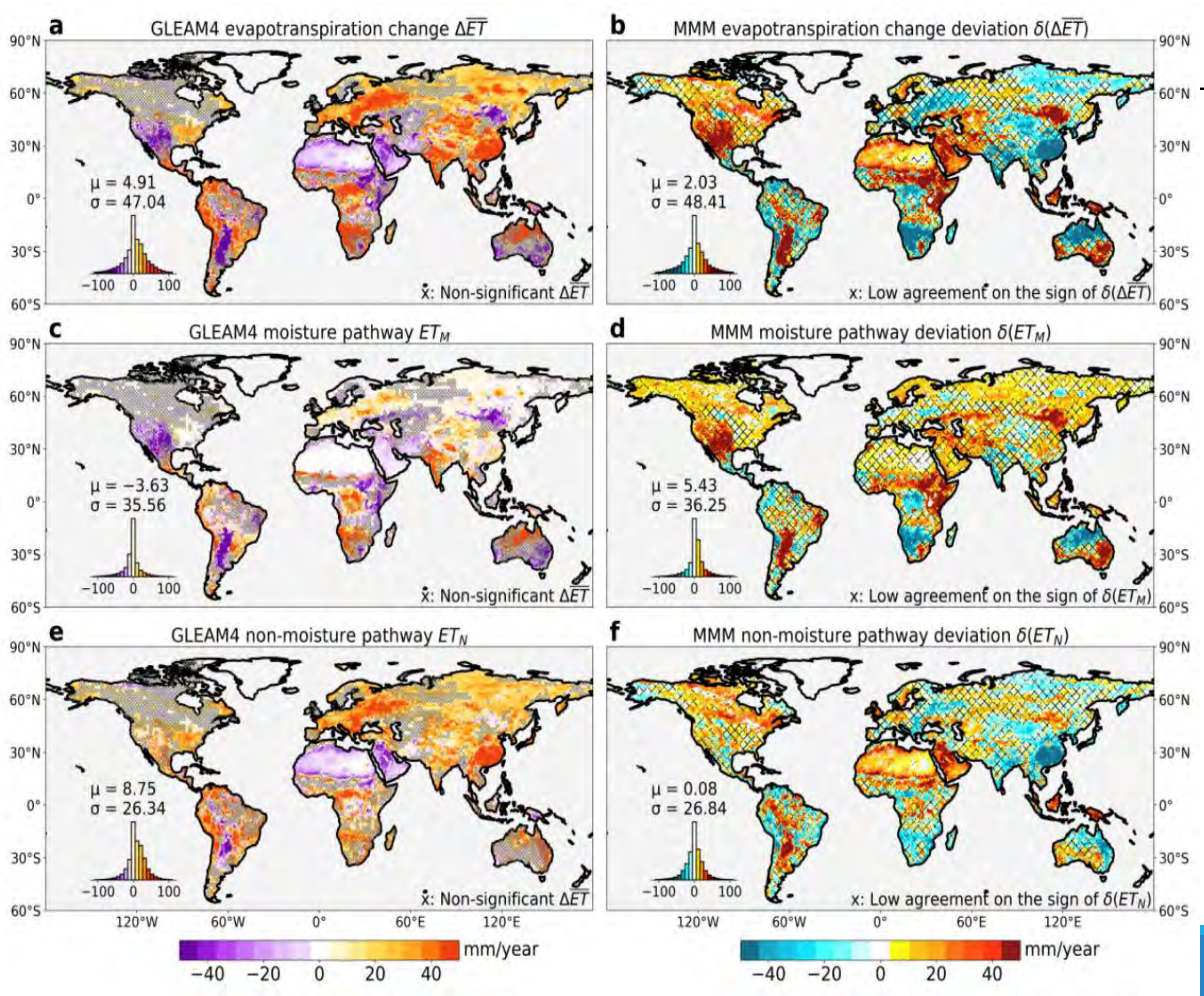
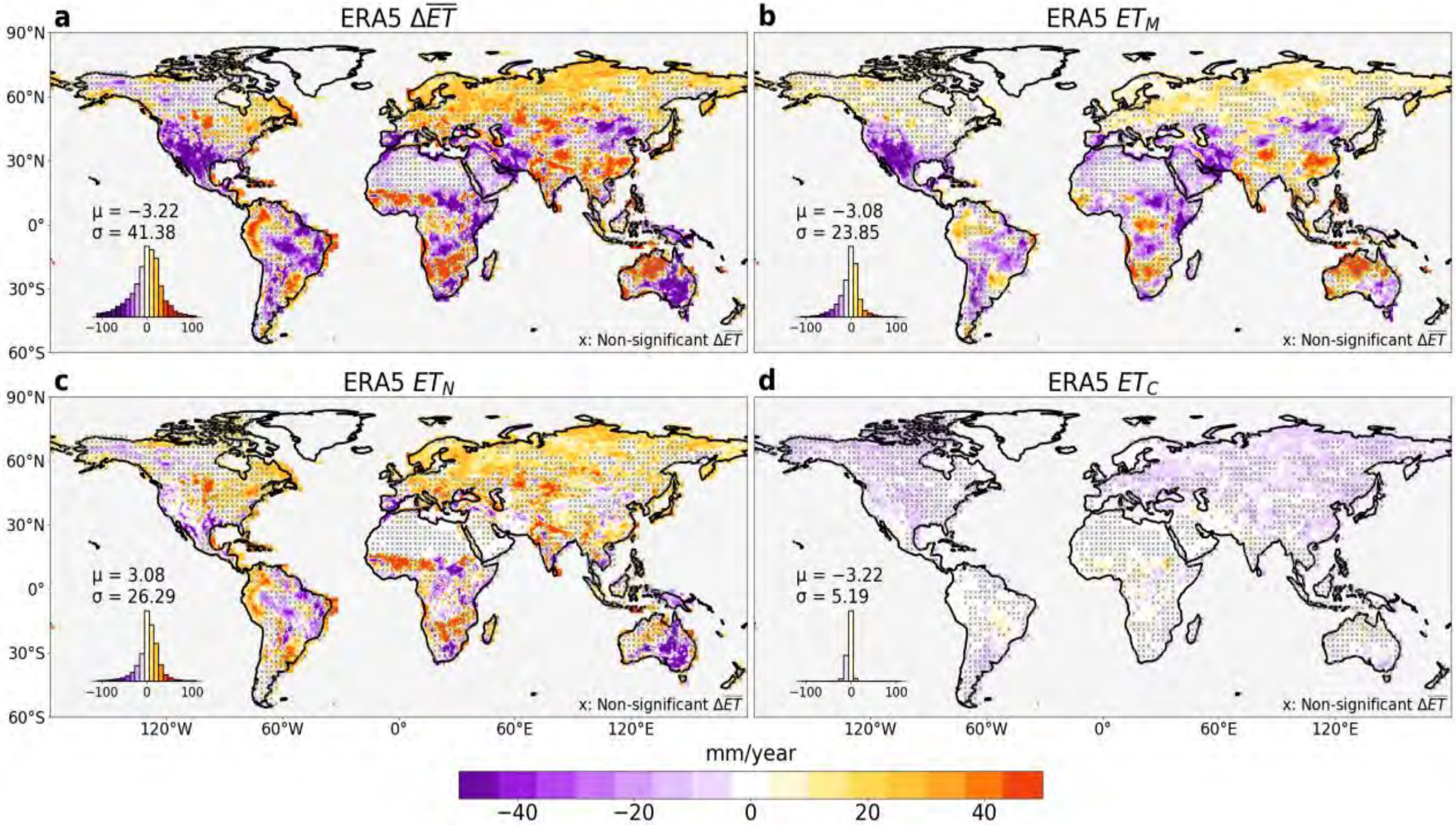
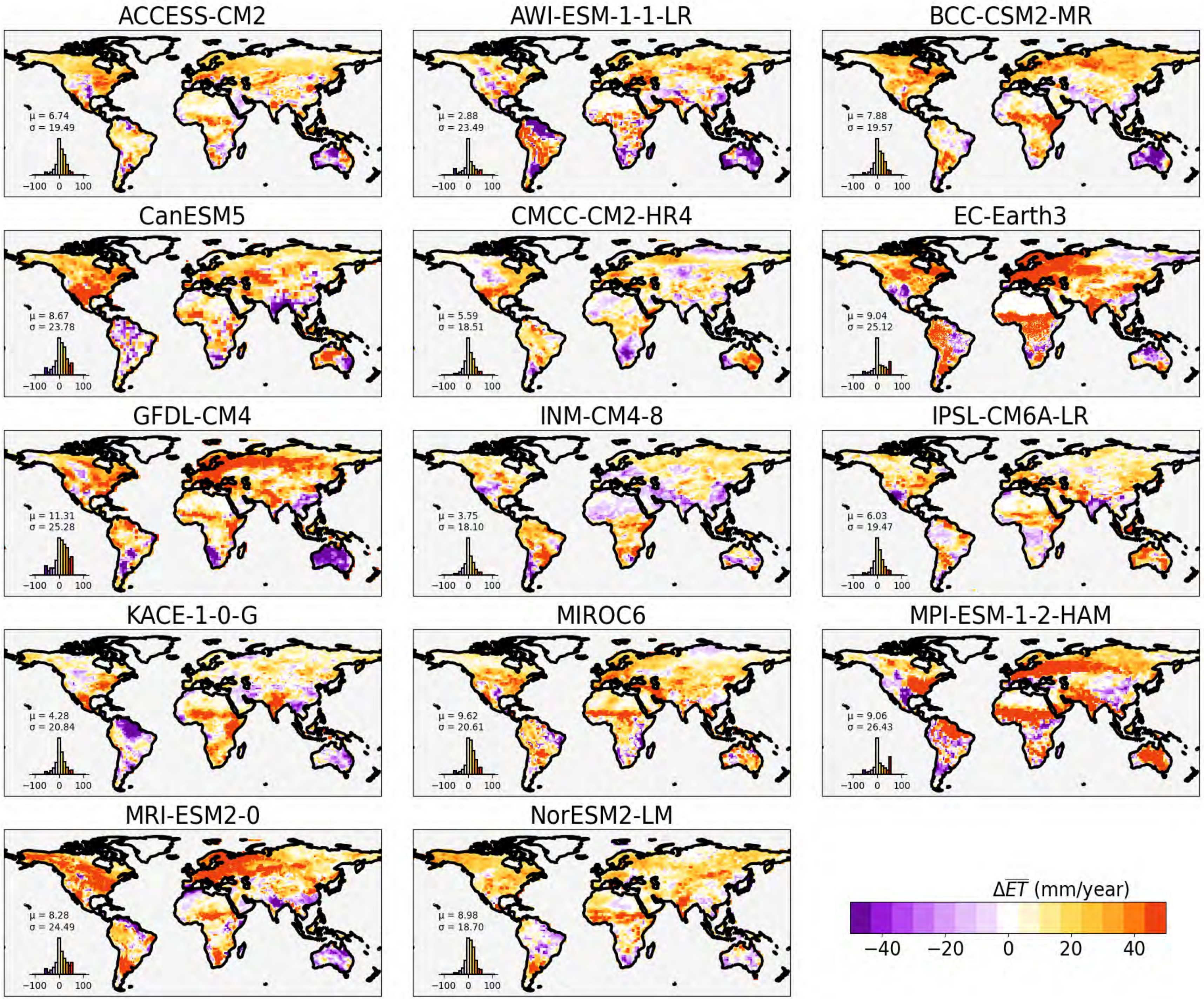
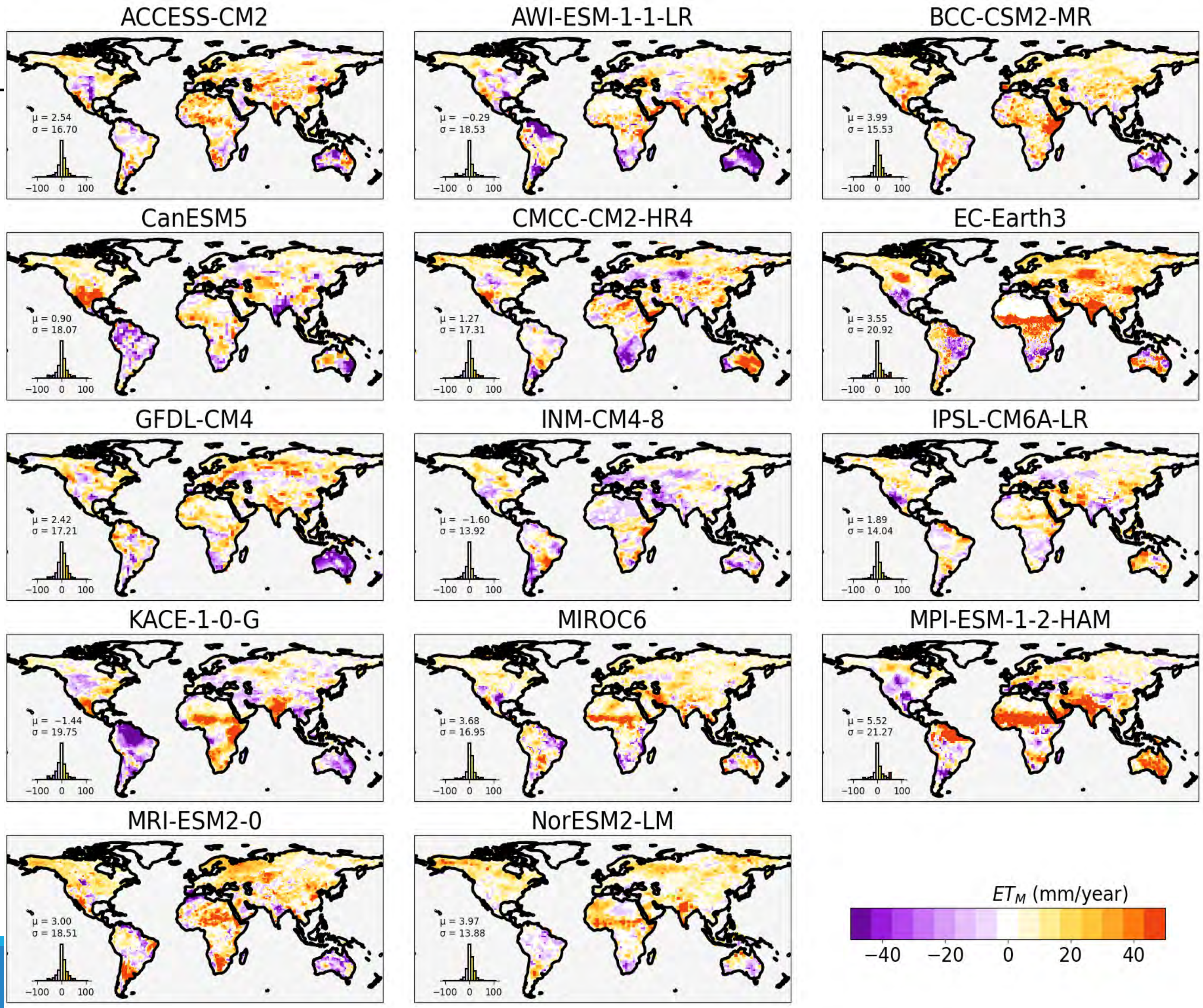

a GLEAM4 evapotranspiration change $\Delta\overline{ET}$
b MMM evapotranspiration change deviation $\delta(\Delta\overline{ET})$
μ = 4.91
σ = 47.04
μ = 2.03
σ = 48.41
x: Non-significant $\Delta\overline{ET}$
x: Low agreement on the sign of $\delta(\Delta\overline{ET})$
c GLEAM4 moisture pathway ET_M
d MMM moisture pathway deviation $\delta(ET_M)$
μ = −3.63
σ = 35.56
μ = 5.43
σ = 36.25
x: Low agreement on the sign of $\delta(ET_M)$
e GLEAM4 non-moisture pathway ET_N
f MMM non-moisture pathway deviation $\delta(ET_N)$
μ = 8.75
σ = 26.34
μ = 0.08
σ = 26.84
x: Low agreement on the sign of $\delta(ET_N)$
90°N 60°N 30°N 0° 30°S 60°S
120°W 60°W 0° 60°E 120°E
−100 0 100
mm/year
−40 −20 0 20 40


a
ERA5 $\Delta\overline{ET}$
b
ERA5 ET_M
c
ERA5 ET_N
d
ERA5 ET_C
90°N
60°N
30°N
0°
30°S
60°S
120°W
60°W
0°
60°E
120°E
μ = −3.22
σ = 41.38
μ = −3.08
σ = 23.85
μ = 3.08
σ = 26.29
μ = −3.22
σ = 5.19
−100
0
100
x: Non-significant $\Delta\overline{ET}$
mm/year
−40
−20
0
20
40

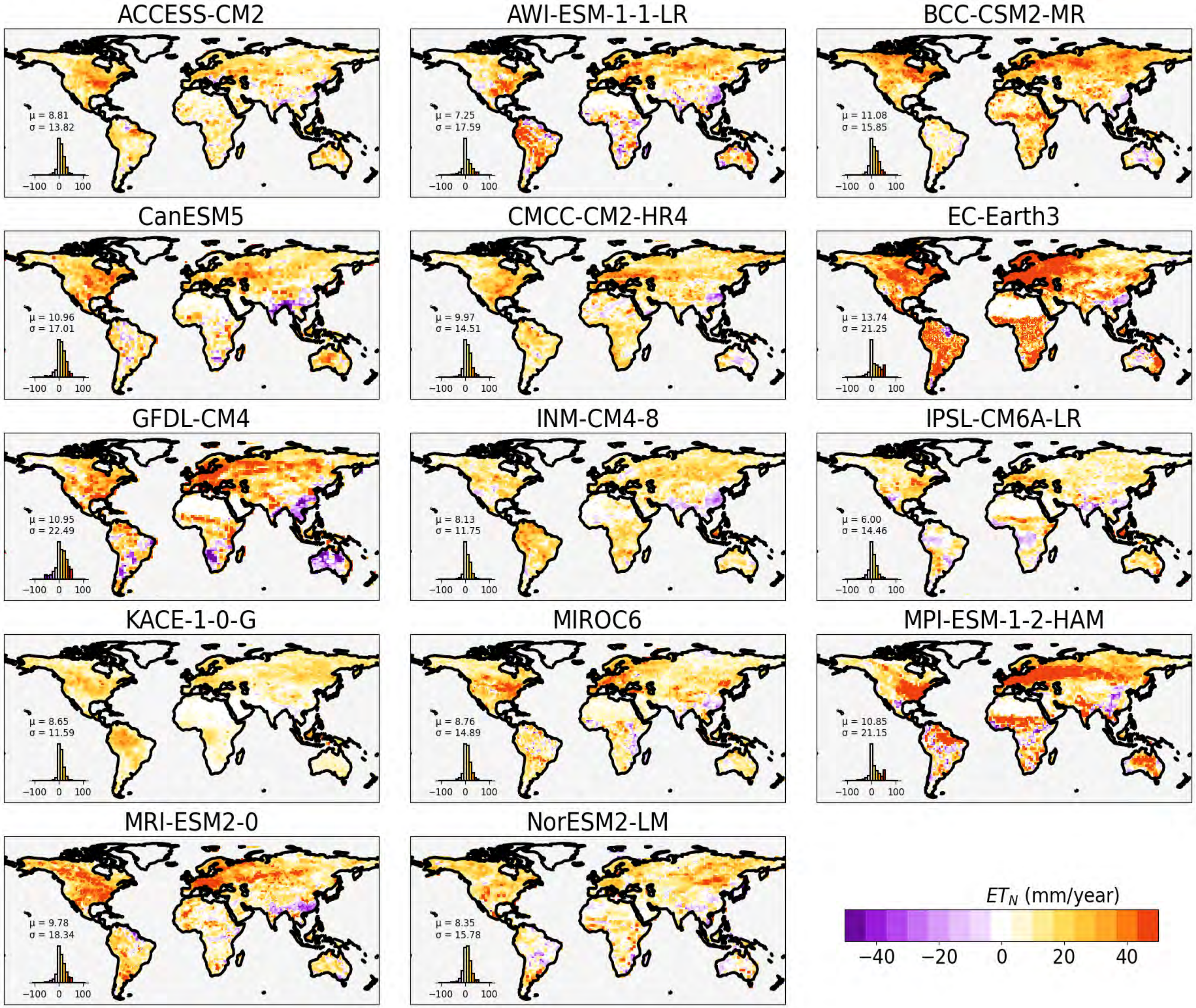
ΔET in different models



ET_M in different models



ET_N in different models



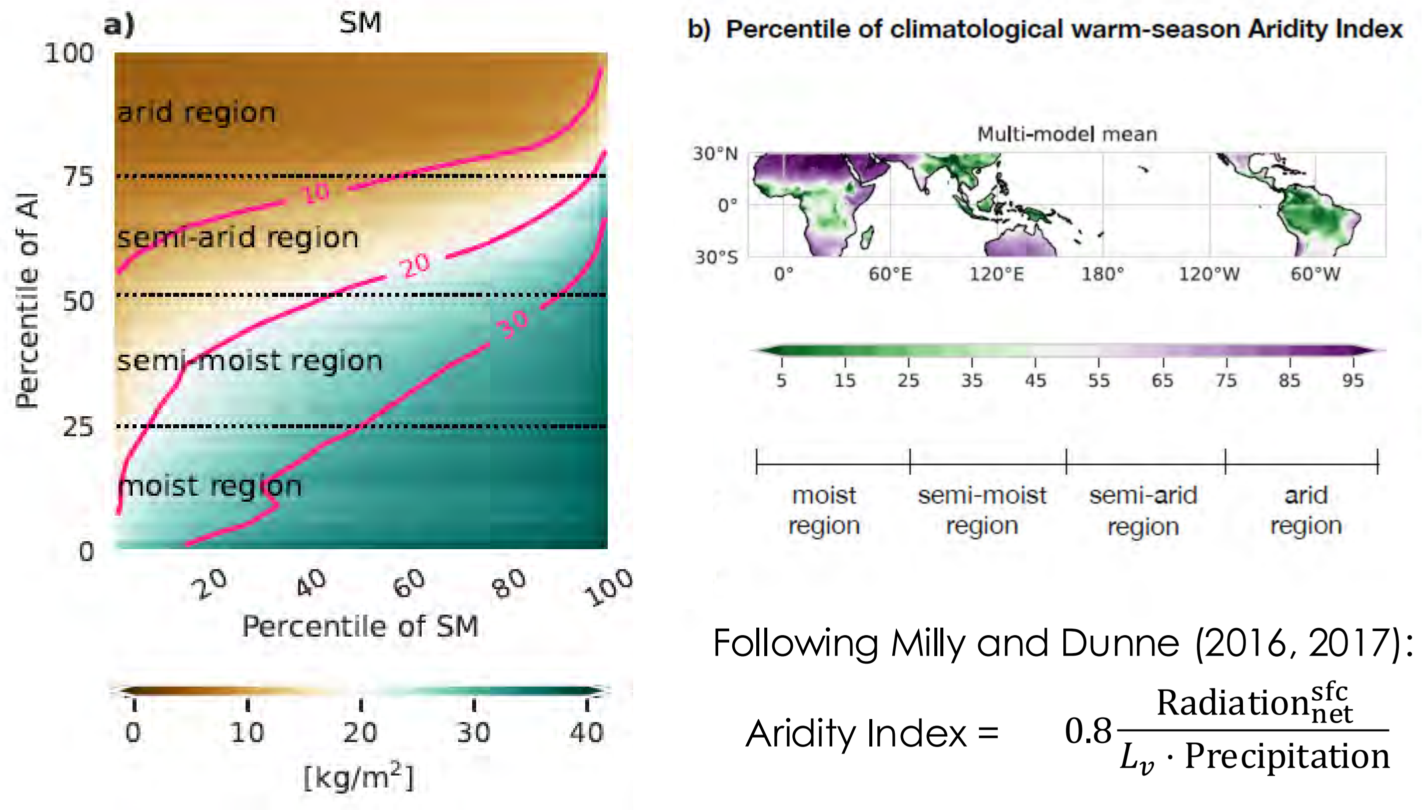
The Soil Moisture - Aridity Index (SM-AI) Percentile phase space

X-axis: daily SM percentiles

- Provides a visual of the PDF of soil moisture
- Can be linked to percent of time a given location is in different SM-ET behavioral regimes

Y-axis: Climatological Aridity Index (AI) percentiles

- An indication of the broad context of each grid point



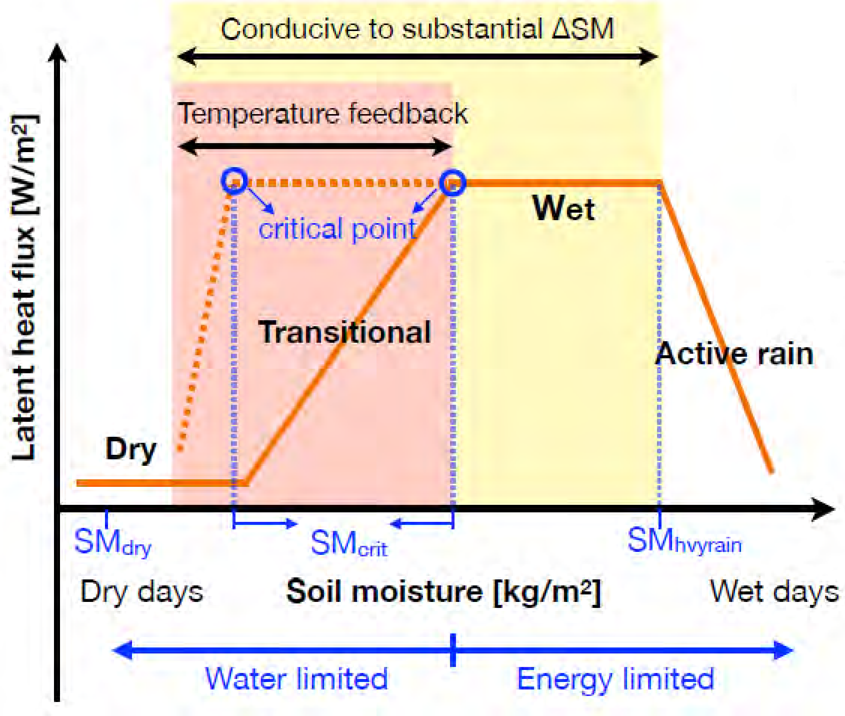
Following Milly and Dunne (2016, 2017):

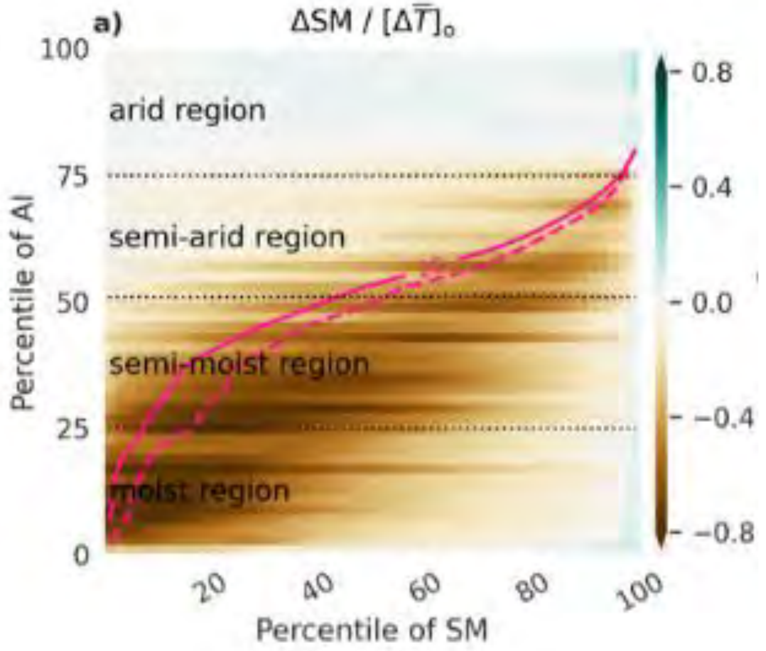
$$\text{Aridity Index} = 0.8\frac{\text{Radiation}_{\text{net}}^{\text{sfc}}}{L_v \cdot \text{Precipitation}}$$

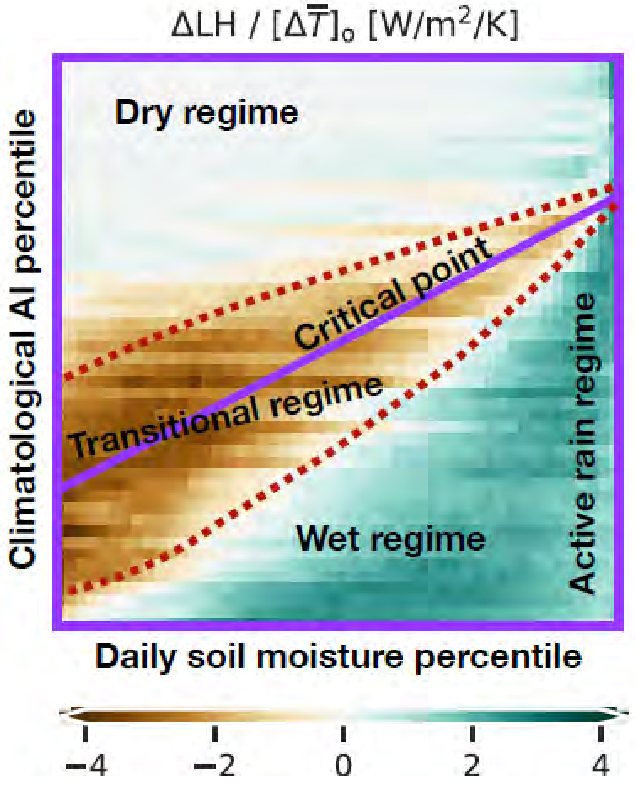
Duan, Findell and Fueglistaler, 2023, *GRL*

Mean pre-industrial control SM and AI of 8 CMIP5 models

The SM-AI Percentile phase space







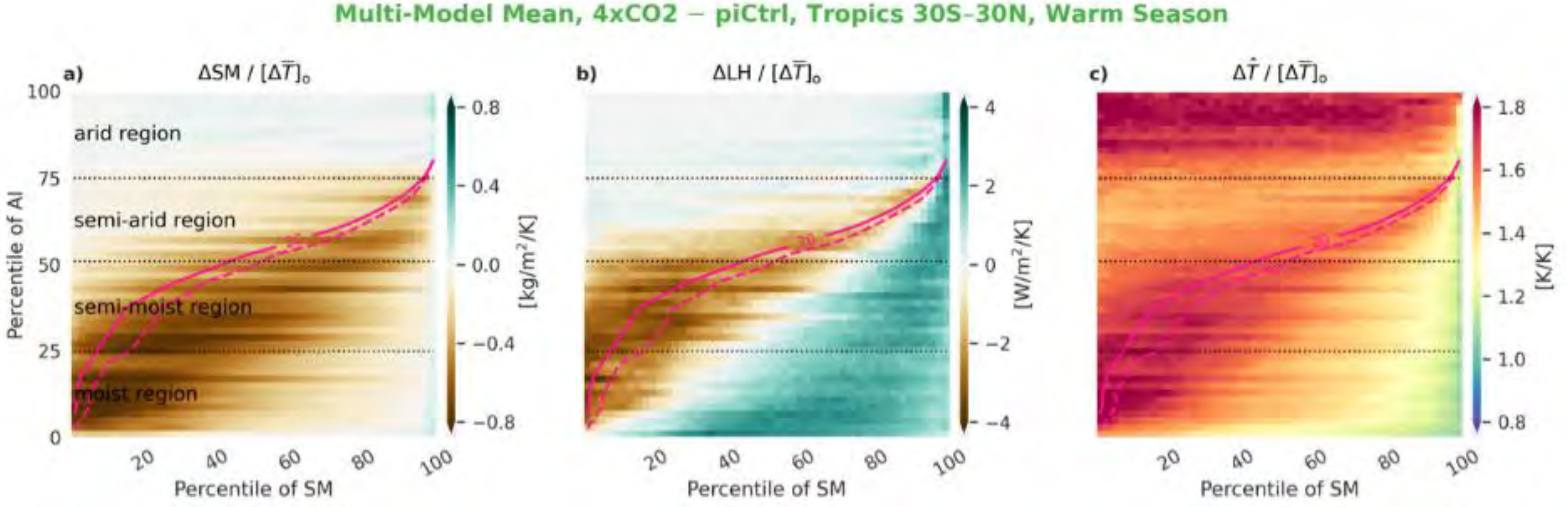
Duan, Findell, and Fueglistaler, 2023, *GRL*

Using 8 CMIP5 models, $4xCO_2$ – preindustrial control experiments

20 kg/m² loosely aligns with the critical point

Temperature response

Duan, Findell, and Fueglistaler, 2023, *GRL*



Daily maximum temperature increases are most pronounced:

- In arid regions: uniform increase on all days
  - PDF change: uniform shift to warmer temperatures
- In moist and semi-moist regions: on days with moisture limitation
  - PDF change: warm shift + lengthening of the warmest tail