Is water availability from the land surface in arid/semi-arid regions mis-represented in CESM?

Isla Simpson, Karen McKinnon, Daniel Kennedy, Dave Lawrence, Flavio Lehner, Richard Seager, KirstenFindell

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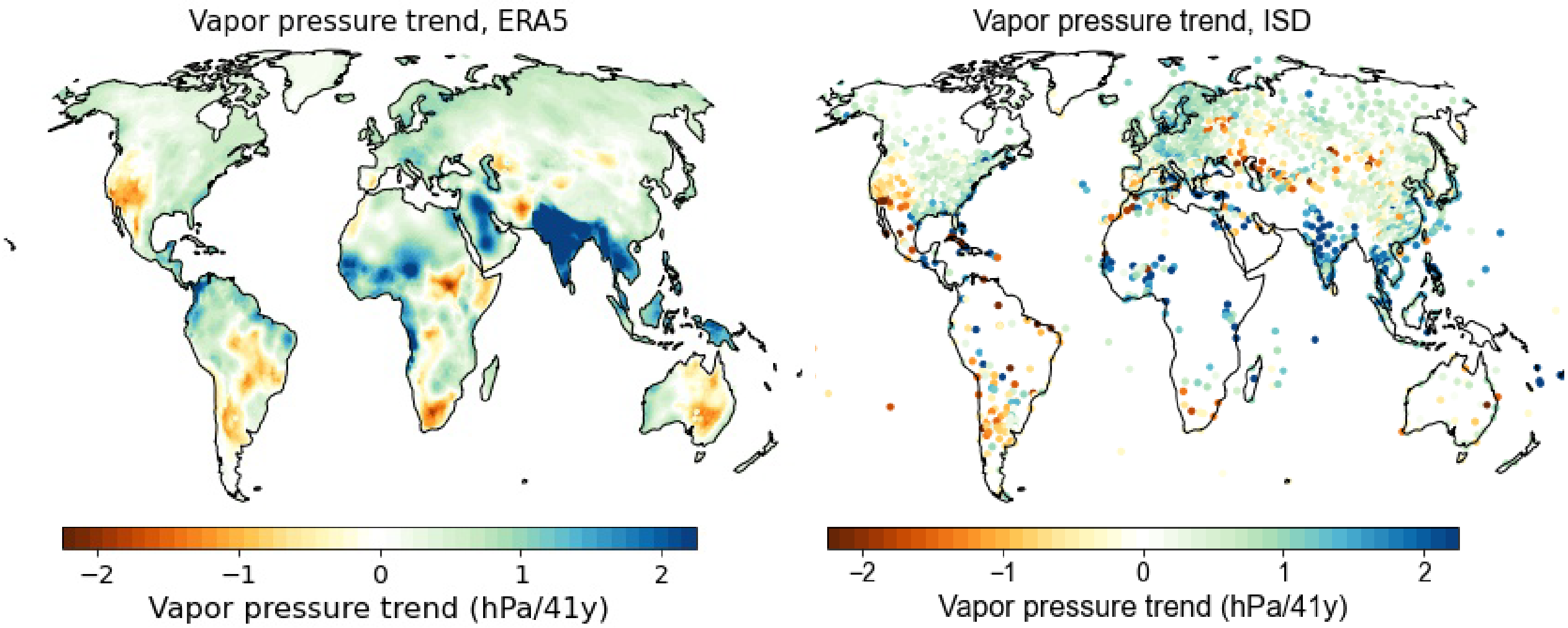
Global near surface vapor pressure trends, annual averaged 1980 -2020



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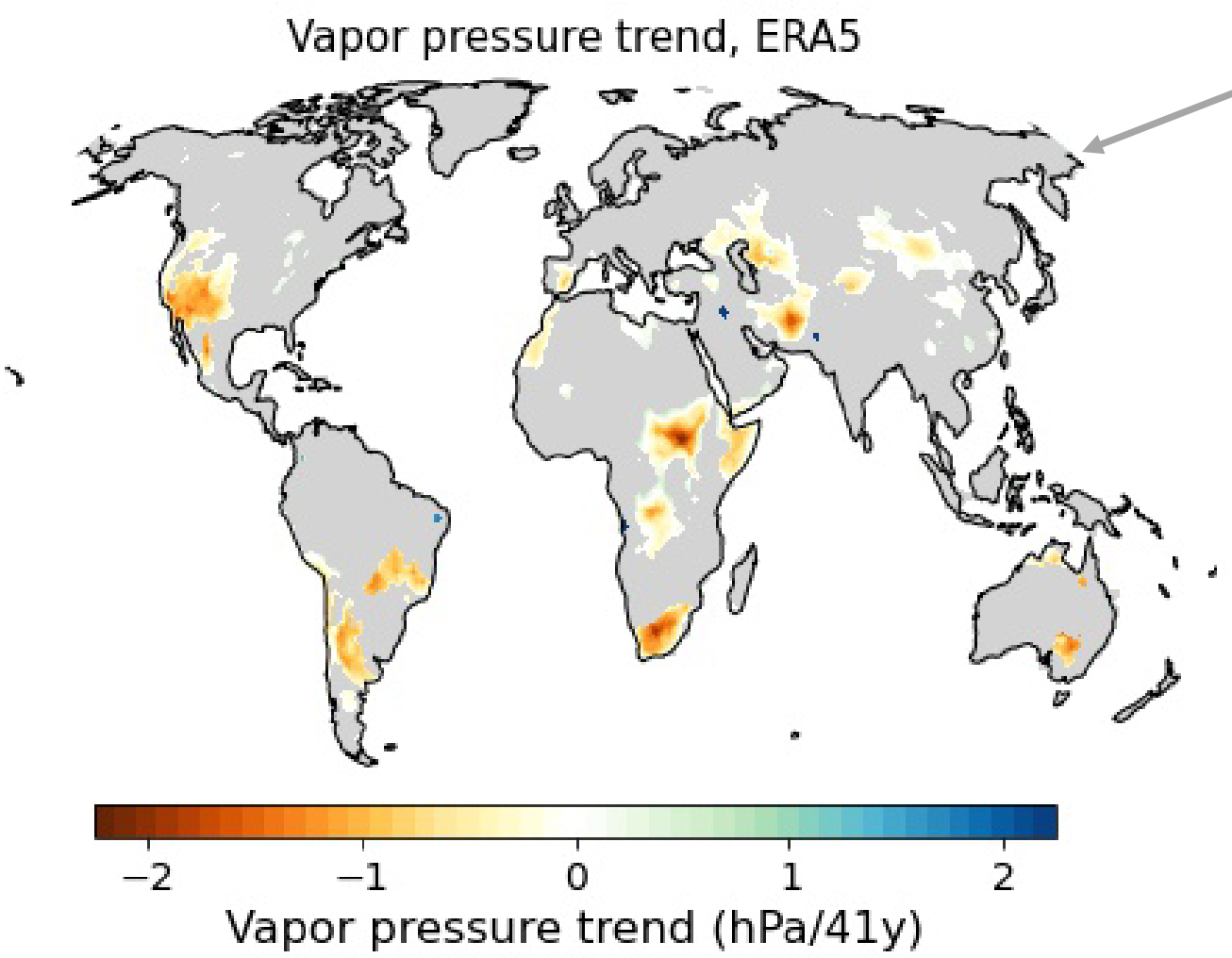

Gray = where the ERA5 trend lies within the spread of the CMIP6 model trends

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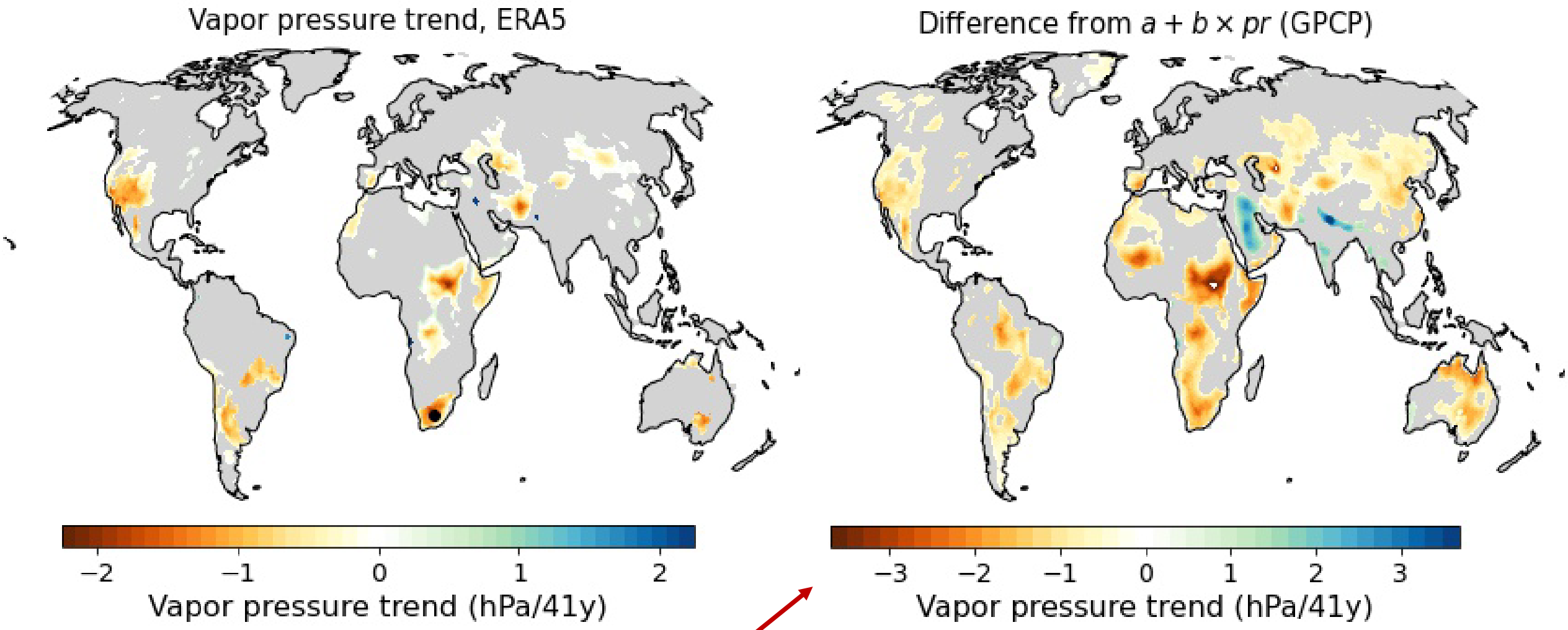

Discrepancy after accounting for local precipitation trends.

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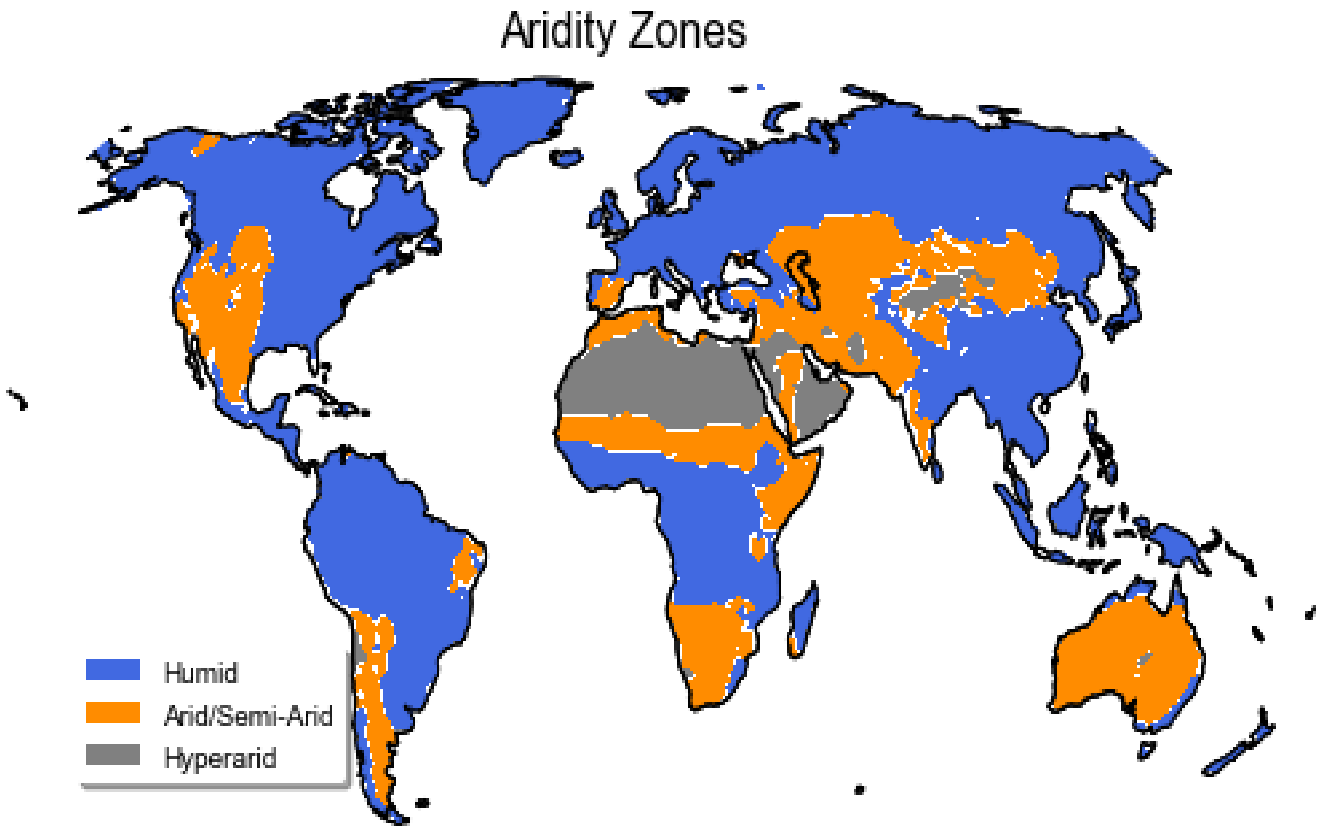
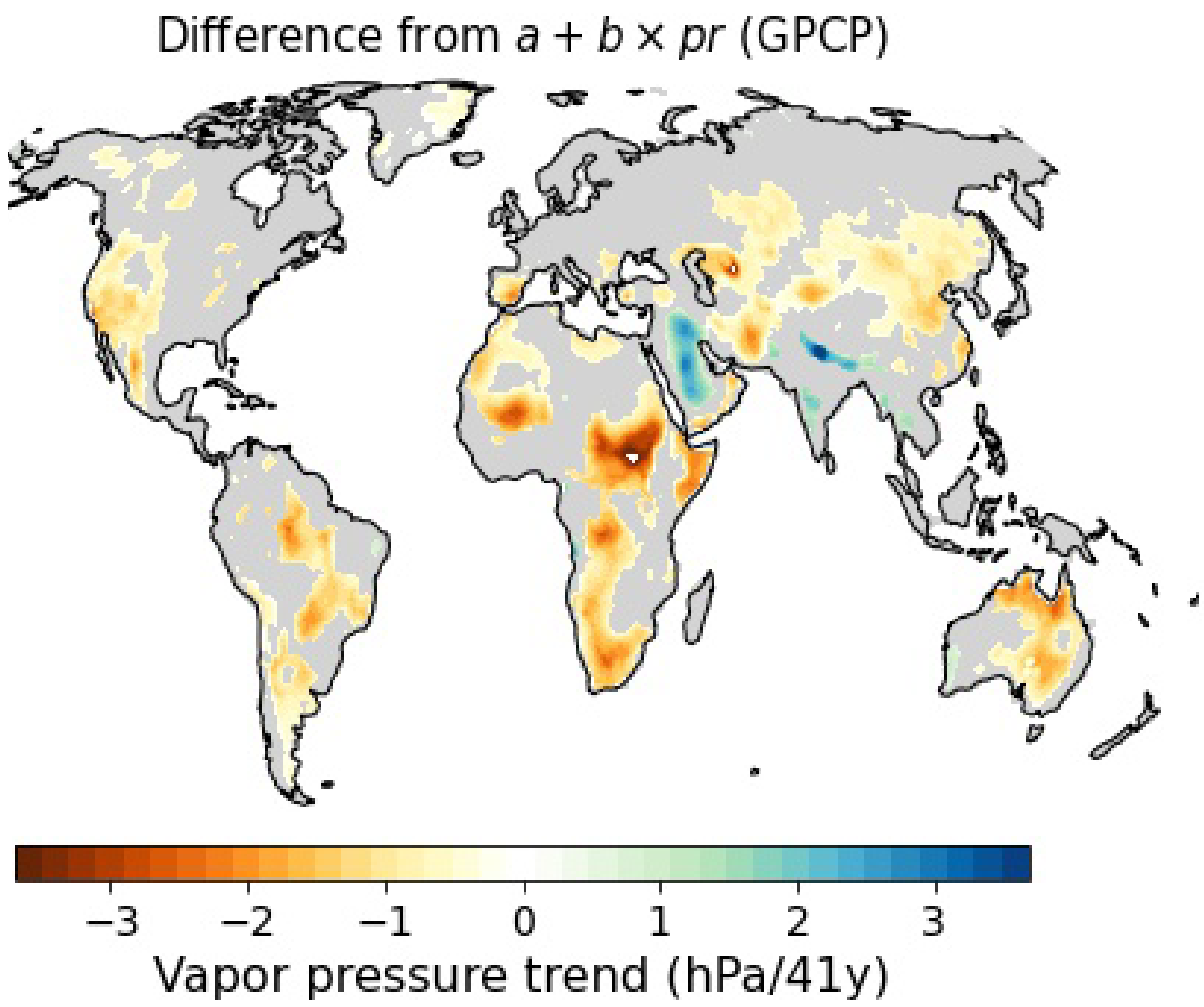


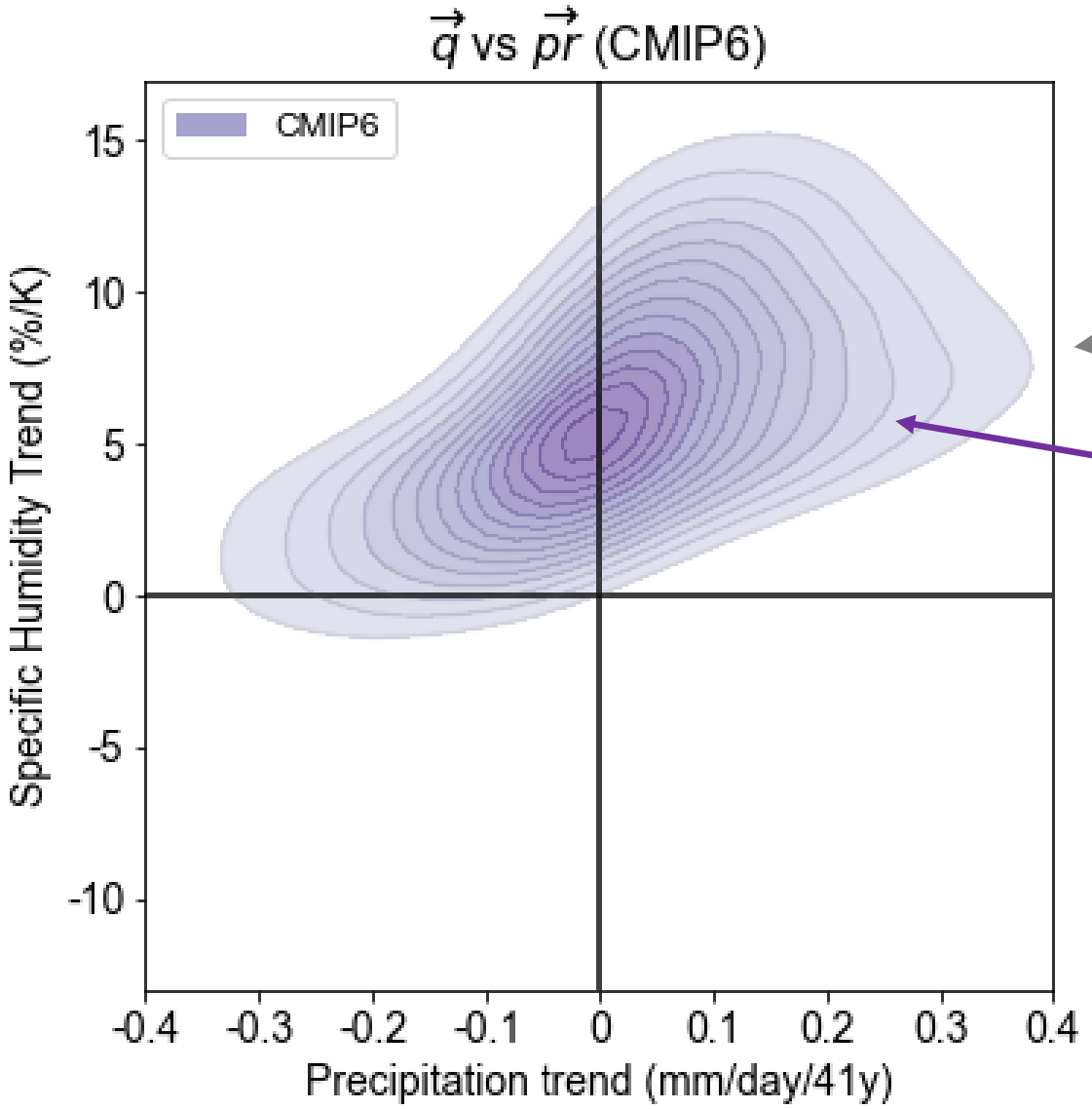


$$\text{Aridity Index} = \frac{P}{PET}$$

Precipitation

Potential Evapotranspiration

Specific humidity trend (%/K) in arid/semi -arid regions versus precipitation trends



Joint pdf of specific humidity trends (expressed as a percentage of the 1980-1990 average, normalized by land area average temperature change) versus precipitation trends.

Relationship across space

CMIP6

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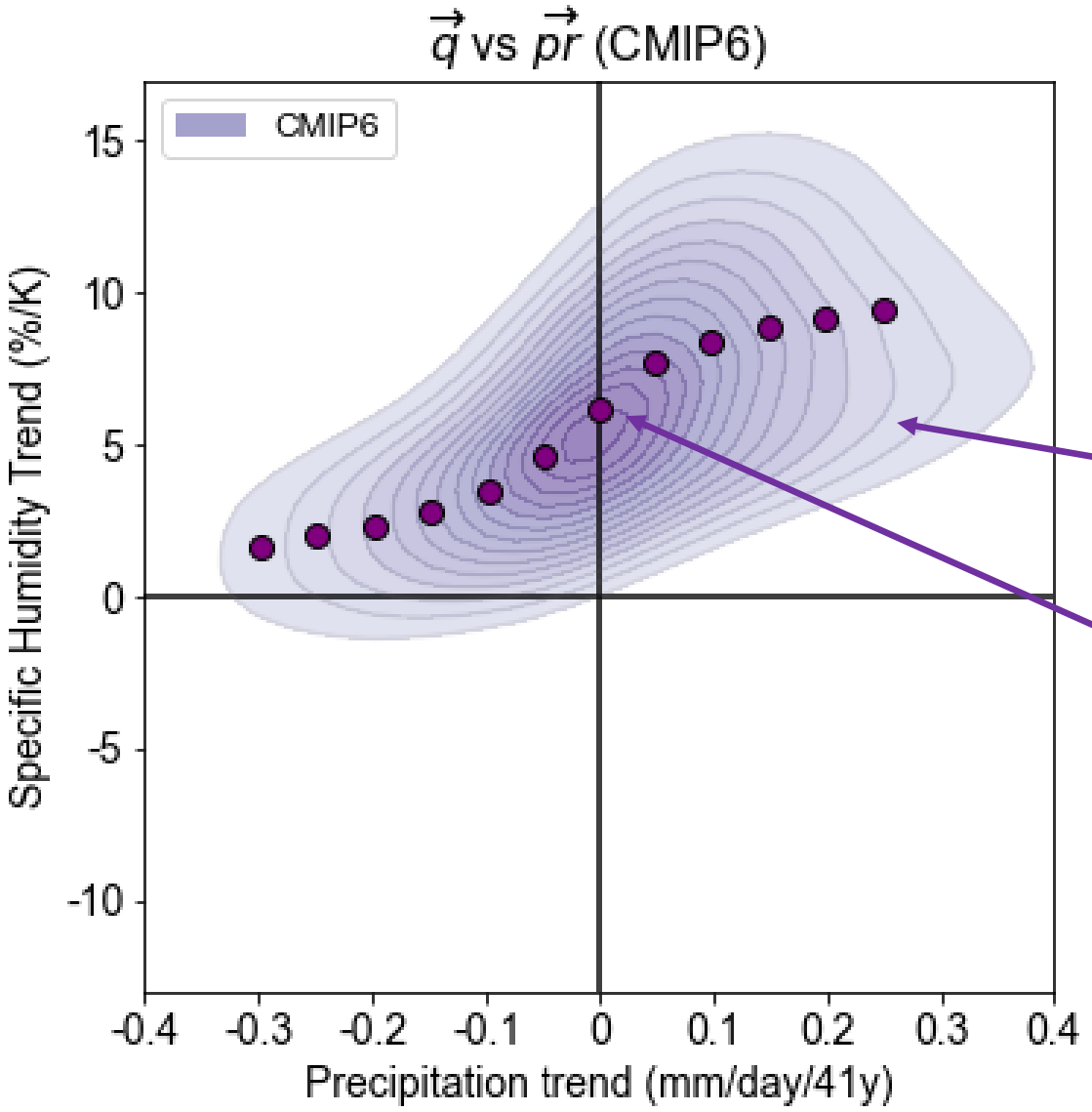

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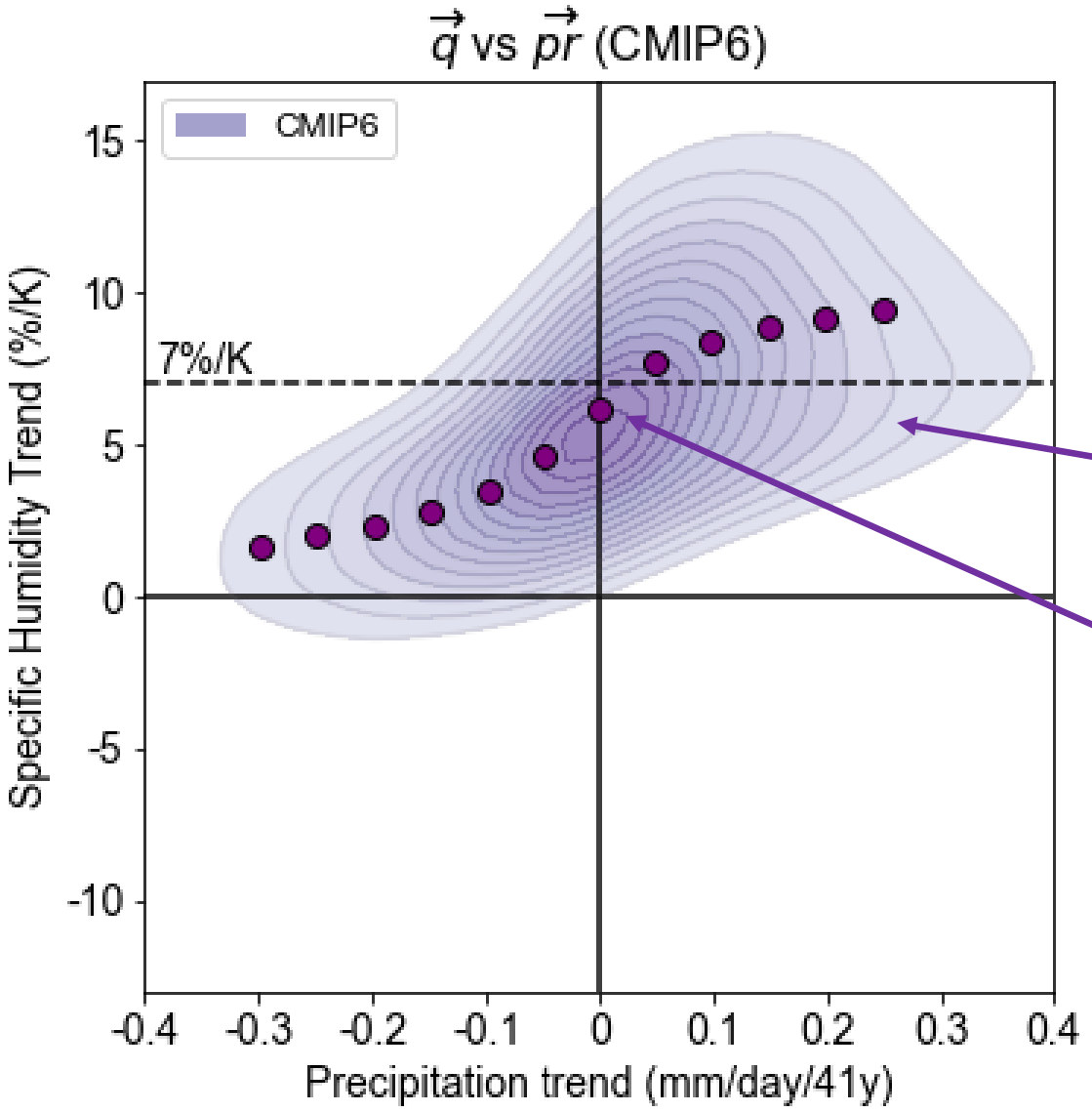

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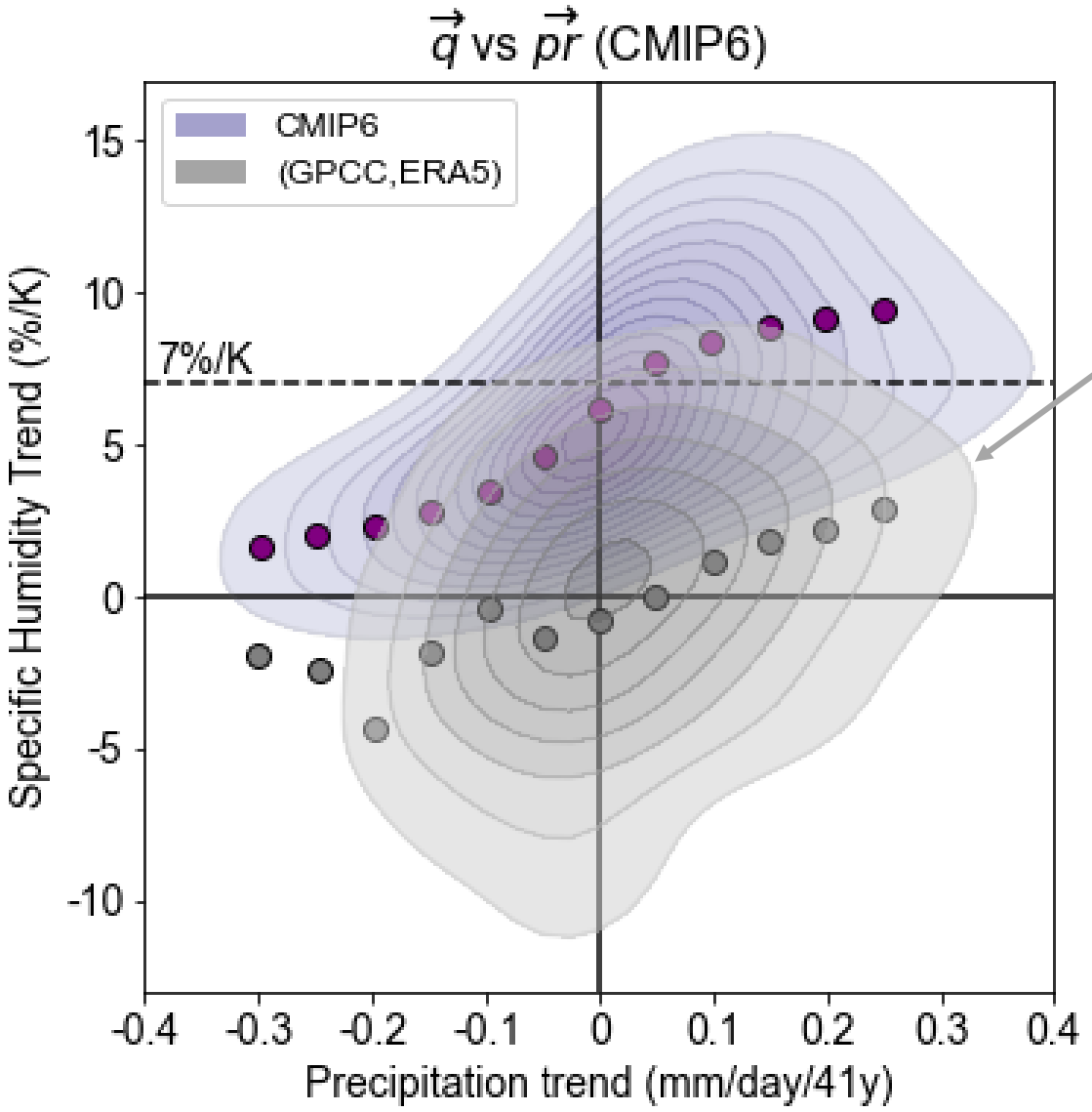

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ERA5 for specific humidity and GPCC for precipitation

Observation-based specific humidity trends are lower at all precipitation trends

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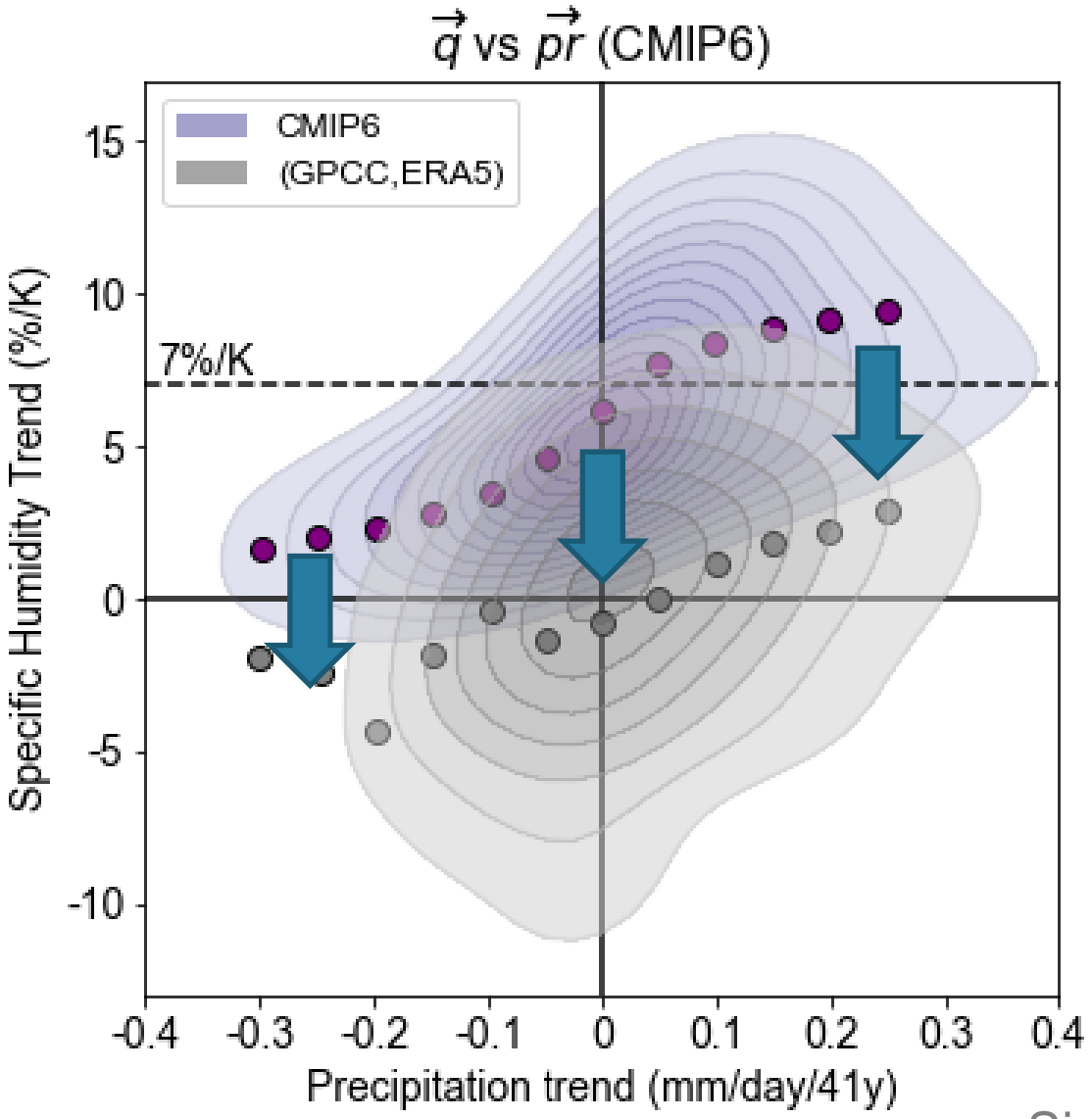

Previous studies have recognized a discrepancy between models and observations in humidity trends (Dunn et al 2017, Douville and Plazotta 2017, Jones and Ricketts 2022, Douville et al 2023)

Simpson et al (2024) PNAS doi:10.1073/pnas.2302480120

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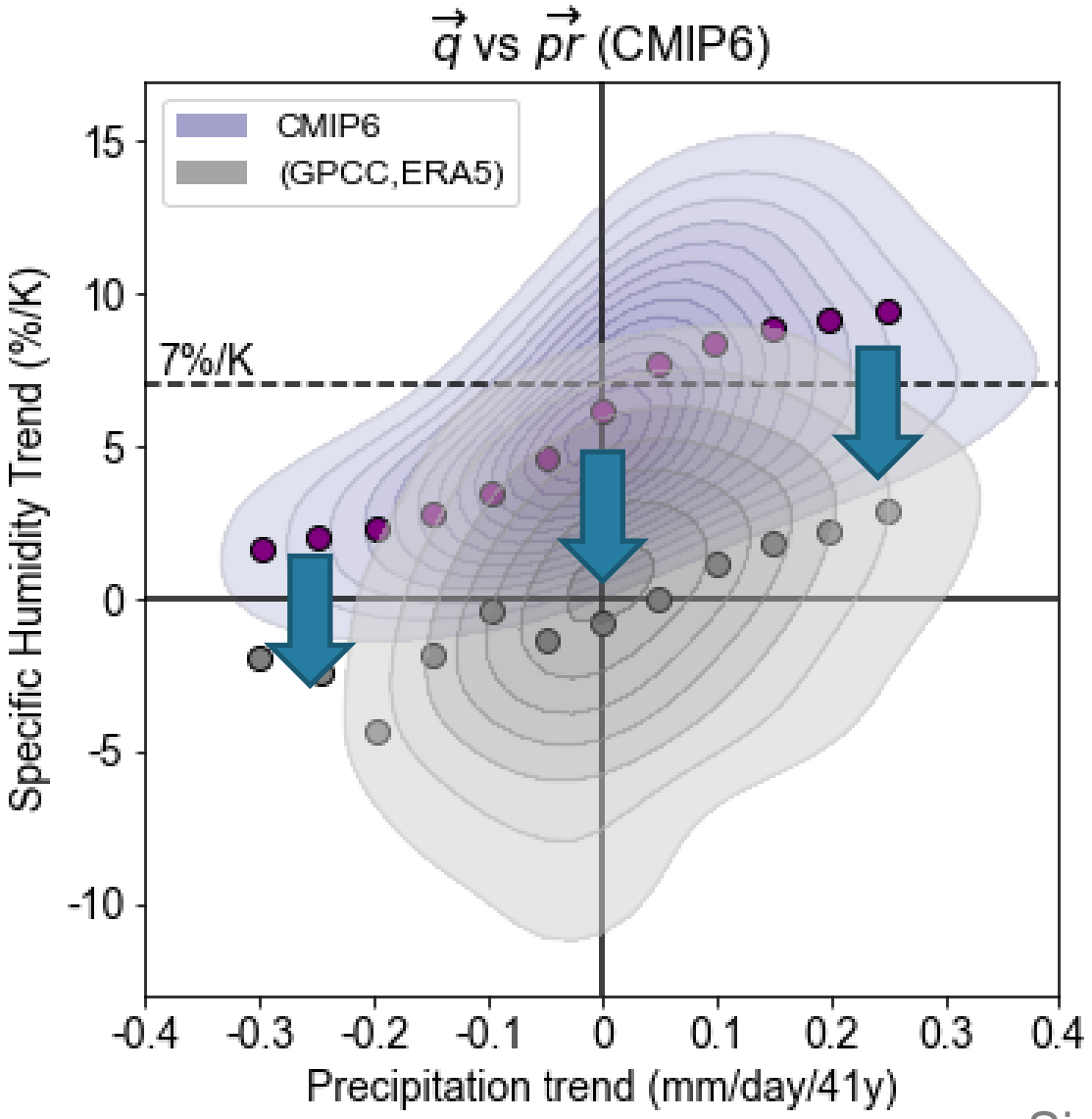

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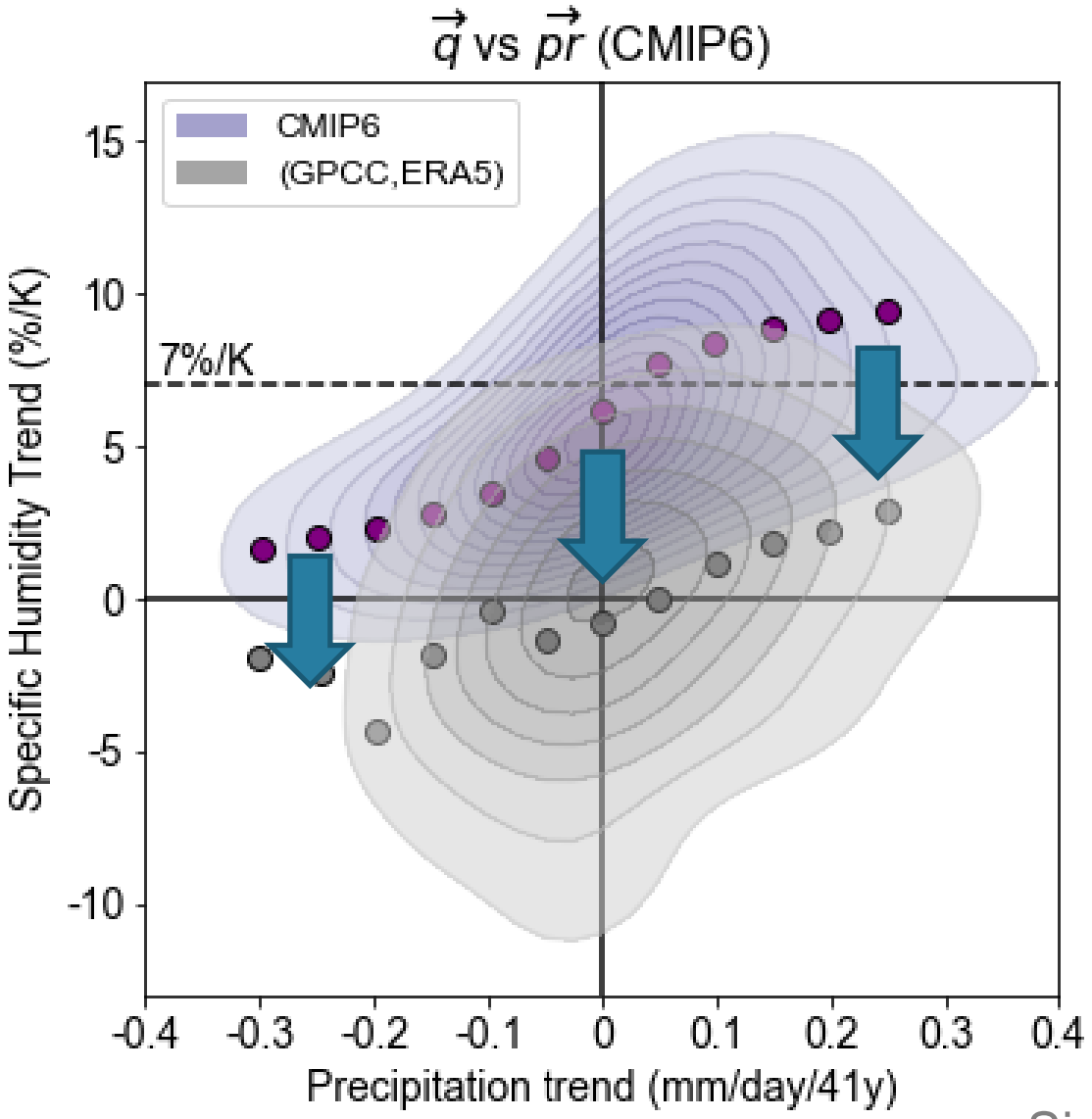

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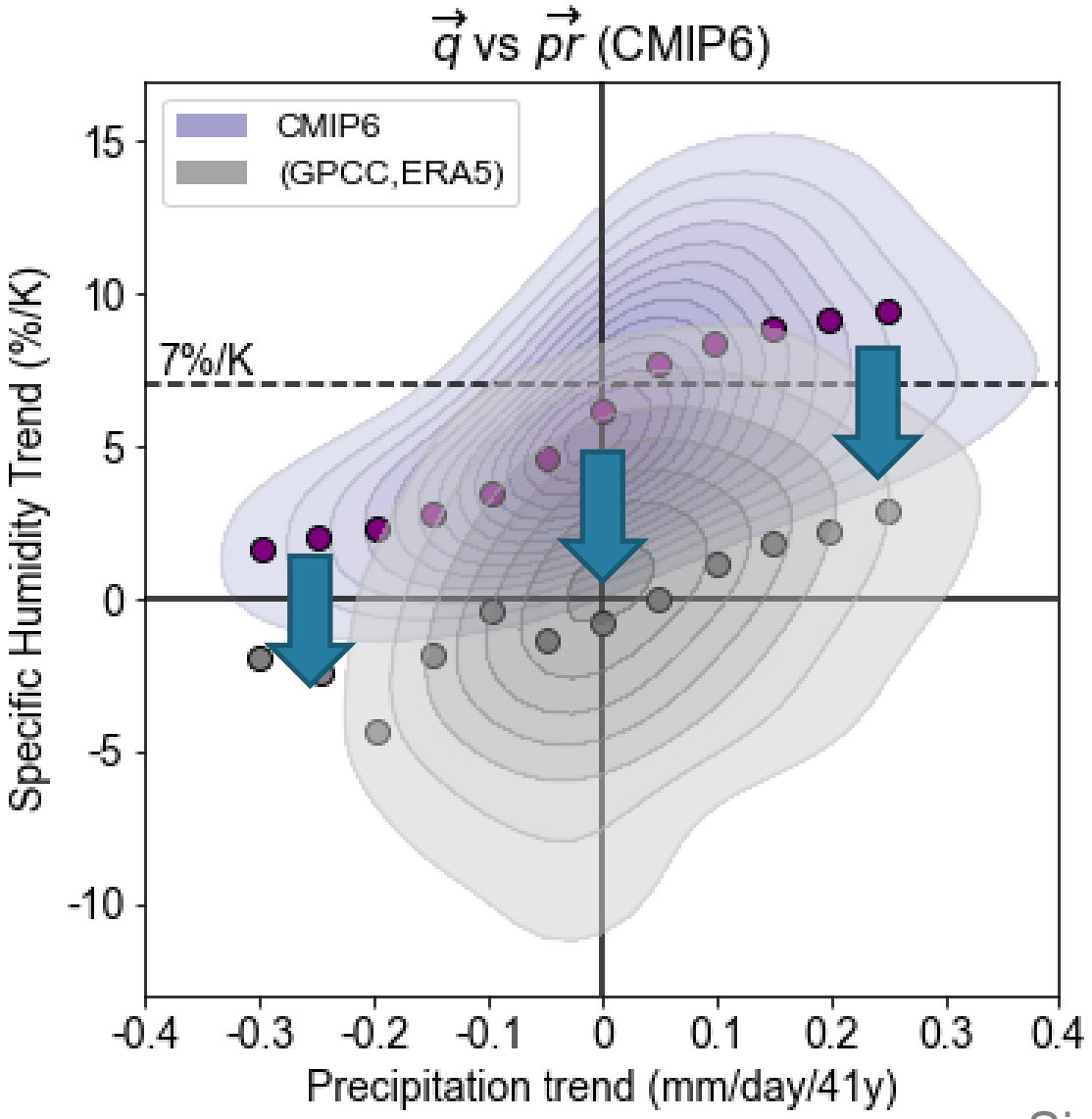

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Something is wrong, which could have potentially severe implications for climate projections.

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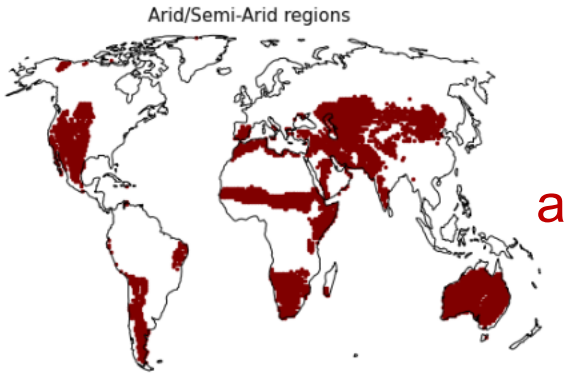
Why is humidity rising in the models and not in reality in arid/semi-arid regions?



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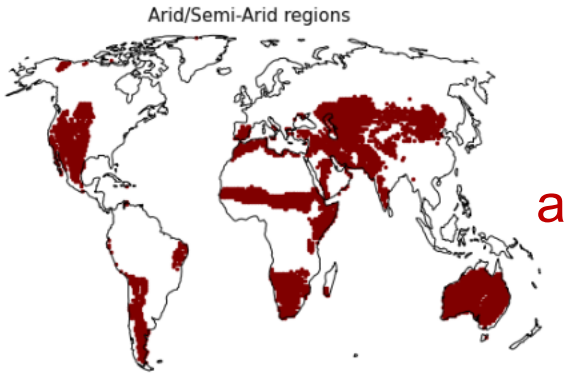

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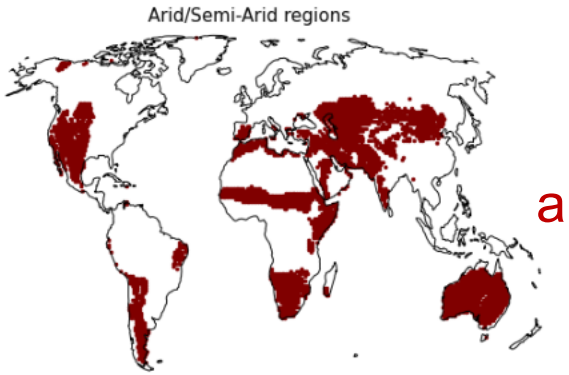

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This analysis is still preliminary

What could be going on?

Something wrong with the observational record

Models and observations differ in the change in atmospheric water vapor transport

Models have more water available at the land surface

Models land surface is not drying out as much as observed

Soil Evaporation is not changing with temperature or radiation in the same way

Plant transpiration is not changing with temperature, radiation, or CO2 in the same way

The vertical structure of humidity trends near the surface might be different

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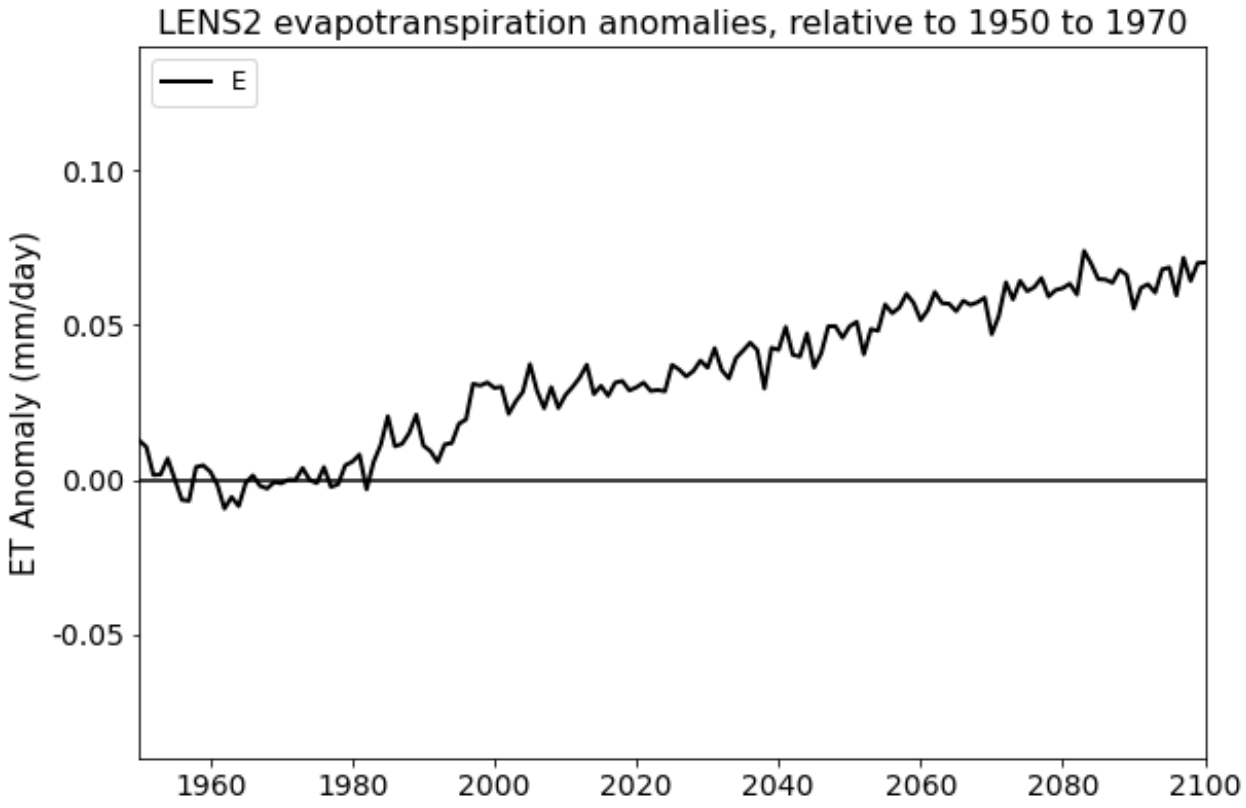

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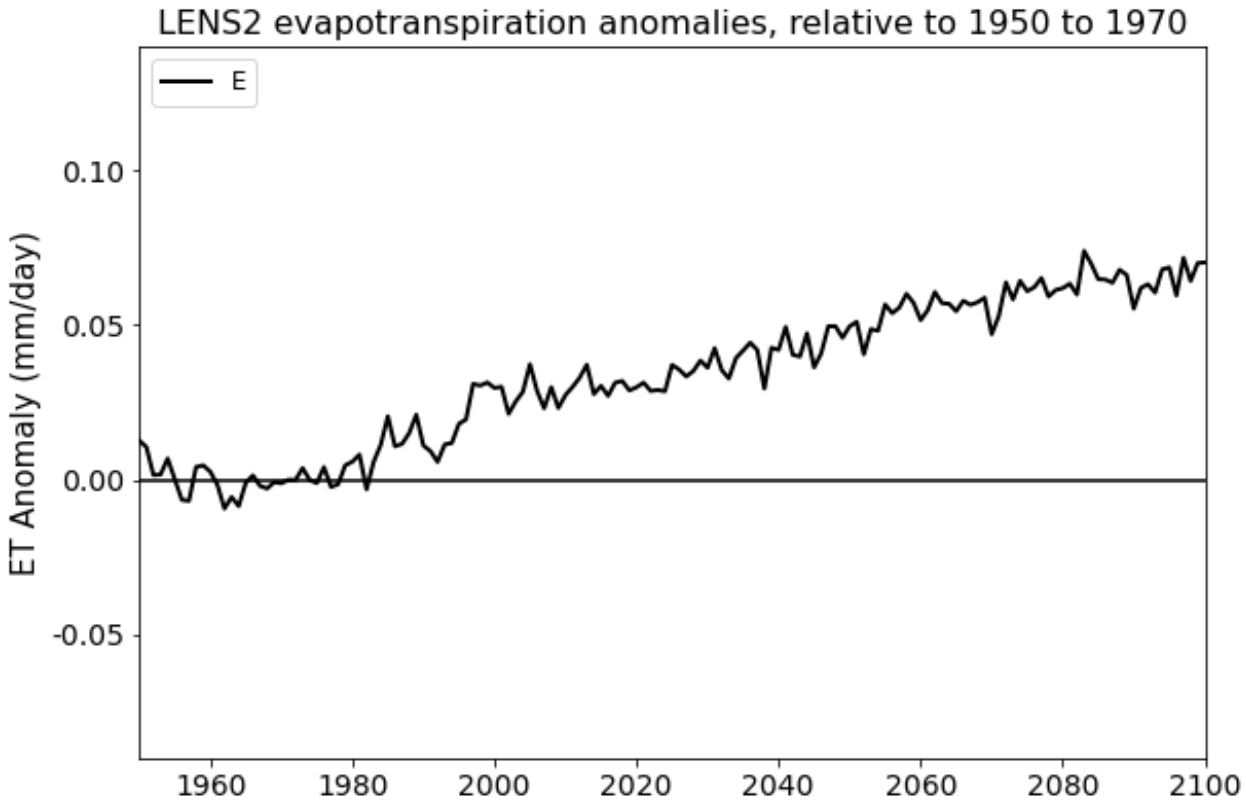

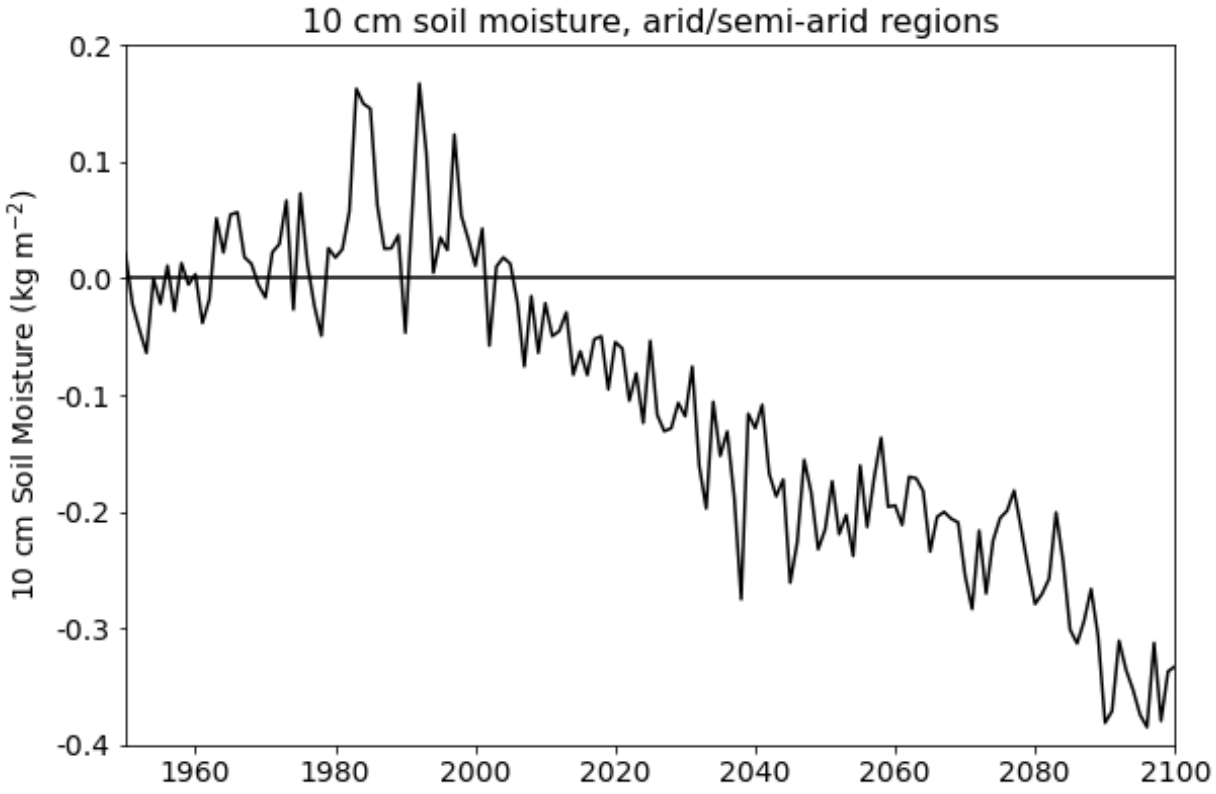

Despite a decline in soil moisture

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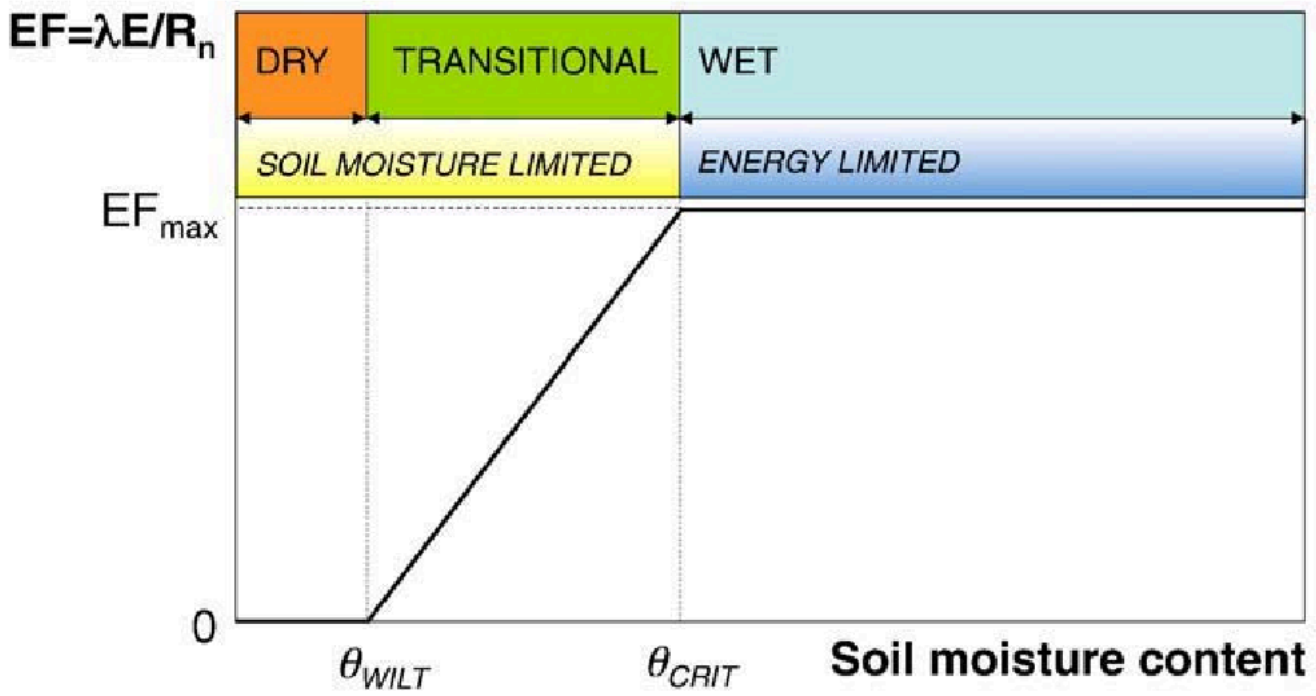
- **Focus on daily average fields**
- **Deseasonalize (remove first 4 harmonics of the seasonal cycle)**
- **Consider the warm season and the cold season separately (defined by the 90 days surrounding the seasonal maximum or minimum at each location)**
- **Remove the seasonal mean for each year to remove variability on timescales longer than the season.**

Soil Moisture and Evapotranspiration Regimes



Seneviratne et al. 2010

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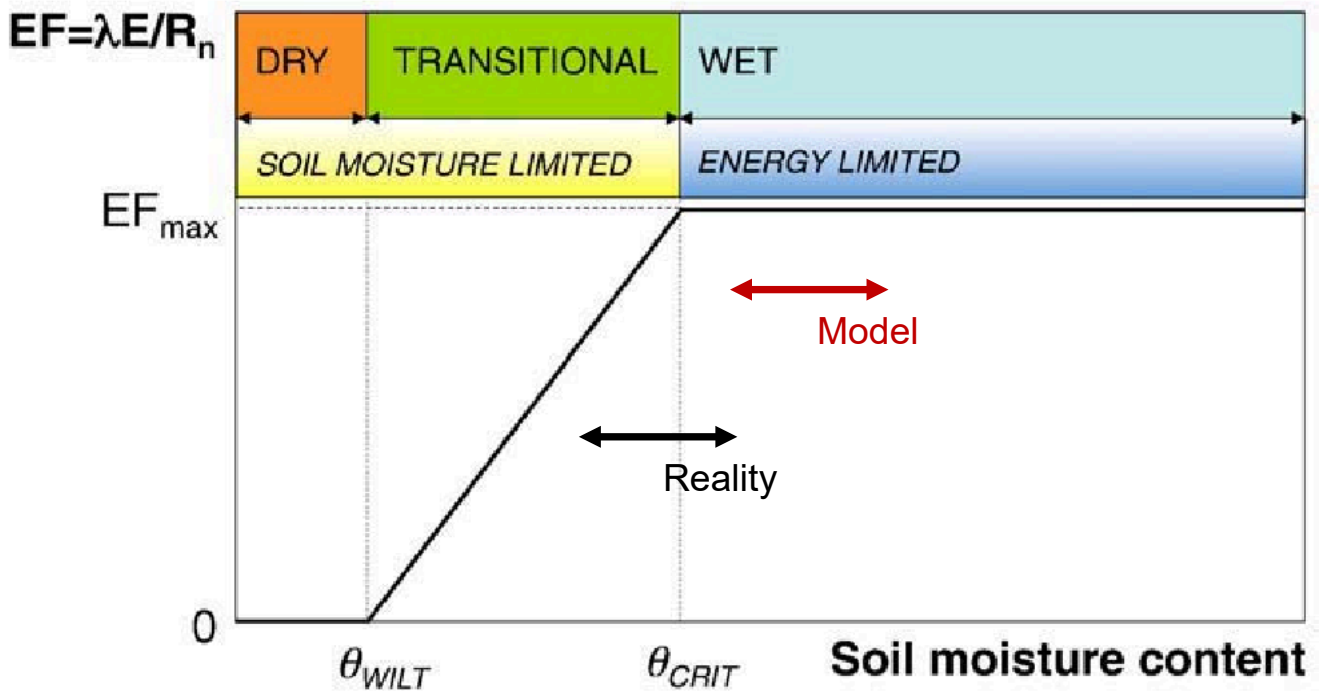

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Are models sitting at a different location on this curve compared to reality?

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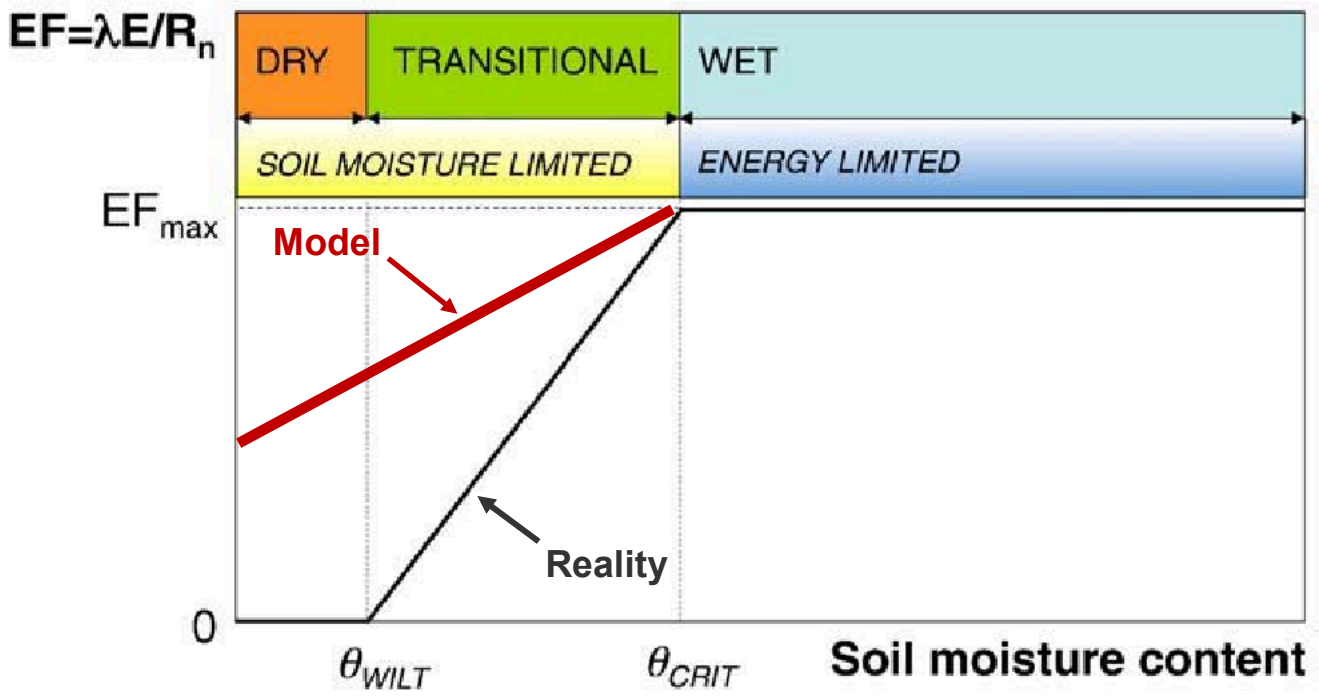

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Is the shape of this curve different in models compared to reality?

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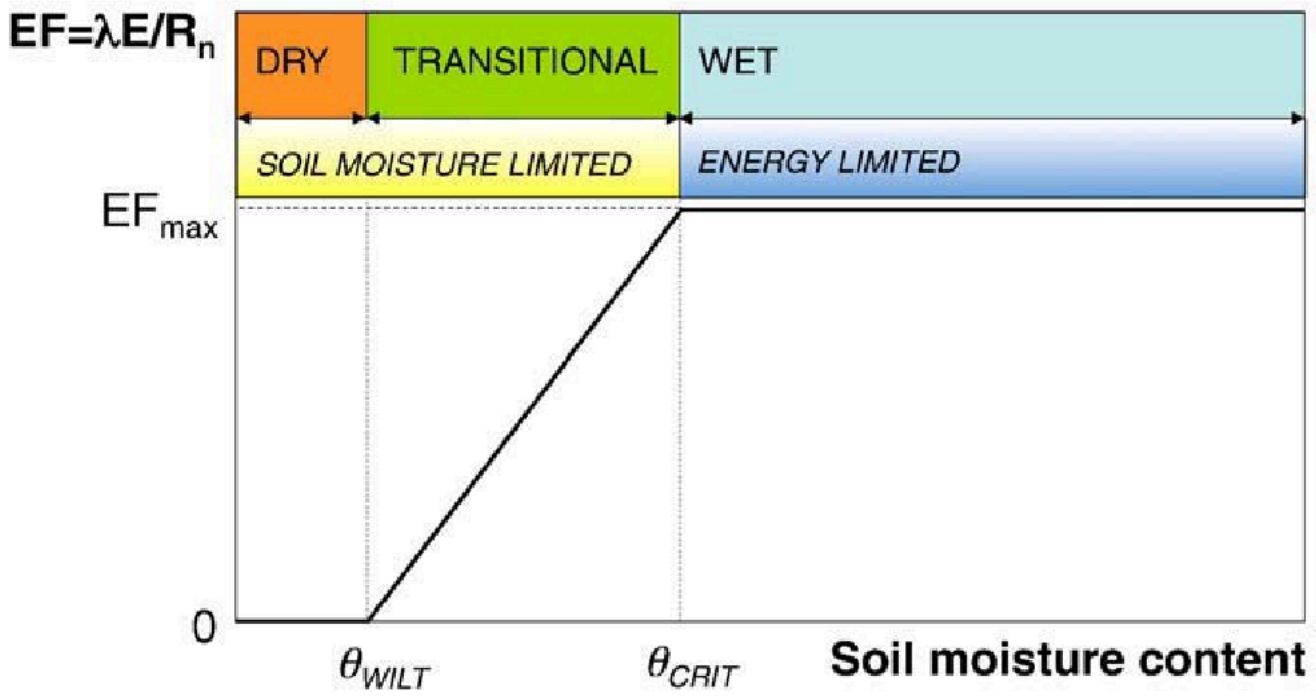

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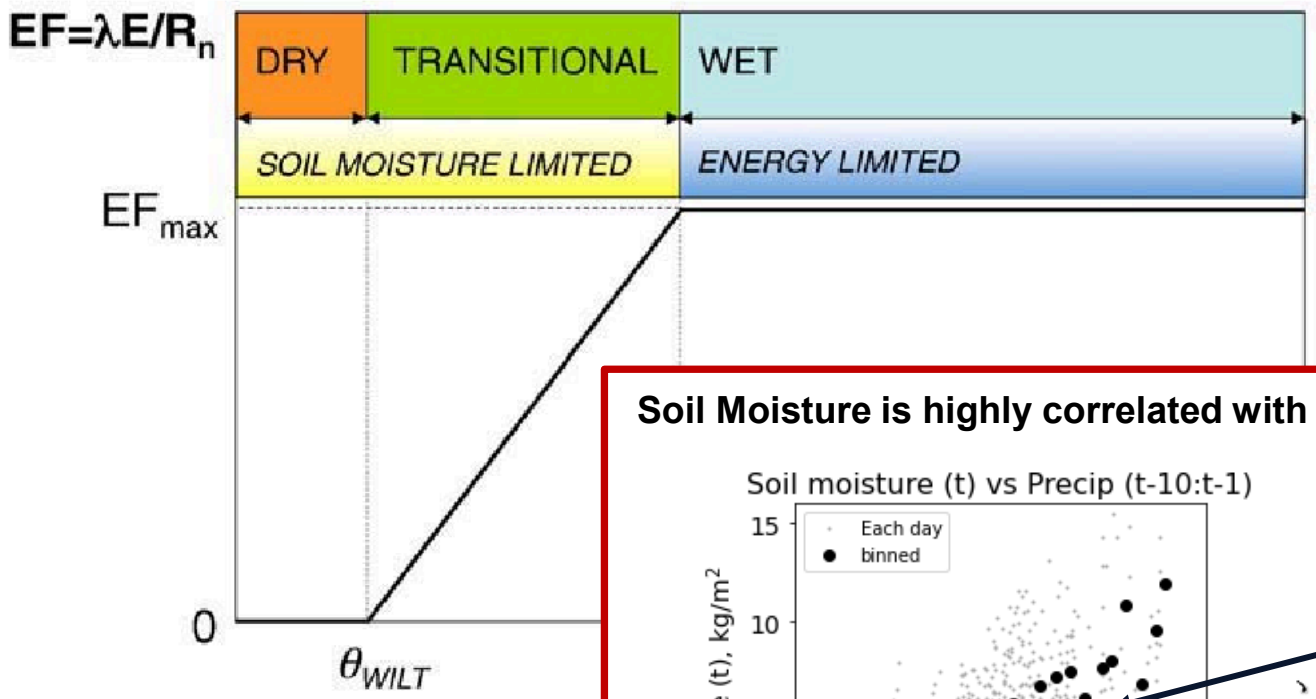
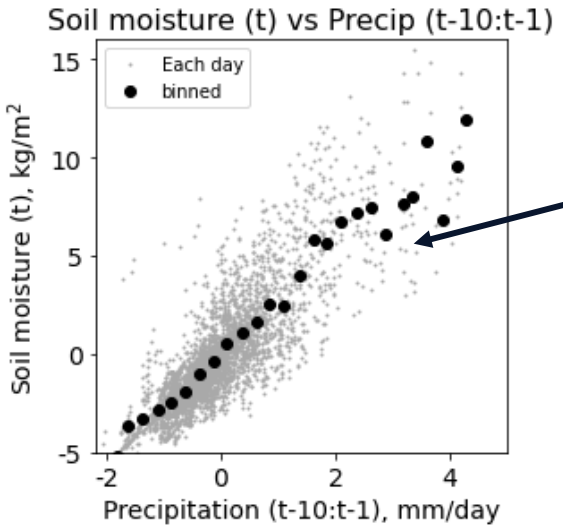
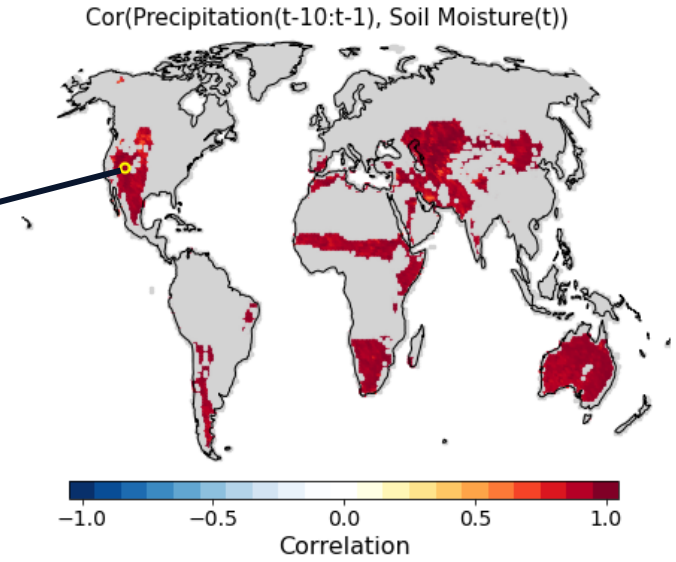


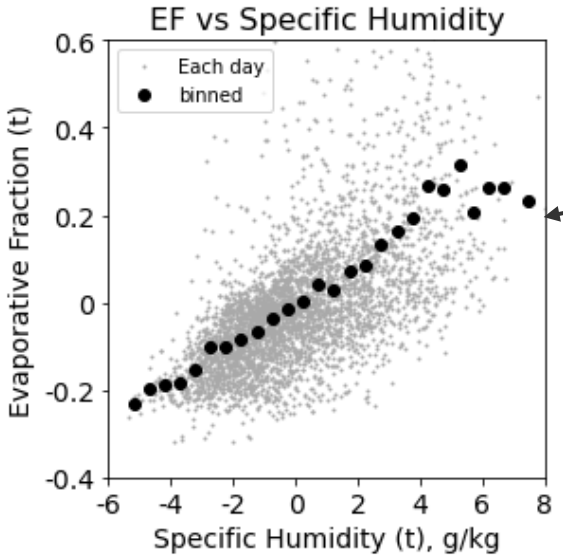
Soil Moisture is highly correlated with precipitation over the prior 10 days

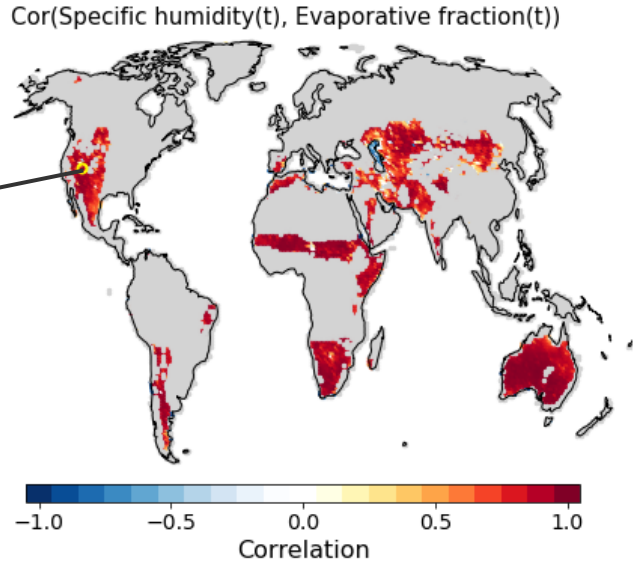




Soil Moisture and Evapotranspiration Regimes

Evaporative fraction is highly correlated with specific humidity





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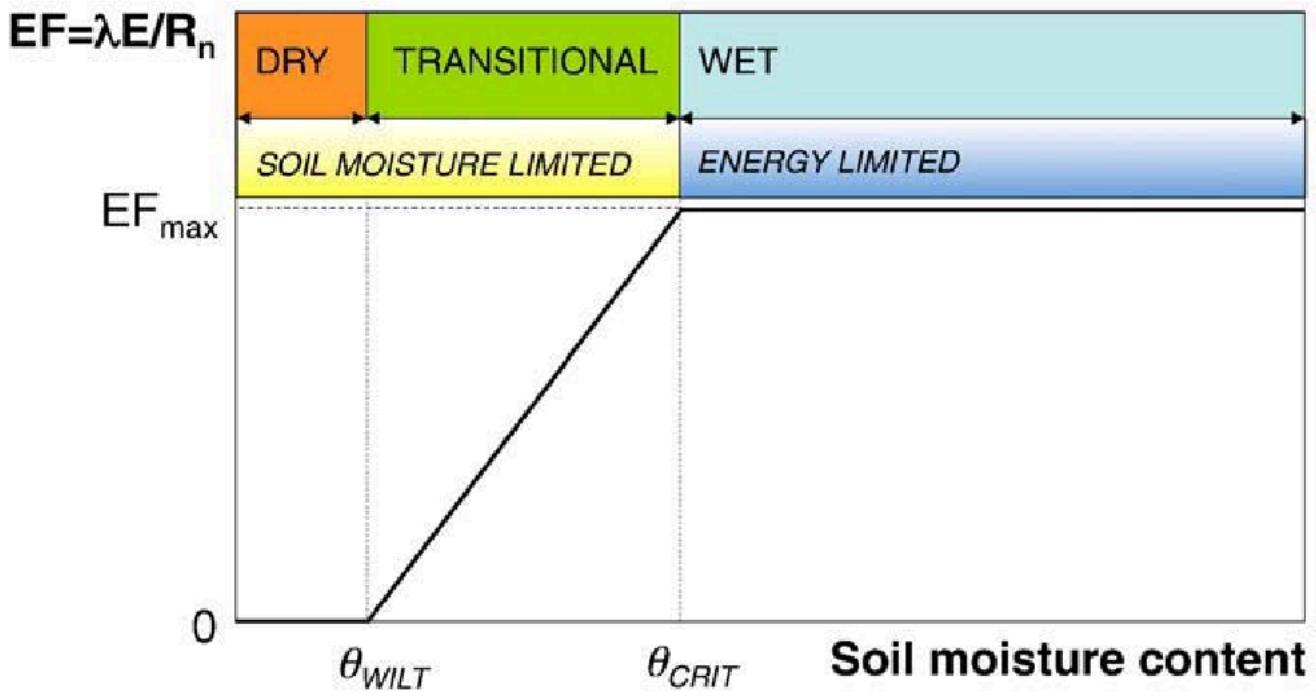

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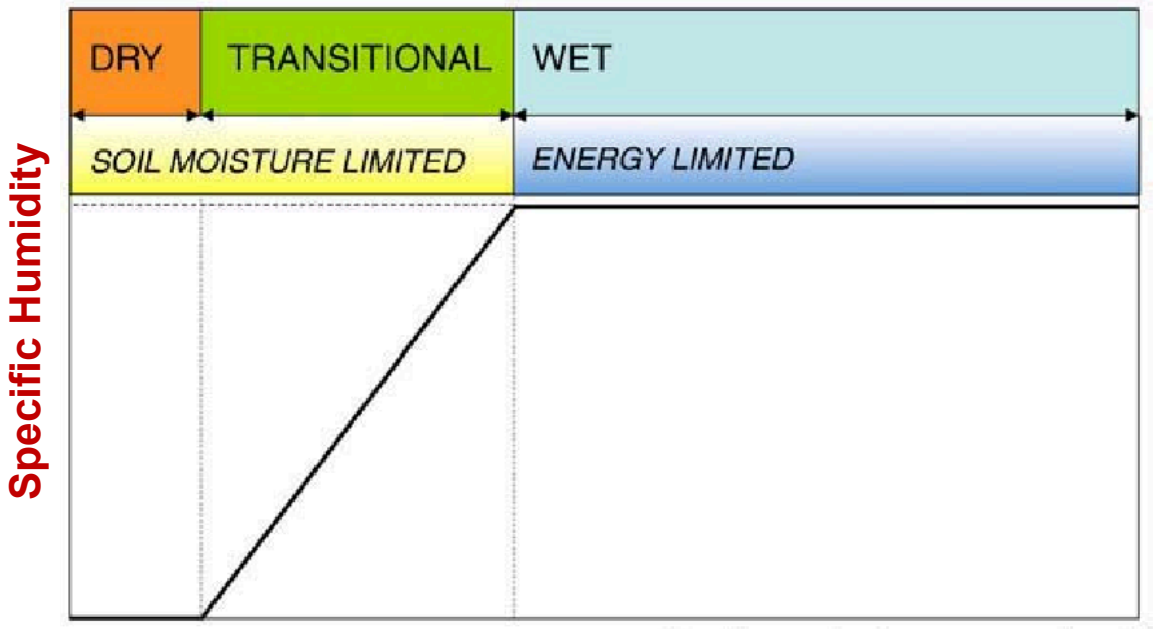
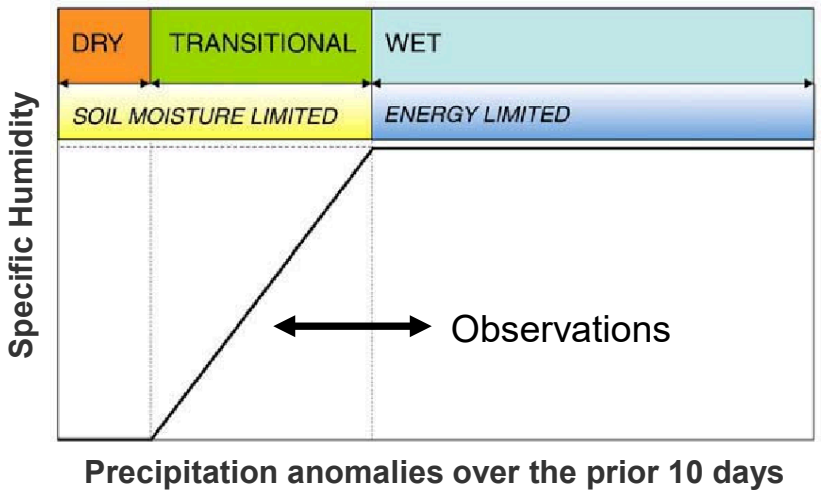
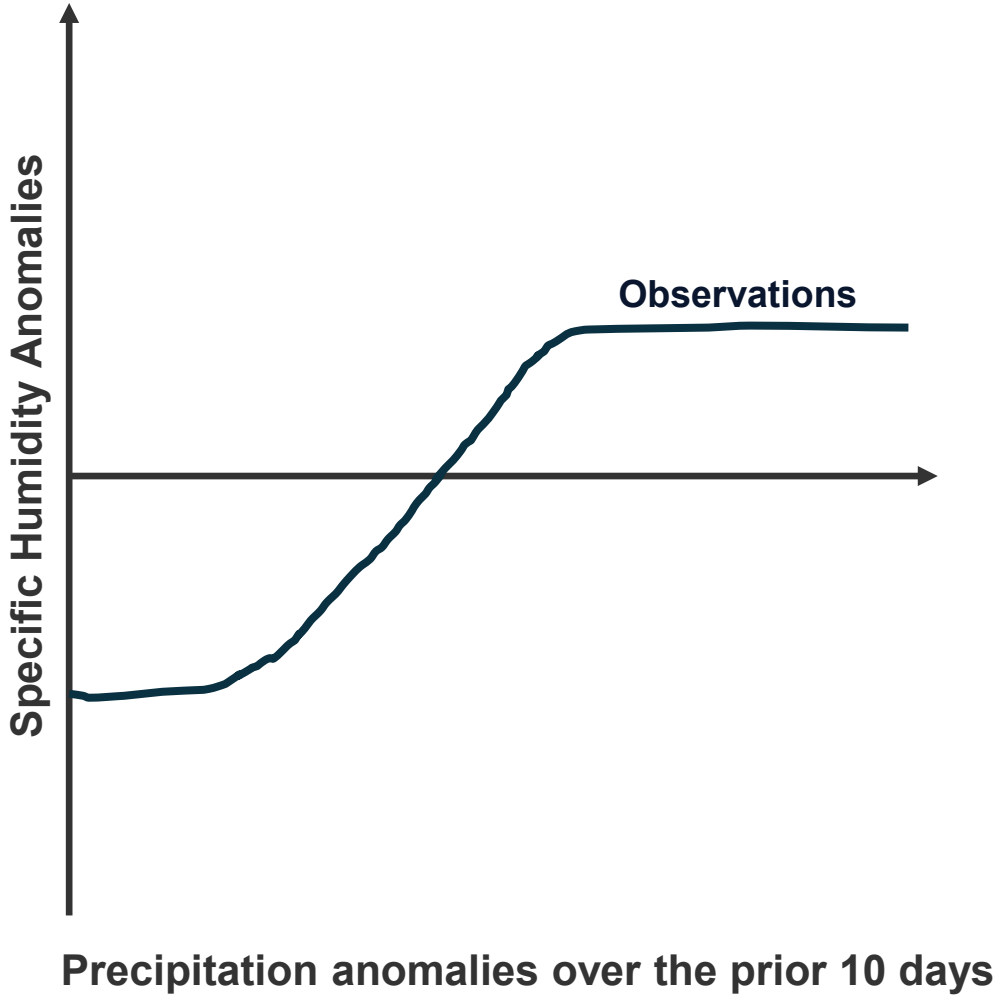


What would we expect if reality was more water limited?





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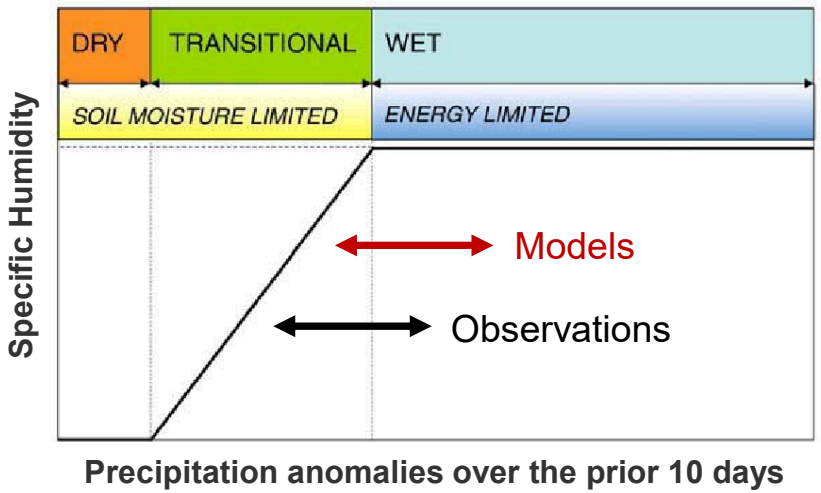

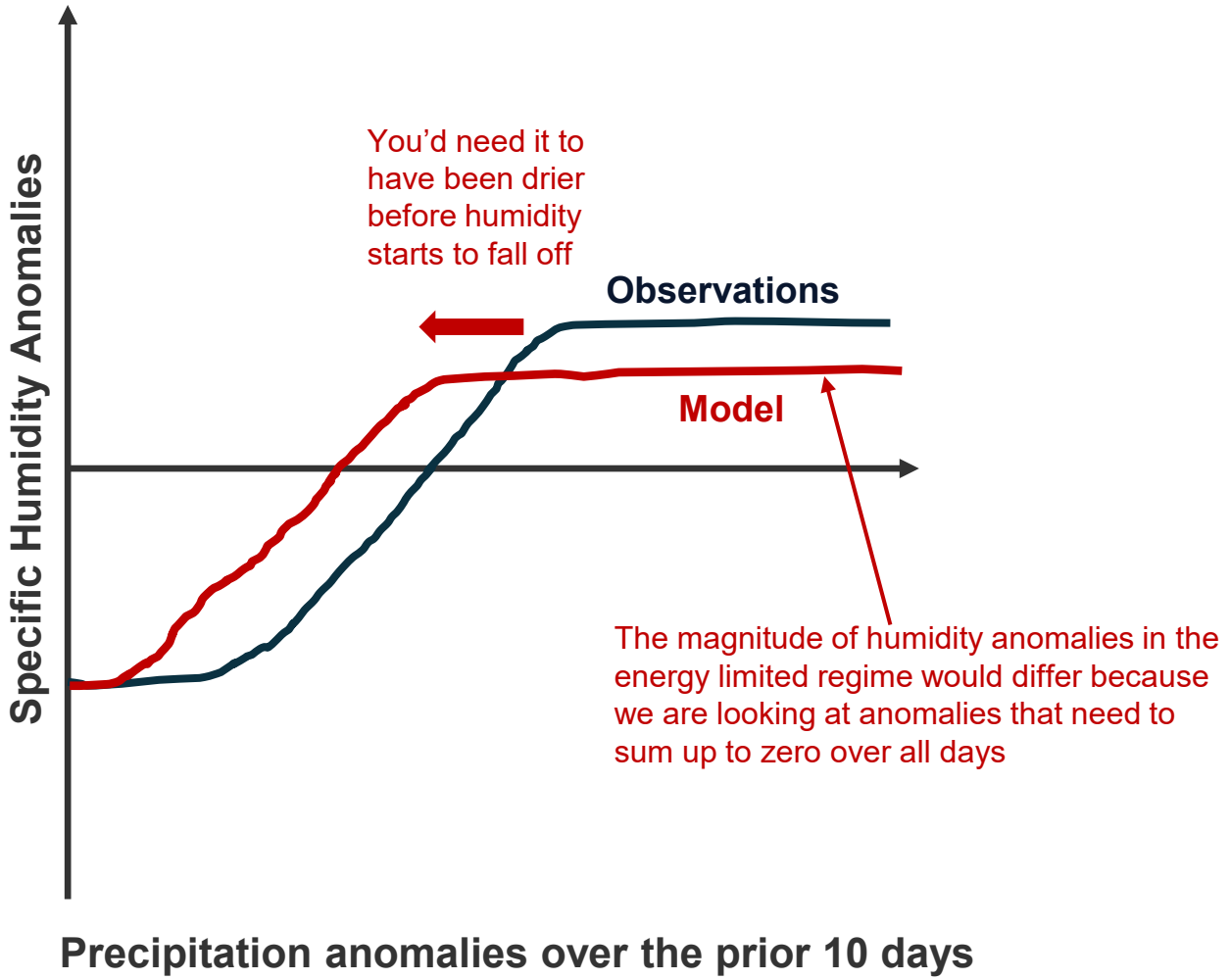

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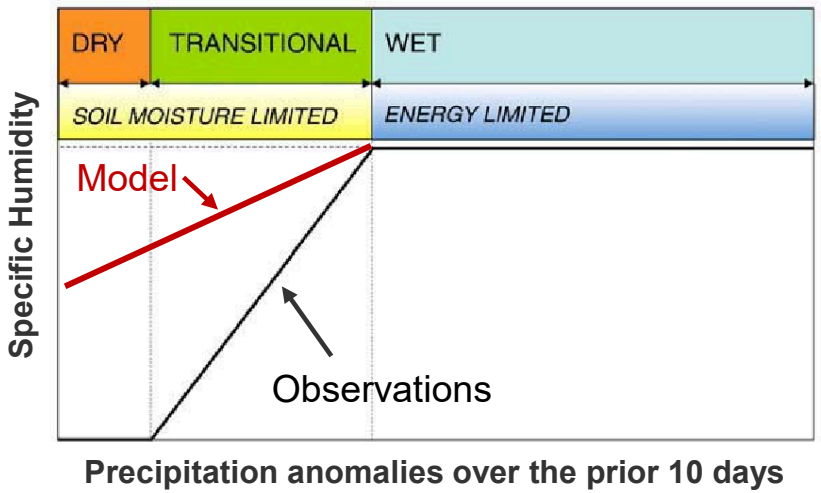

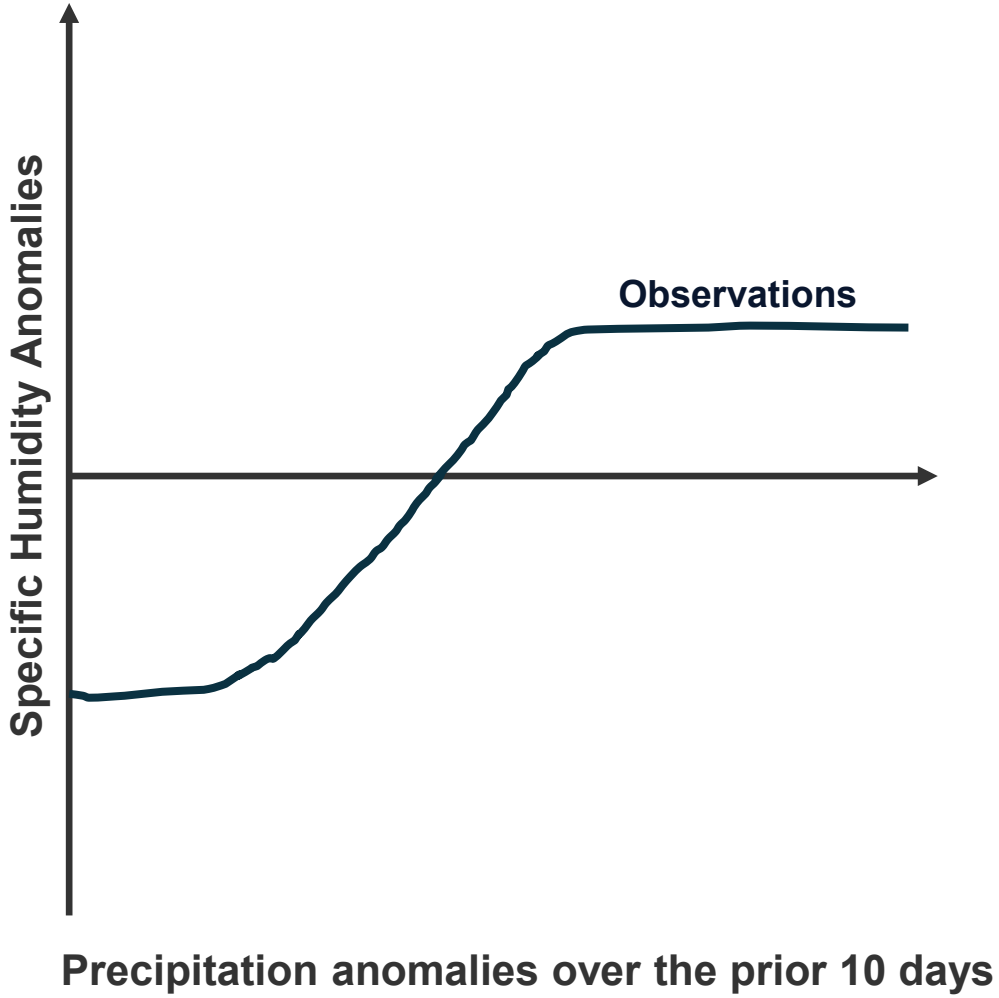

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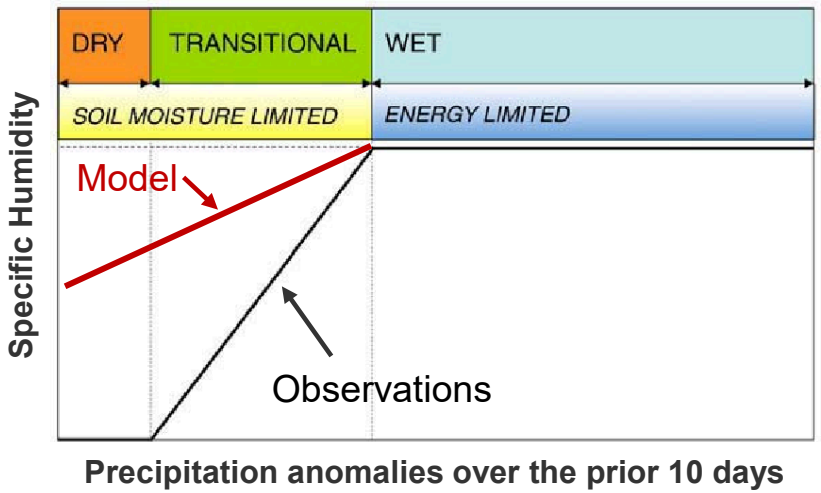
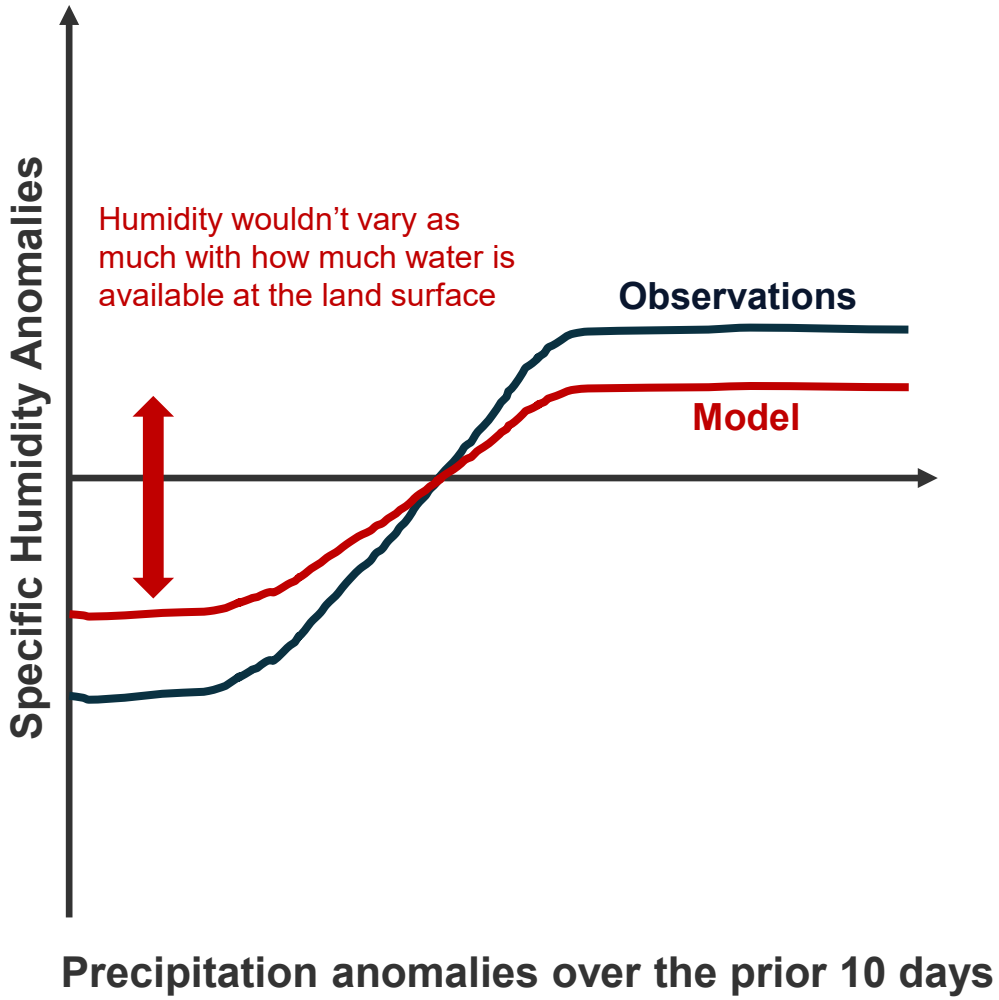
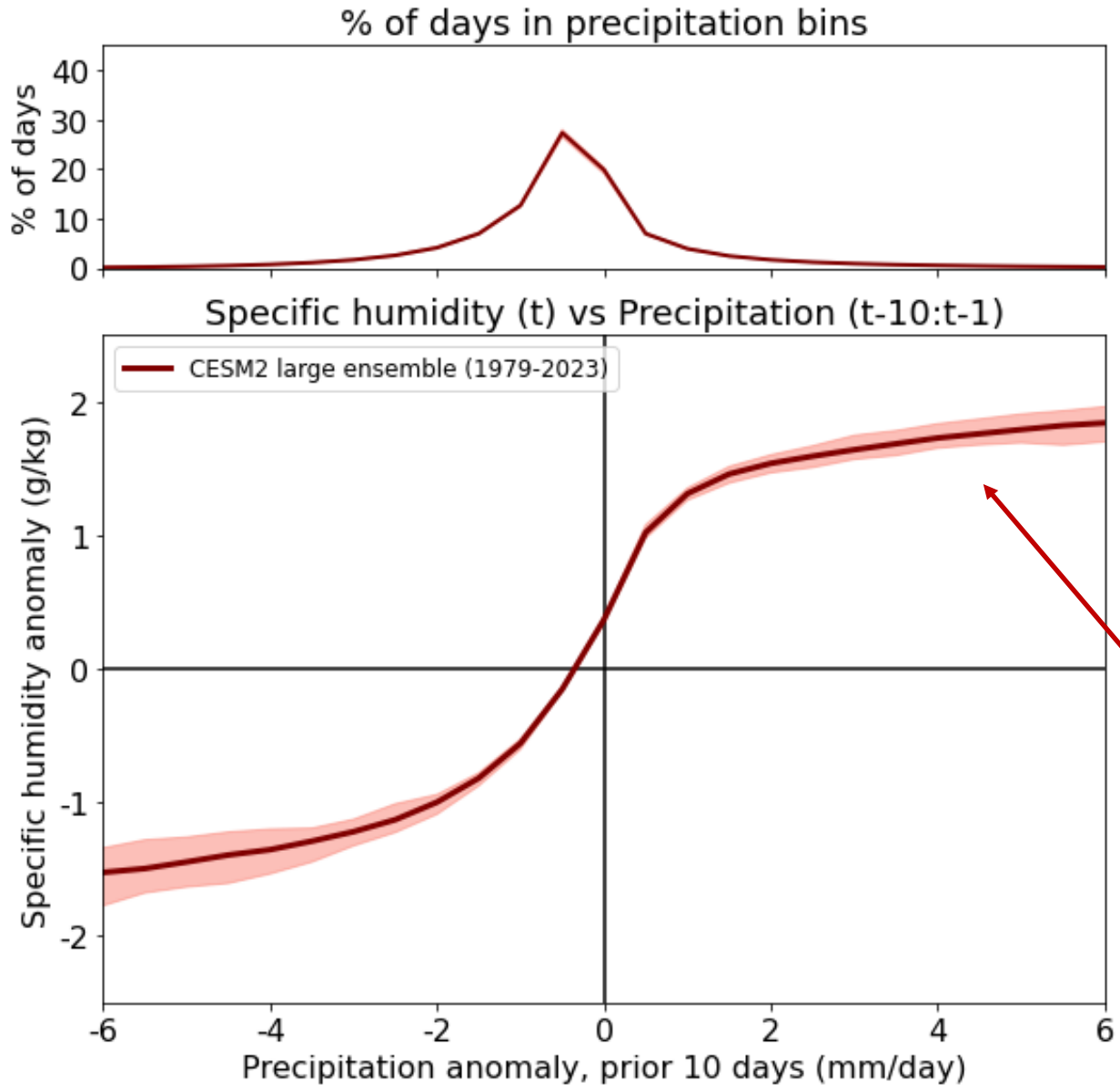




Specific Humidity versus precipitation averaged over the prior 10 days



Warm season

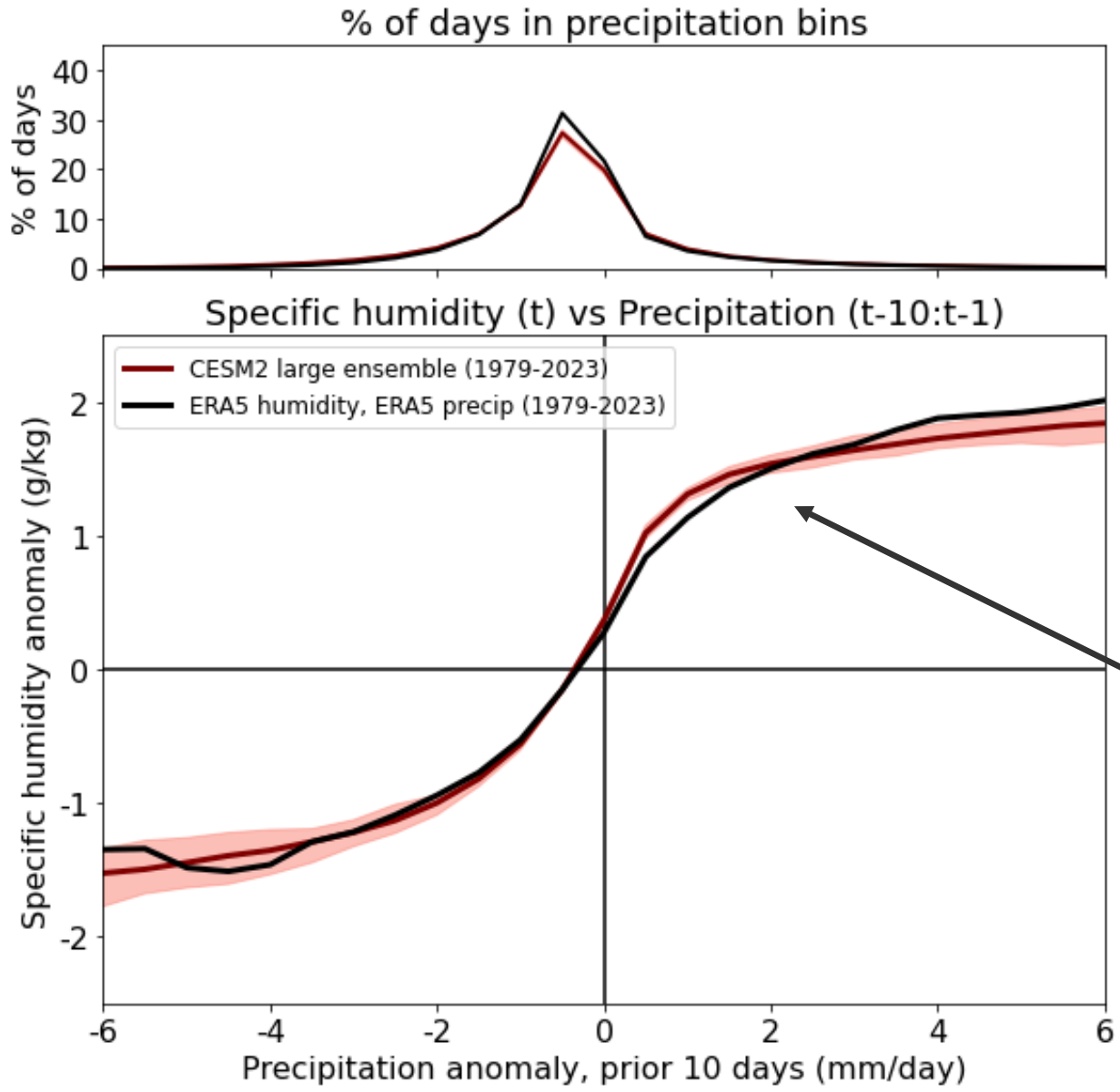
Distribution of prior 10 day precipitation

Specific humidity as a function of prior precipitation

Average over all arid/semi-arid locations

CESM2 large ensemble (mean and min to max range)

Specific Humidity versus precipitation averaged over the prior 10 days



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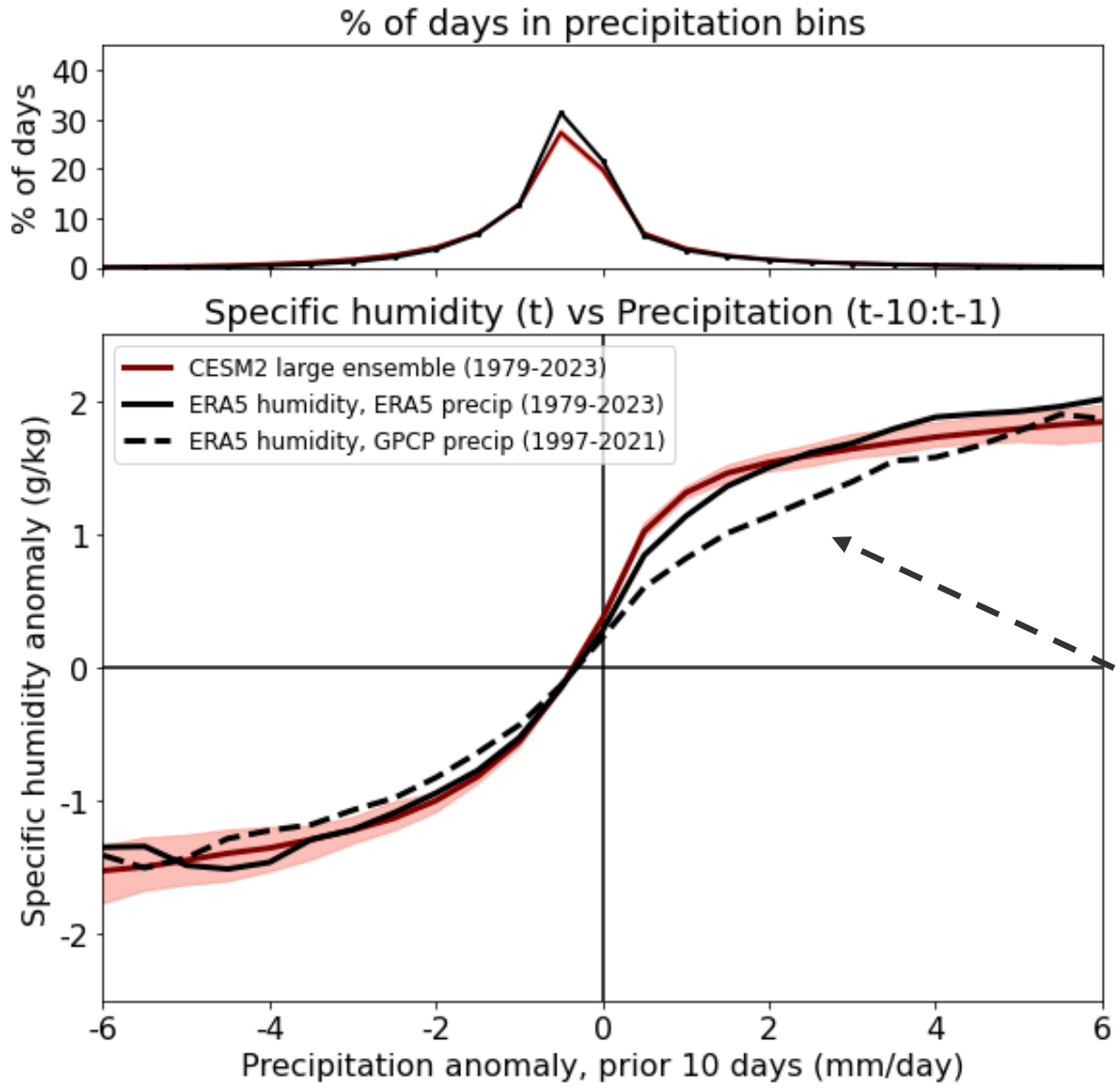

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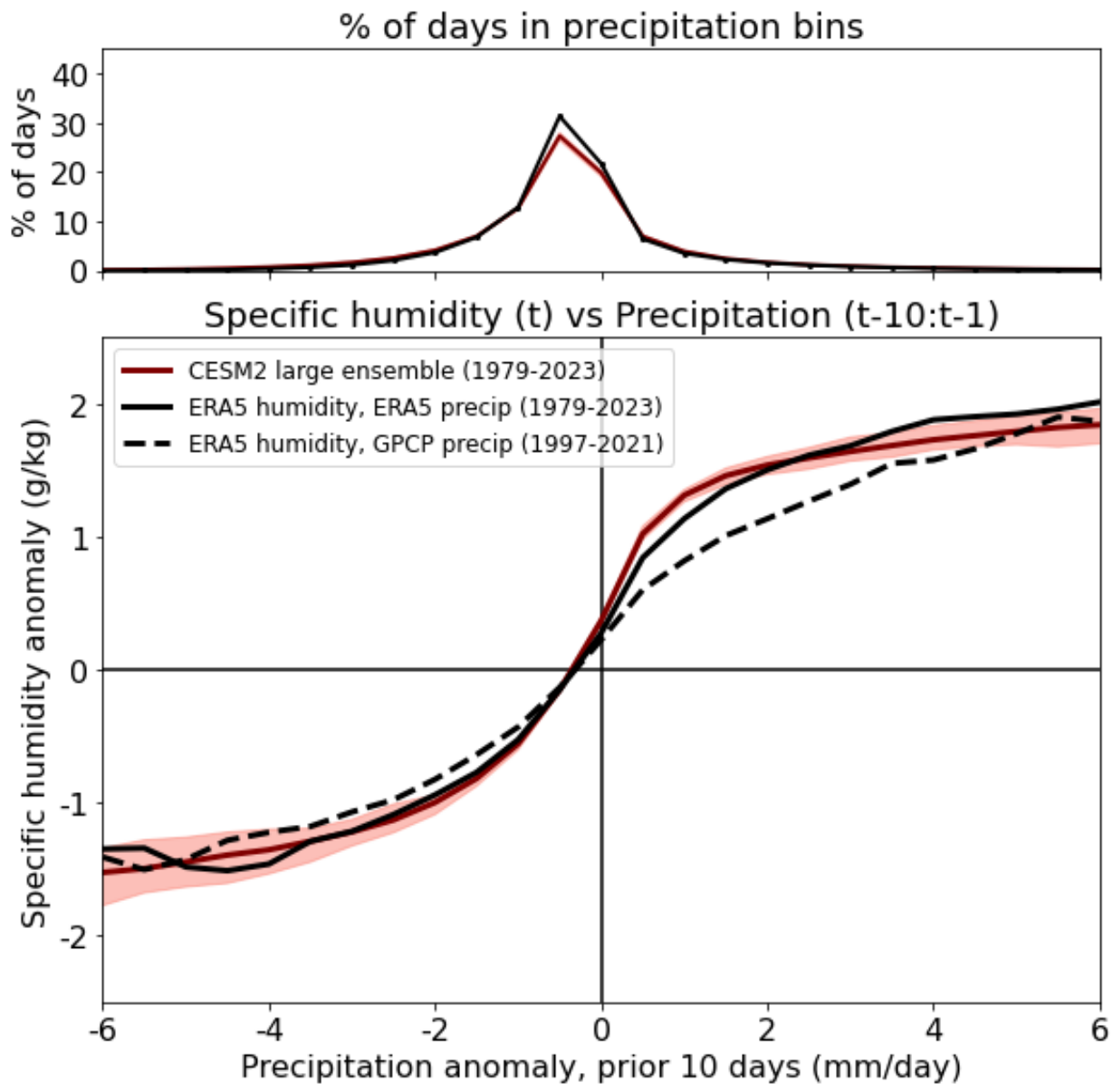
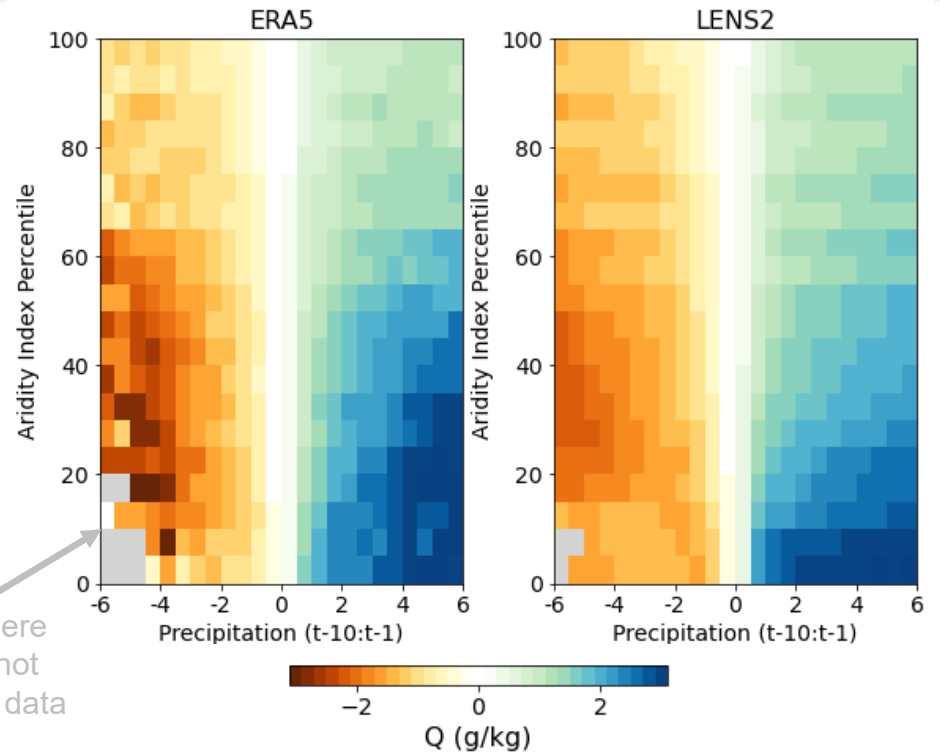




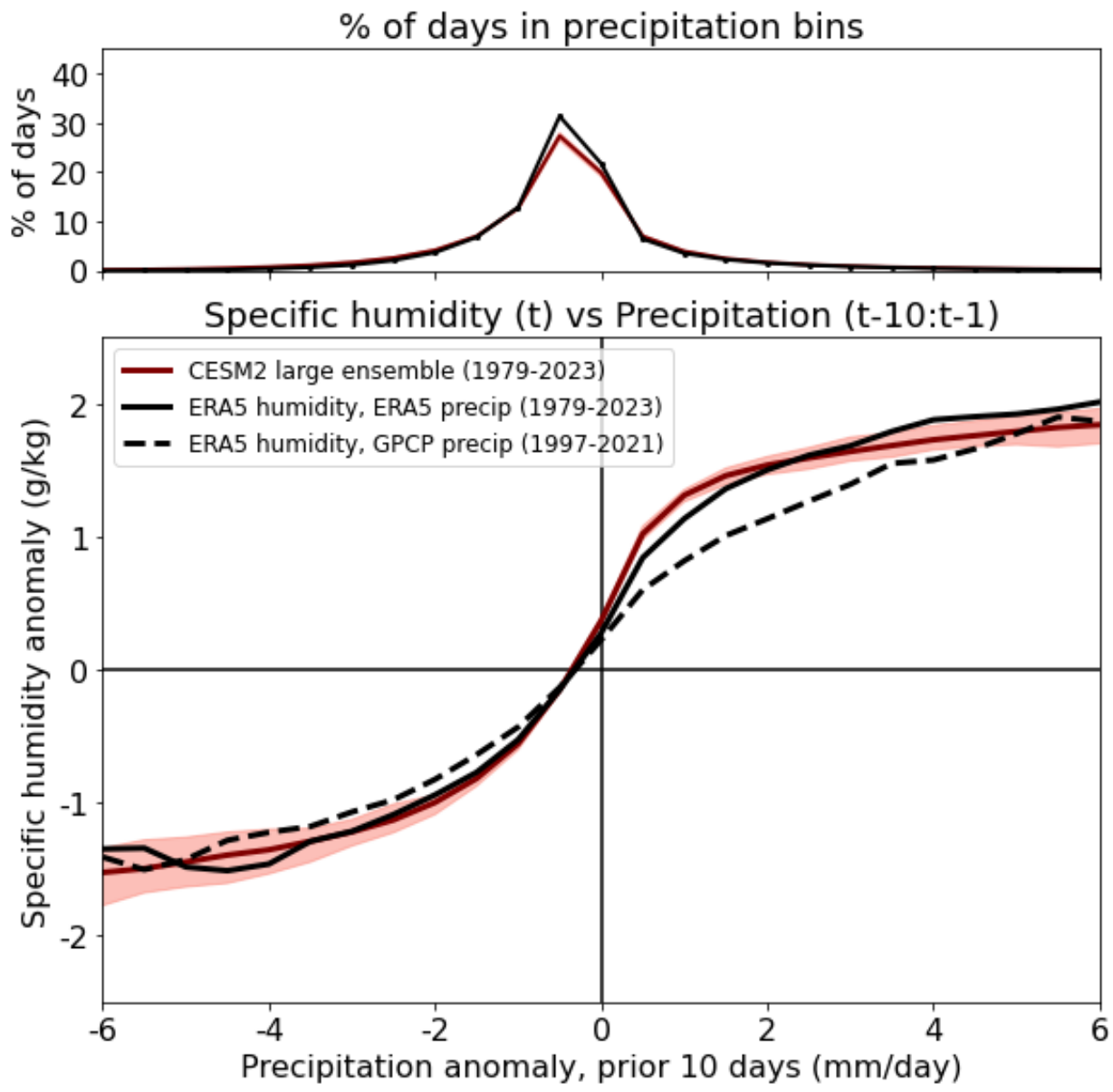
Most Humid

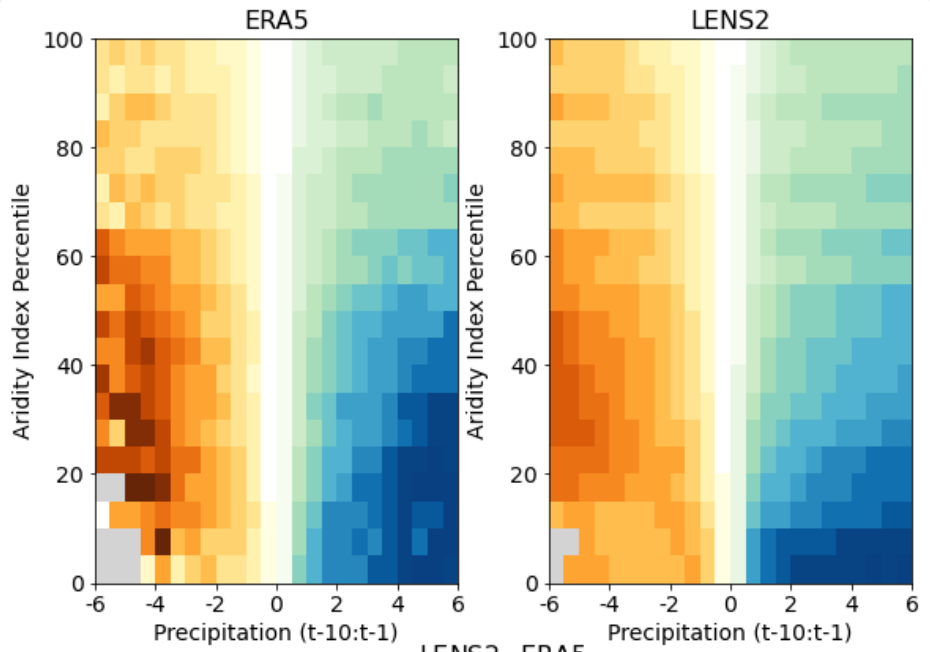
Ordering all the arid/semi-arid locations according to the annual mean aridity

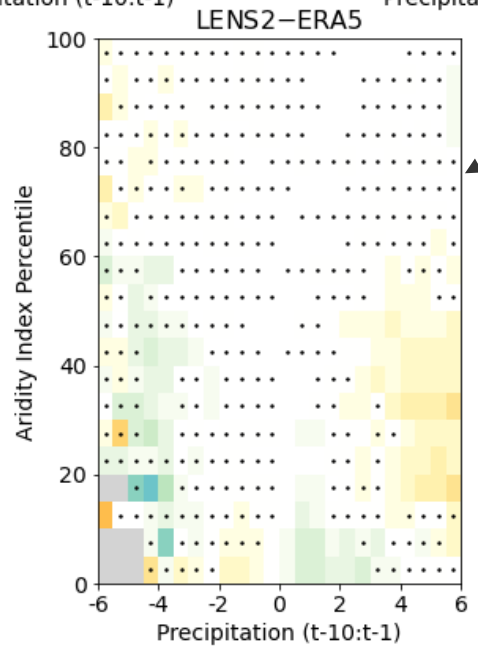
Most Arid

Bins where there's not enough data

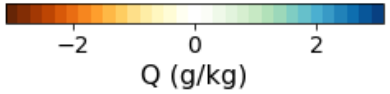
Specific Humidity versus precipitation averaged over the prior 10 days



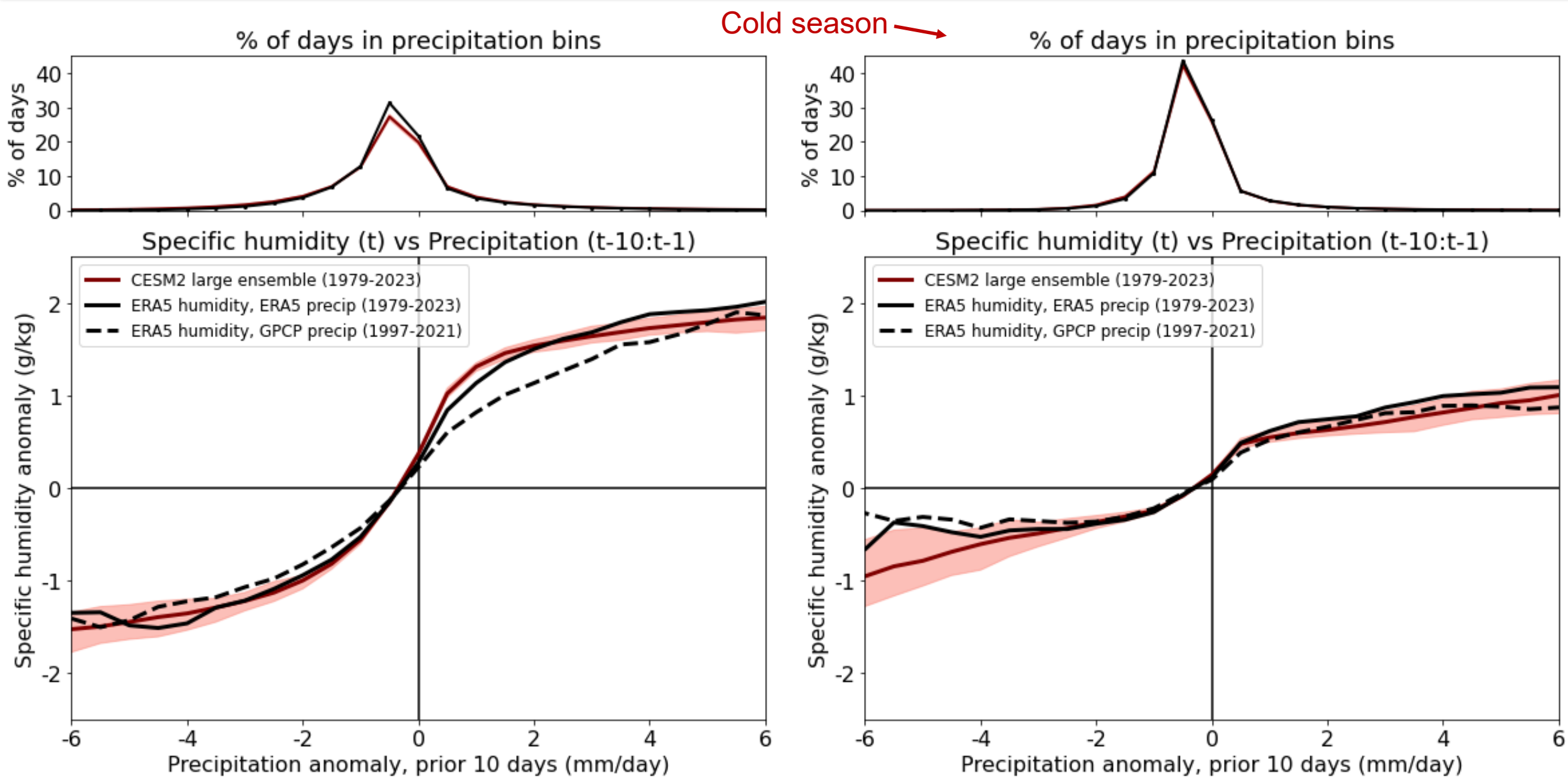




Stippling = where ERA5 lies within the LENS2 distribution



Specific Humidity versus precipitation averaged over the prior 10 days



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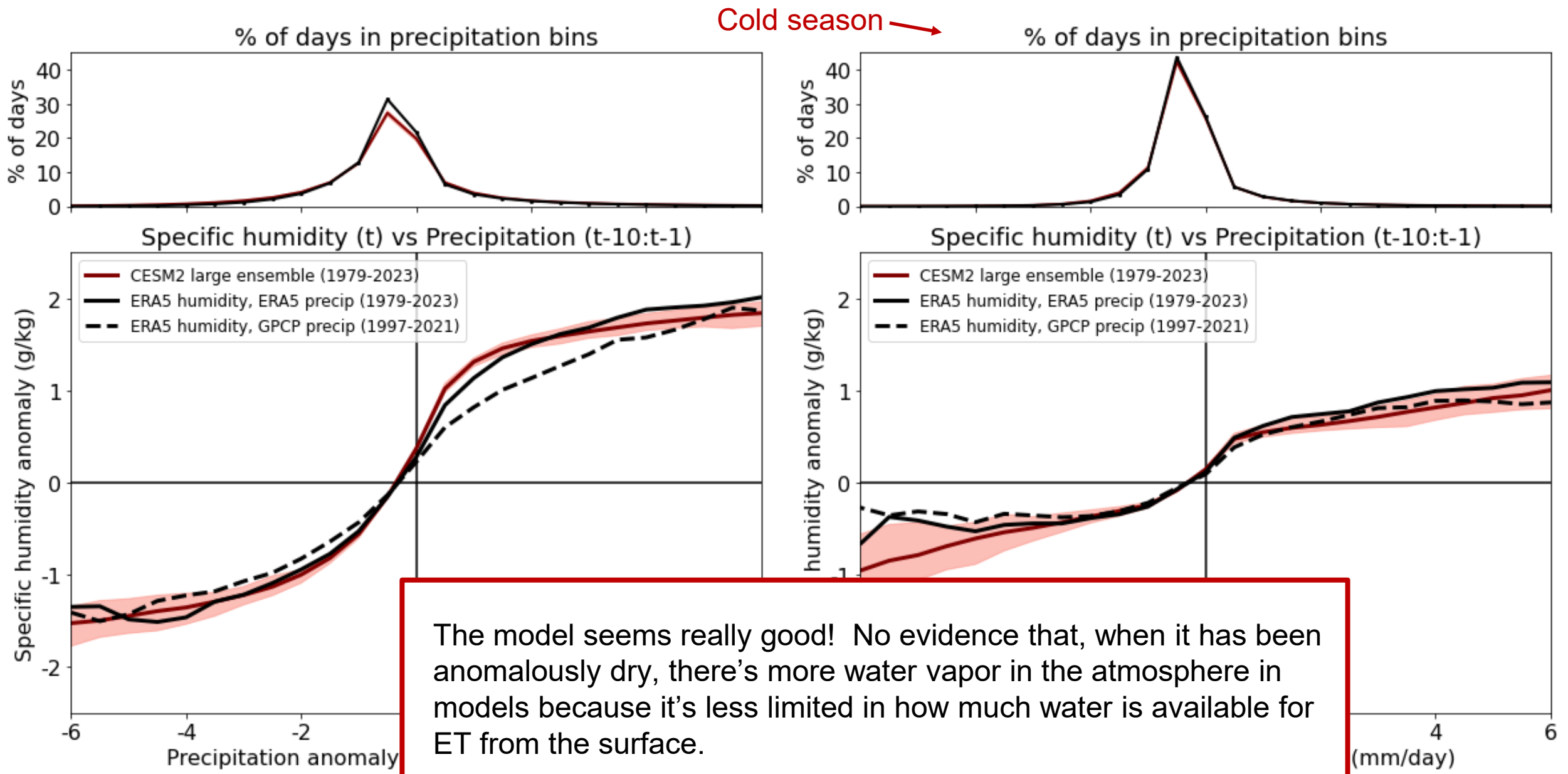
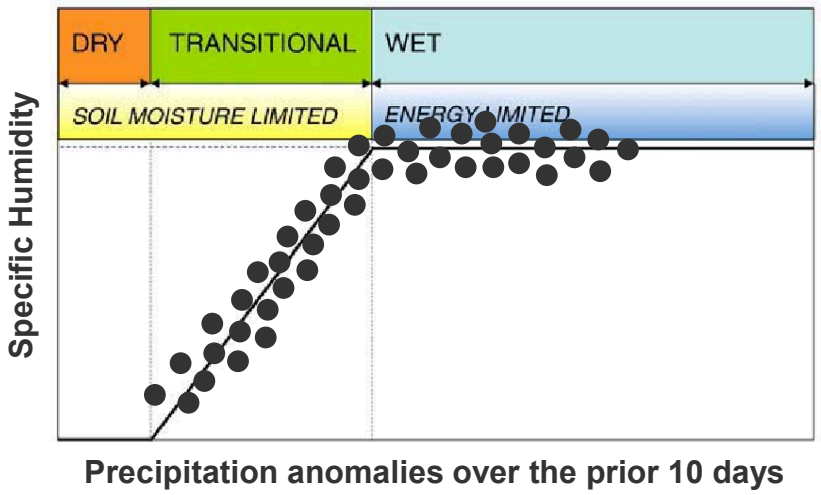
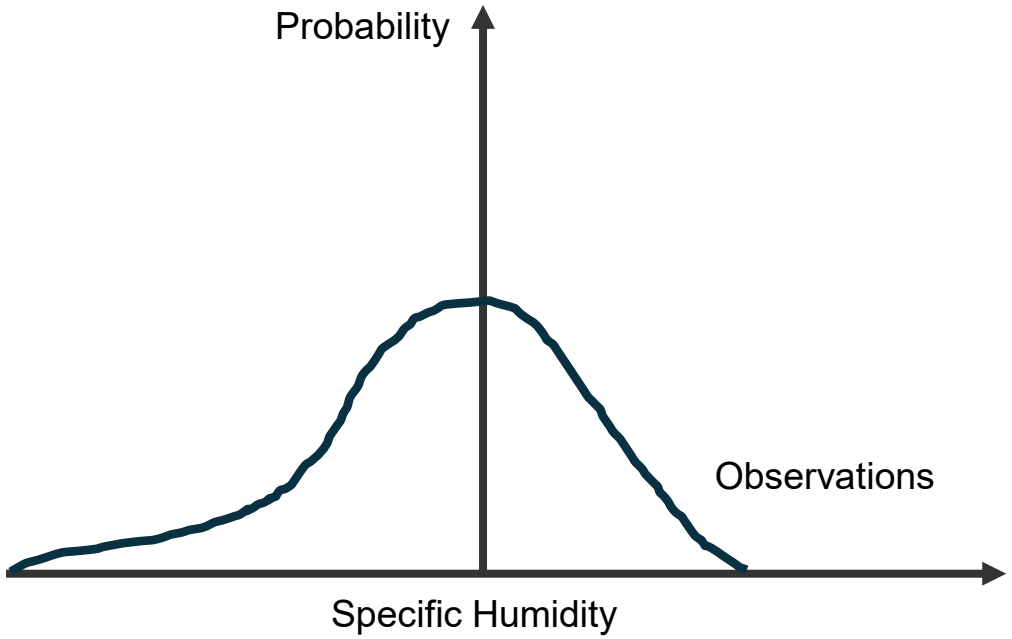


The model seems really good! No evidence that, when it has been anomalously dry, there's more water vapor in the atmosphere in models because it's less limited in how much water is available for ET from the surface.

Specific humidity distribution - what would we expect if reality was more water limited?





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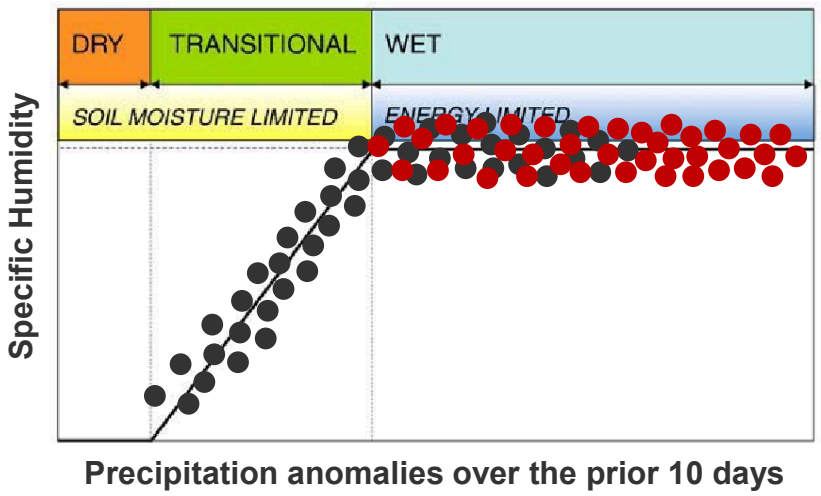

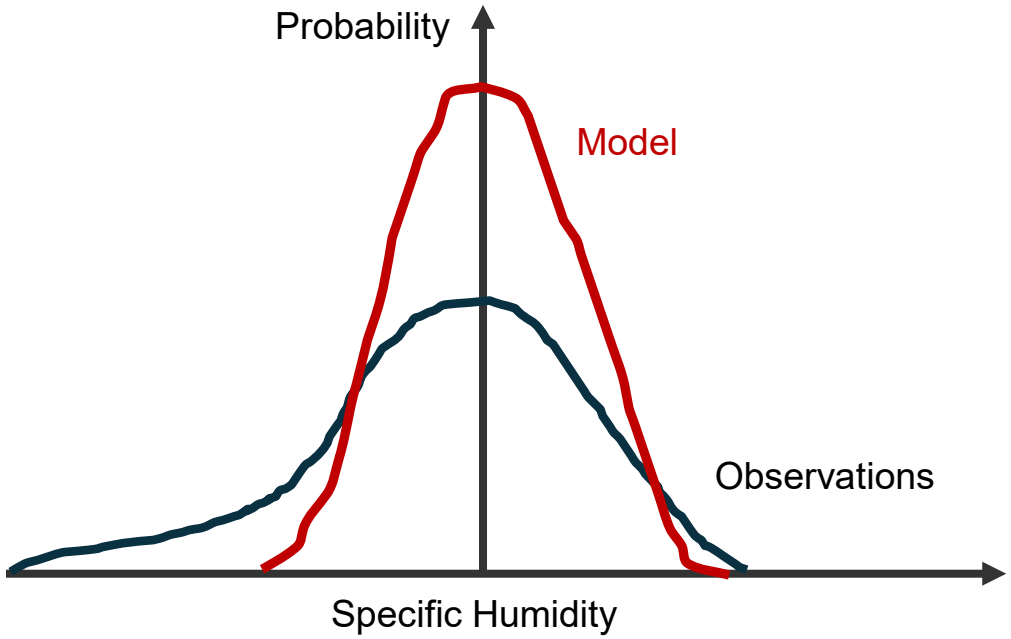

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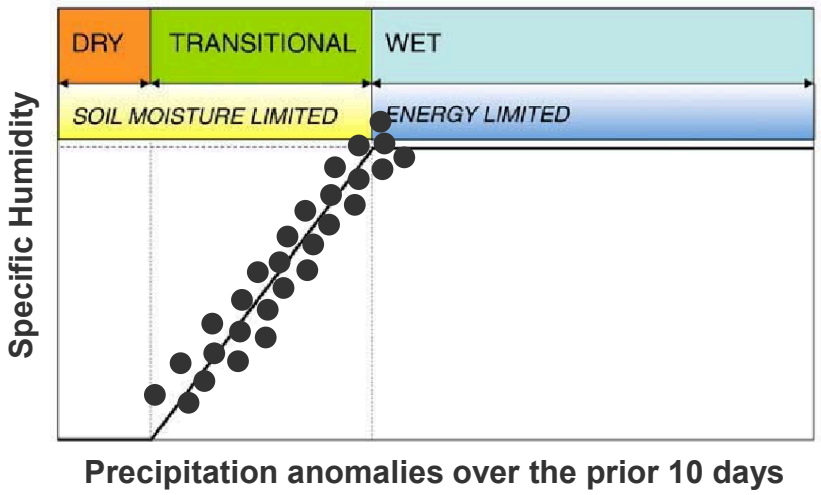

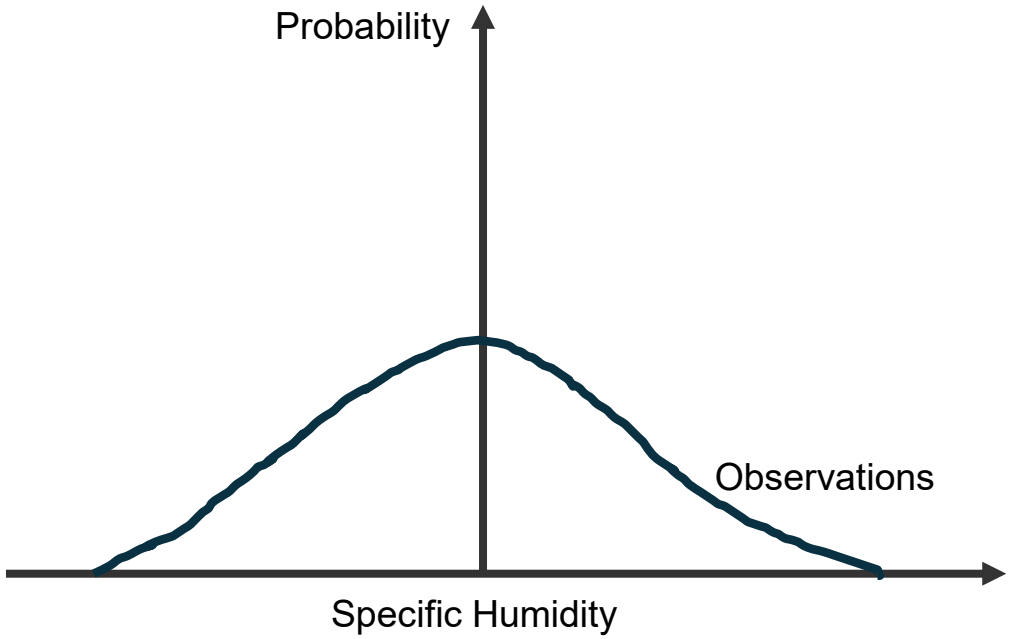

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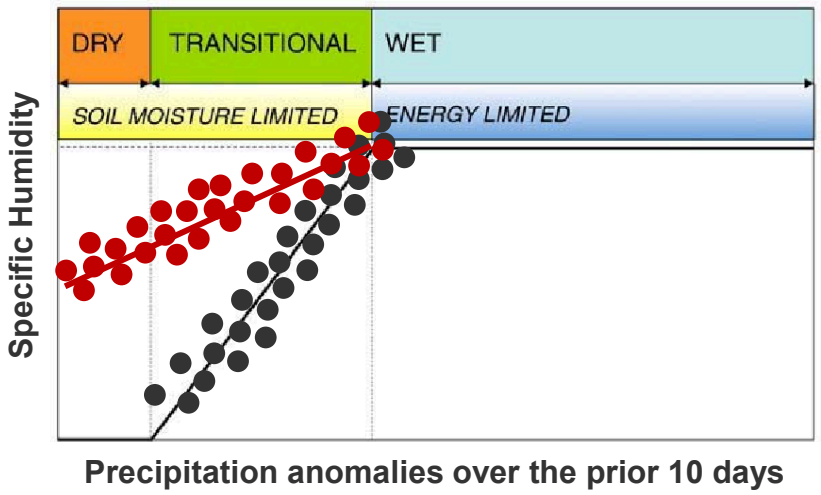

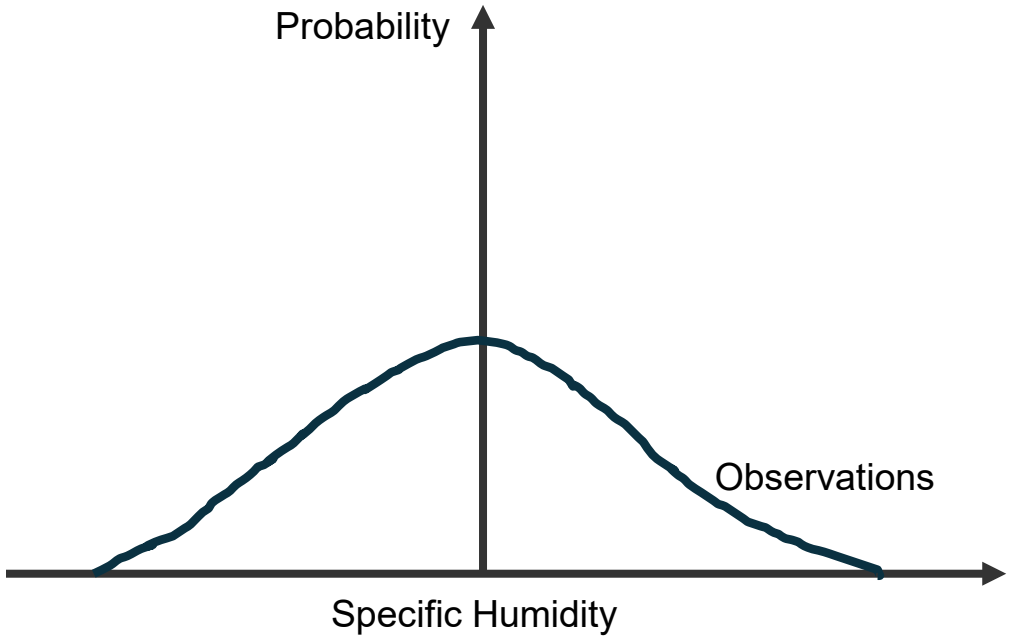

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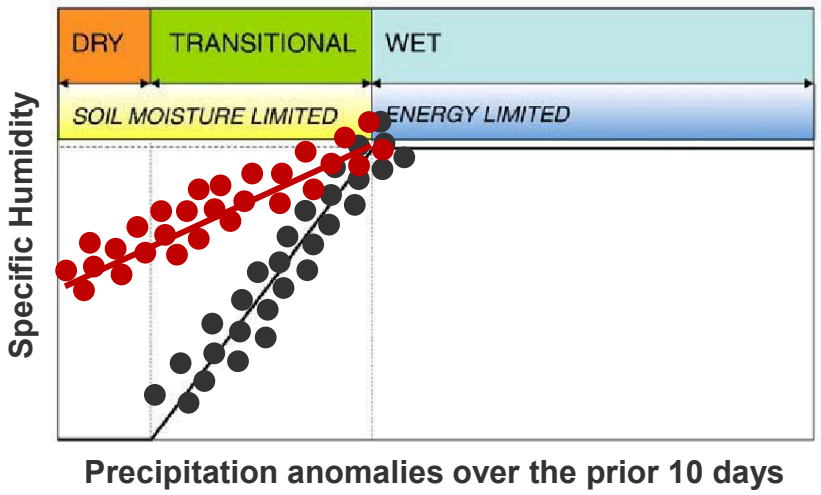
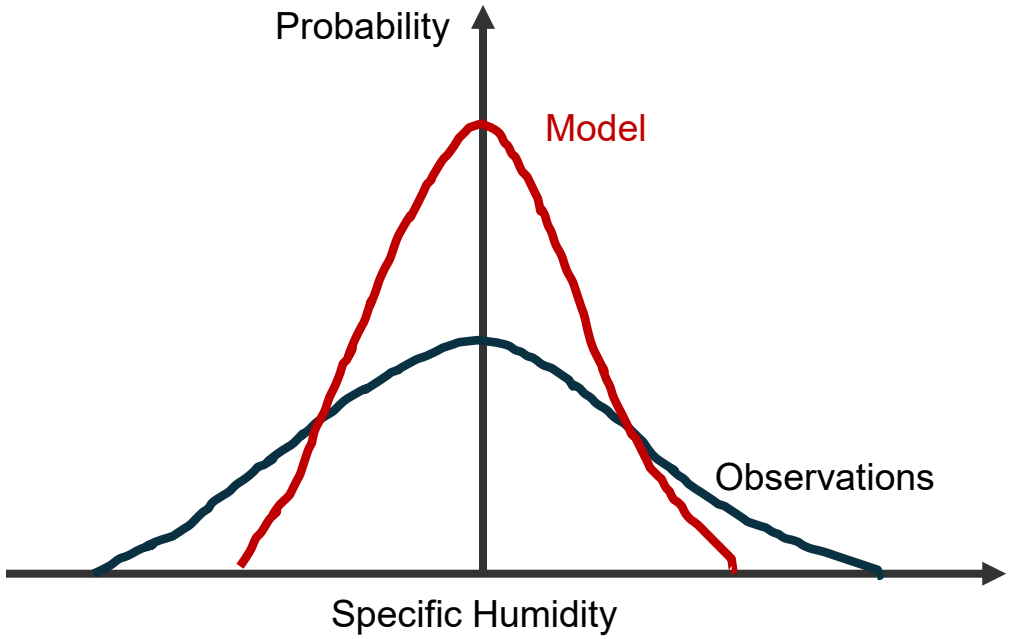
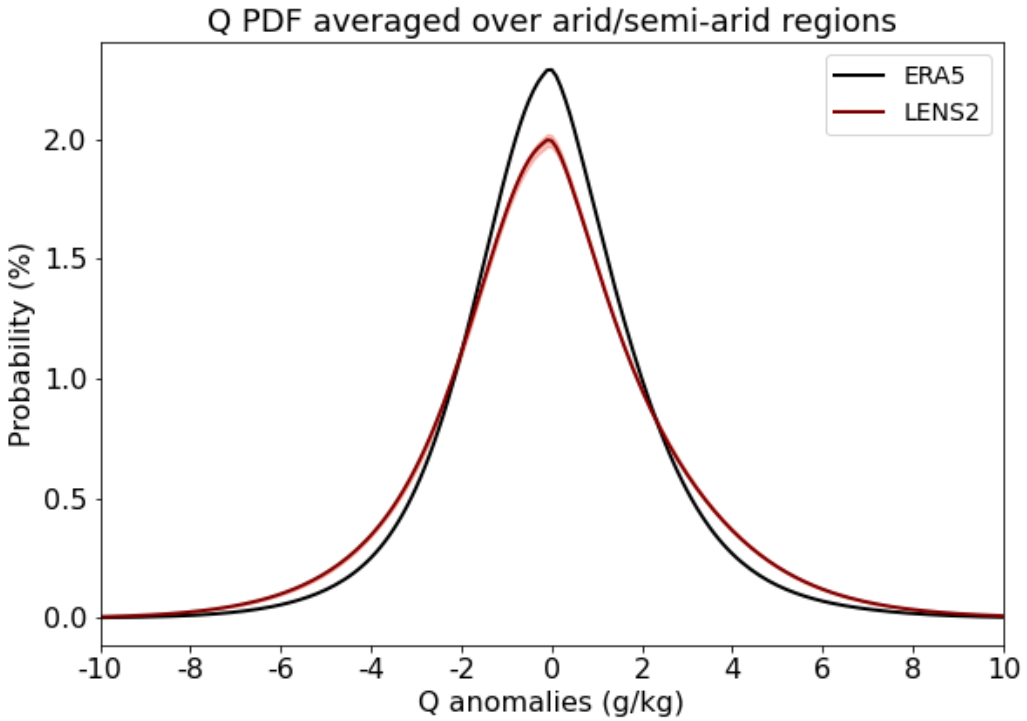
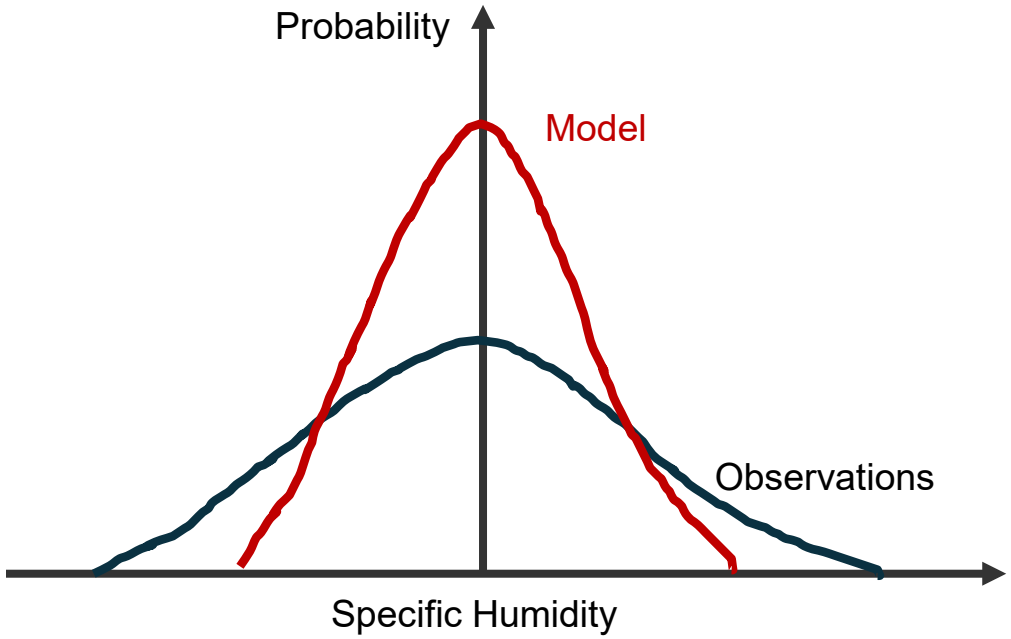




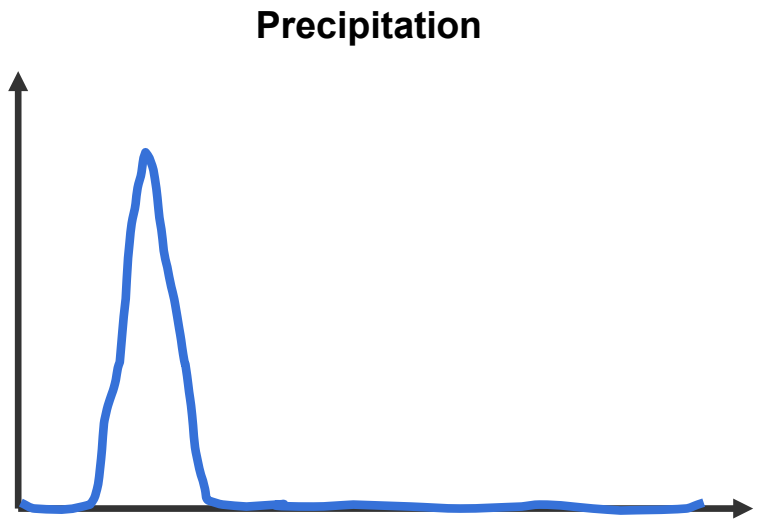
Distribution of daily specific humidity

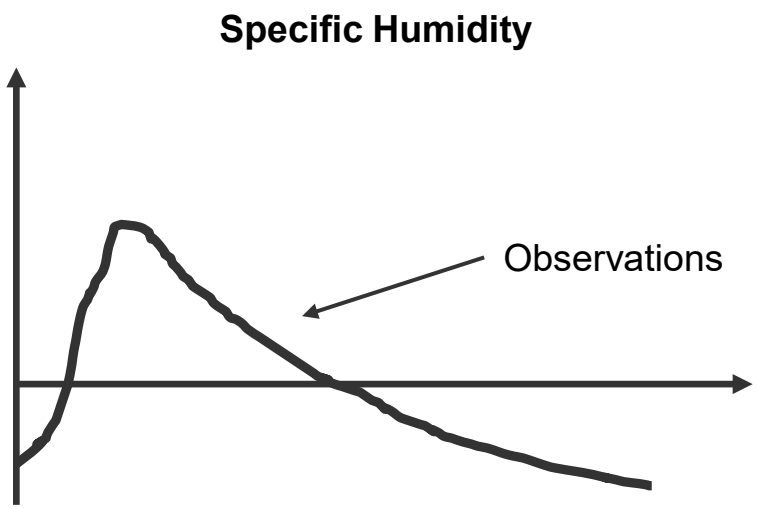


Warm Season



Drydowns - the evolution of near surface humidity after precipitation events.





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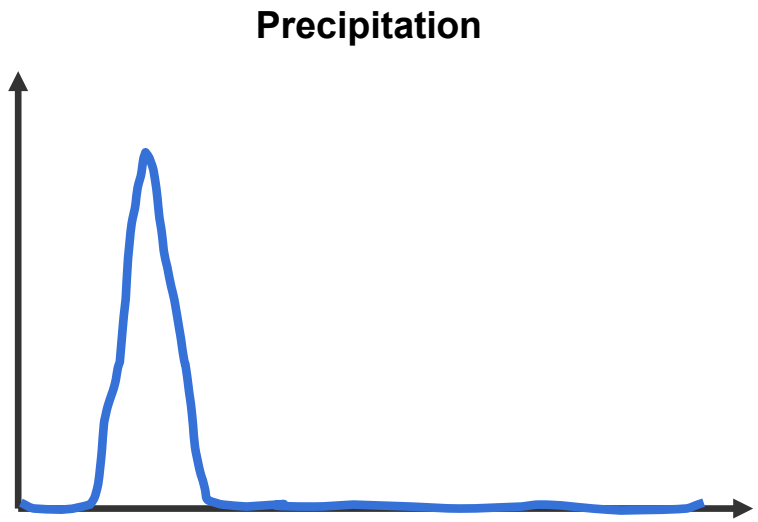
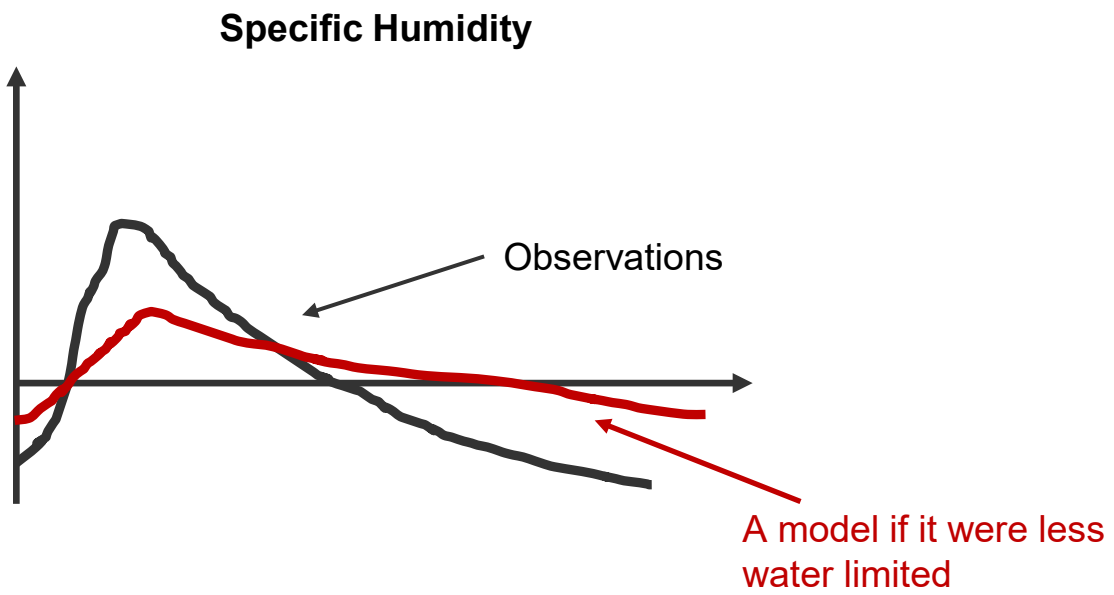
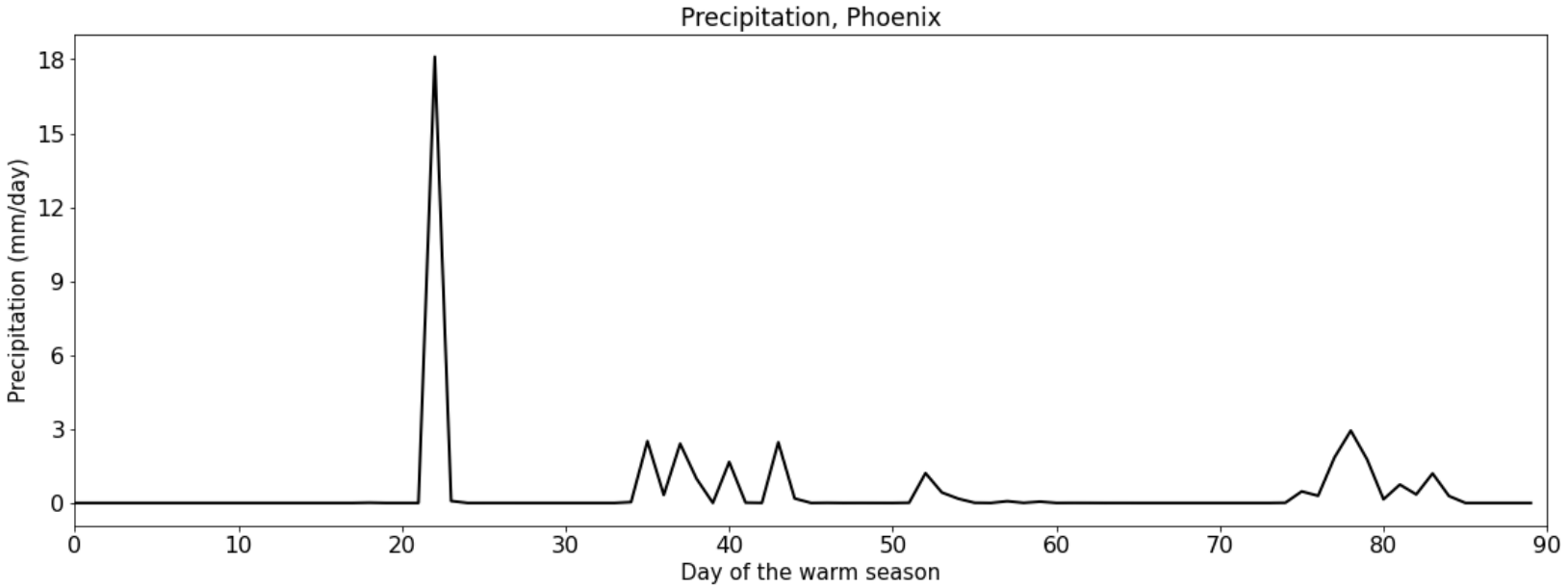
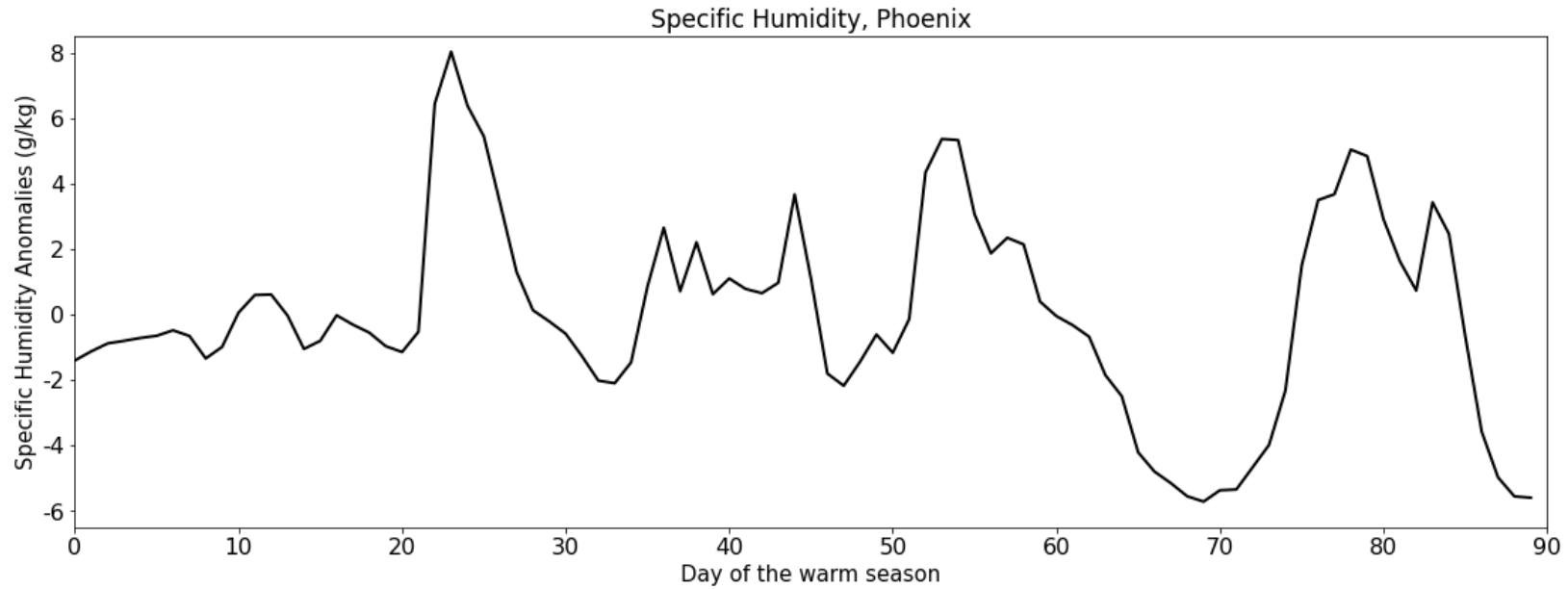




Drydown composite methodology





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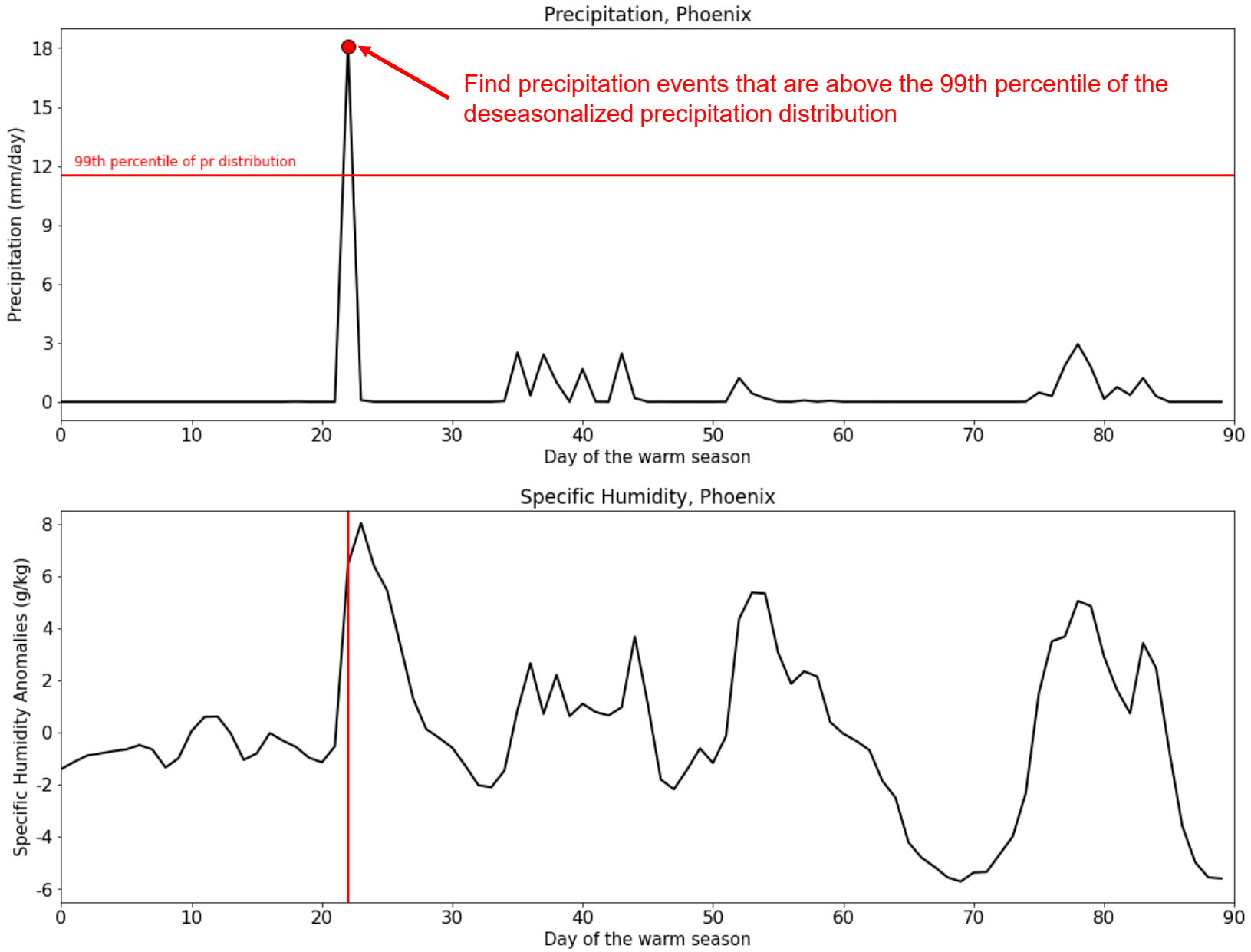

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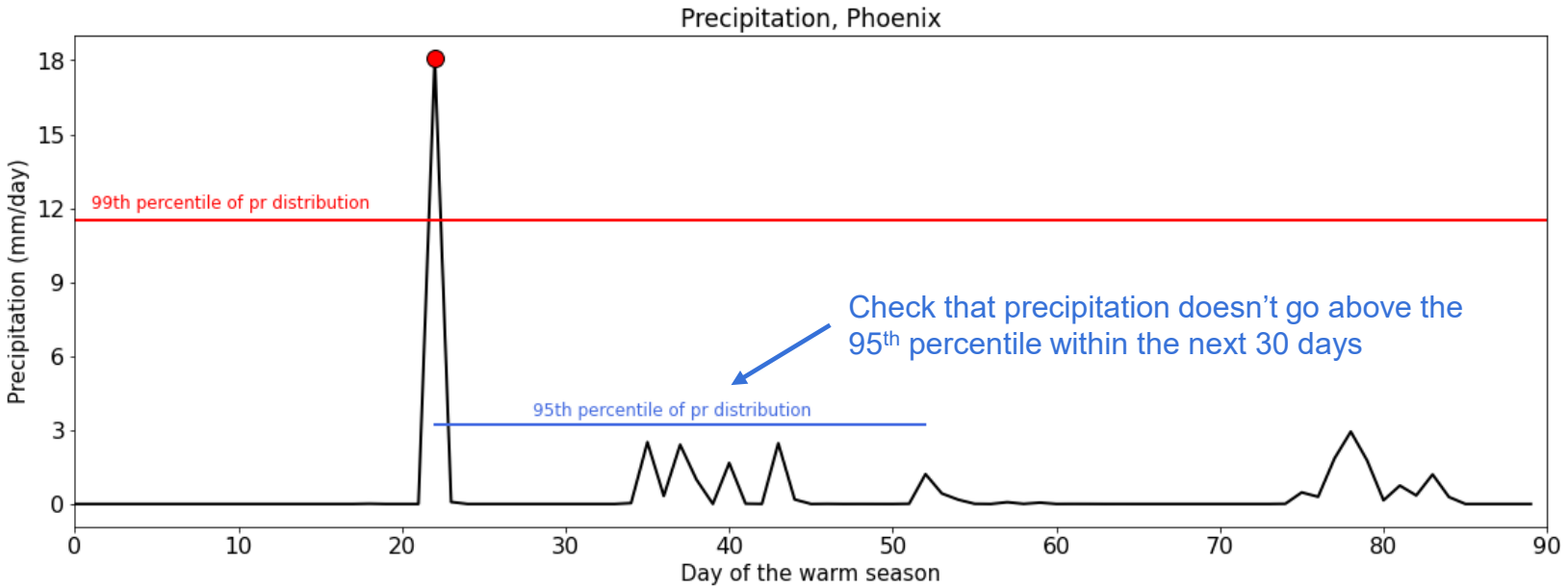
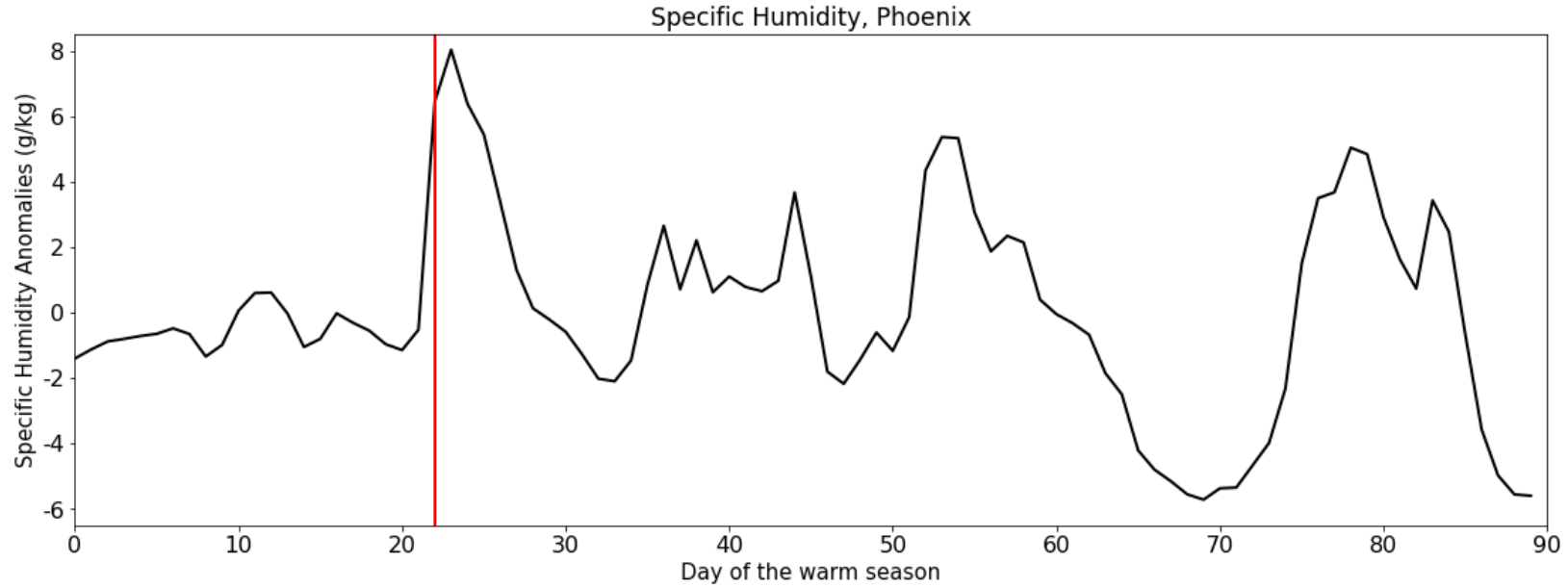
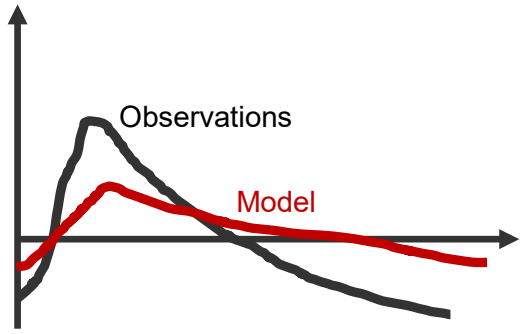




Drydowns (Precipitation and Specific Humidity)



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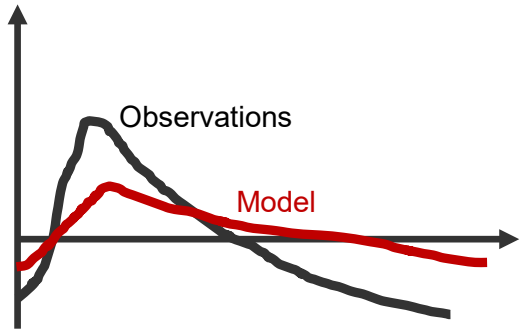

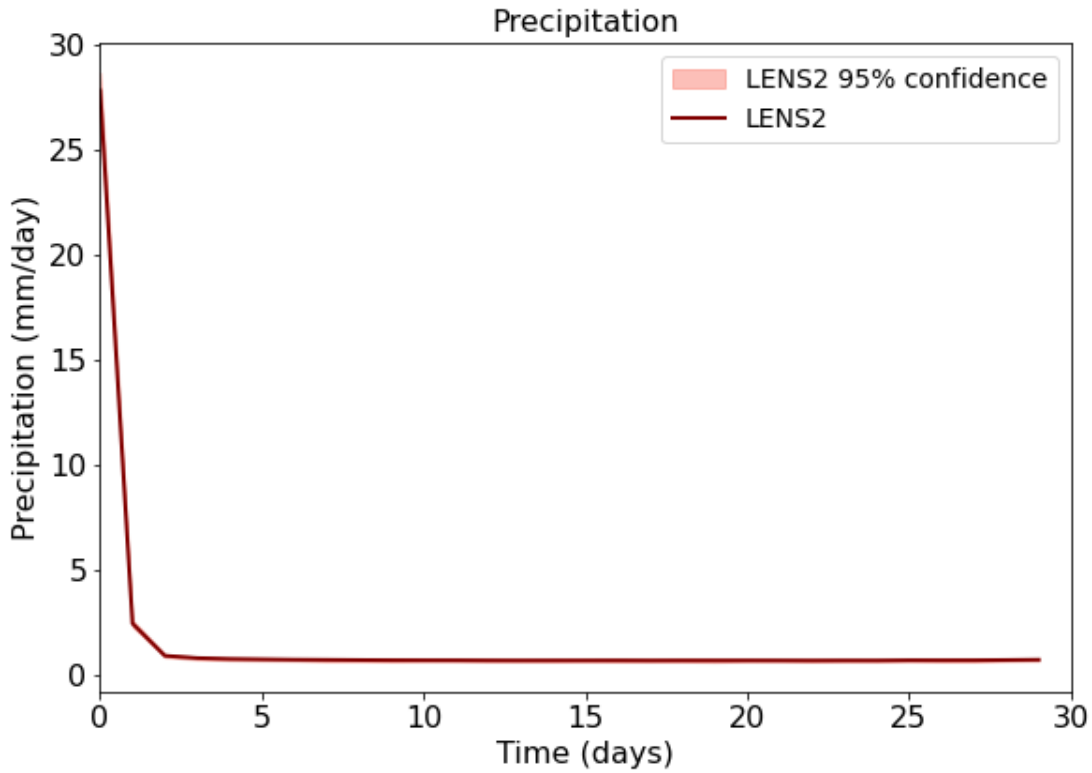

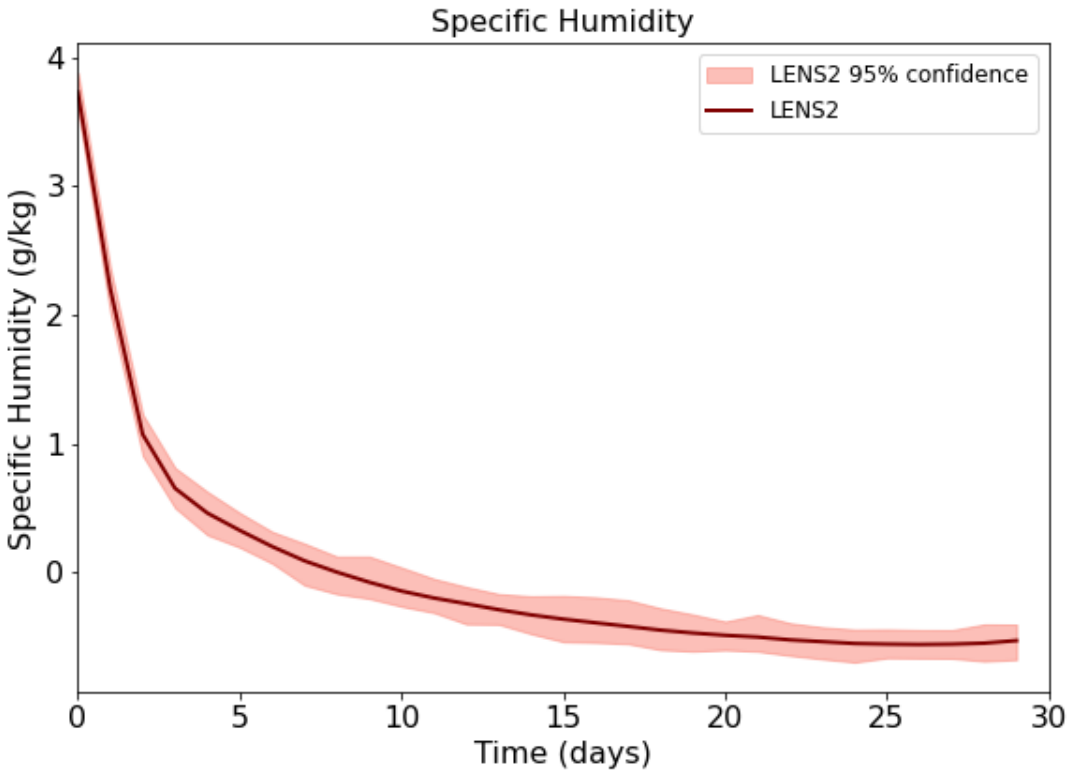

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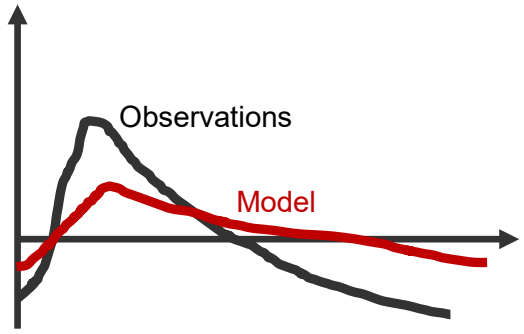

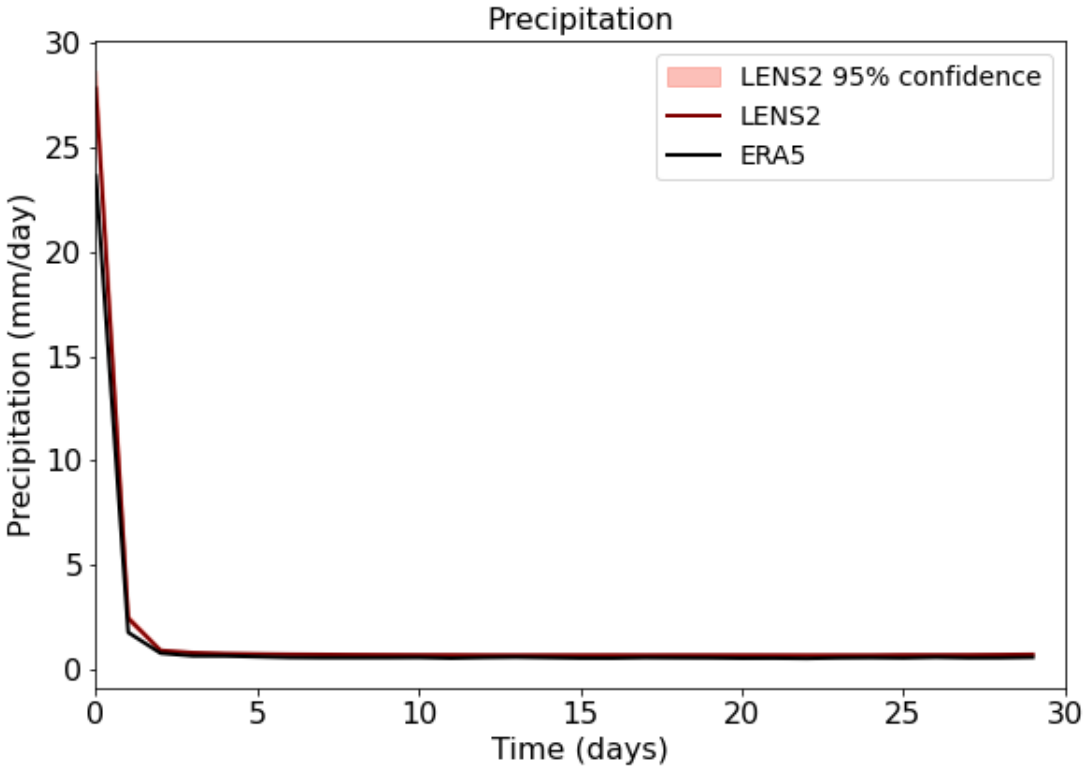

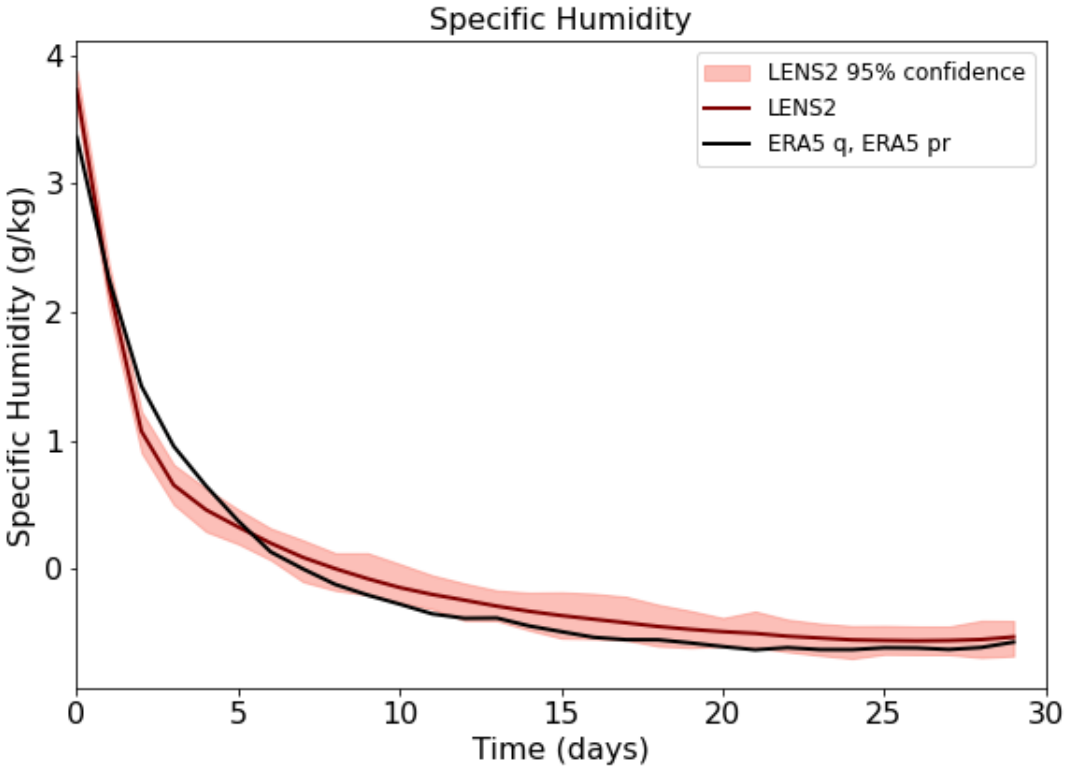

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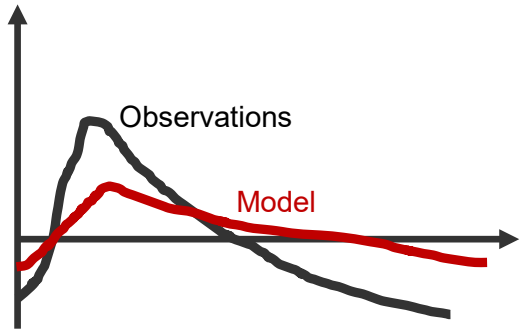
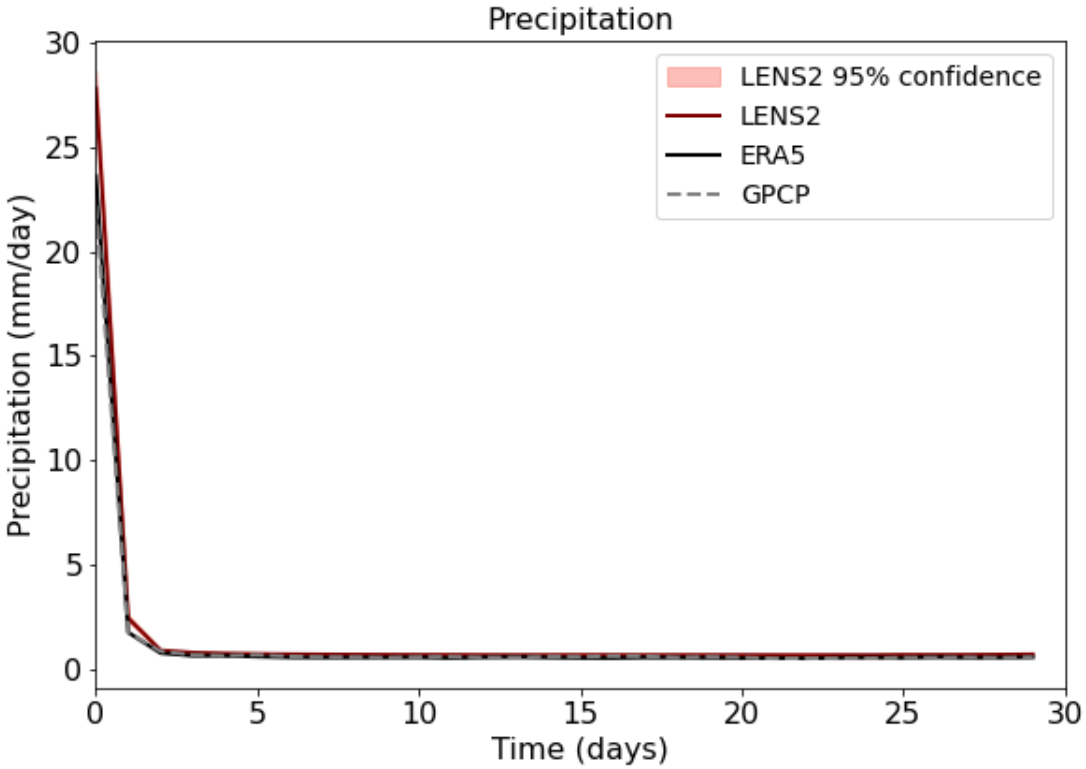
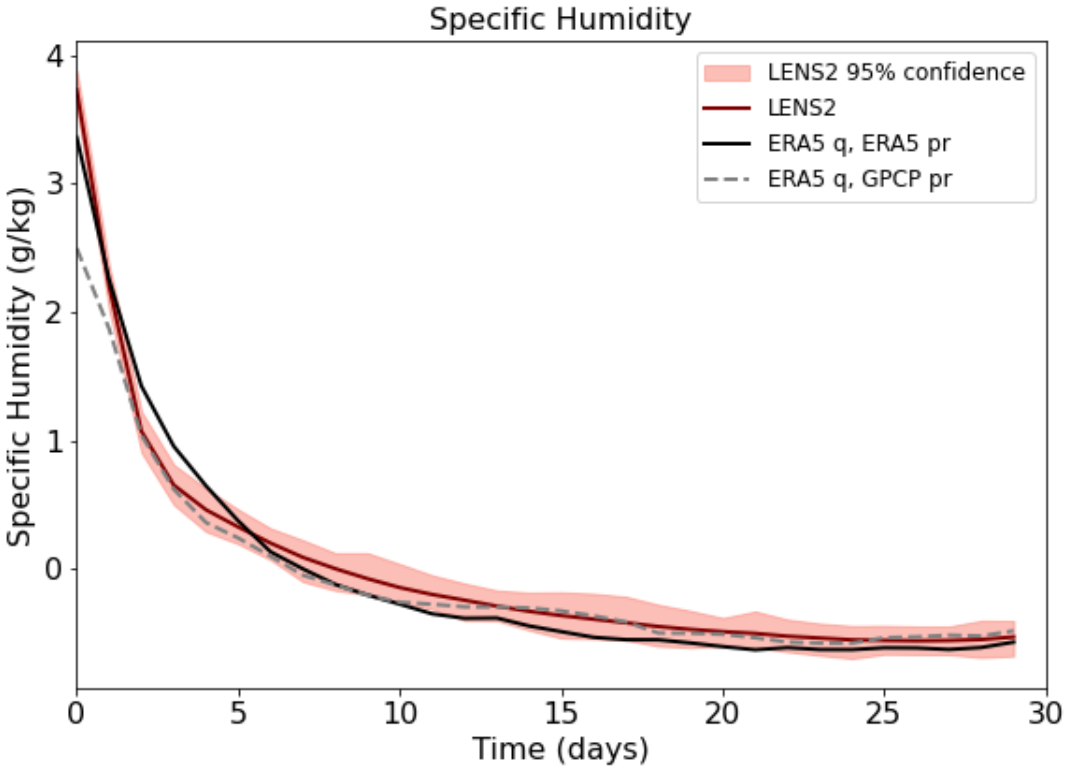
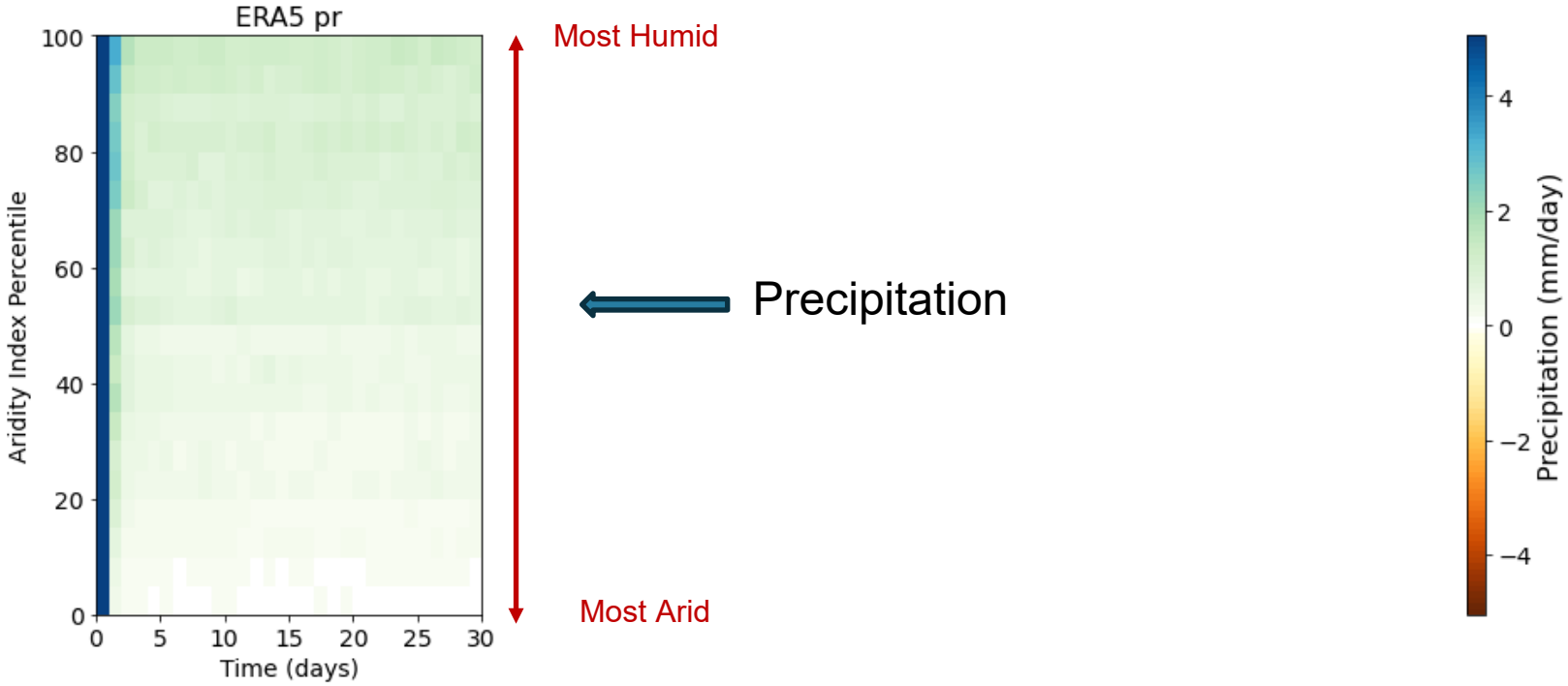
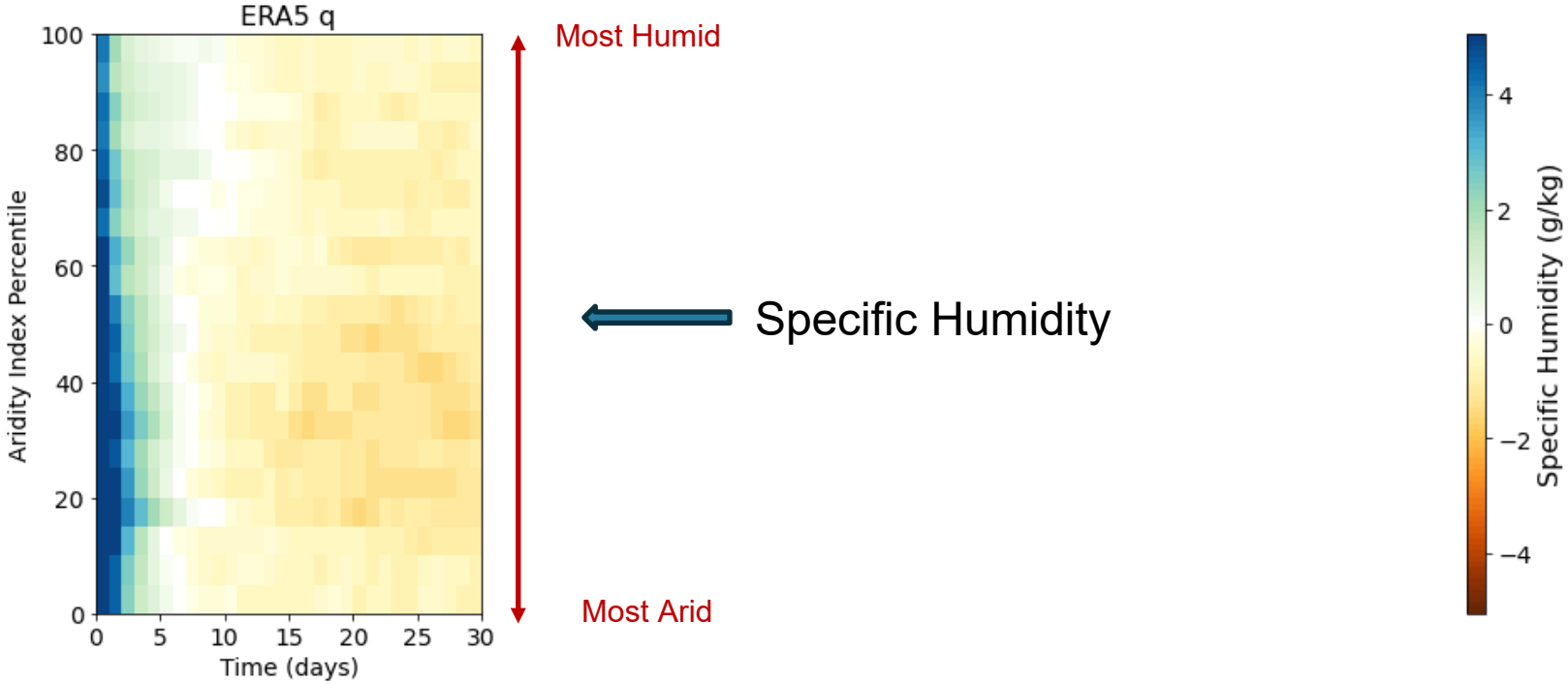
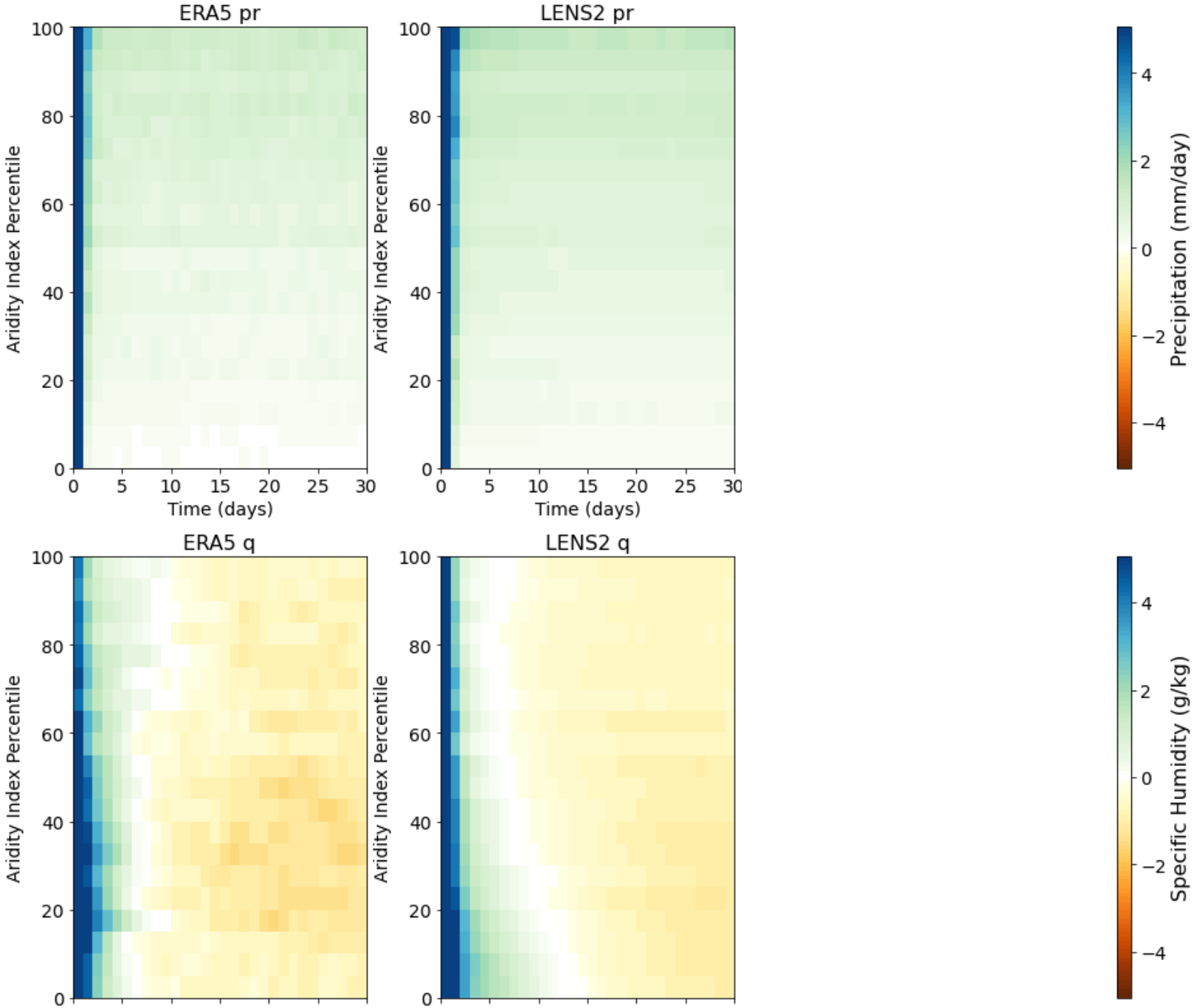


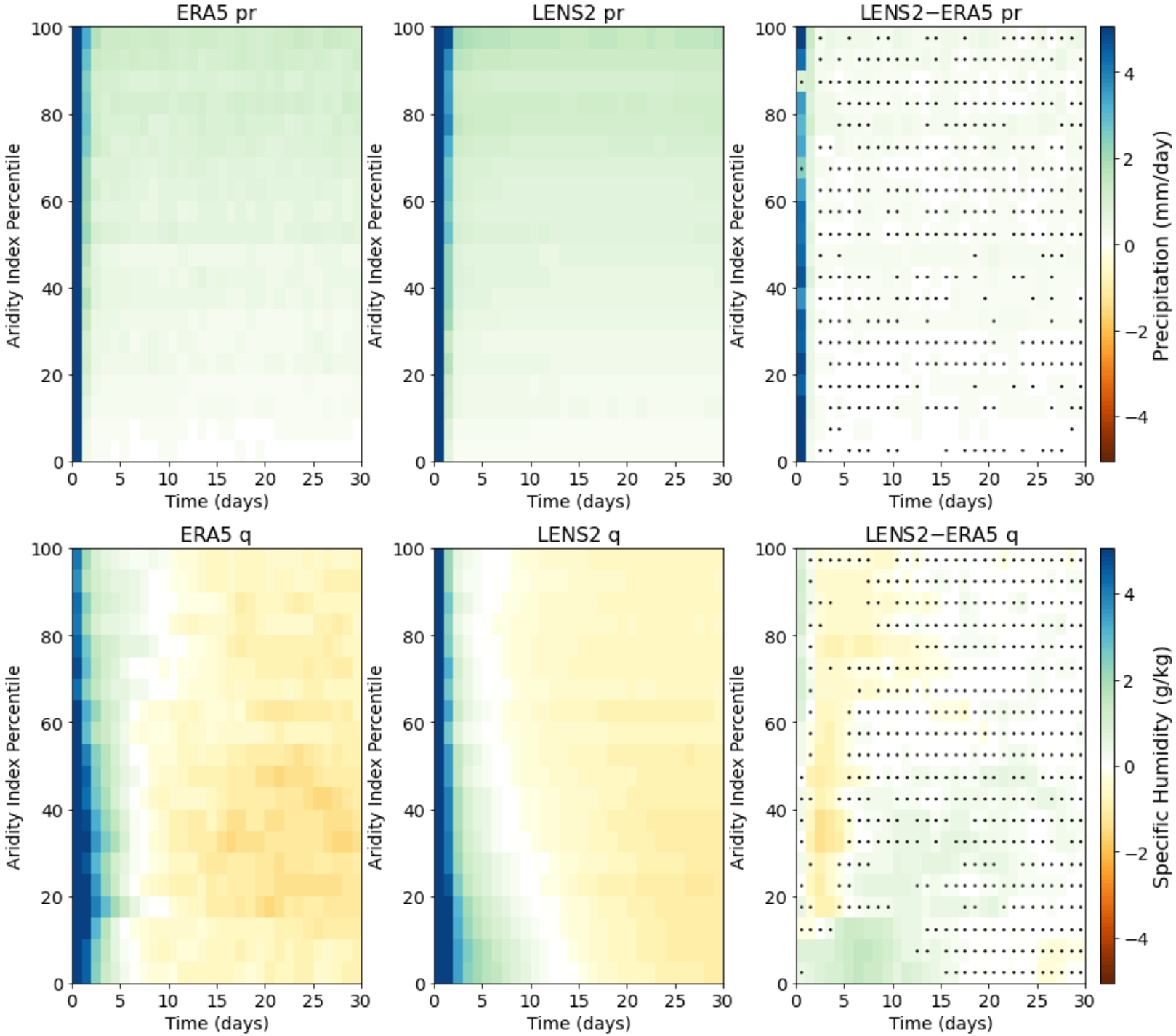





ERA5 pr
Aridity Index Percentile
Time (days)
Most Humid
Most Arid
Precipitation
Precipitation (mm/day)


ERA5 q
Aridity Index Percentile
Time (days)
Most Humid
Most Arid
Specific Humidity
Specific Humidity (g/kg)


ERA5 pr
LENS2 pr
ERA5 q
LENS2 q
Aridity Index Percentile
Time (days)
0
20
40
60
80
100
0
5
10
15
20
25
30
Precipitation (mm/day)
Specific Humidity (g/kg)
4
2
0
−2
−4


ERA5 pr
LENS2 pr
LENS2−ERA5 pr
ERA5 q
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All these point toward the model being in a similar regime to reality

Next Steps

(1) Verify these conclusions with flux tower sites and other soil moisture and ET products

(2) Search for any time evolution of these metrics over the historical record.

(3) Carry on investigating all the other possibilities.

Thanks to NOAA MAPP funding NA23OAR4310634-T1-01

MAPP
Modeling, Analysis, Predictions, and Projections

What could be going on?

Something wrong with the observational record

Models and observations differ in the change in atmospheric water vapor transport

Models have more water available at the land surface

Models land surface is not drying out as much as observed

Soil Evaporation is not changing with temperature or radiation in the same way

Plant transpiration is not changing with temperature, radiation, or CO2 in the same way

The vertical structure of humidity trends near the surface might be different

?????????????

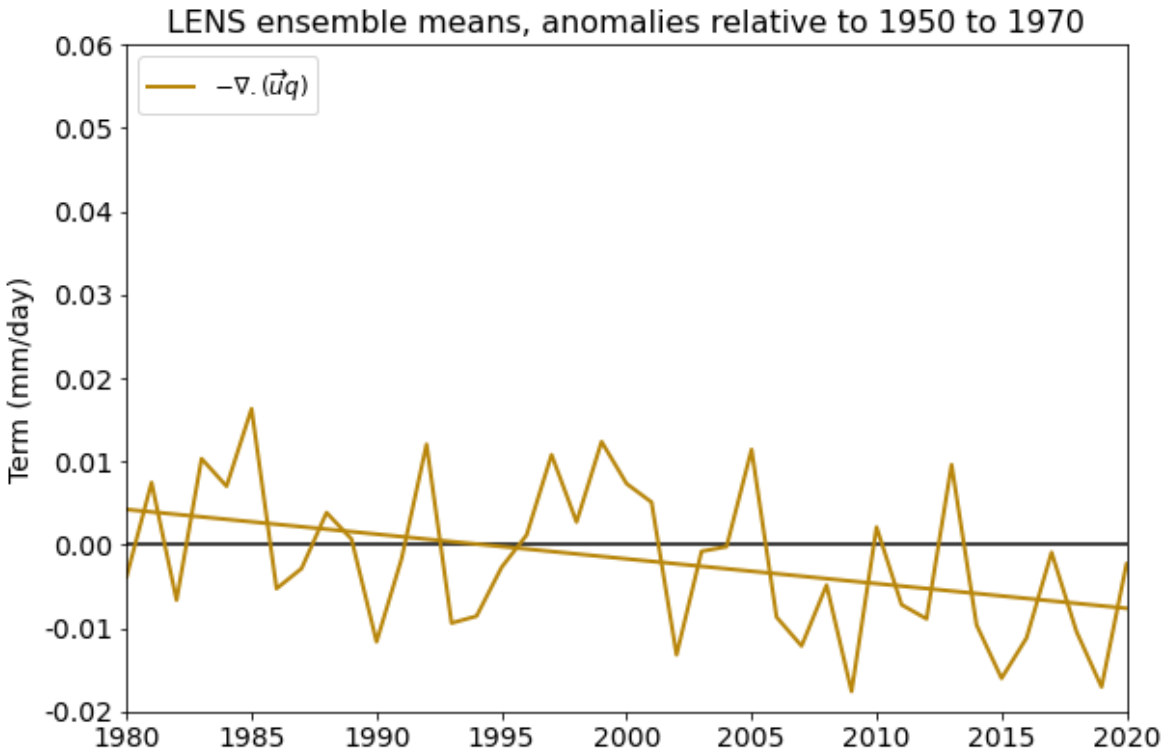
Extra Slides

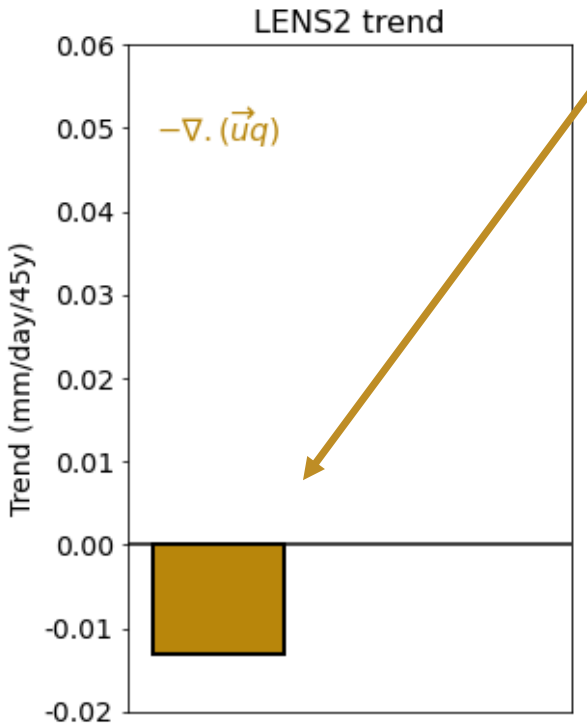
The evolution of the moisture budget terms in the CESM2 large ensemble

[_] = vertical integral

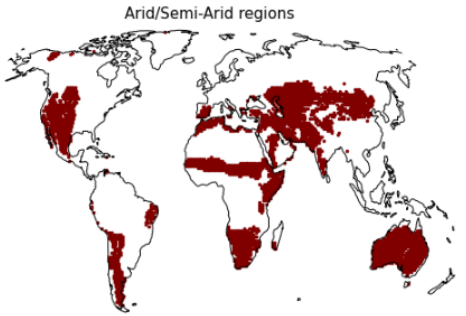
$$\frac{\partial [q]}{\partial t} = -[\nabla.(\vec{u}q)] + E - P$$

Large ensemble average, averaged over arid/semi-arid regions





Convergence of moisture by the atmosphere is declining



The evolution of the moisture budget terms in the CESM2 large ensemble

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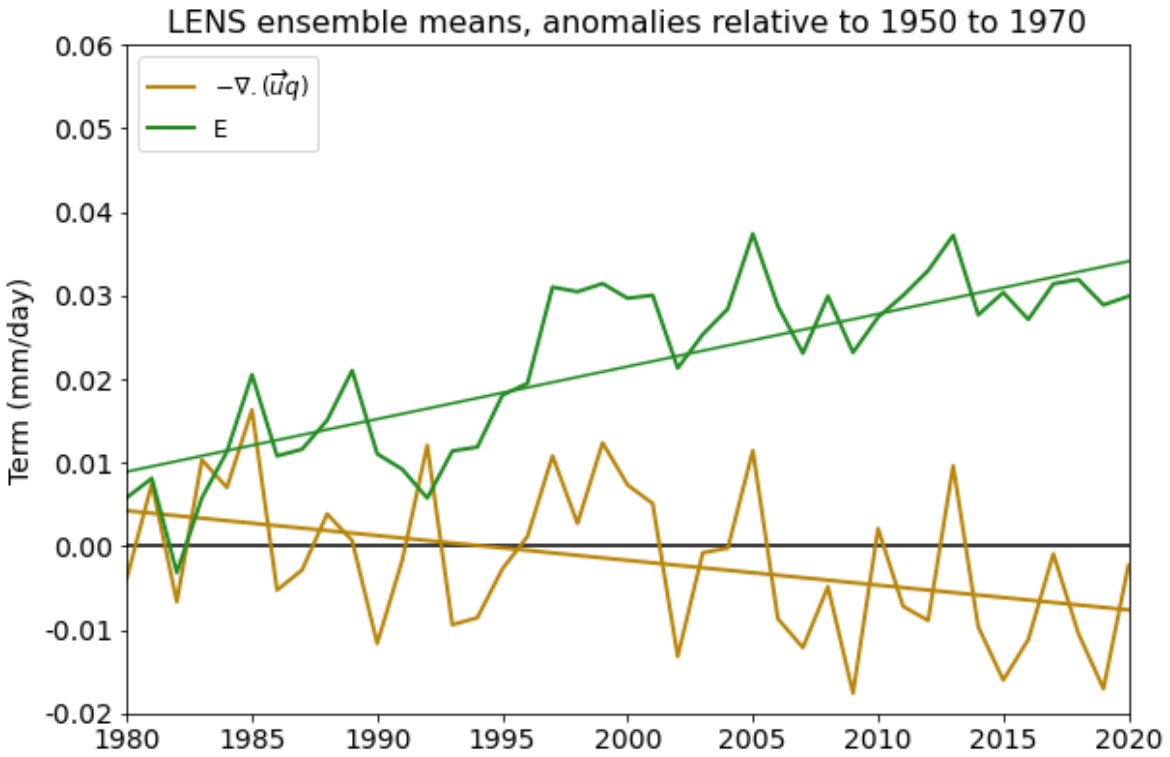
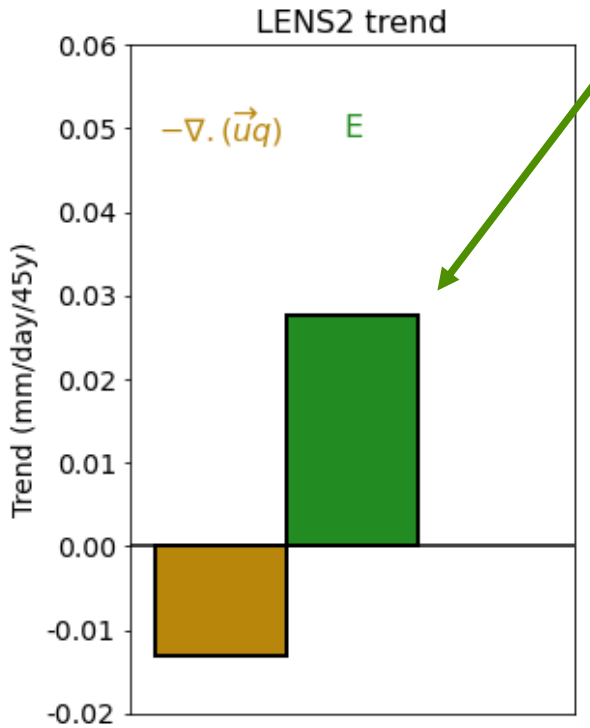
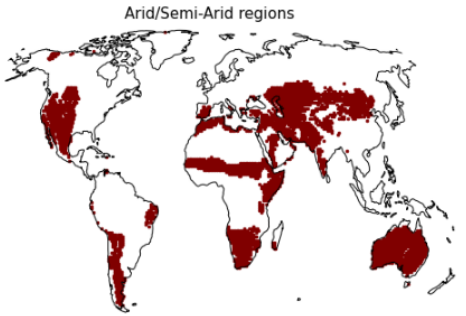
Large ensemble average, averaged over arid/semi-arid regions

Evaporation is increasing







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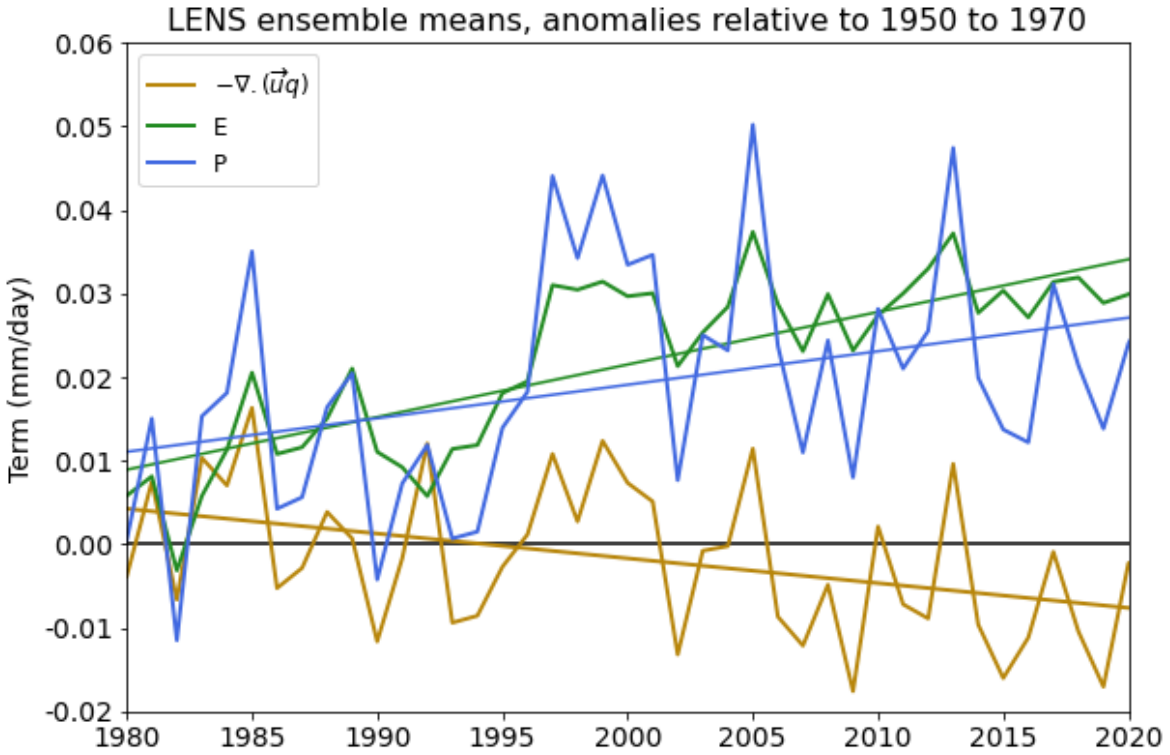
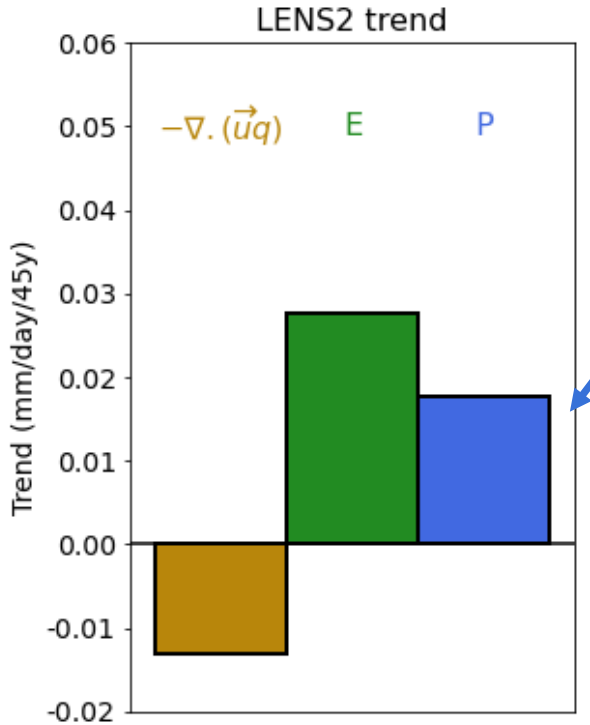
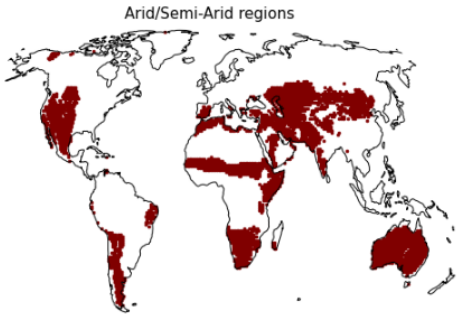
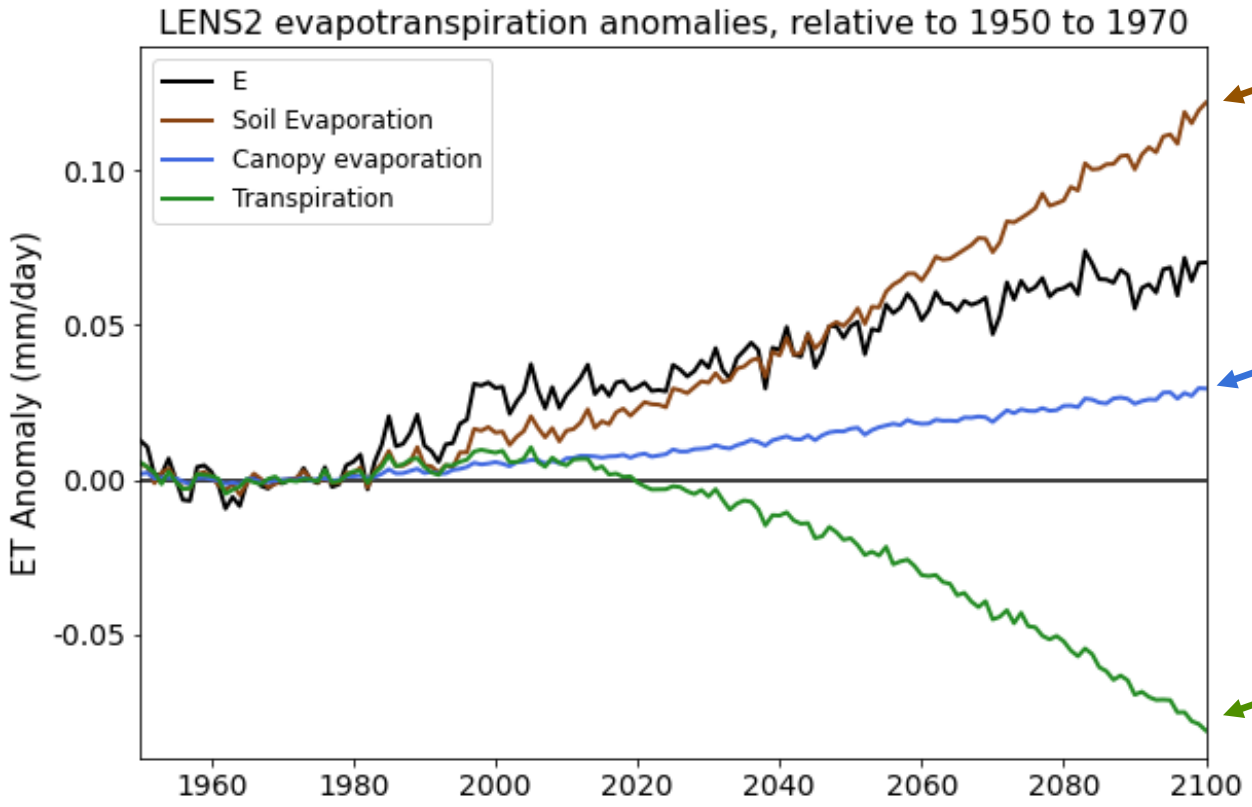




Precipitation is also increasing but not as much as evapotranspiration



Evapotranspiration keeps on rising out to 2100 in LENS2

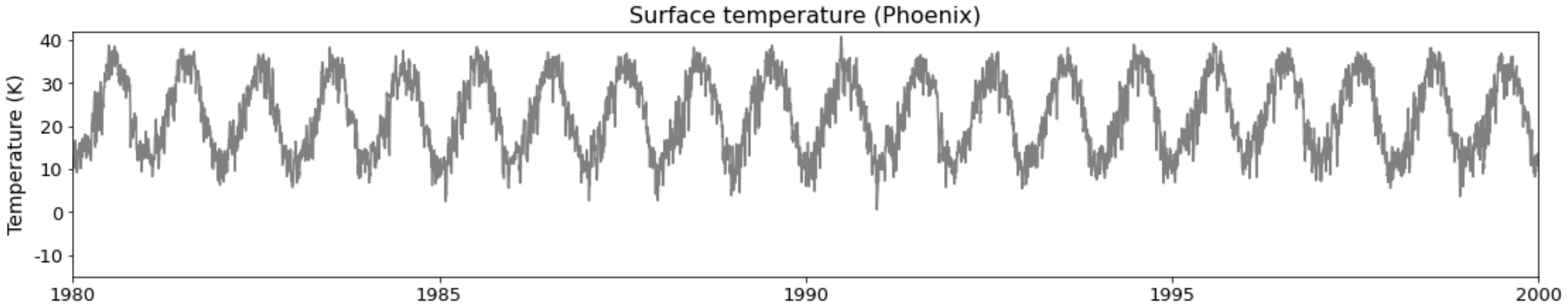


Evaporation from the soil keeps on rising

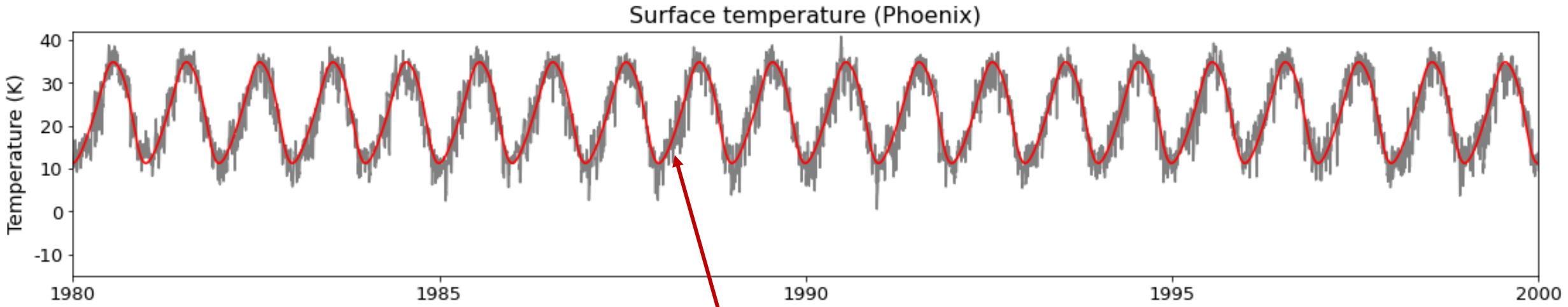
So does evaporation from the canopy

Partly offset by a decline in transpiration

Deseasonalizing and detrending approach

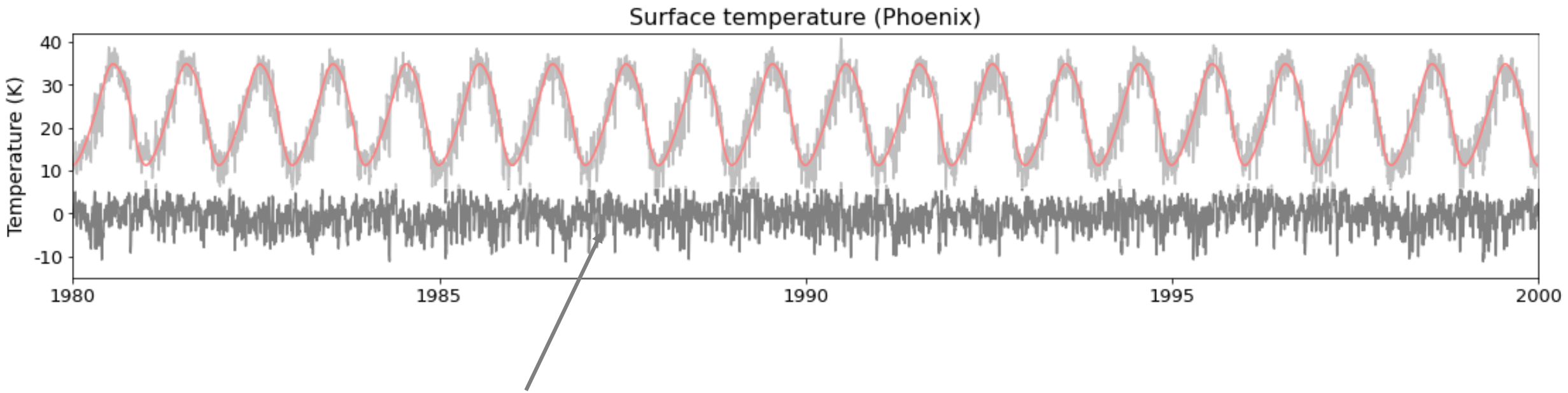


Deseasonalizing and detrending approach



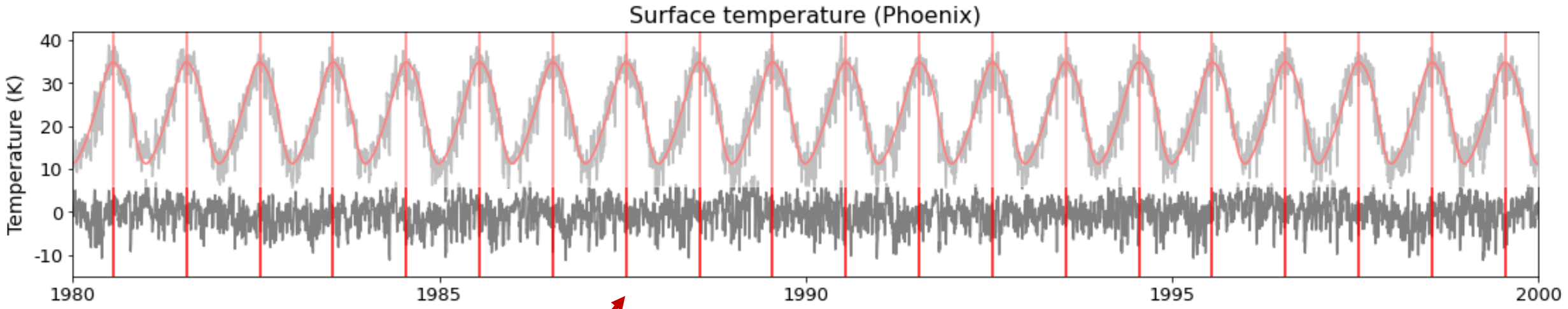
Seasonal cycle. First four harmonics of the seasonally varying climatology.

Deseasonalizing and detrending approach



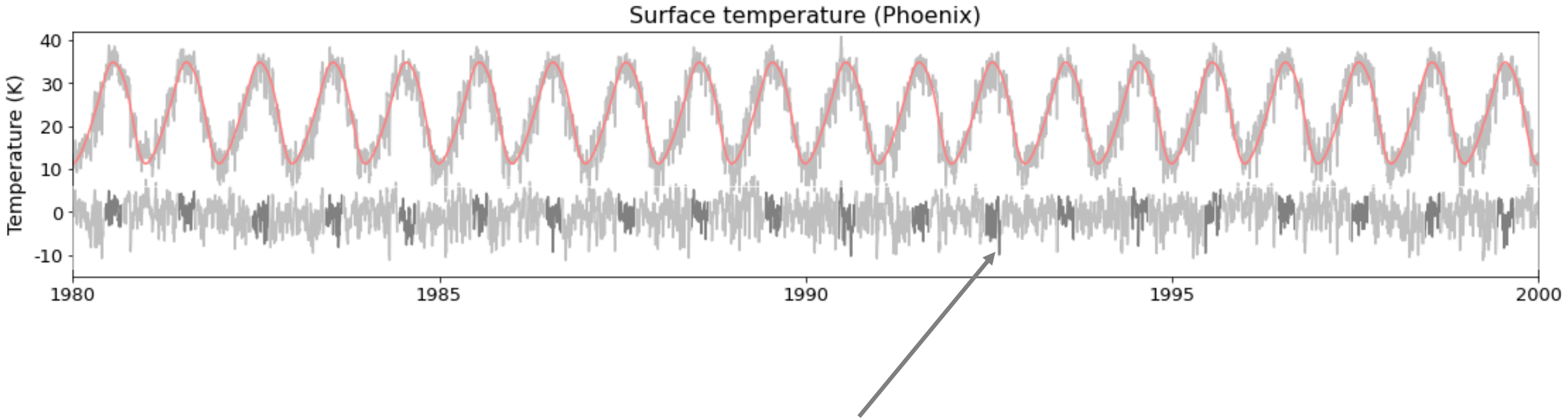
Anomalies from the seasonal cycle

Deseasonalizing and detrending approach



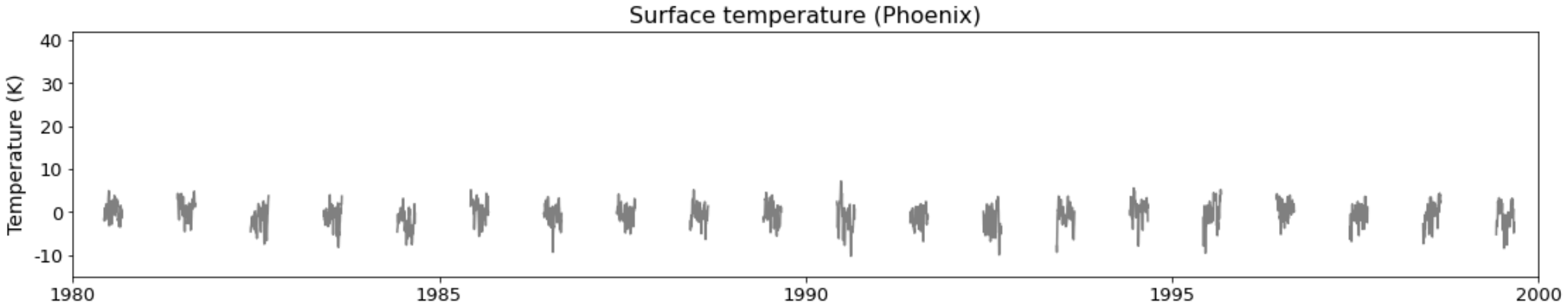
Seasonal cycle maximum

Deseasonalizing and detrending approach

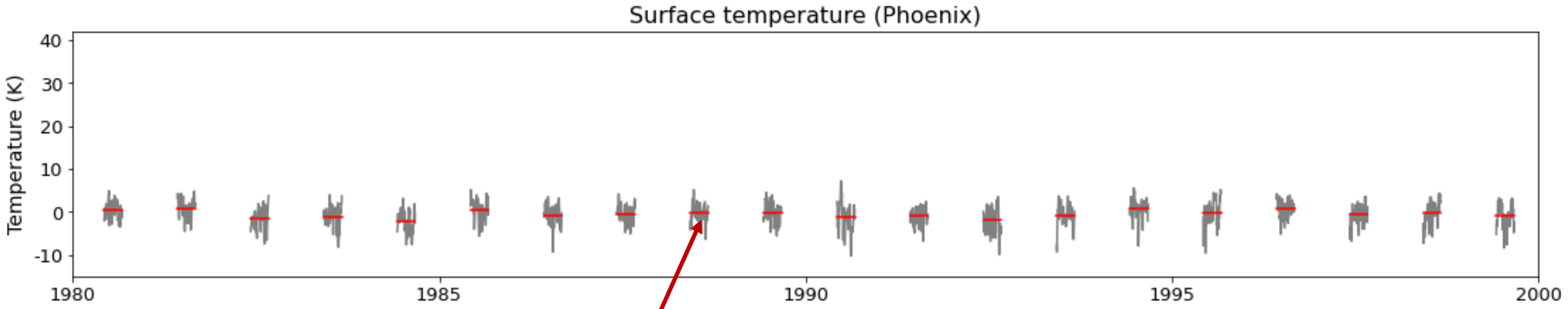


90 days centered on the middle of the warm season.

Deseasonalizing and detrending approach

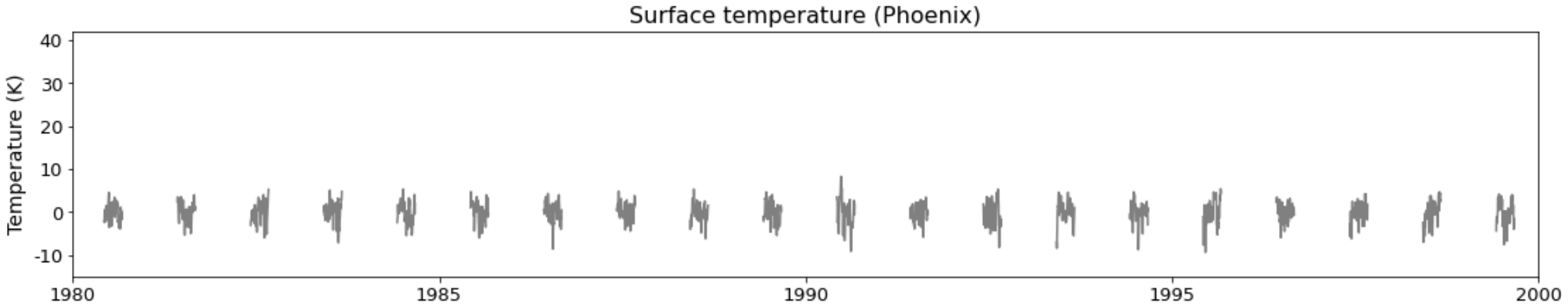


Deseasonalizing and detrending approach



Seasonal mean for each year.

Deseasonalizing and detrending approach



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