A global discrepancy in atmospheric water vapor trends between models and observations

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MAPP
Modeling, Analysis, Predictions, and Projections

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Two reasons why we care about atmospheric water vapor…

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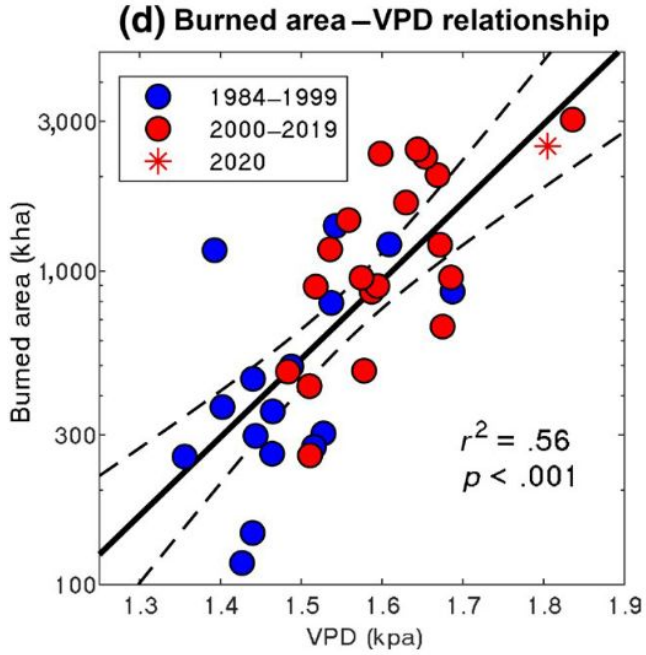
Close links between vapor pressure deficit and wildfire

$$VPD = e_s - e_a$$

Saturation Vapor Pressure (Depends on Temperature)

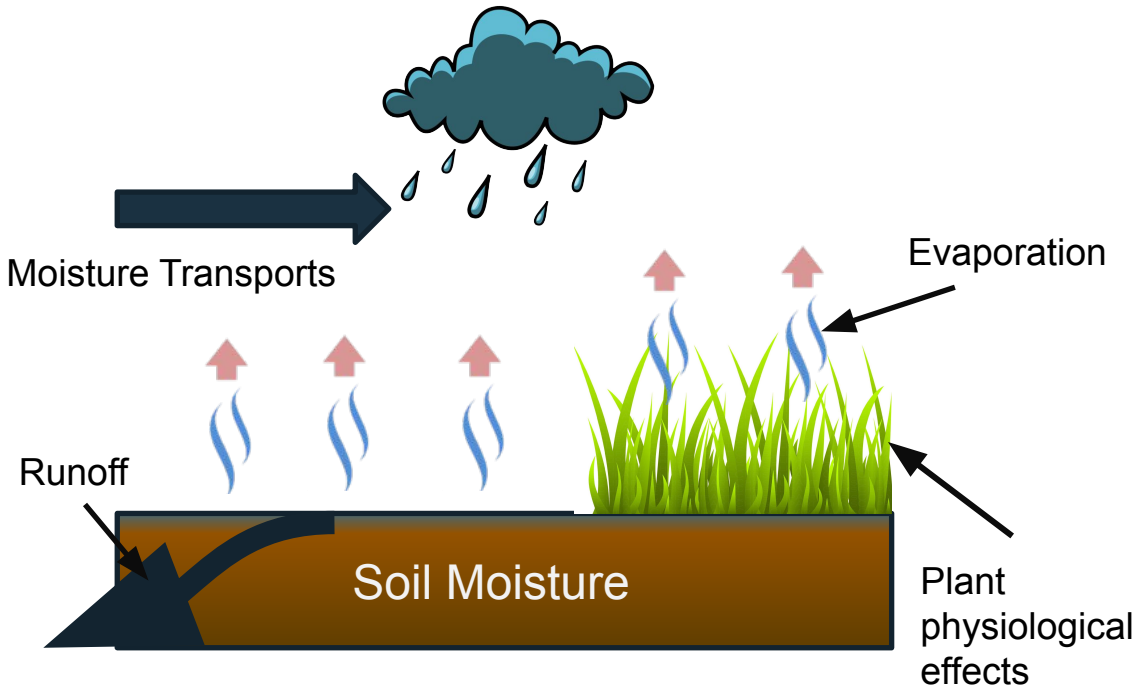
Actual Vapor Pressure

Higuera and Abatzoglou (2020) - over the US southwest, you have a larger burned area in a fire season when the VPD is high



Two reasons why we care about atmospheric water vapor…

An indicator of trends in processes that (a) we don't necessarily have good observations of and (b) we may not have a perfect representation of in our Earth System Models



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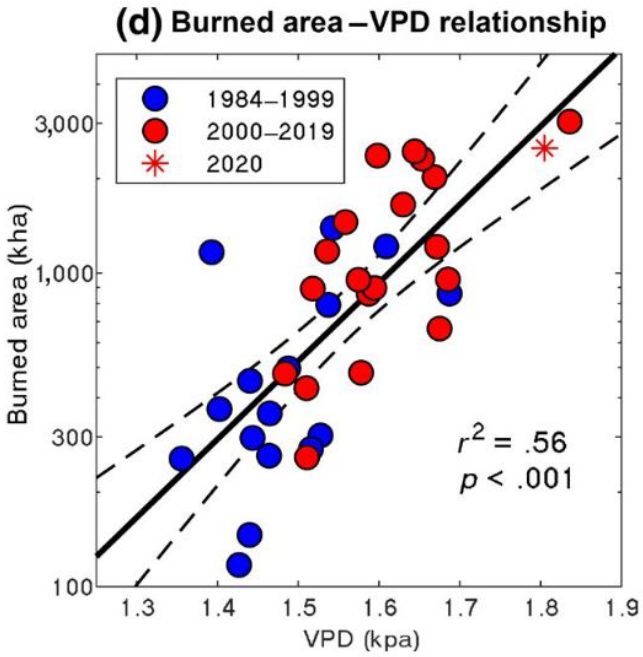
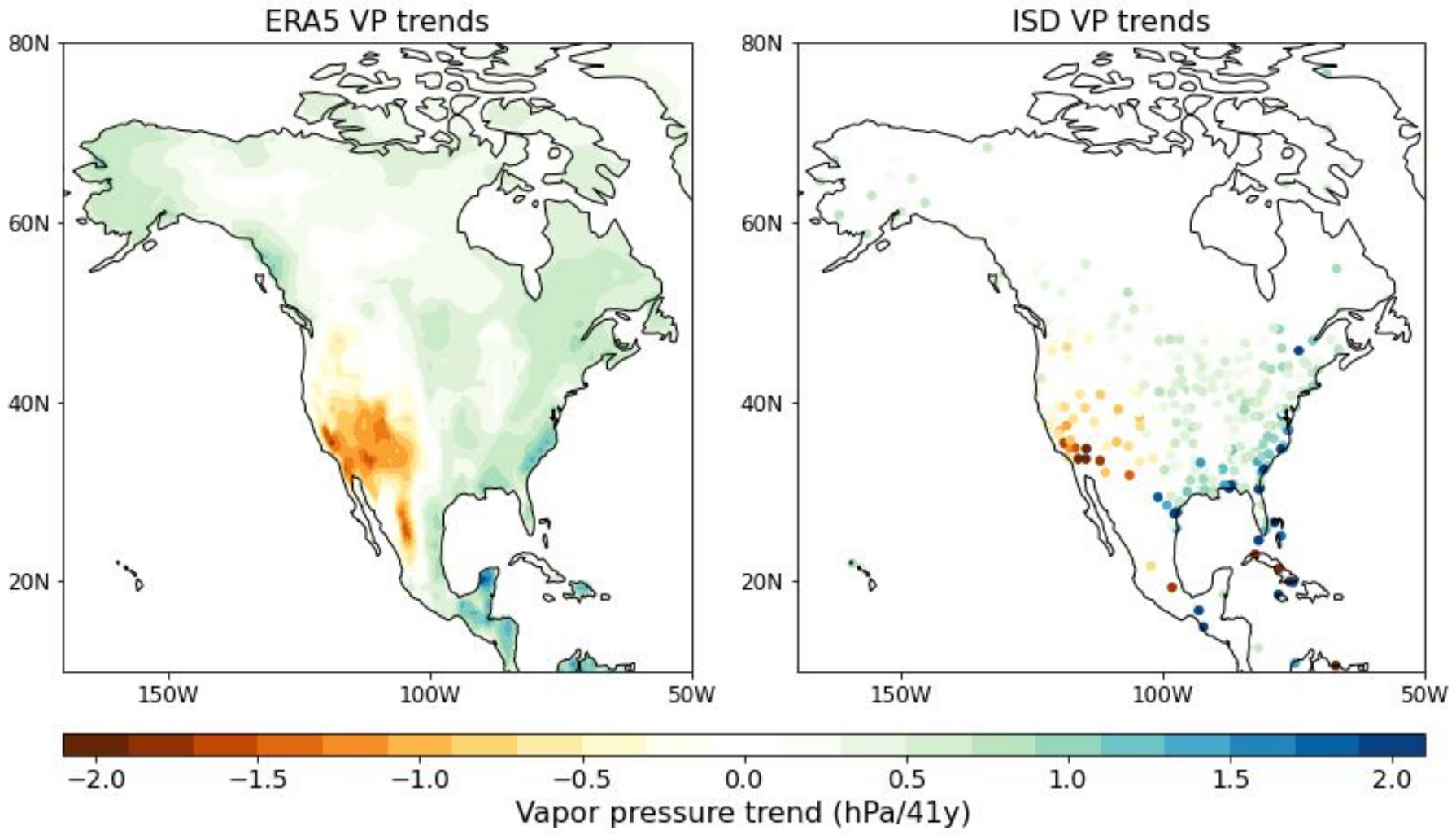


A case study: the US Southwest

Annual mean 2m vapor pressure trends, 1980-2020

ERA5



ISD stations

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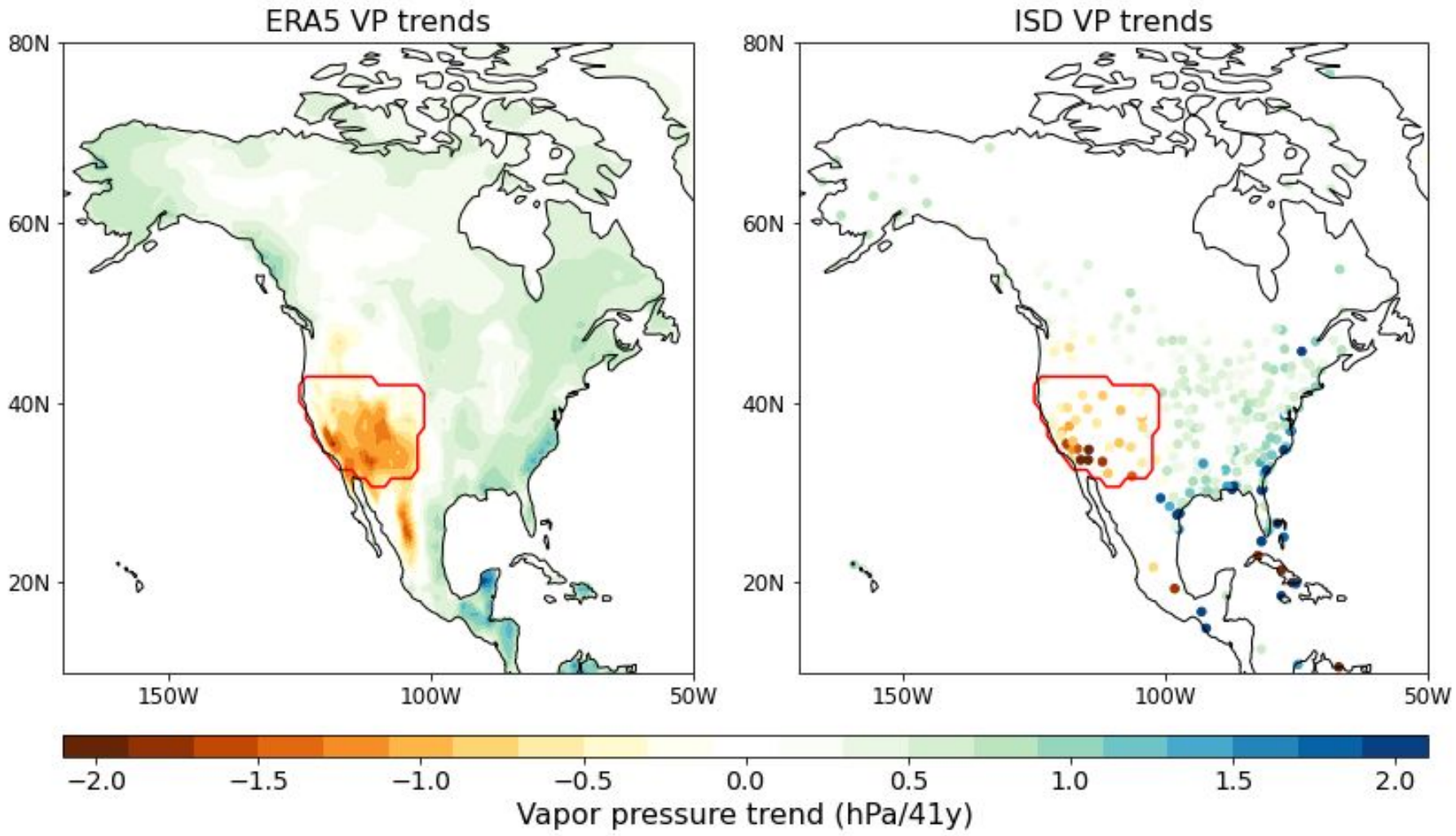
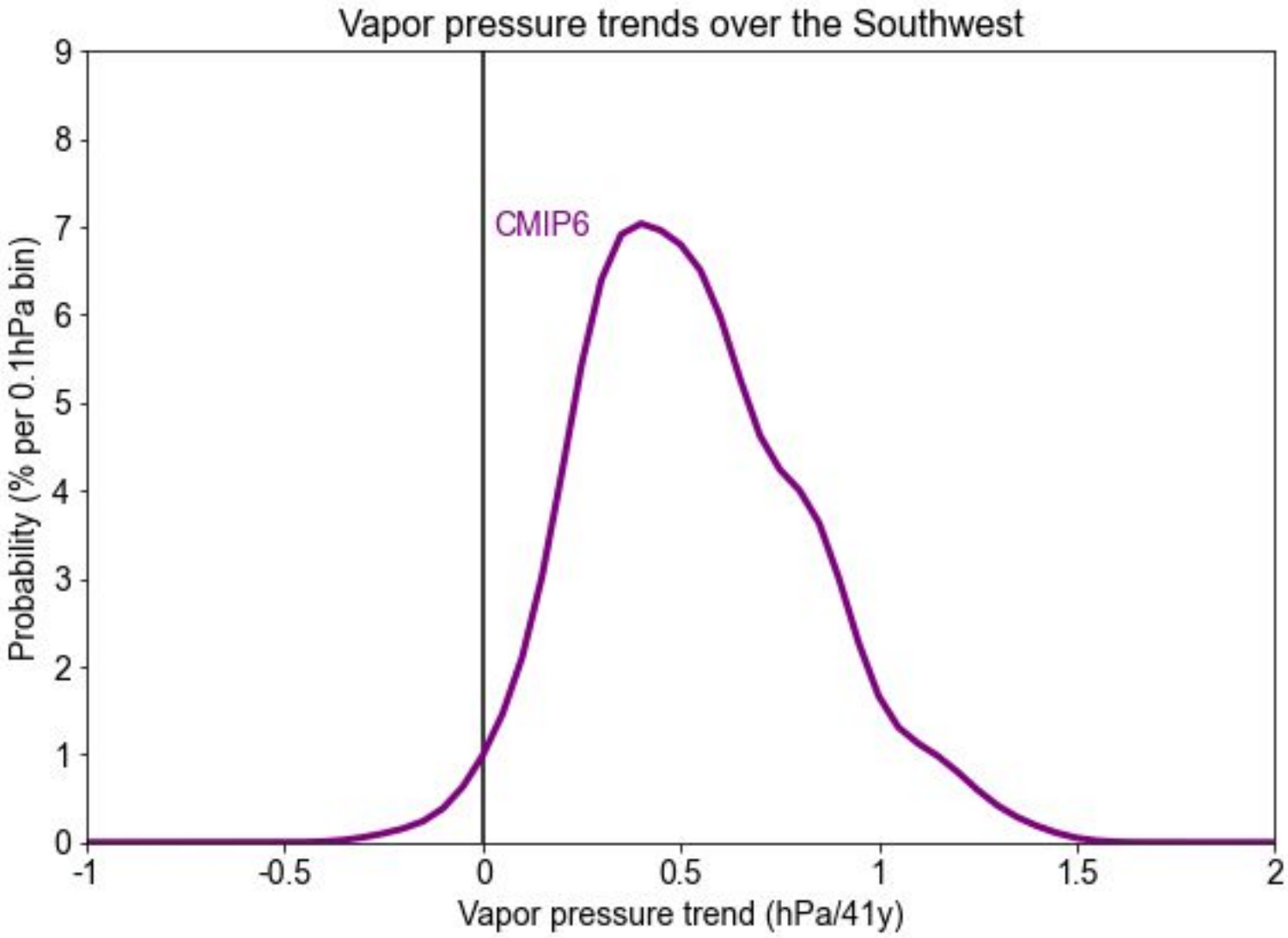


ISD stations

Vapor pressure trends averaged over the Southwest



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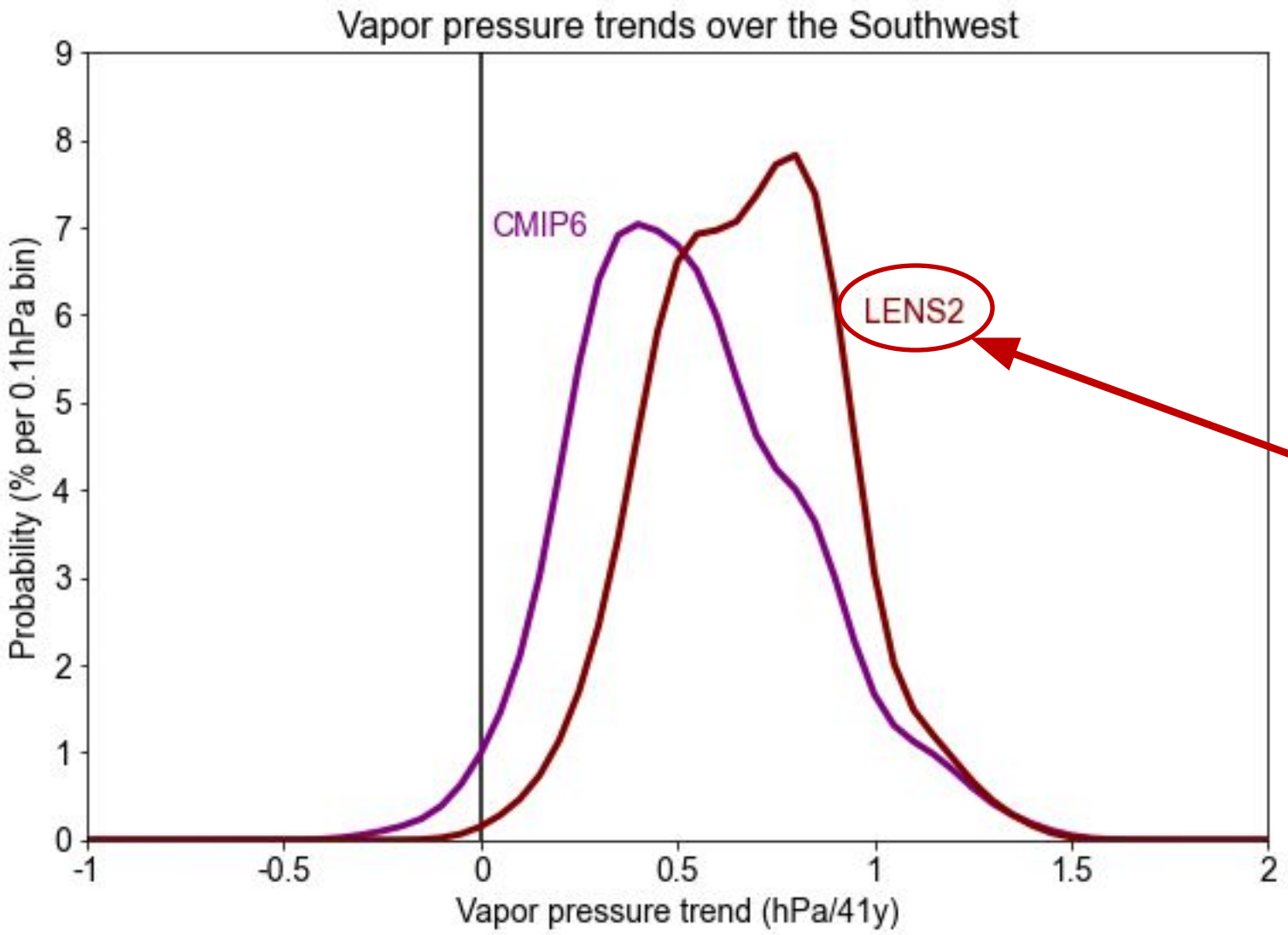

CESM2 large ensemble
(Rodgers et al 2021)

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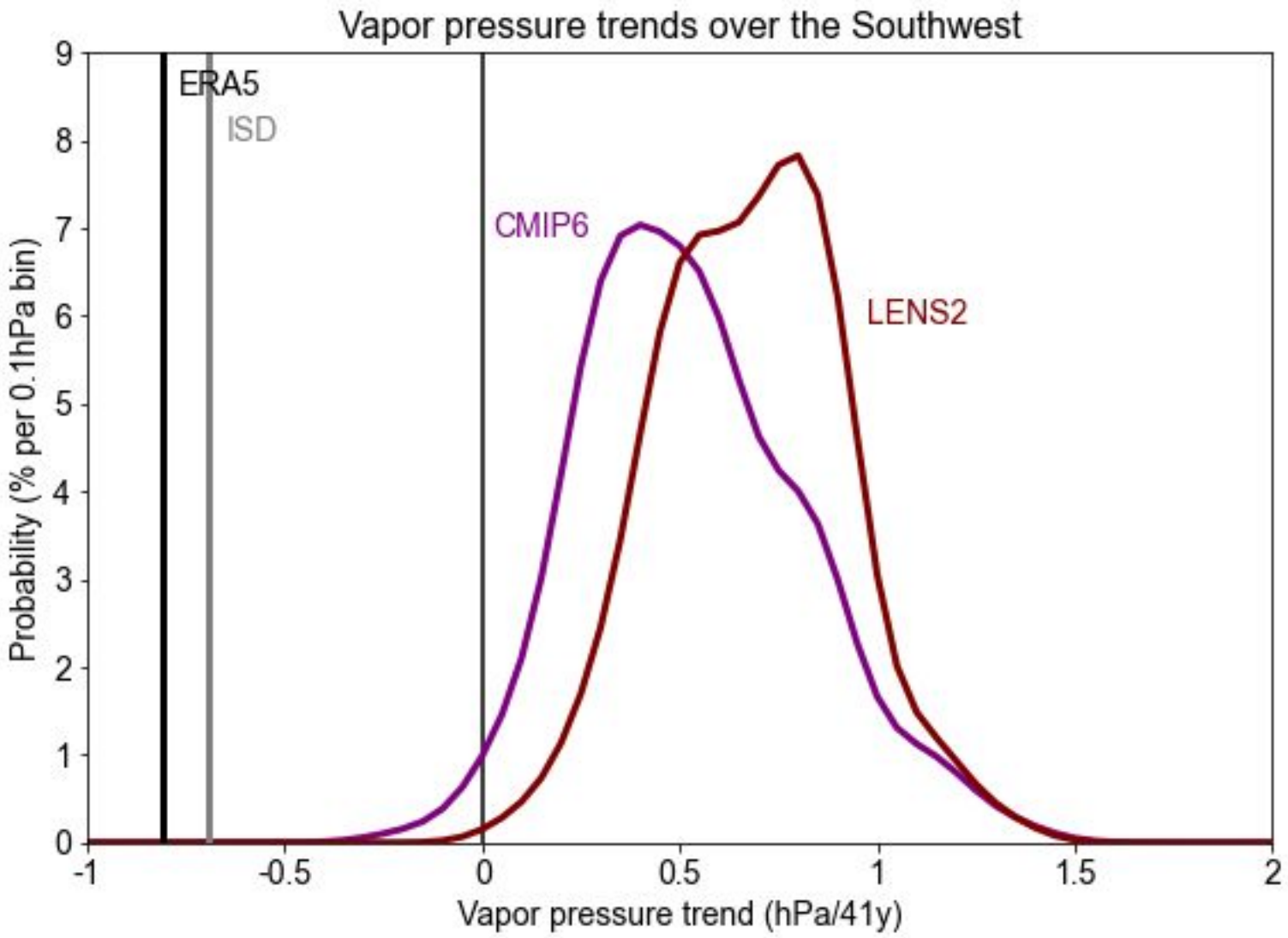

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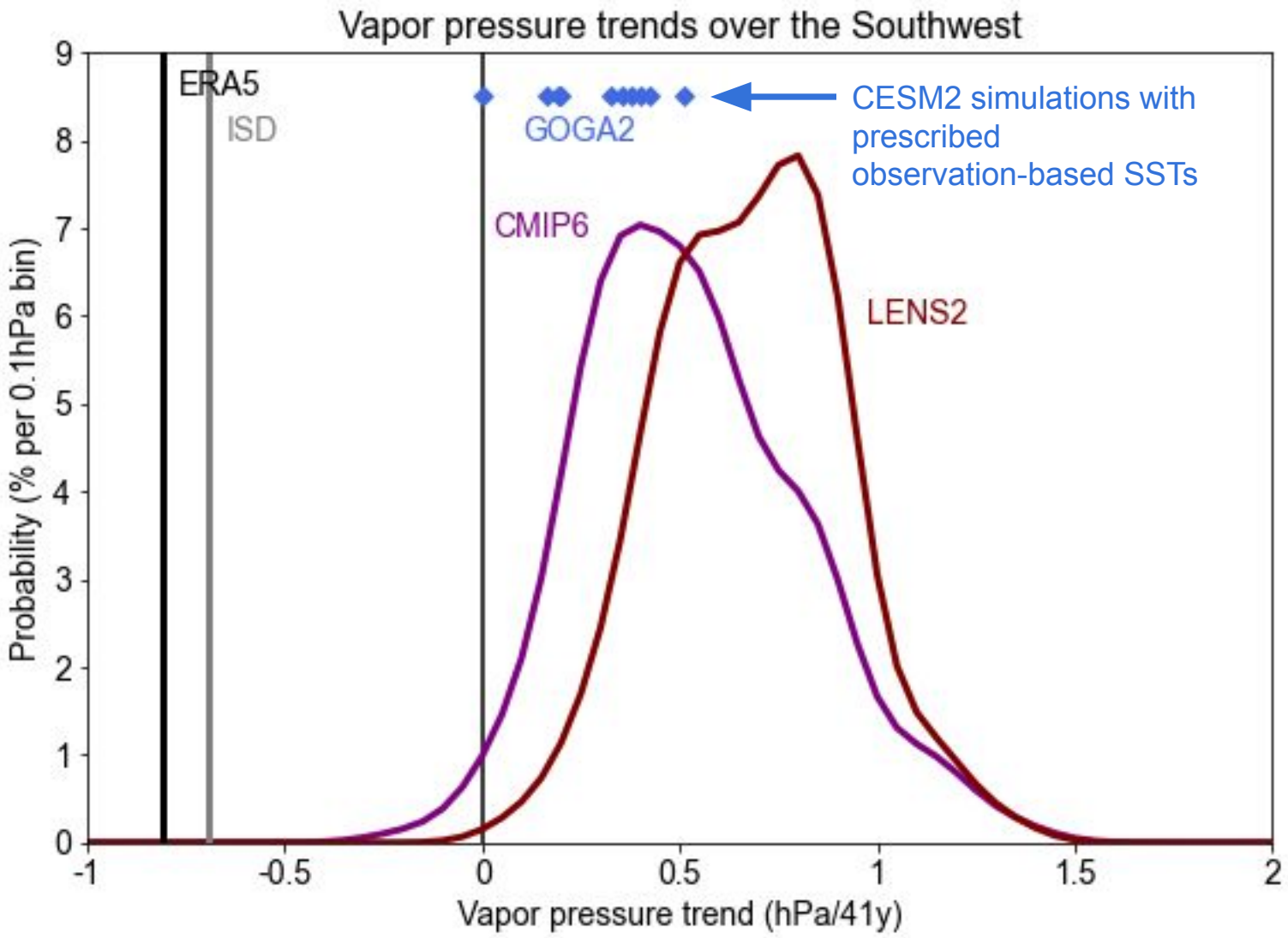

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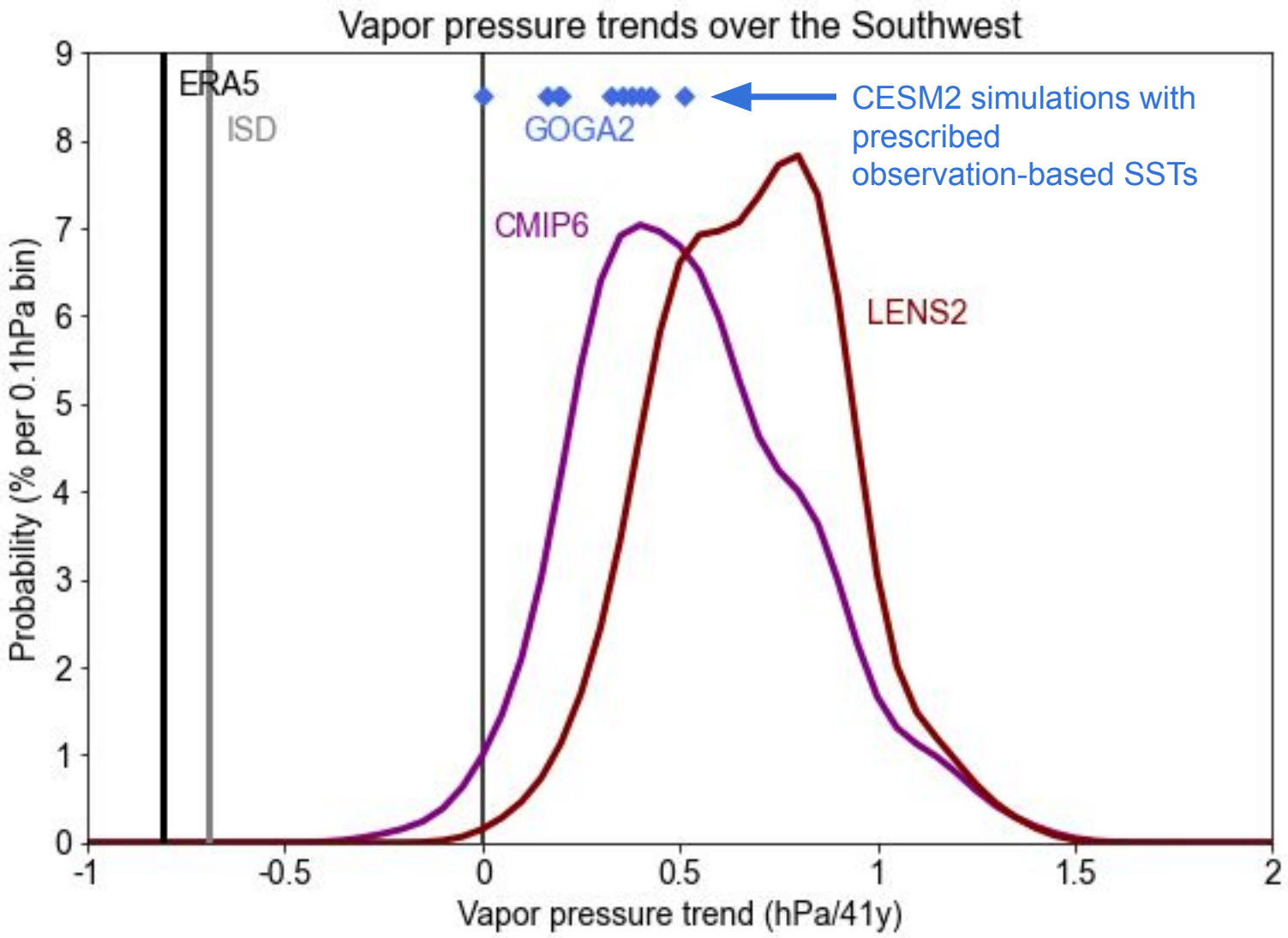
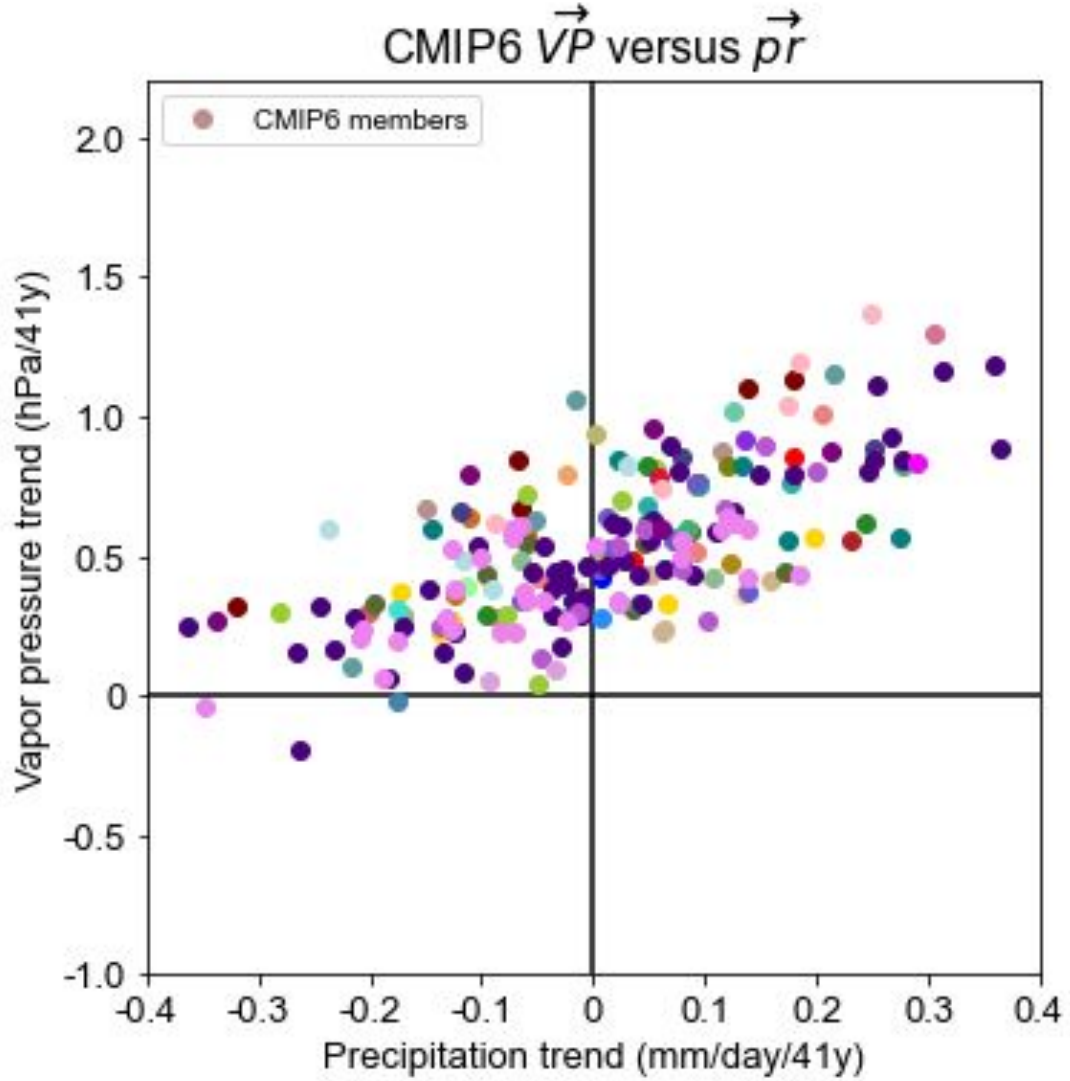
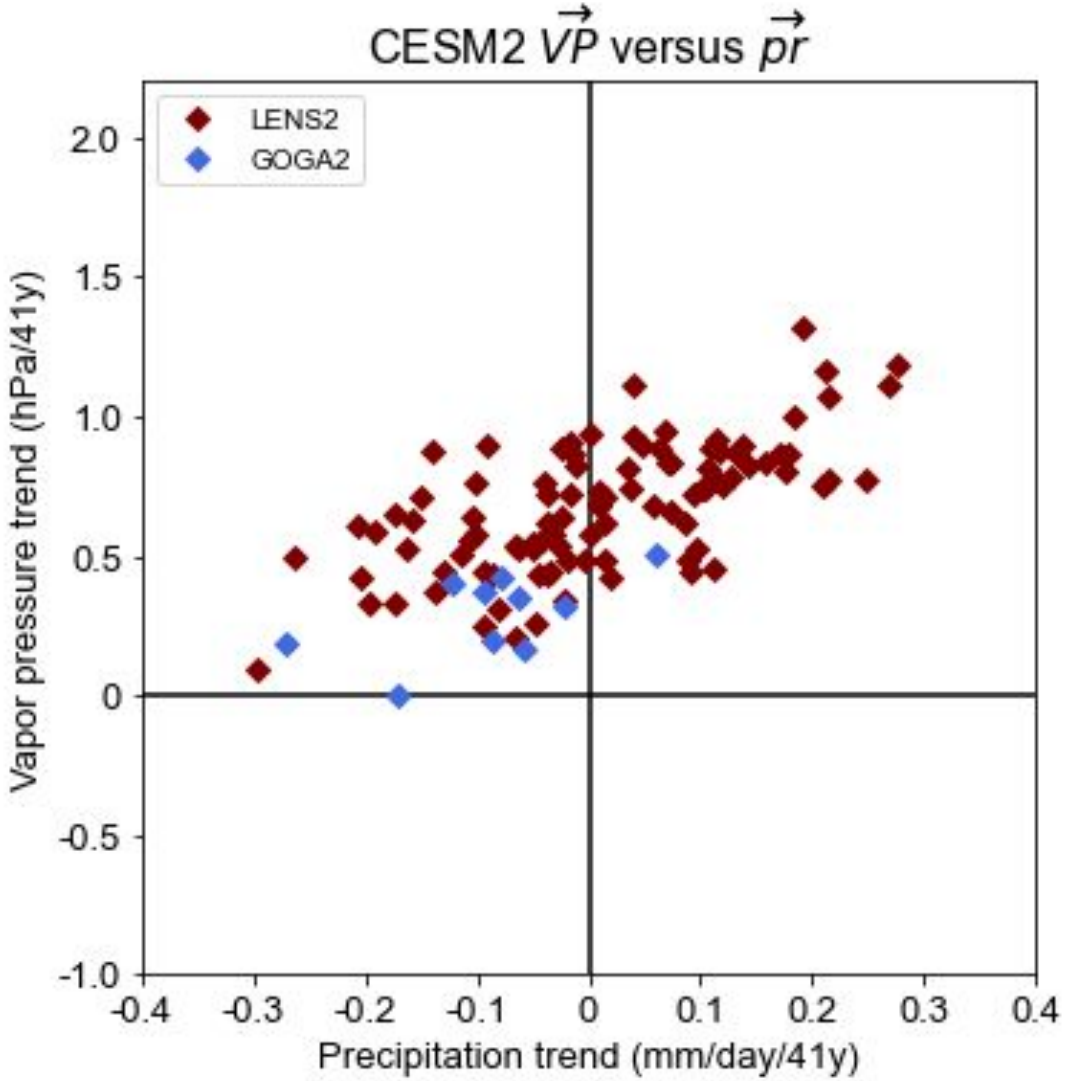


Our models come nowhere close to simulating the negative vapor pressure trend that we have observed

The US Southwest has experienced a precipitation decline since 1980 (Lehner et al 2018). Is this decline in vapor pressure in observations related to that precipitation change?

Relationship between vapor pressure and precipitation trends in the US southwest





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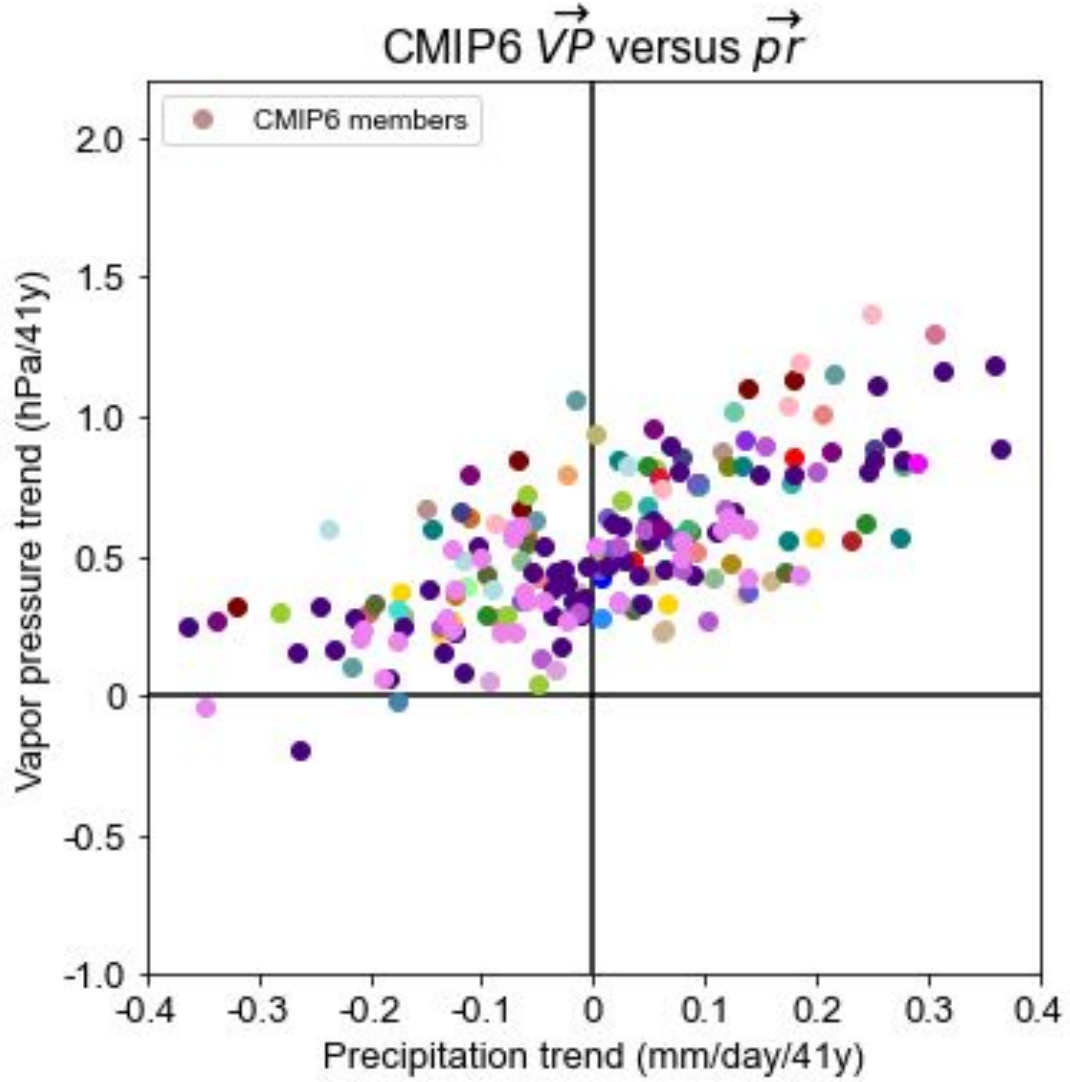

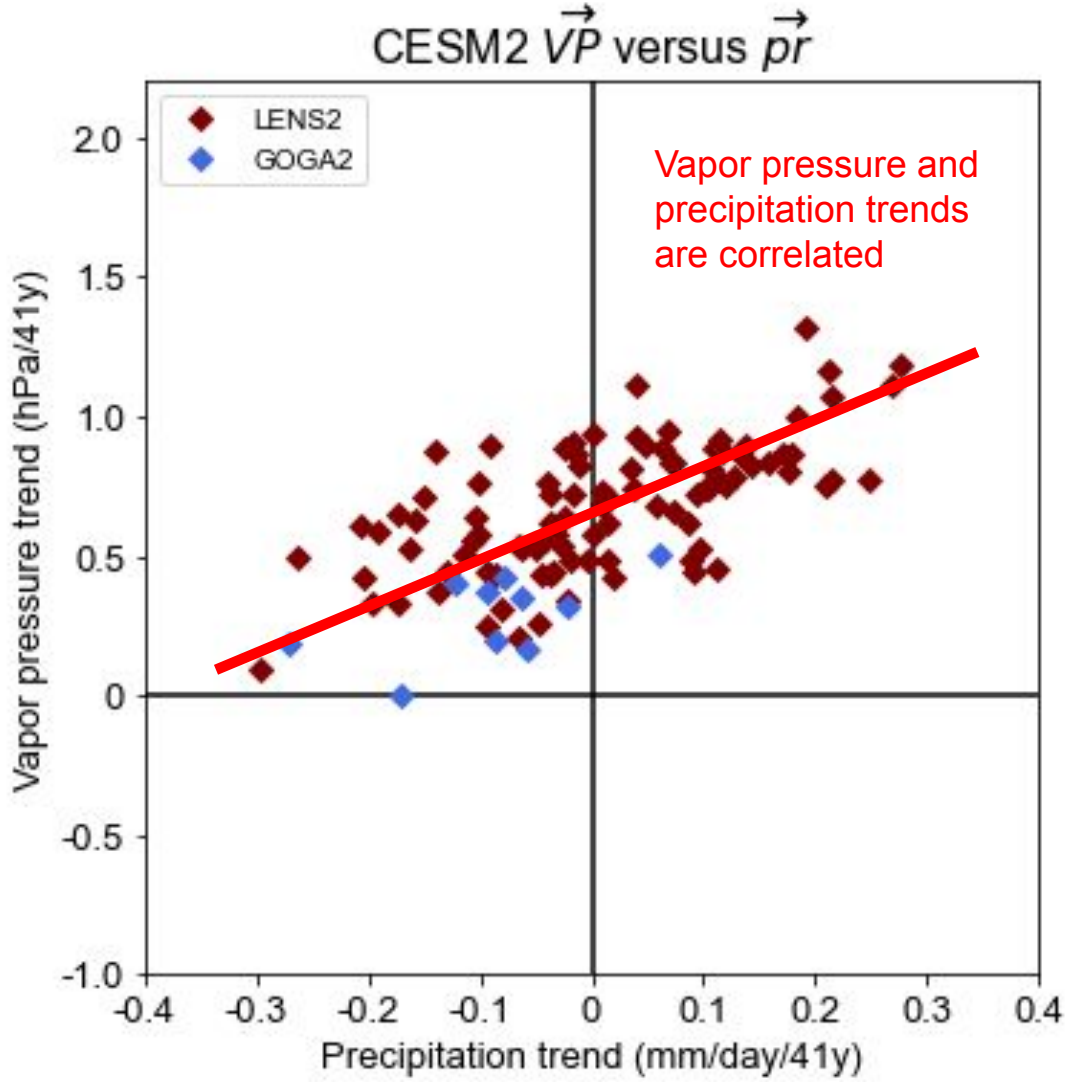

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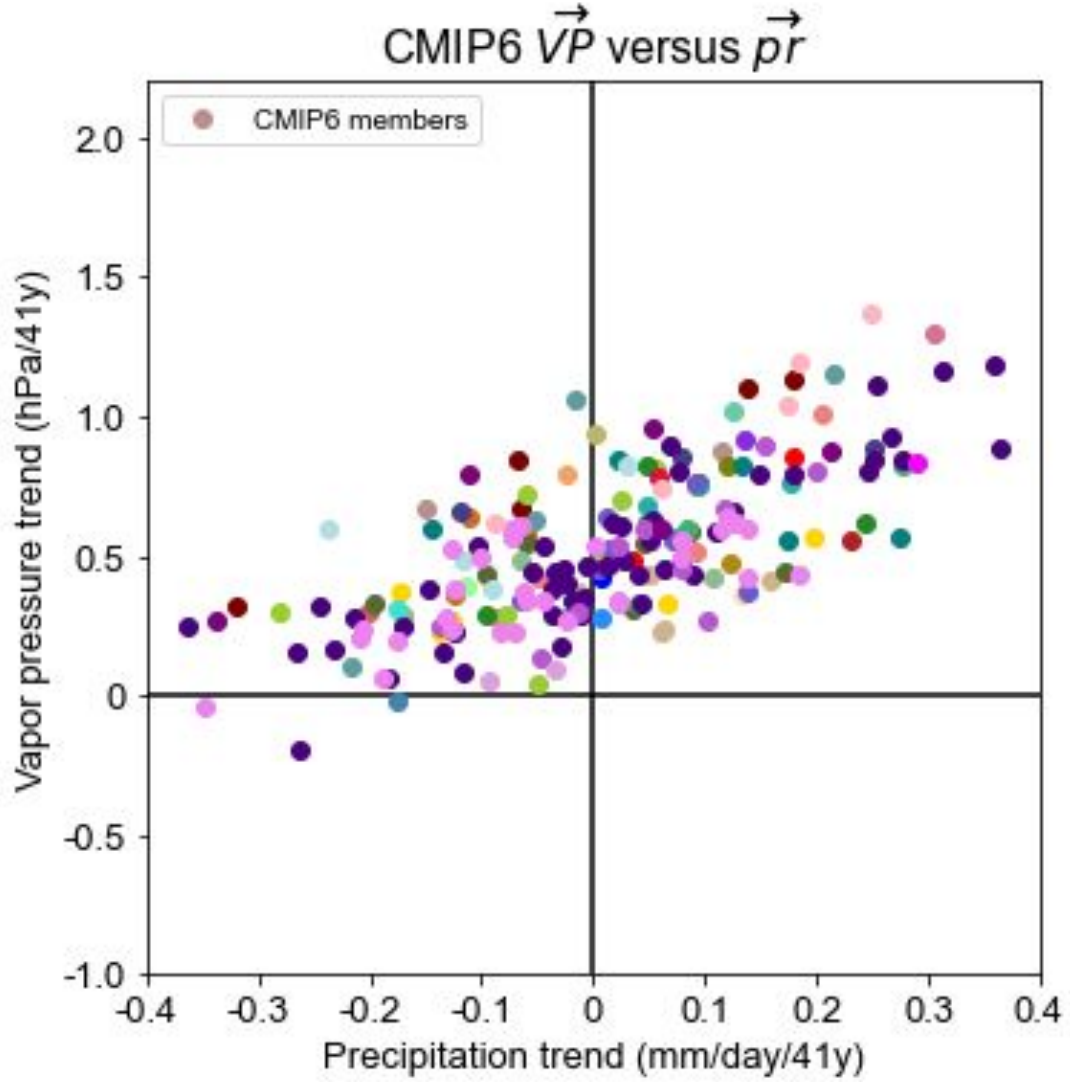

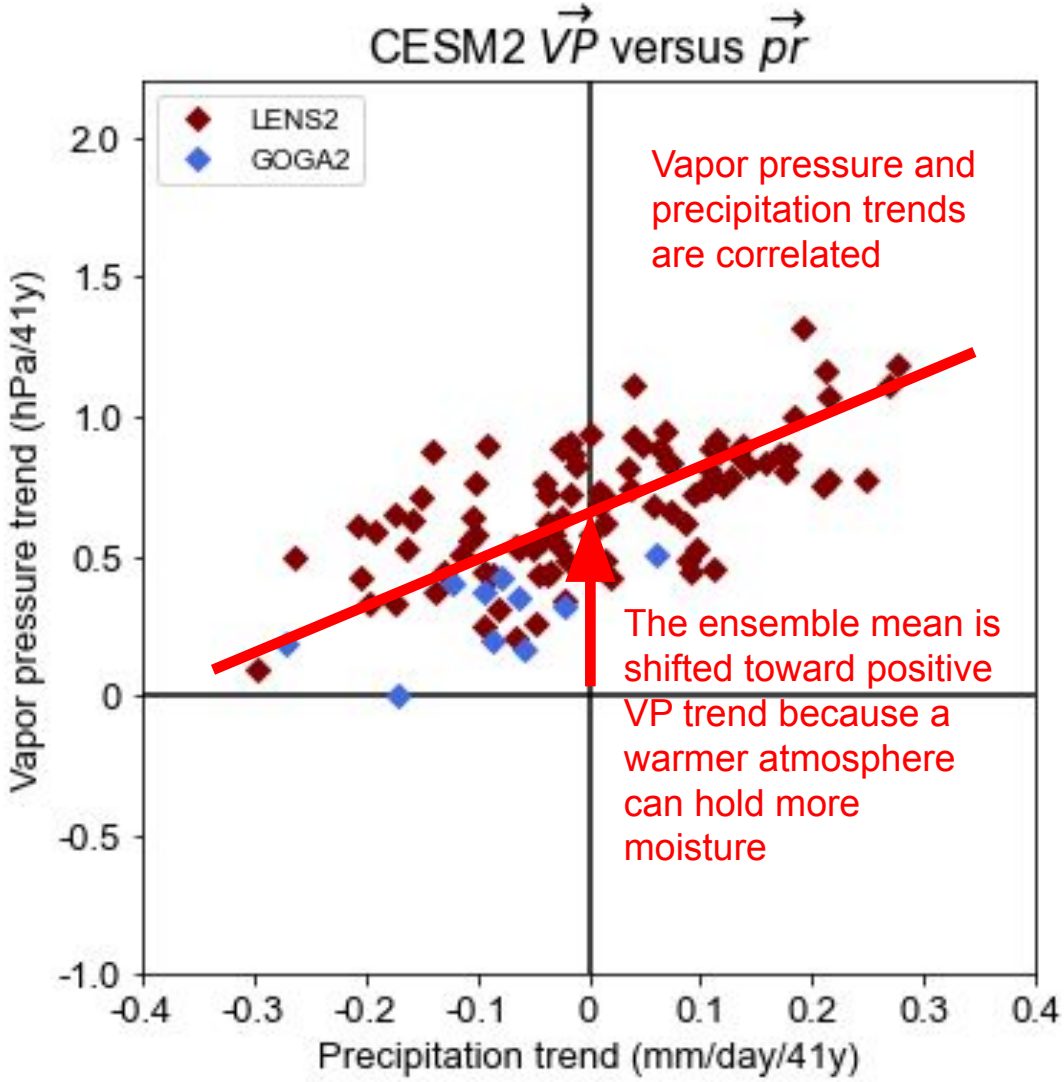

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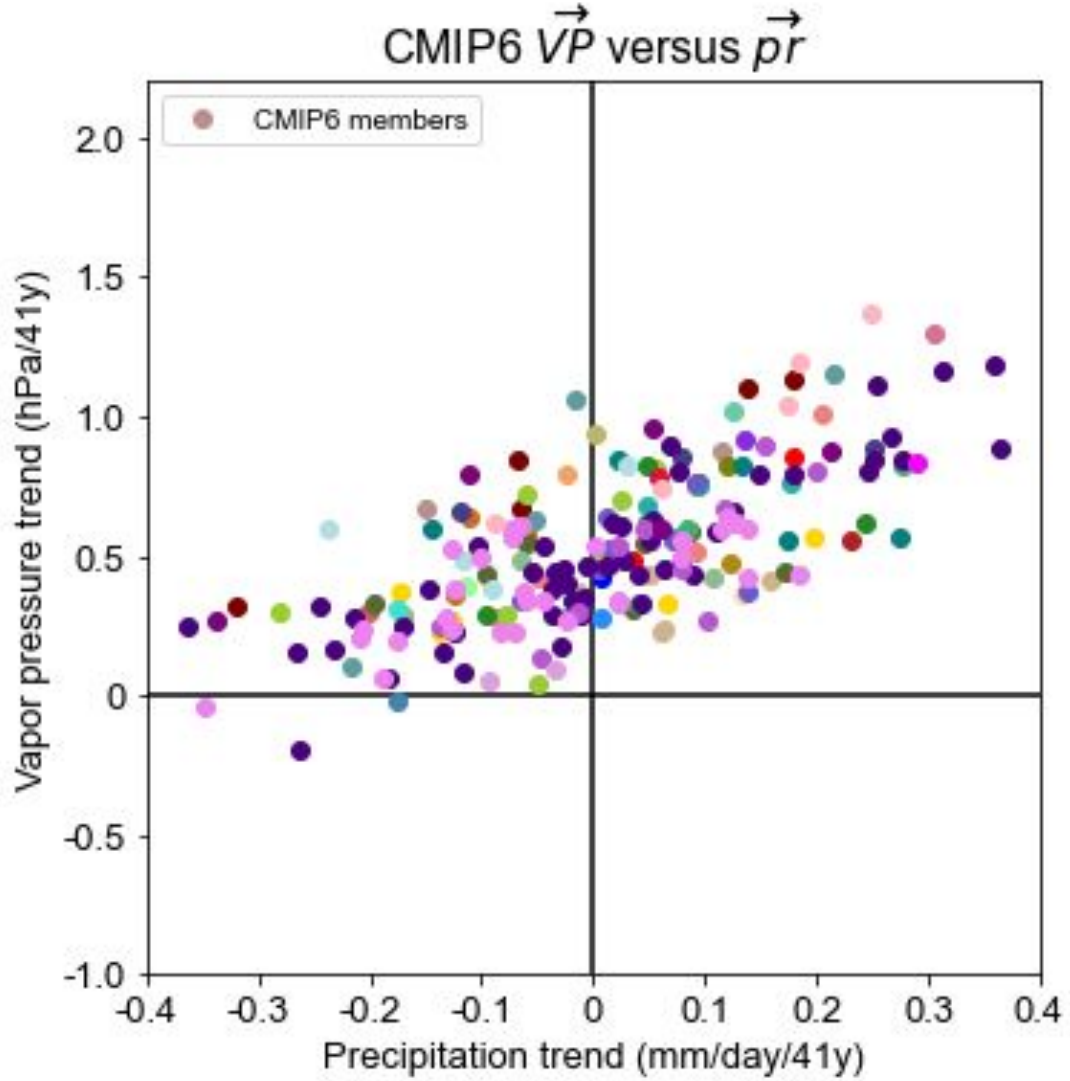

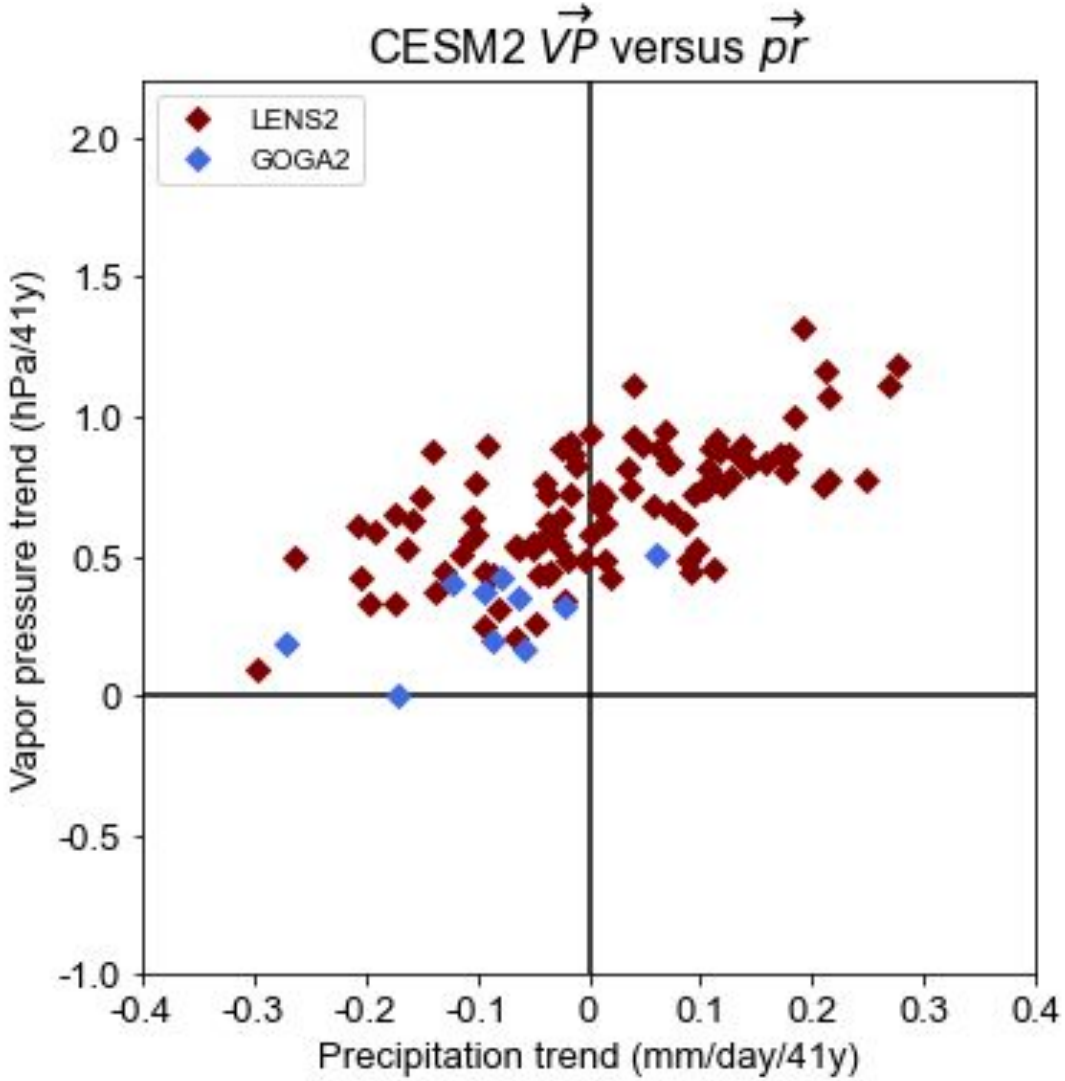

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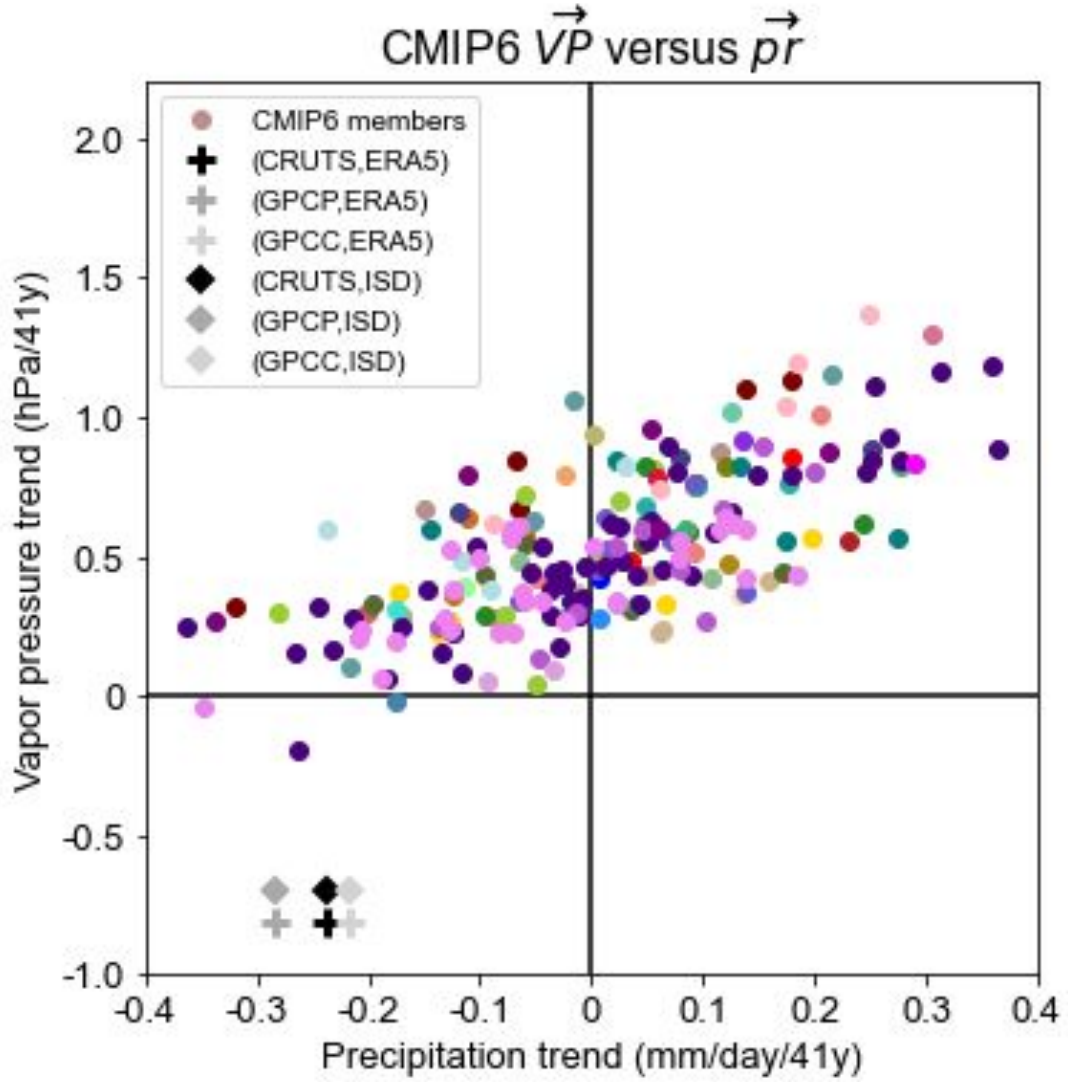

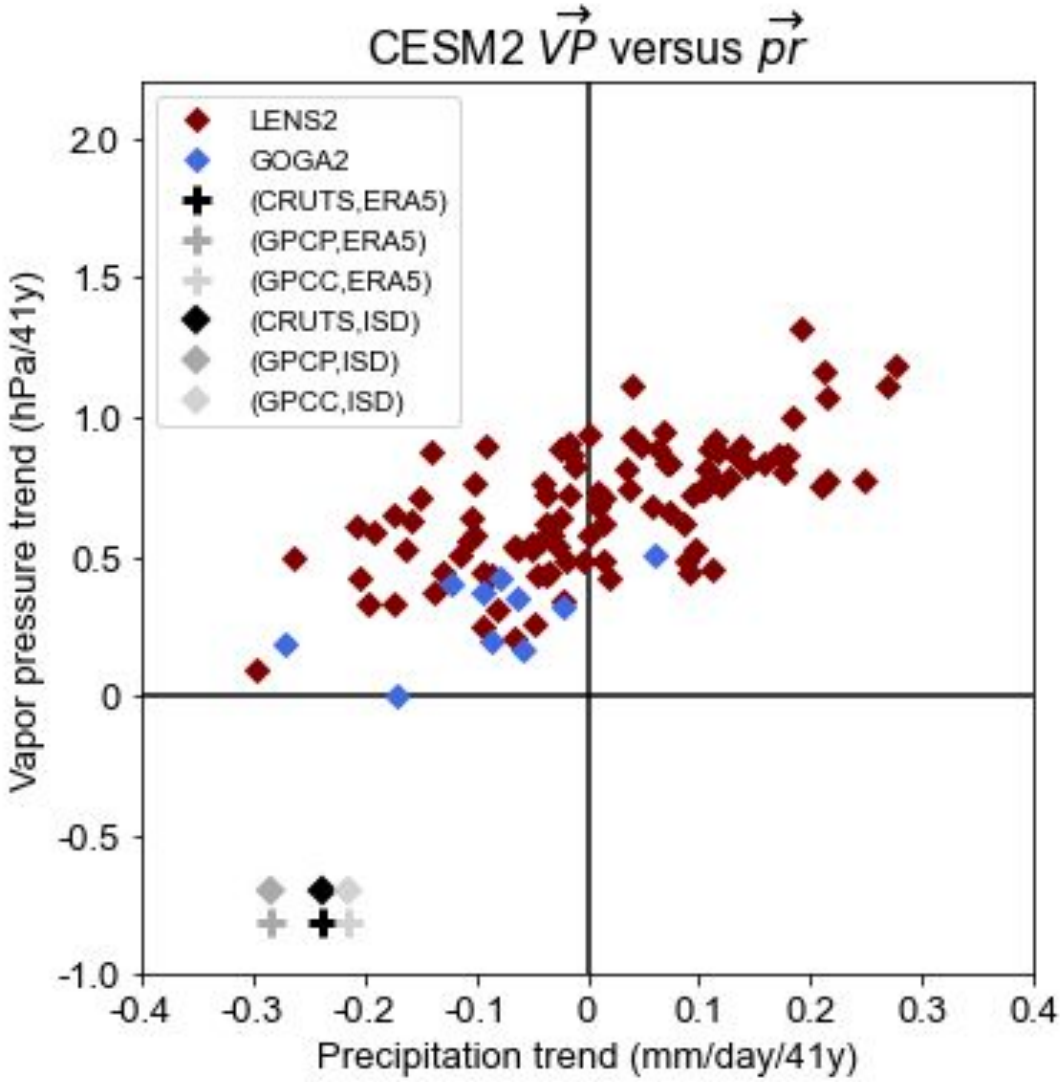

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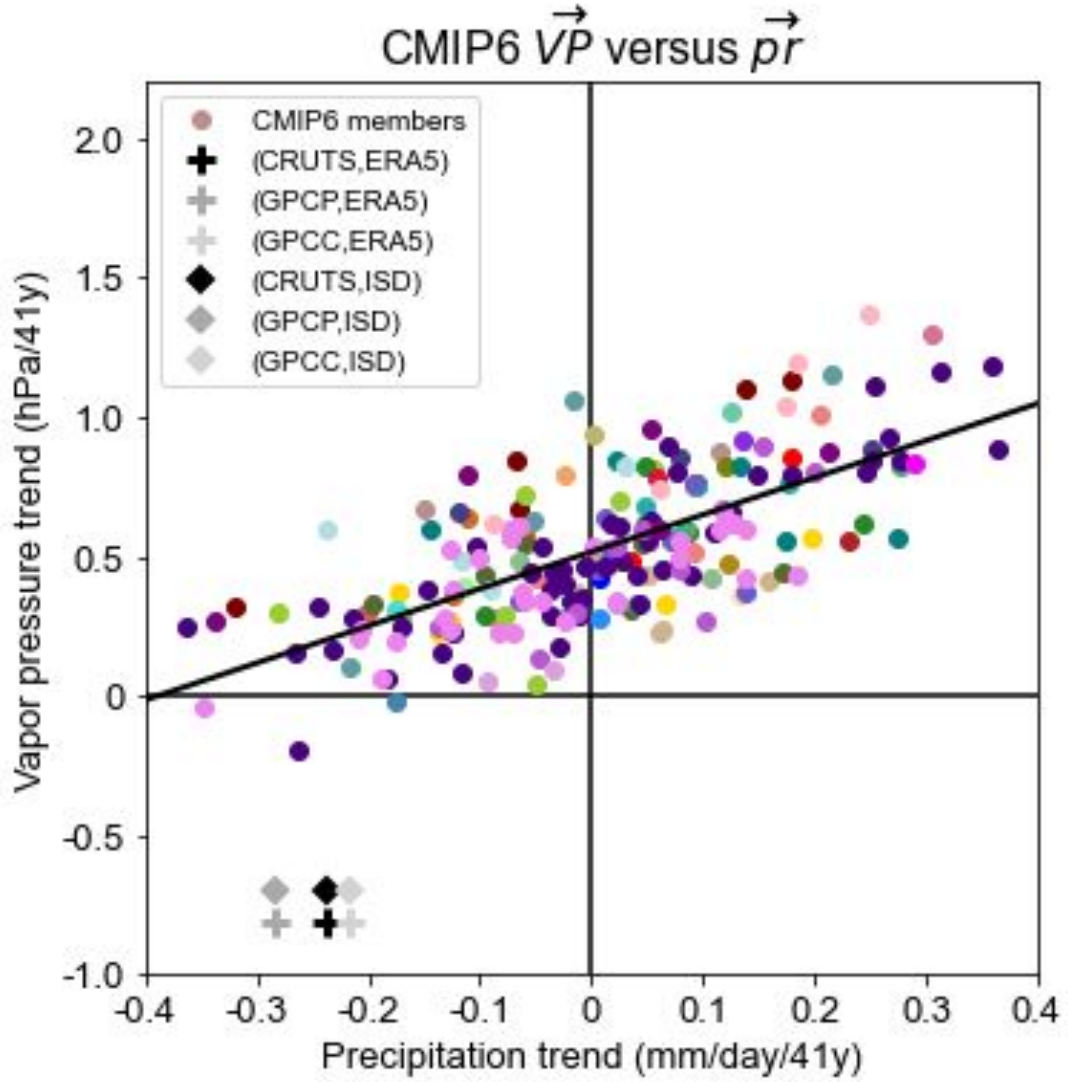

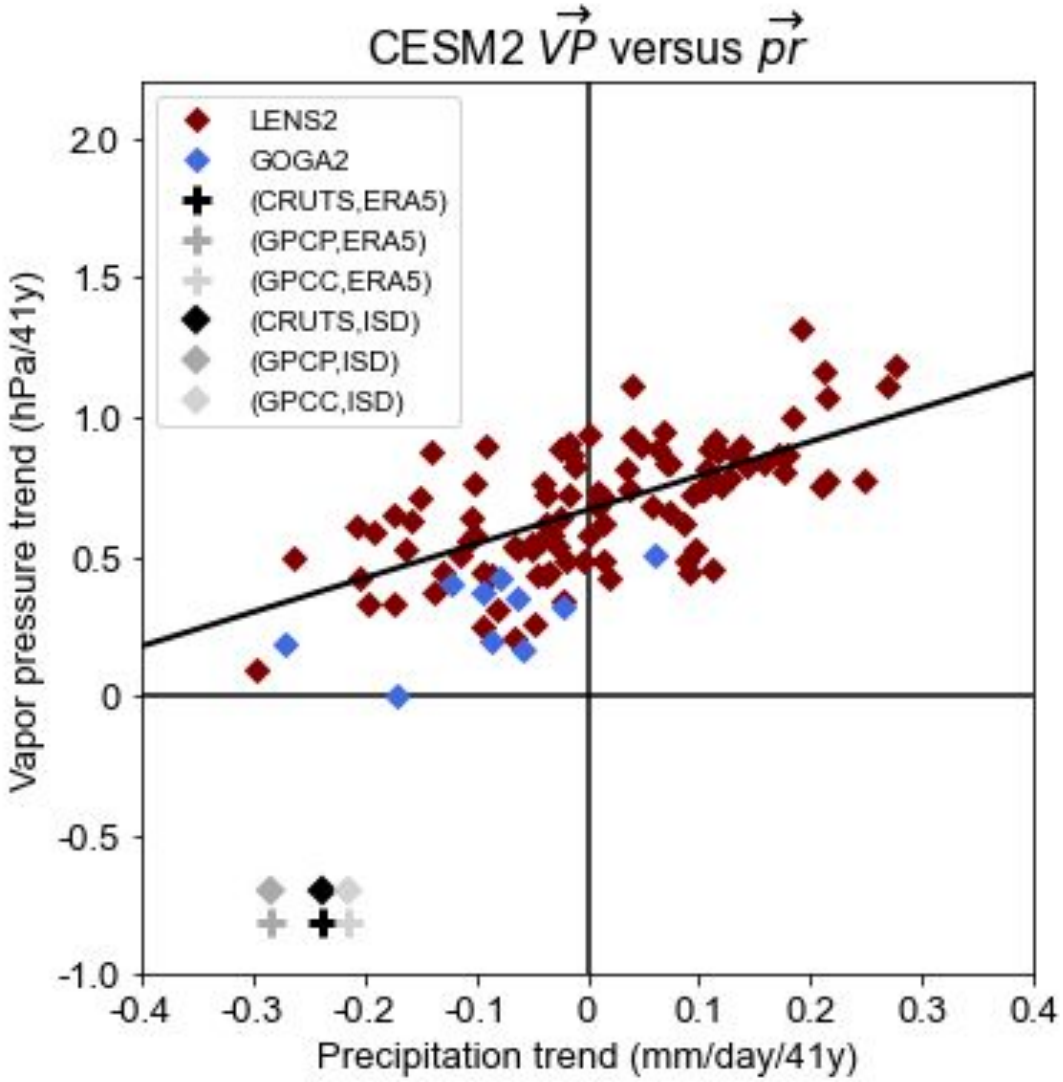

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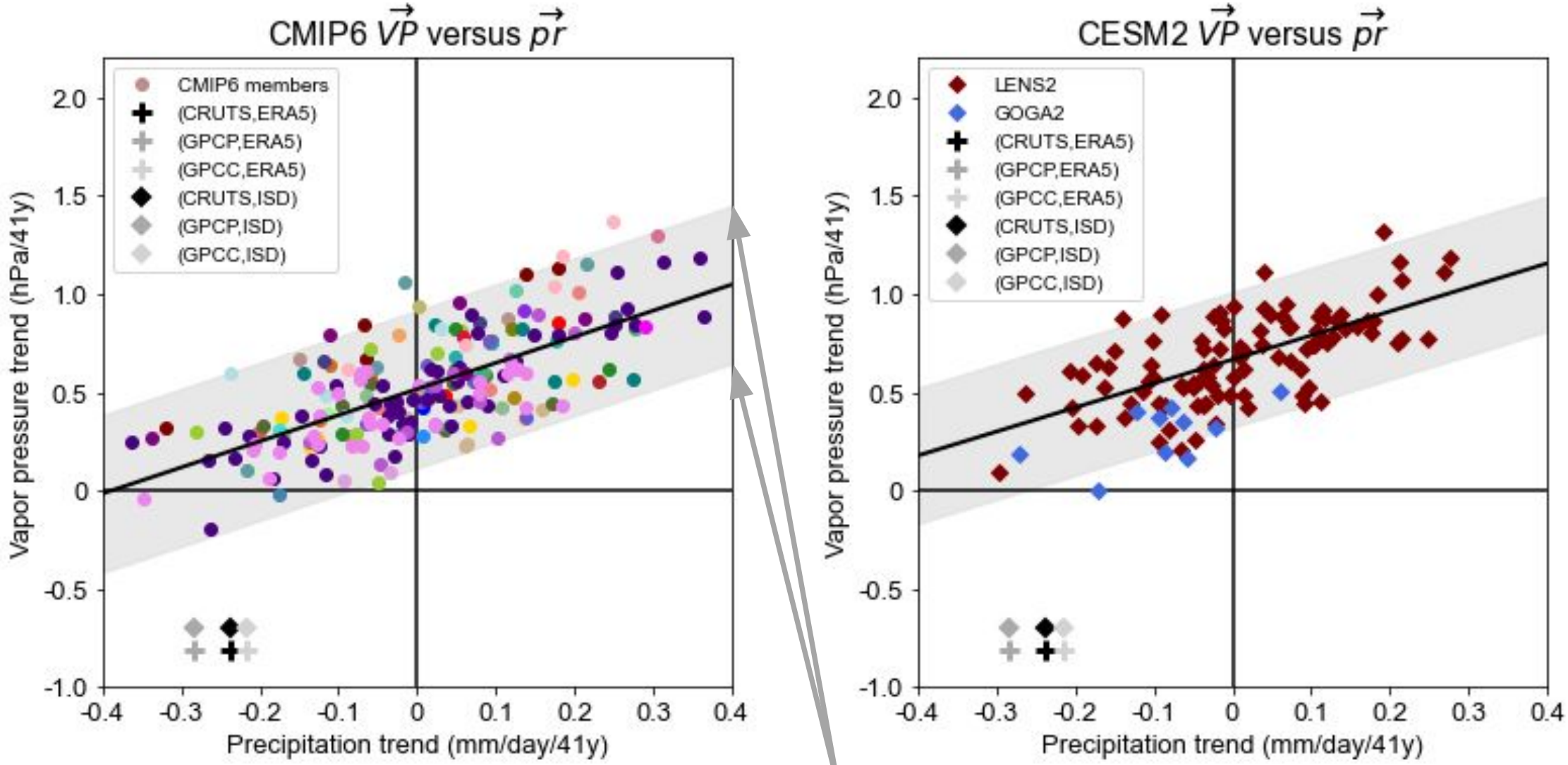
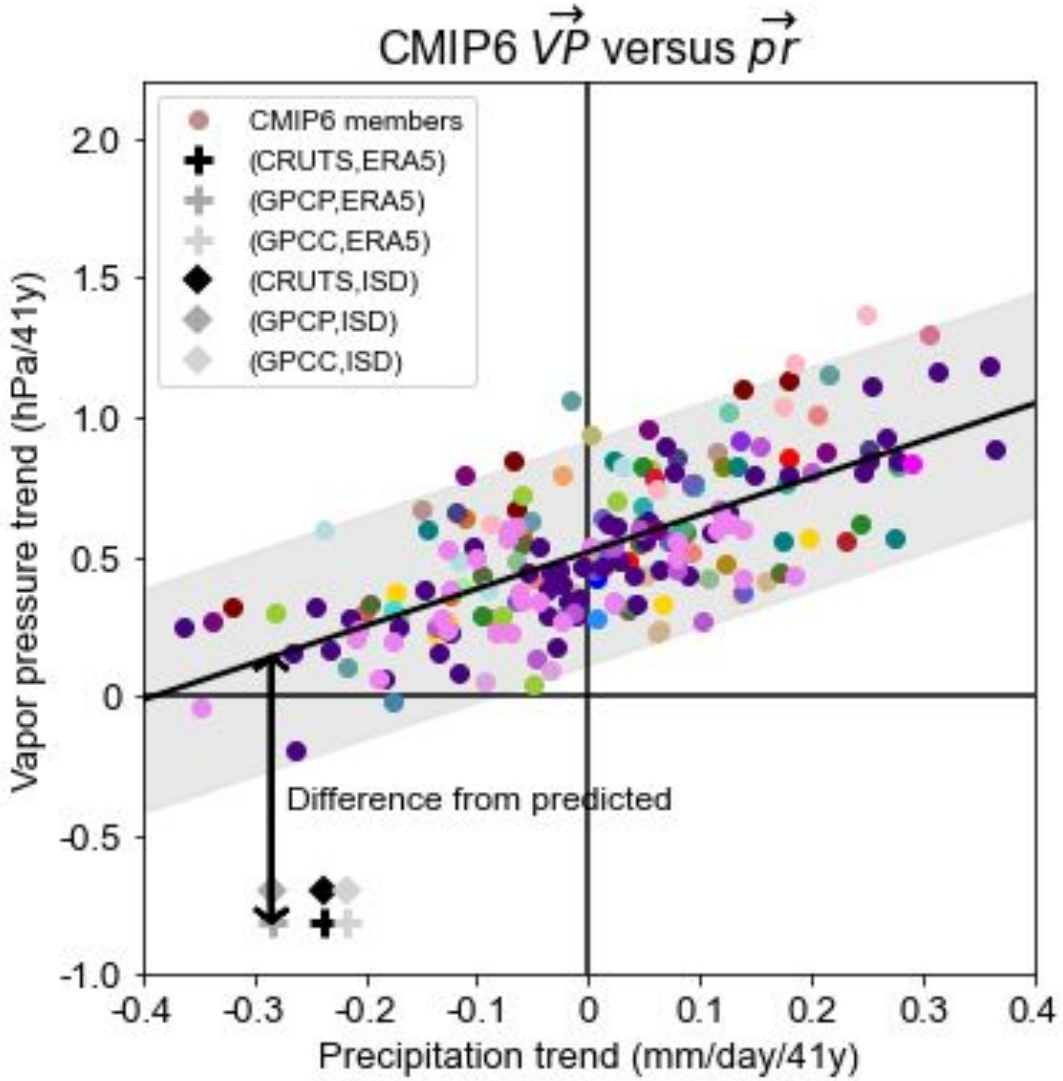
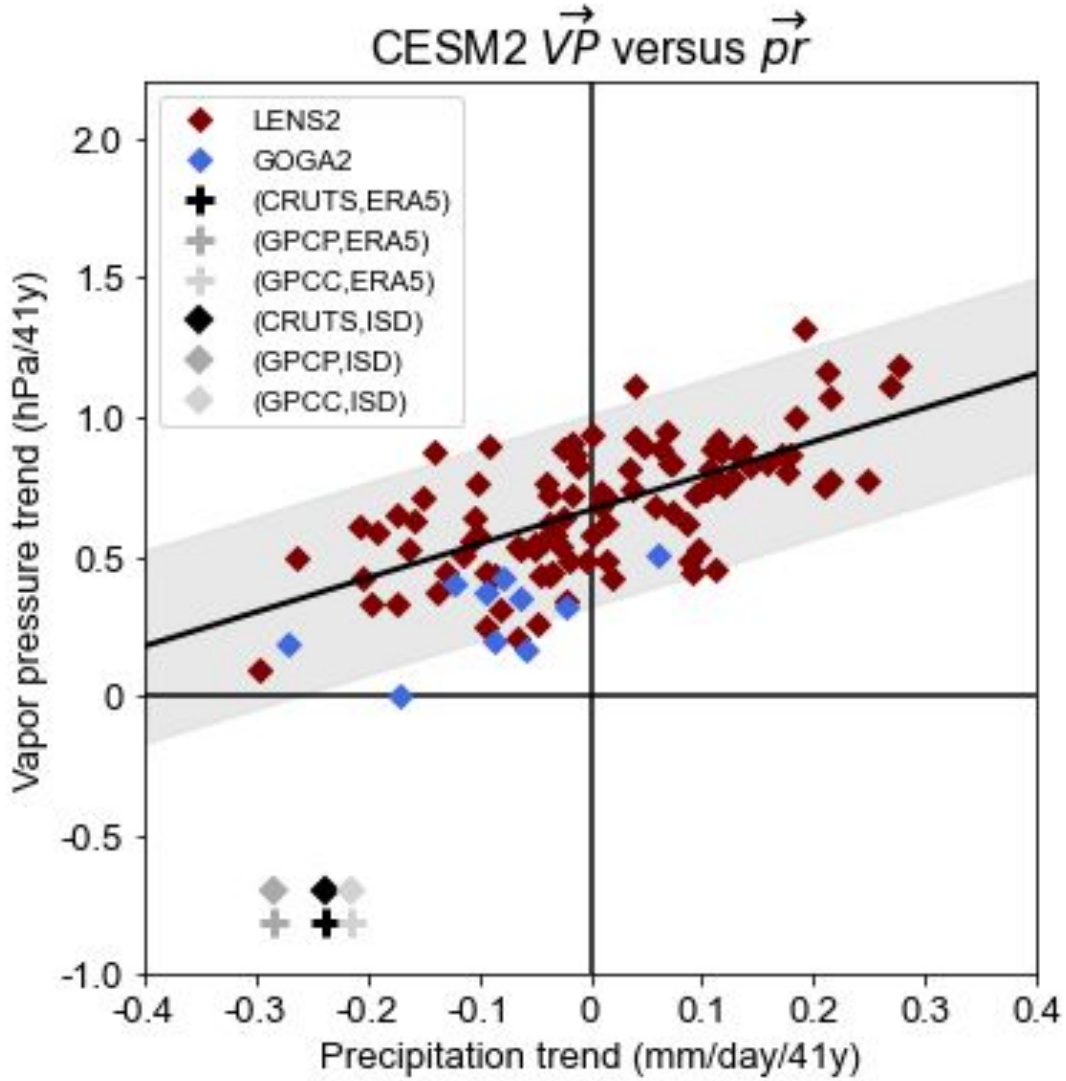


+/- 2 standard deviations of the residuals around the regression line

Global vapor pressure trends





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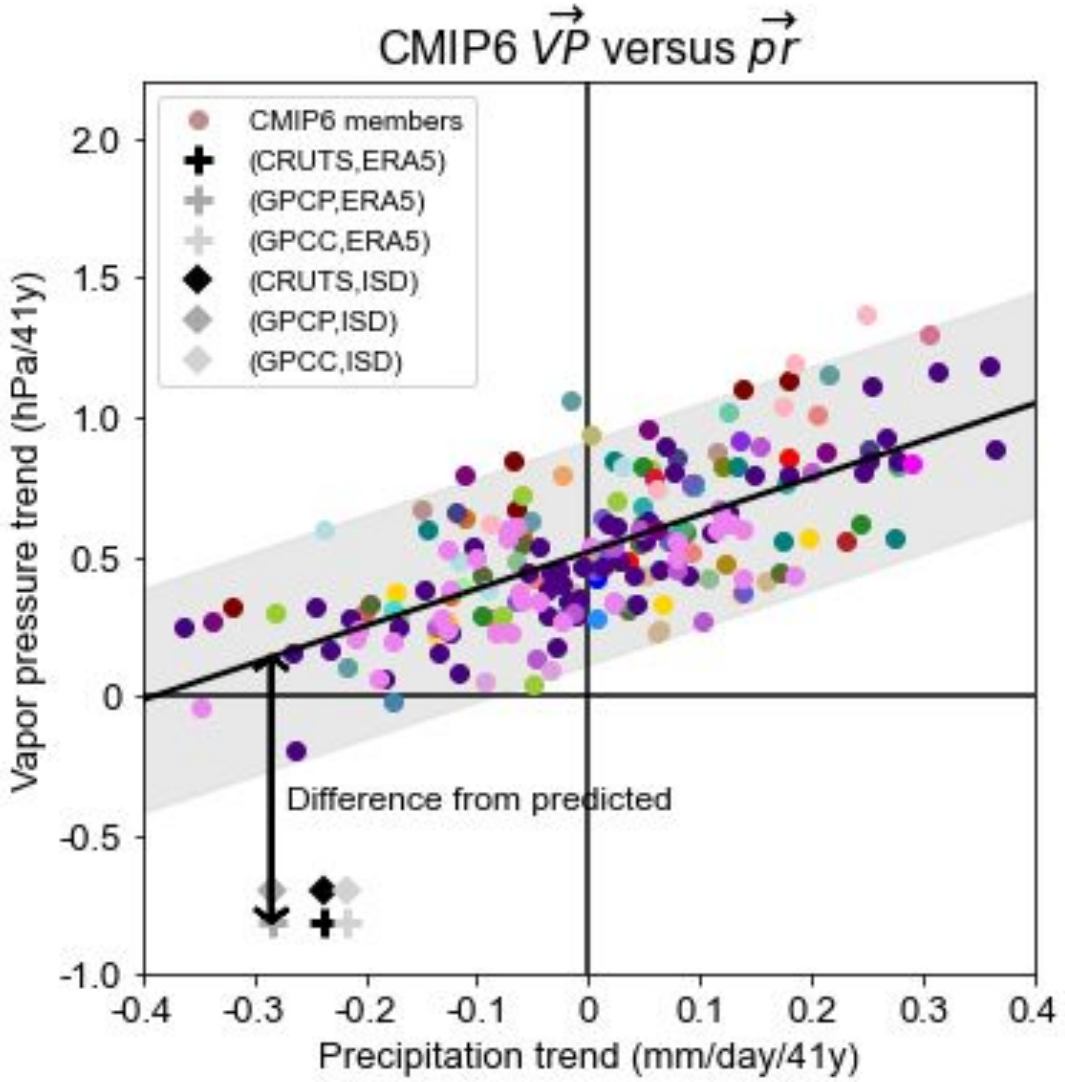
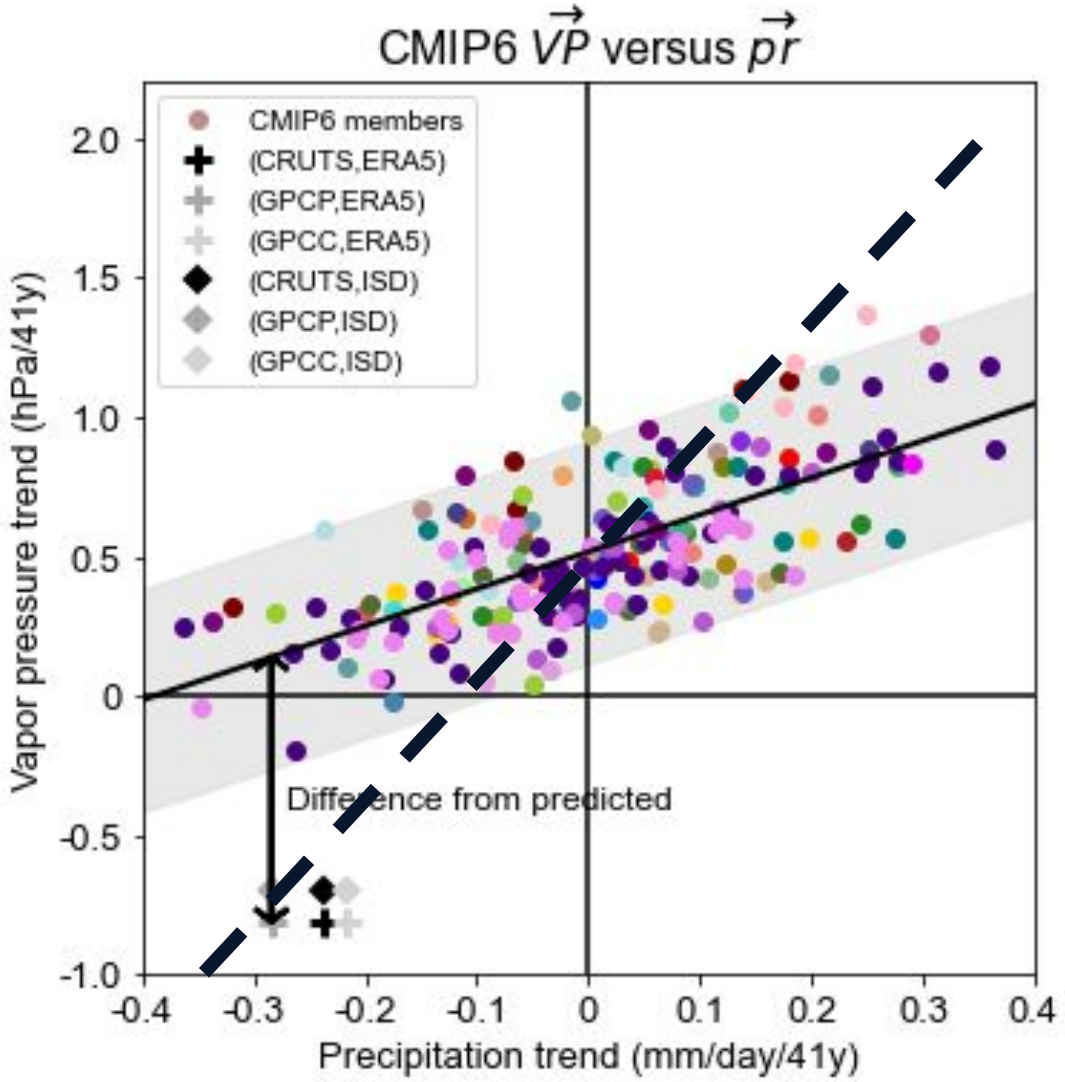


Three possibilities:

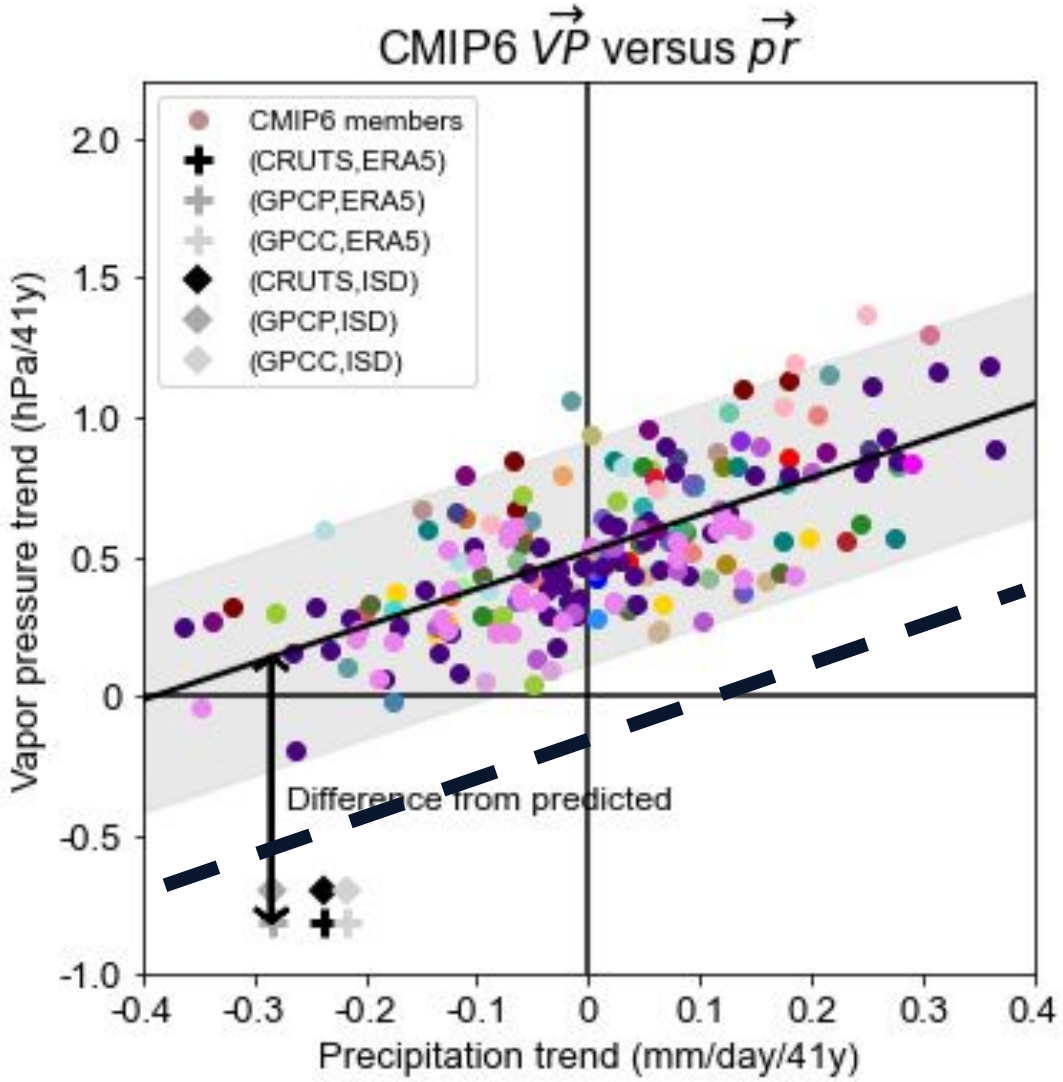
Global vapor pressure trends



Three possibilities:

(1) The relationship between precip and vapor pressure is not represented correctly

Global vapor pressure trends

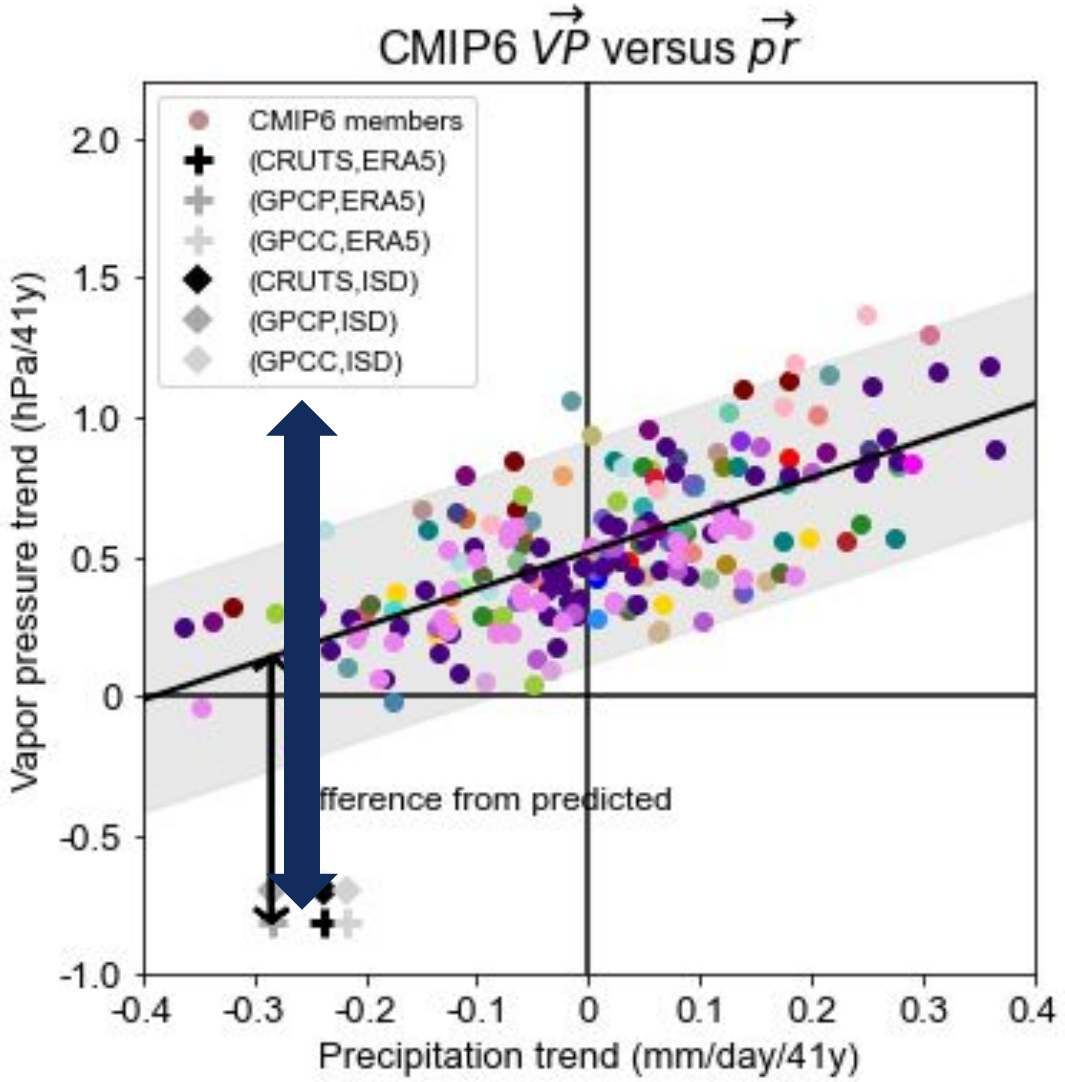


Three possibilities:

(1) The relationship between precip and vapor pressure is not represented correctly

(2) The forced thermodynamic trend in vapor pressure is incorrect

Global vapor pressure trends



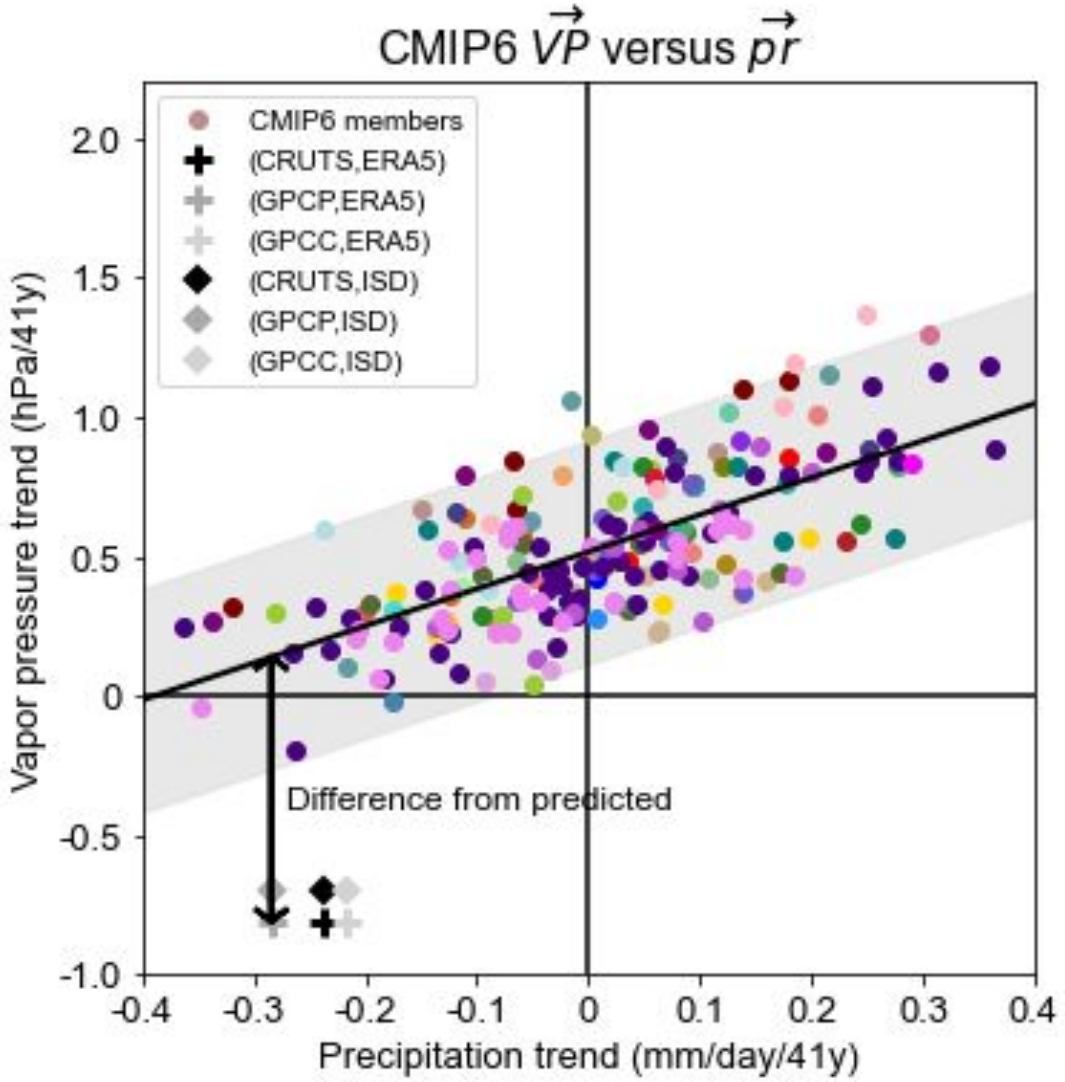
Three possibilities:

(1) The relationship between precip and vapor pressure is not represented correctly

(2) The forced thermodynamic trend in vapor pressure is incorrect

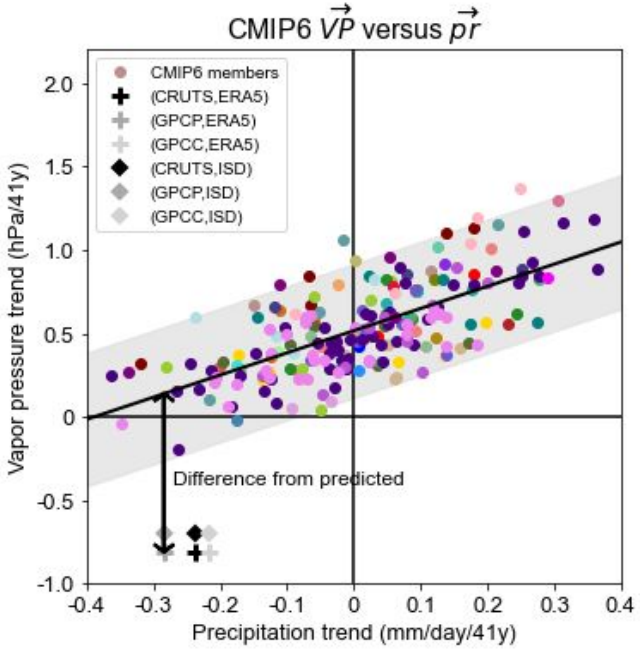
(3) Some additional missing variability

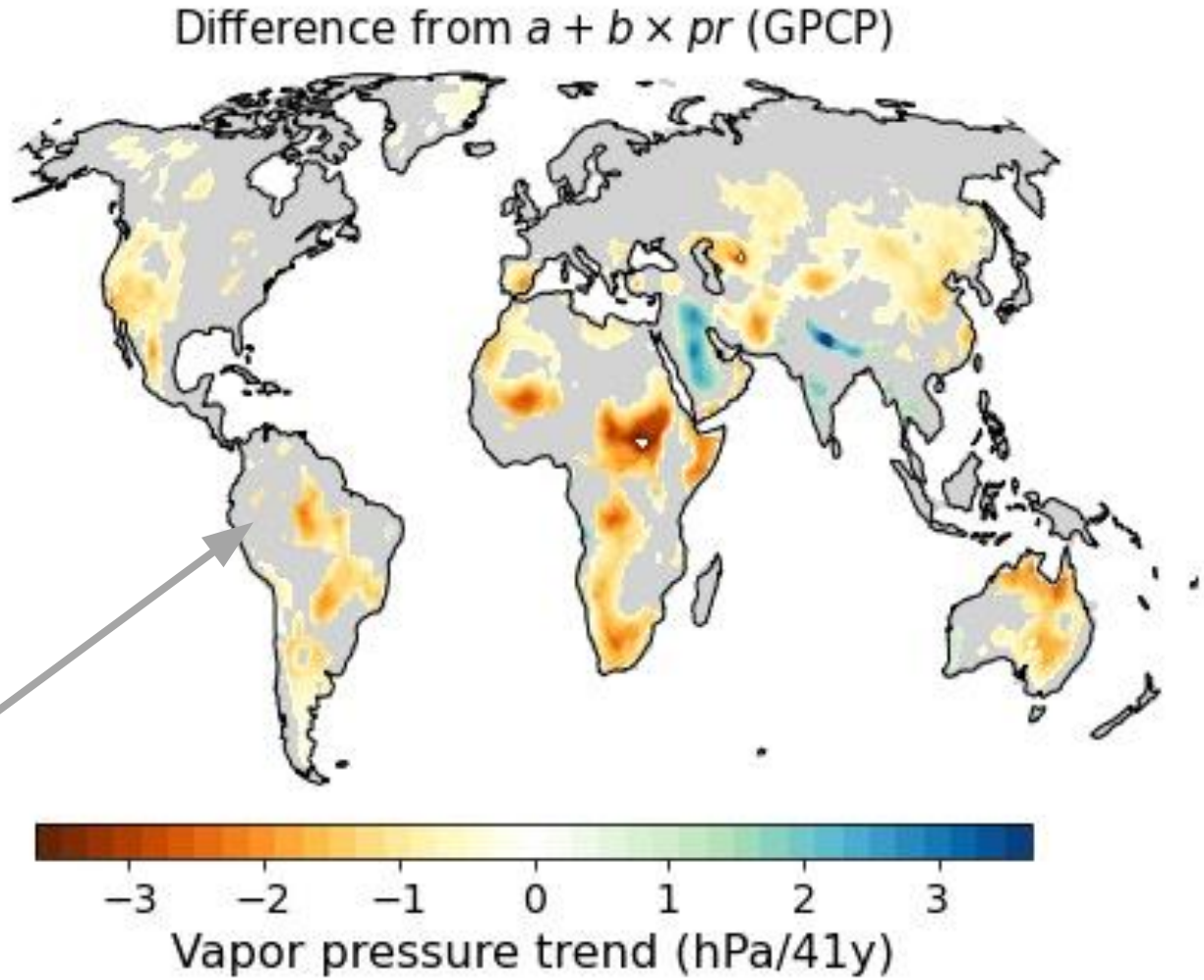
Global vapor pressure trends



We'll go through this same procedure but at each 1 degree grid box and assess the difference from what would be predicted based on GPCC precipitation trends and the CMIP6 relationship between vapor pressure and precipitation trends.

Global vapor pressure trends

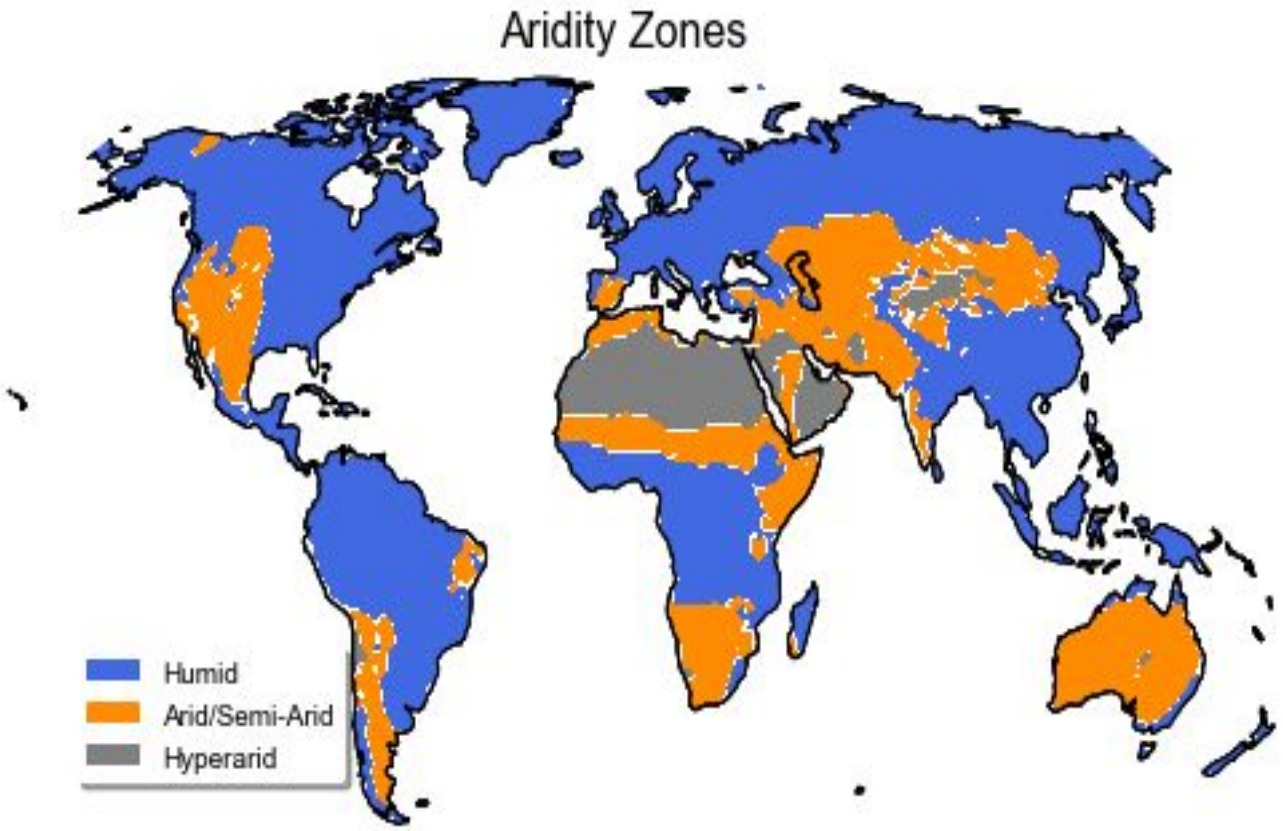


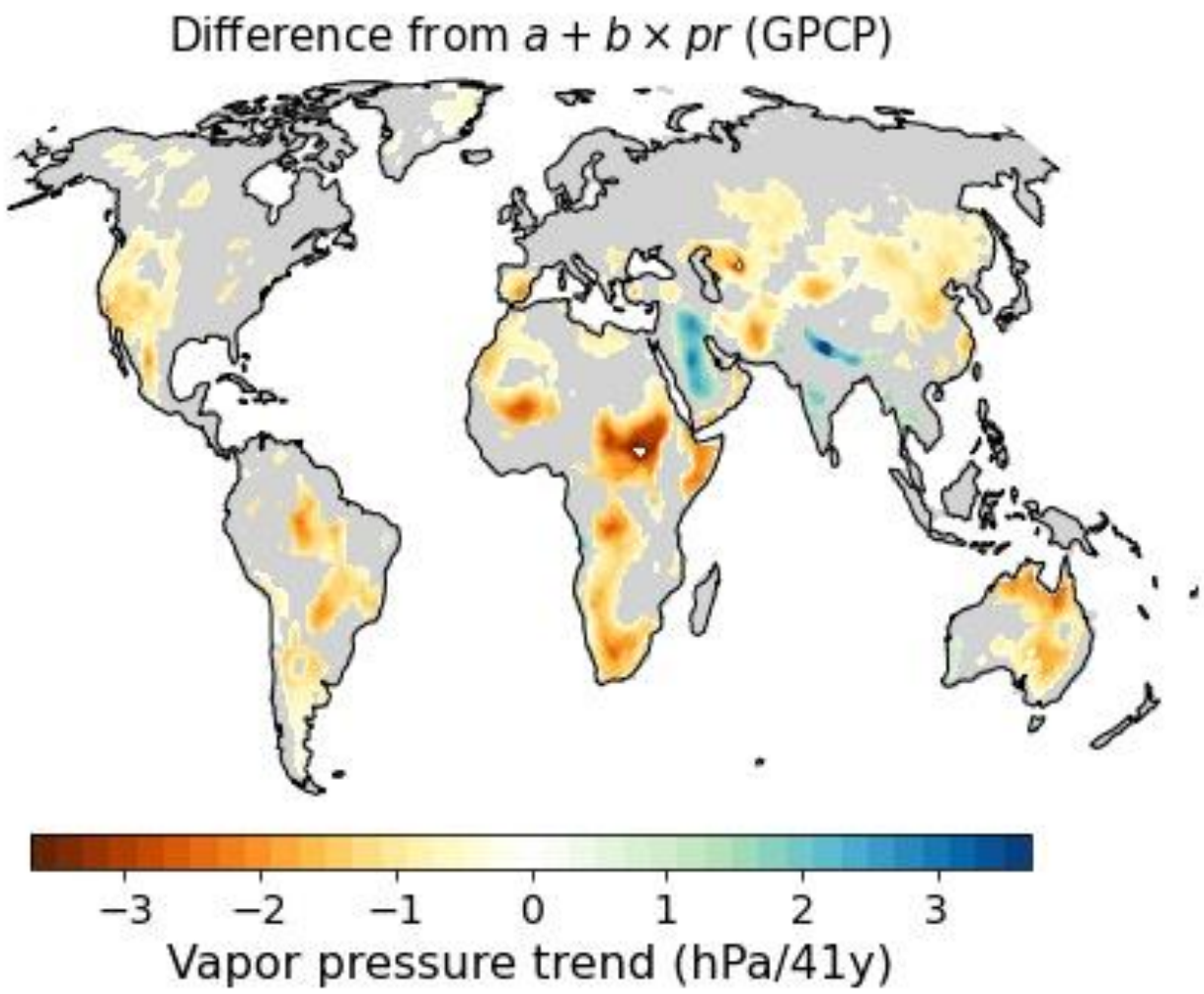


Gray = not outside of the +/- 2 standard deviation of the residuals range from the regression line based on CMIP6

(ERA5 and ISD also agree well in other regions of the world)

Global vapor pressure trends

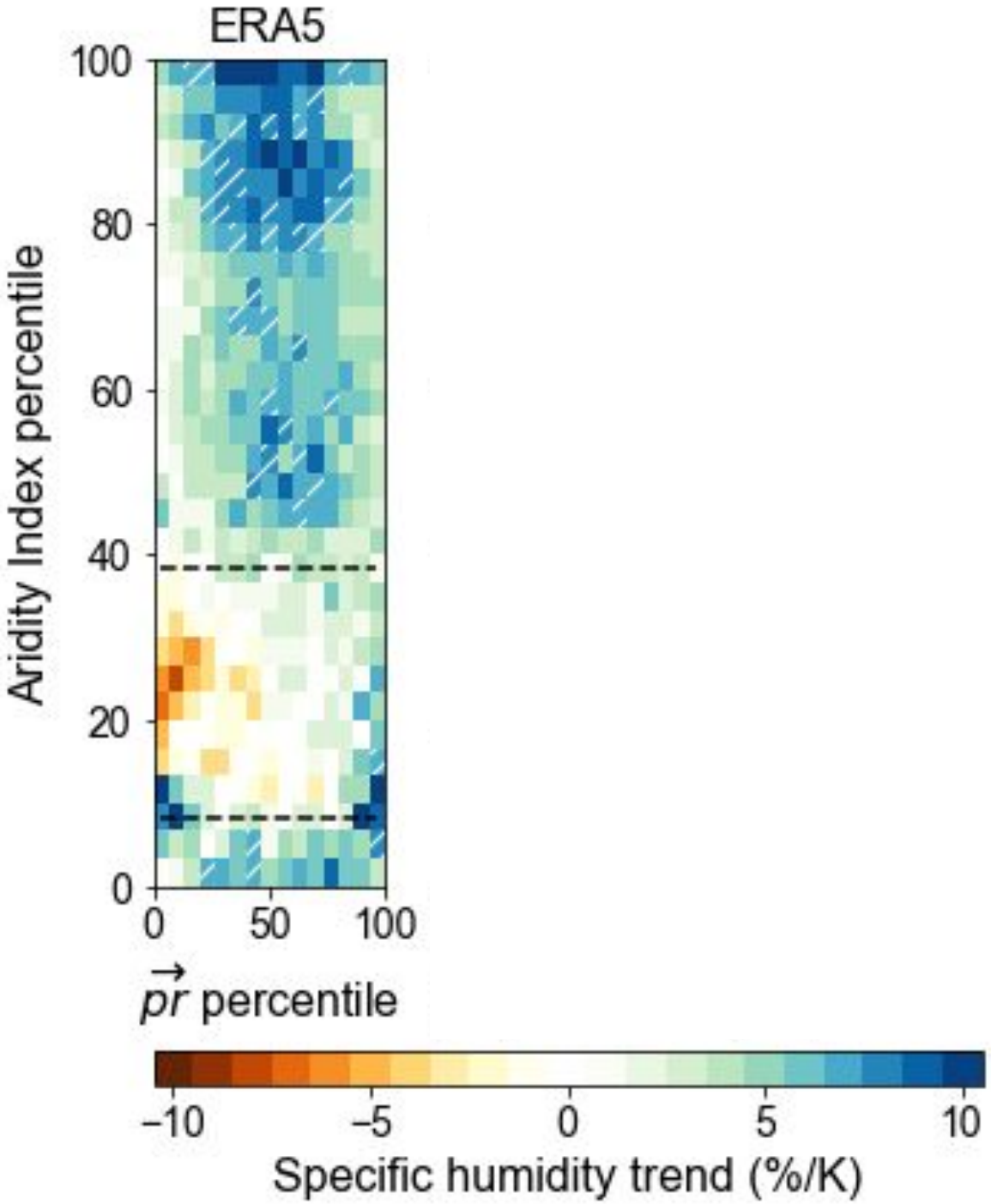




$$\text{Aridity Index} = \frac{P}{PET}$$

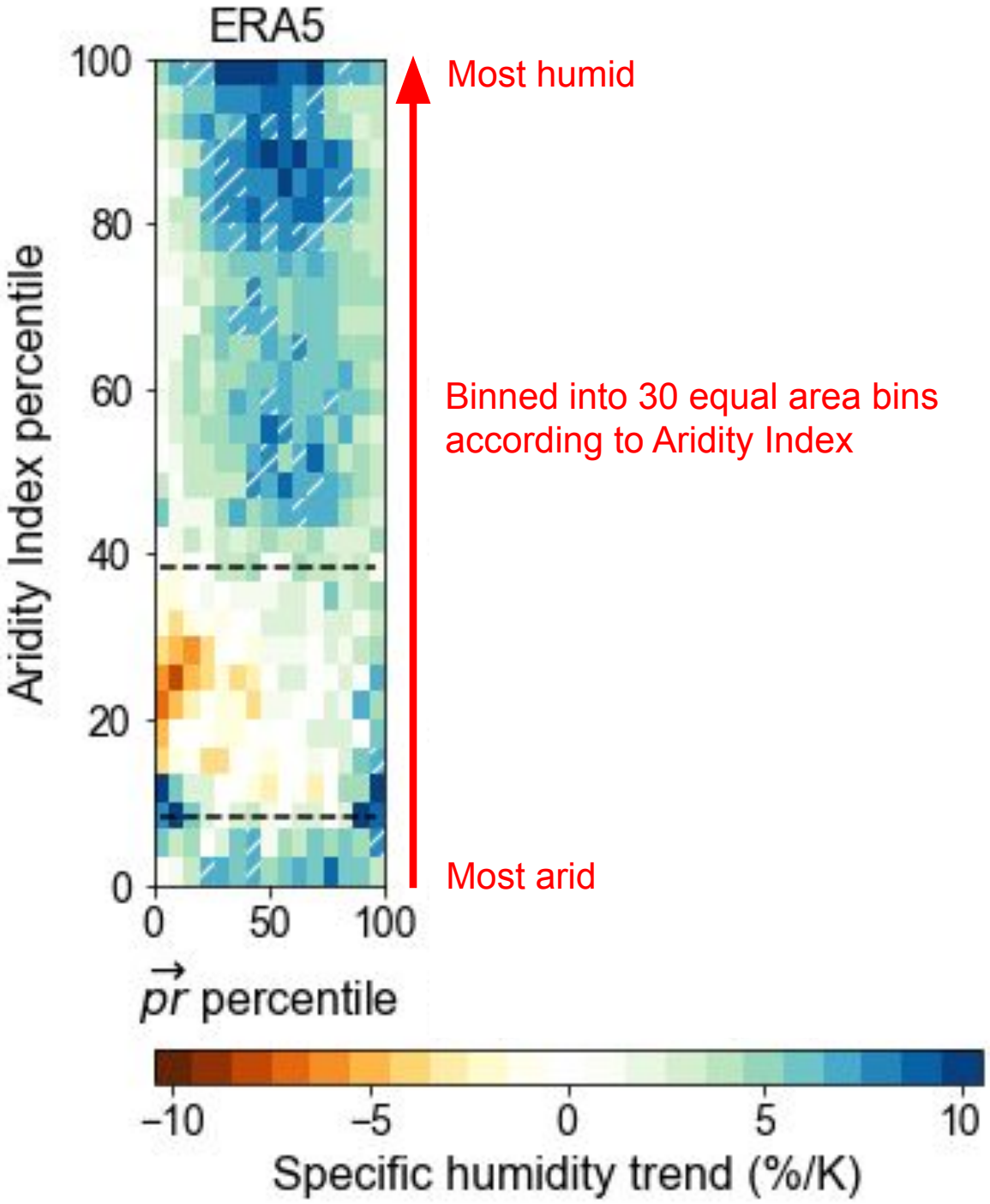
Precipitation

Potential Evapotranspiration



Specific humidity trends expressed as a percentage of the 1980-1990 climatology, normalized by land area average near surface air temperature change

Using ERA5 for observed VP and GPCC for observed precip



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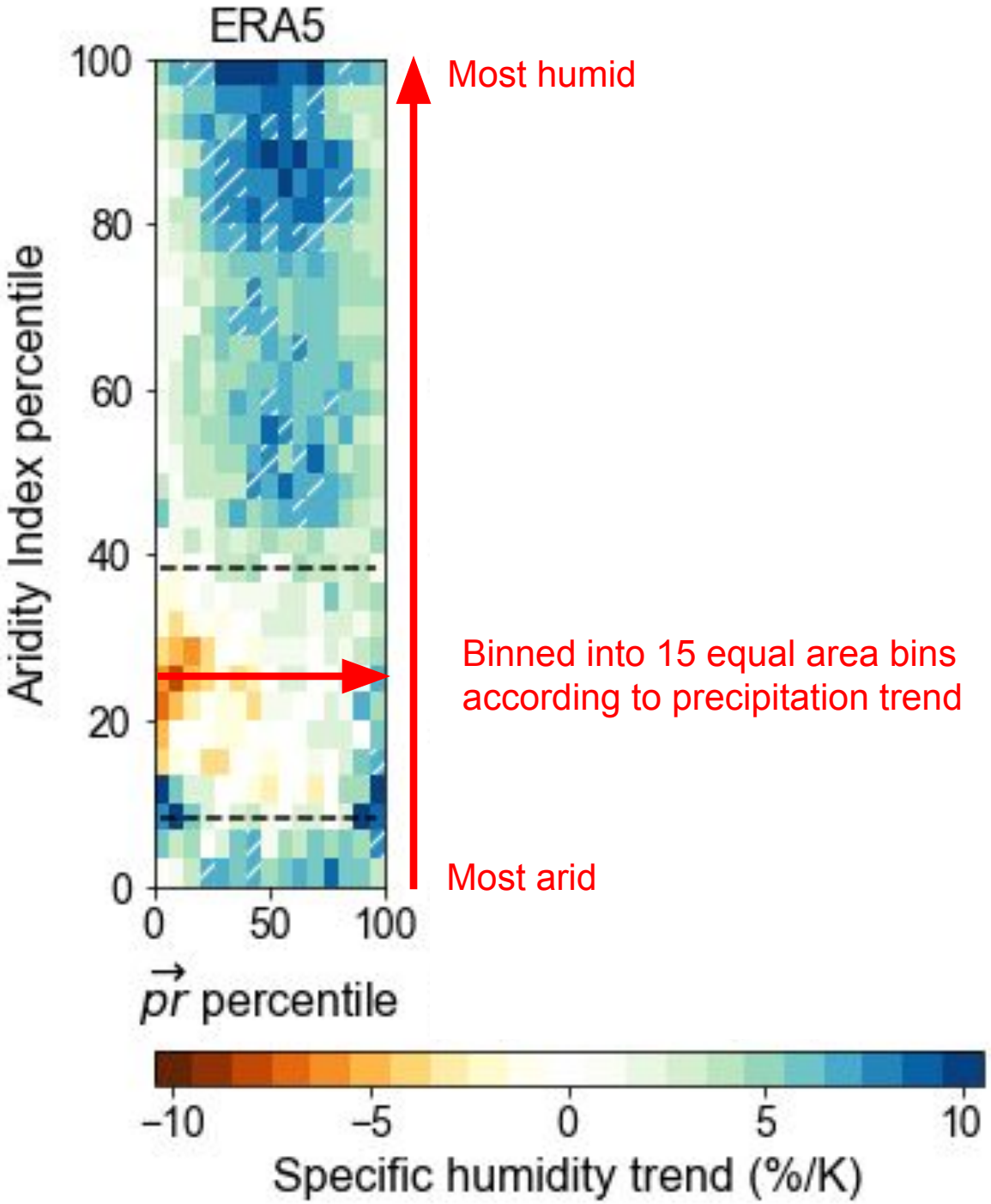

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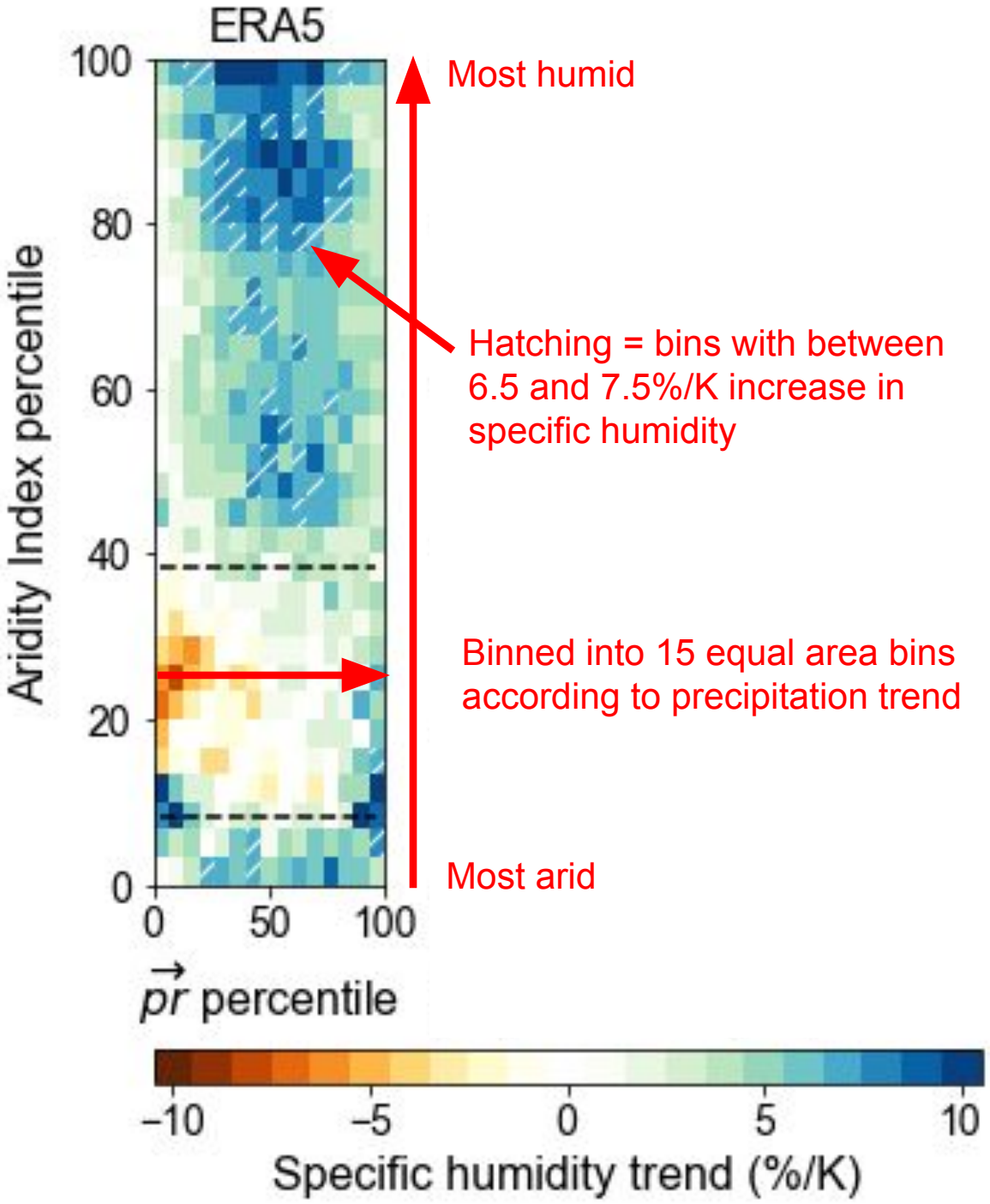

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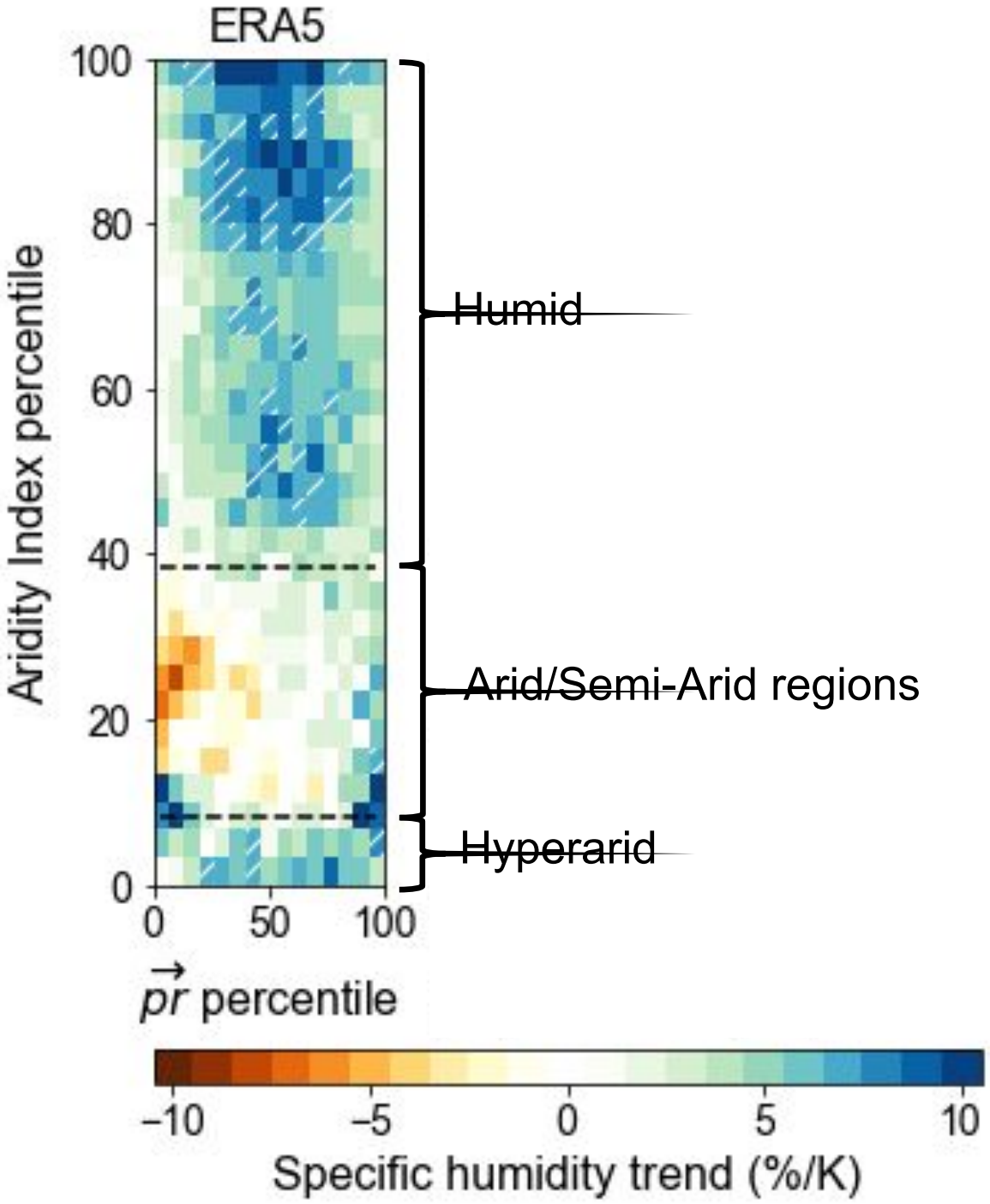

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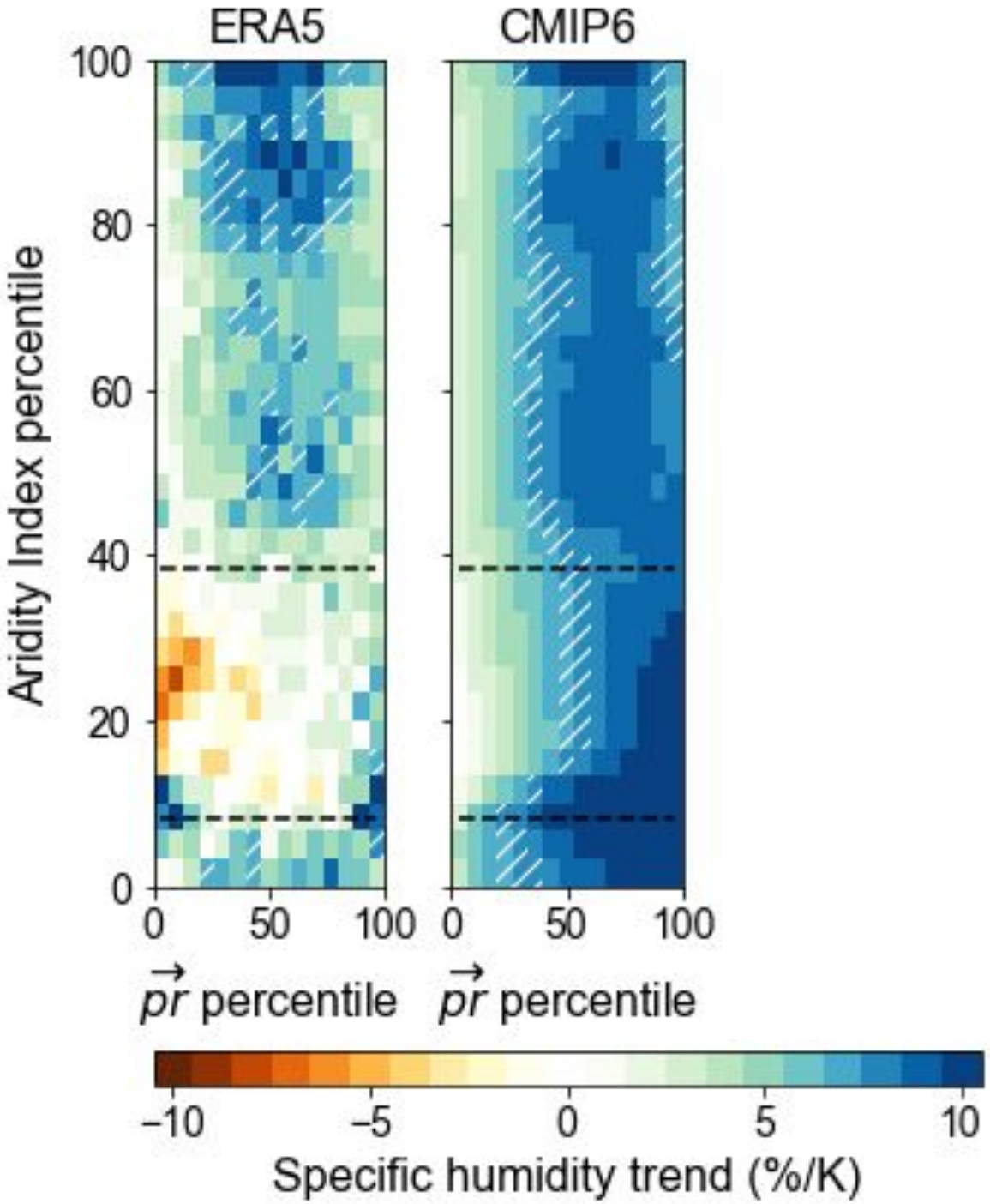

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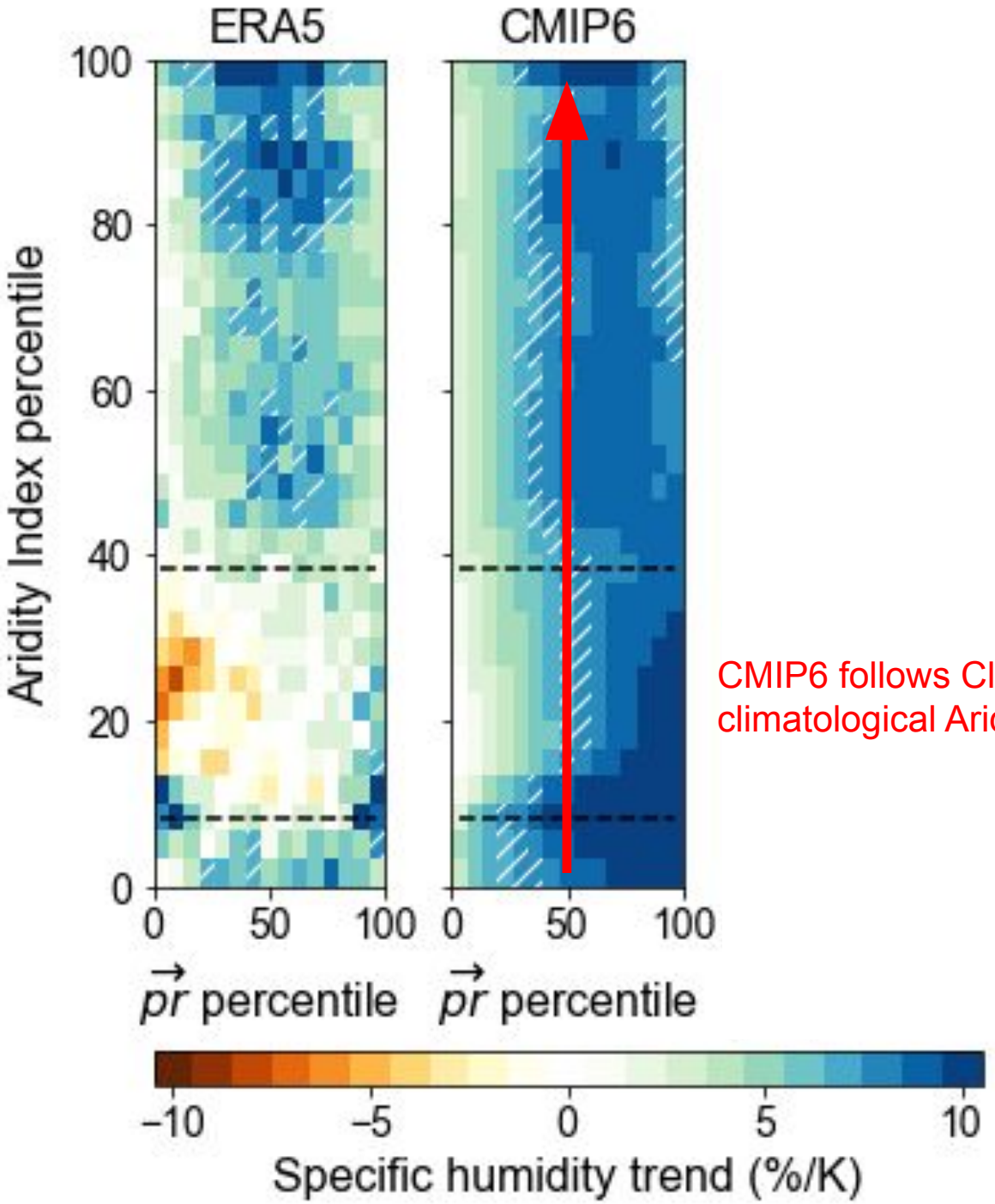

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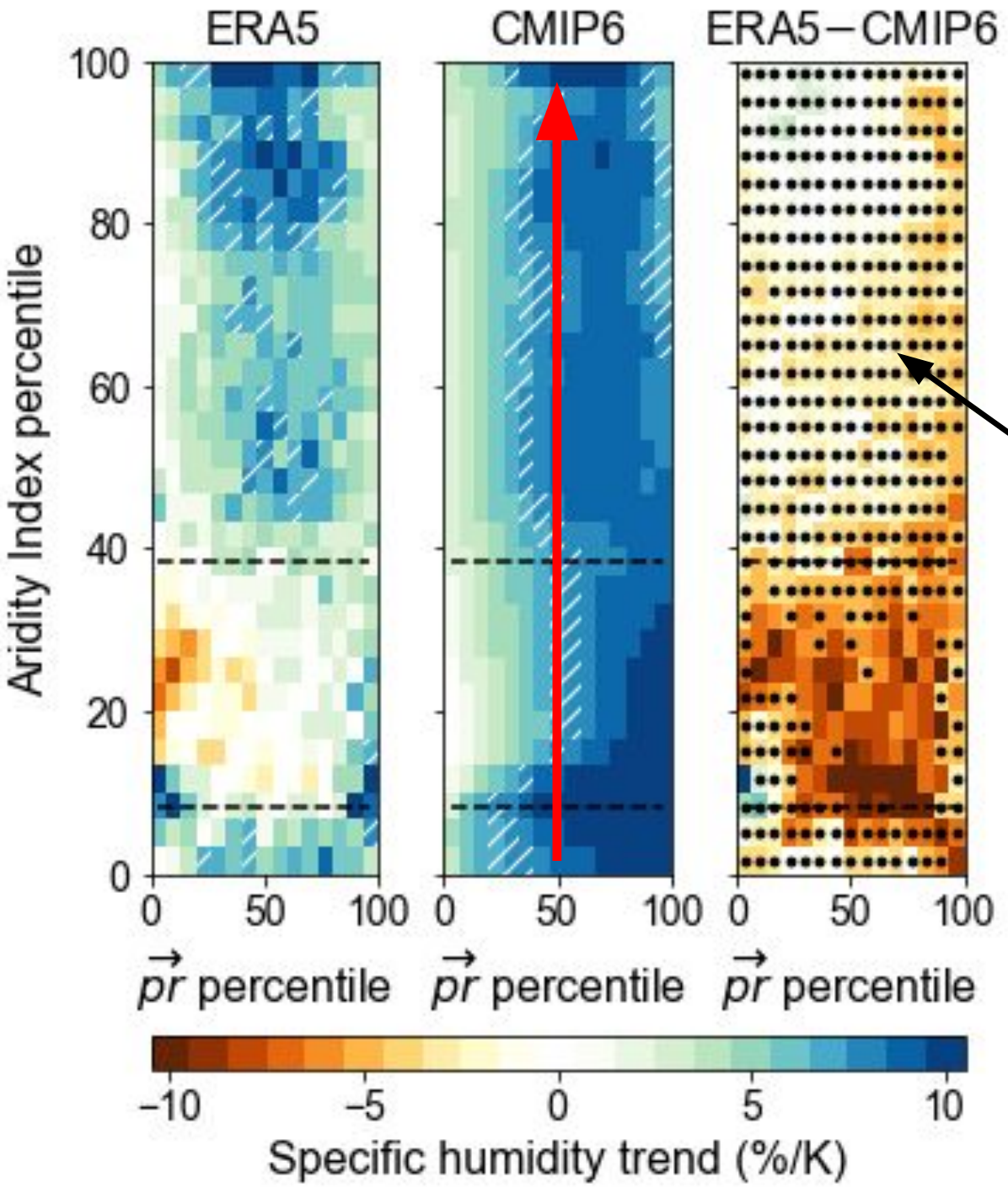
CMIP6 follows Clausius Clapeyron scaling regardless of the climatological Aridity (~7%/K with near zero precipitation trend).



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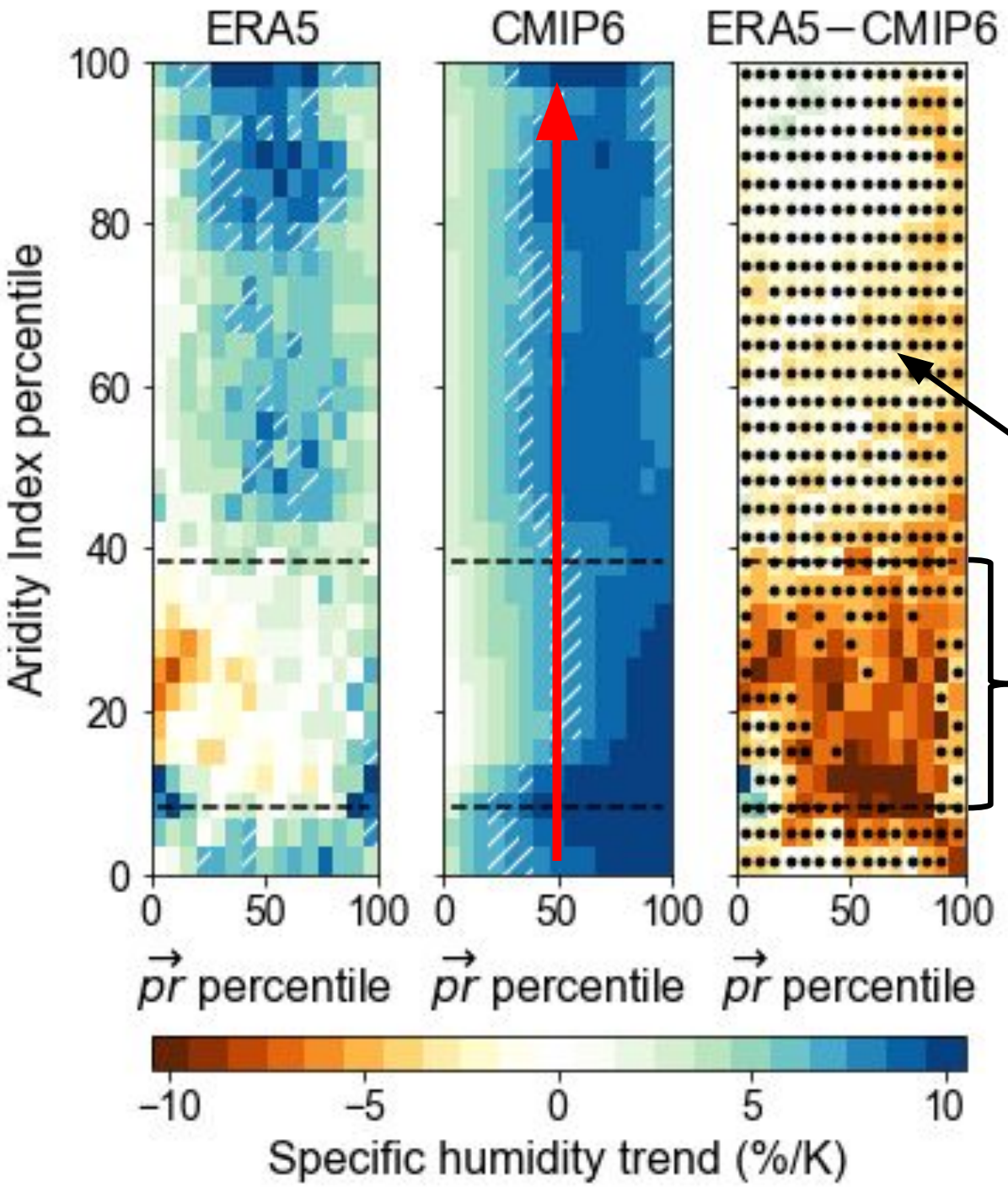
Stippling = ERA5 lies within the CMIP6 ensemble spread



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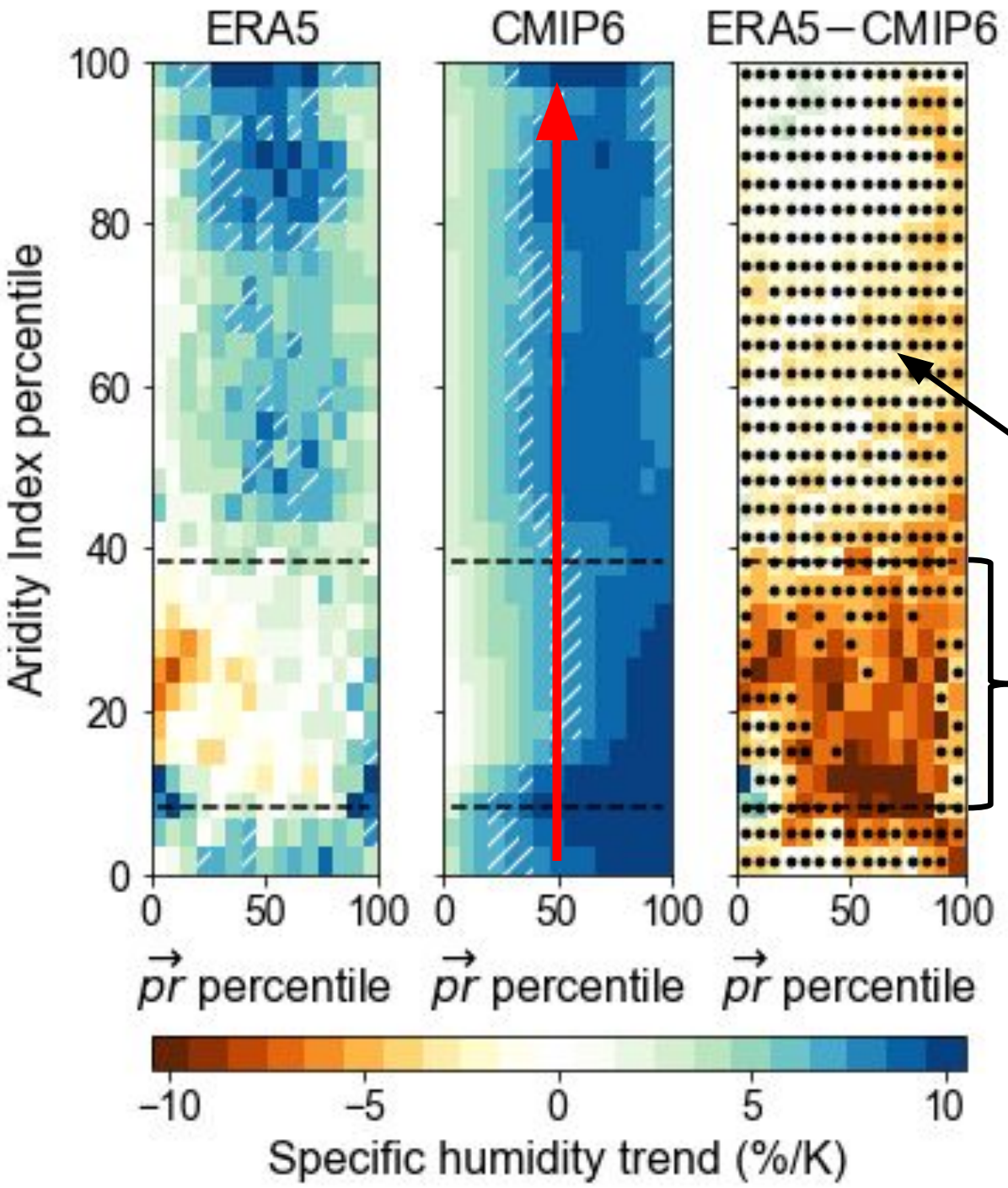
Stippling = ERA5 lies within the CMIP6 ensemble spread

ERA5 shows reduced specific humidity trends compared to CMIP6 in arid/semi-arid regions.



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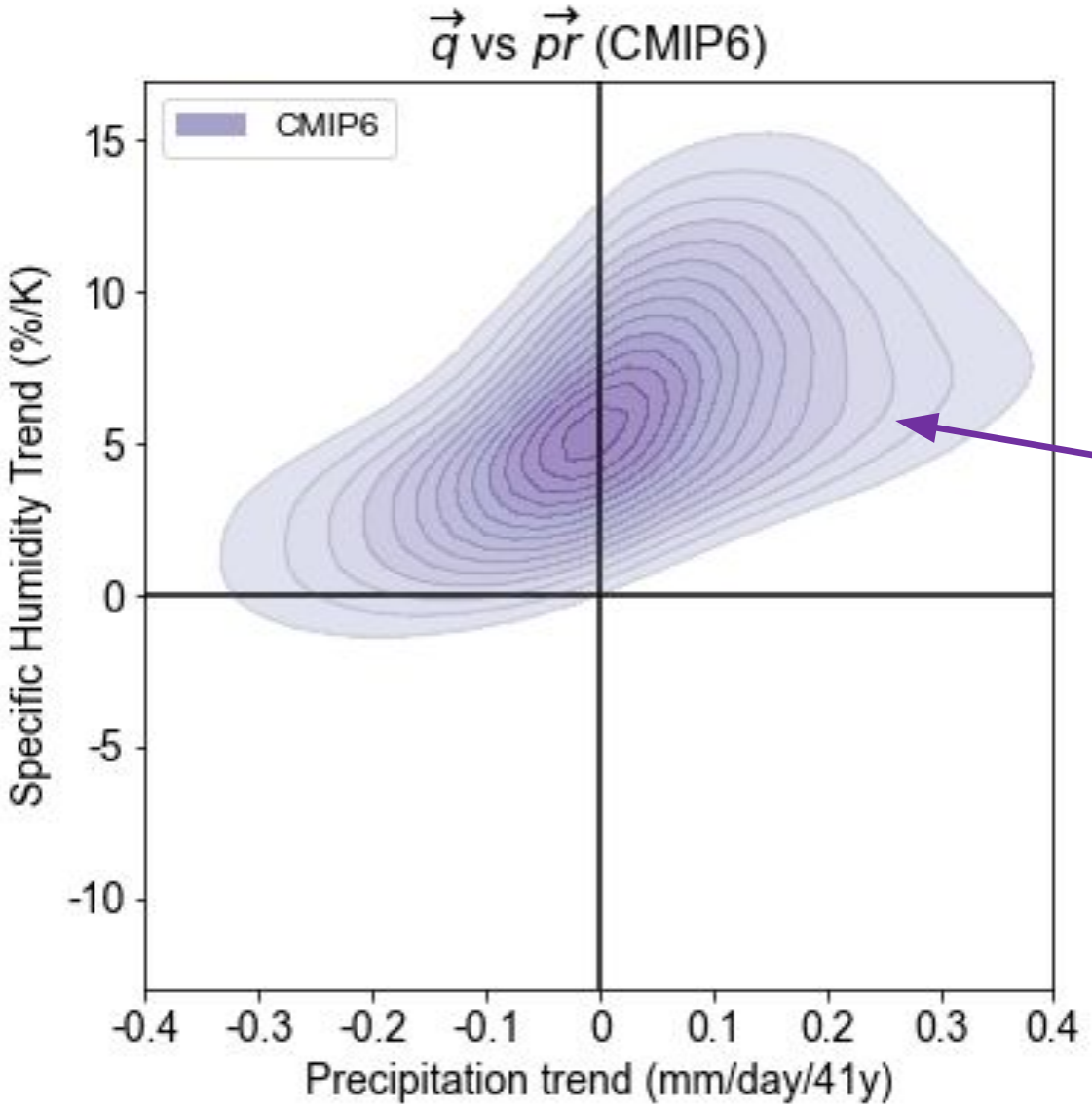
Now we'll just focus on arid and semi-arid grid points

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.

ERA5 for specific humidity and GPCC for precipitation

CMIP6

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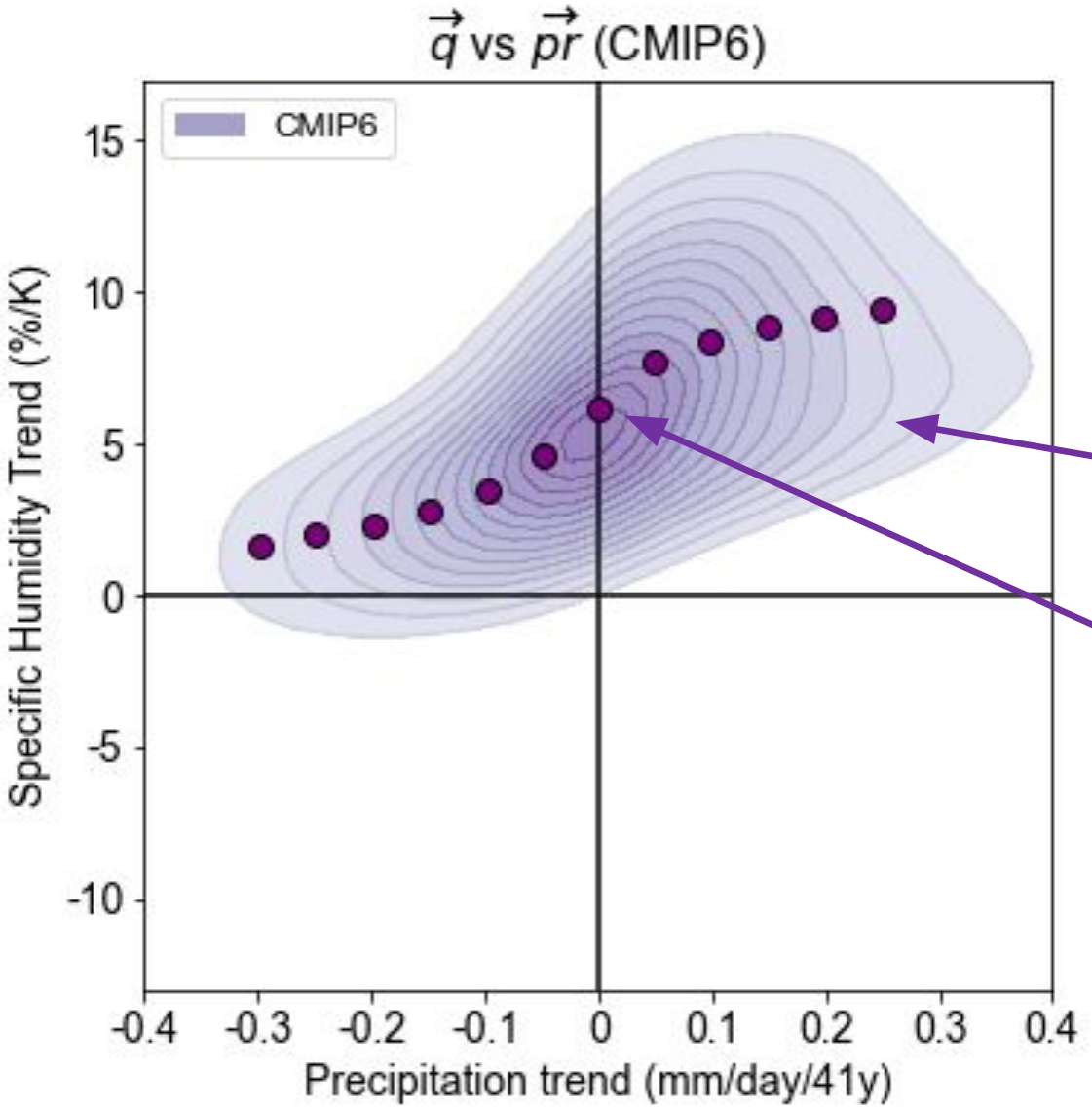

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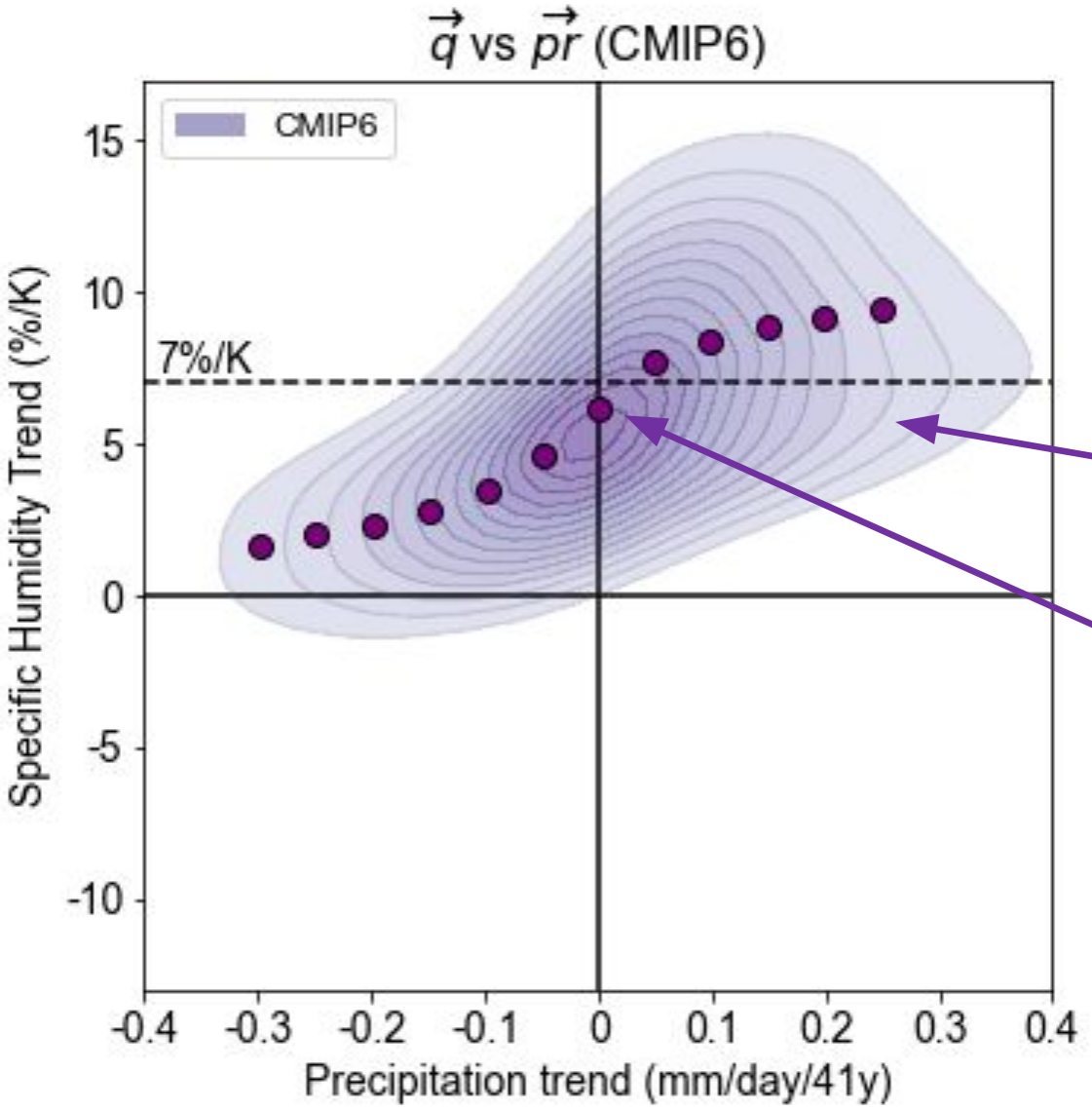
CMIP6

Average over precipitation bins of width 0.05 mm/day/41y

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



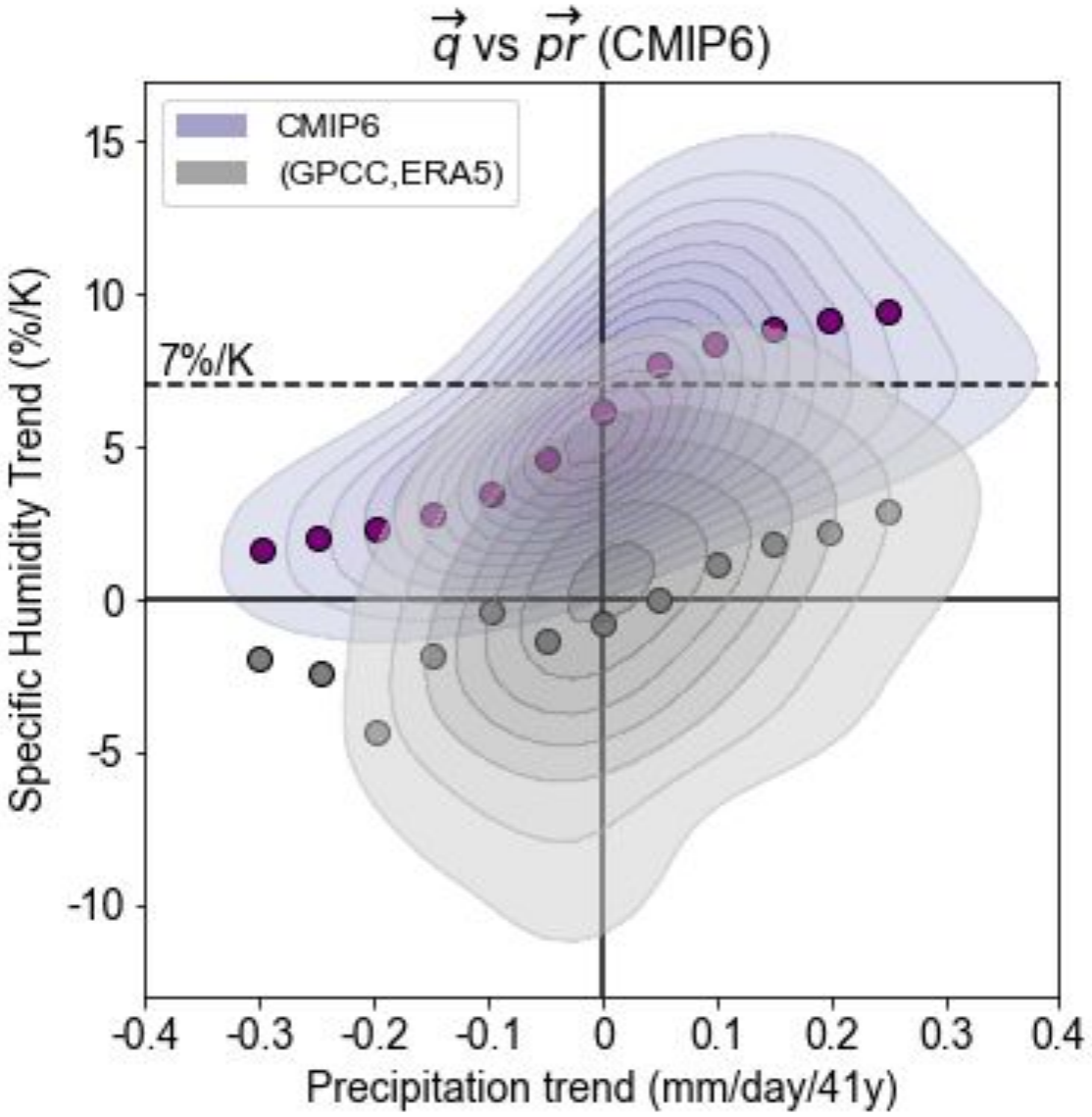
Joint pdf of specific humidity trends (expressed as a percentage of the 1980-1990 average, normalized by land area average temperature change) versus precipitation trends.

ERA5 for specific humidity and GPCC for precipitation

CMIP6

Average over precipitation bins of width 0.05 mm/day/41y

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.

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

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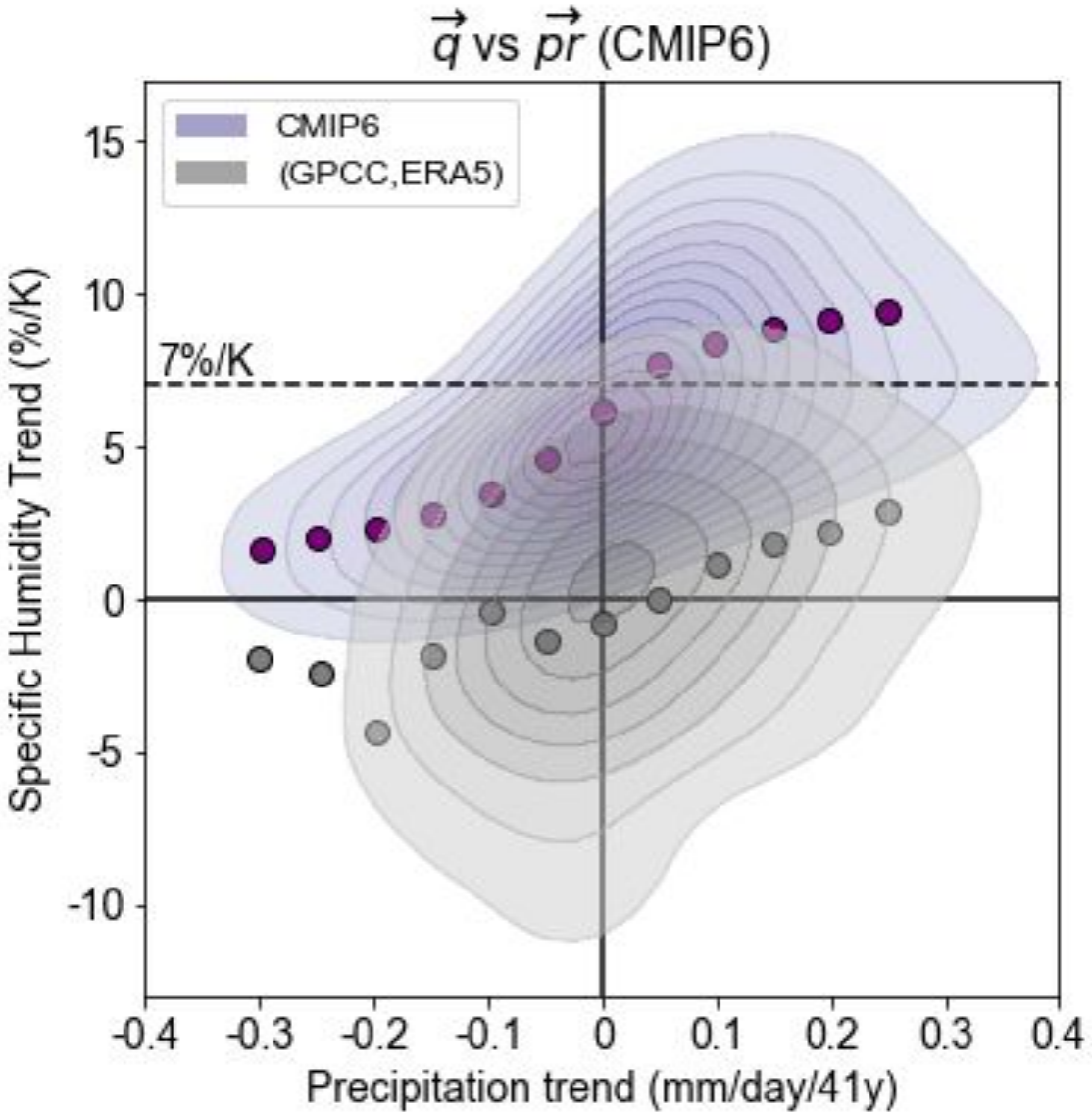
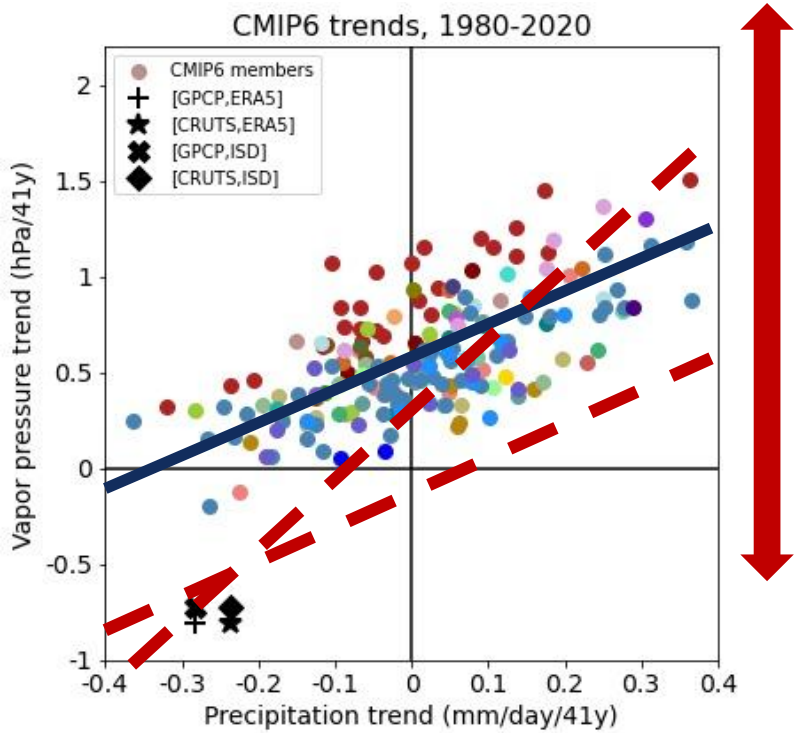


VP trends in the Southwest for individual members



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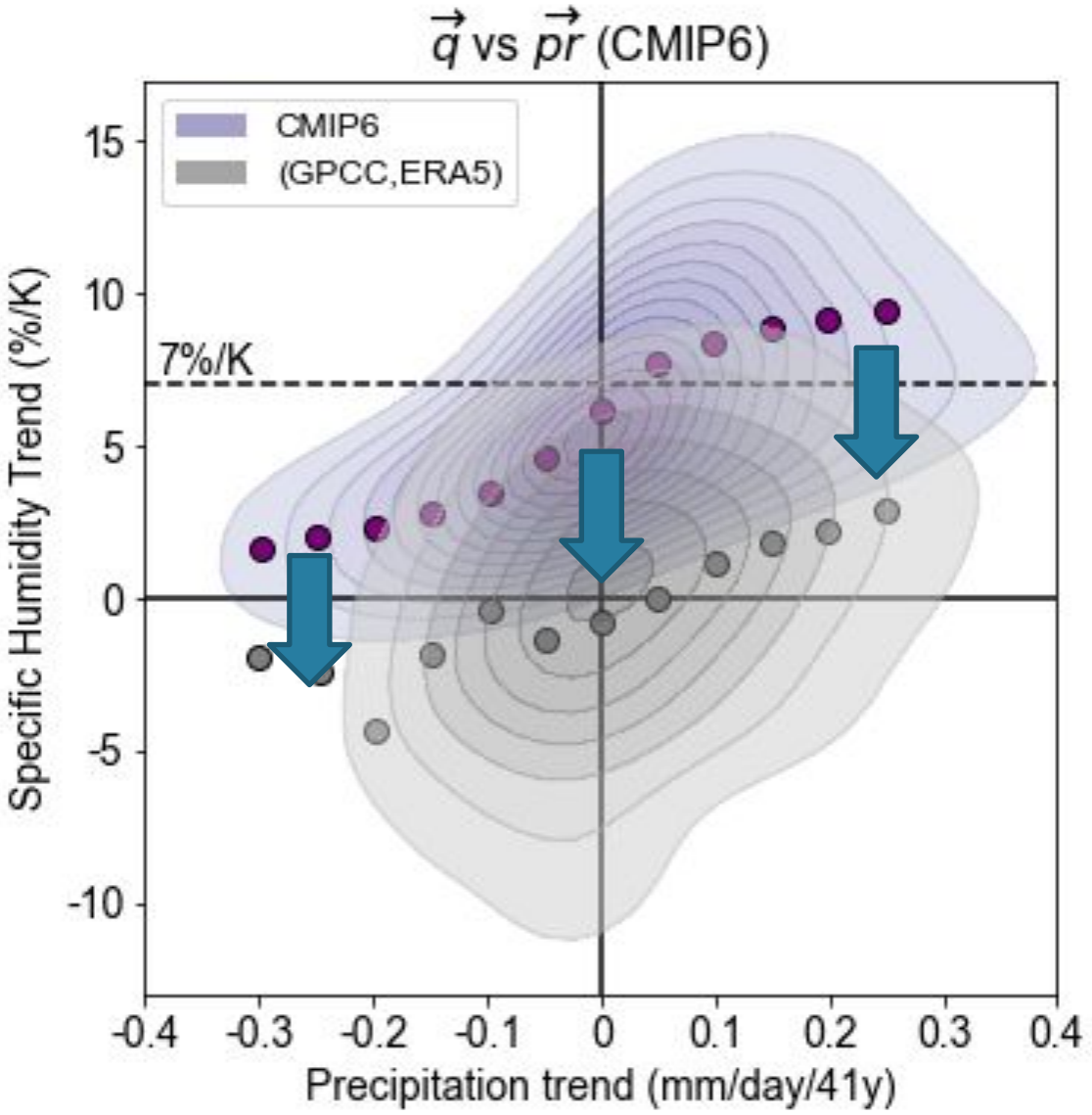
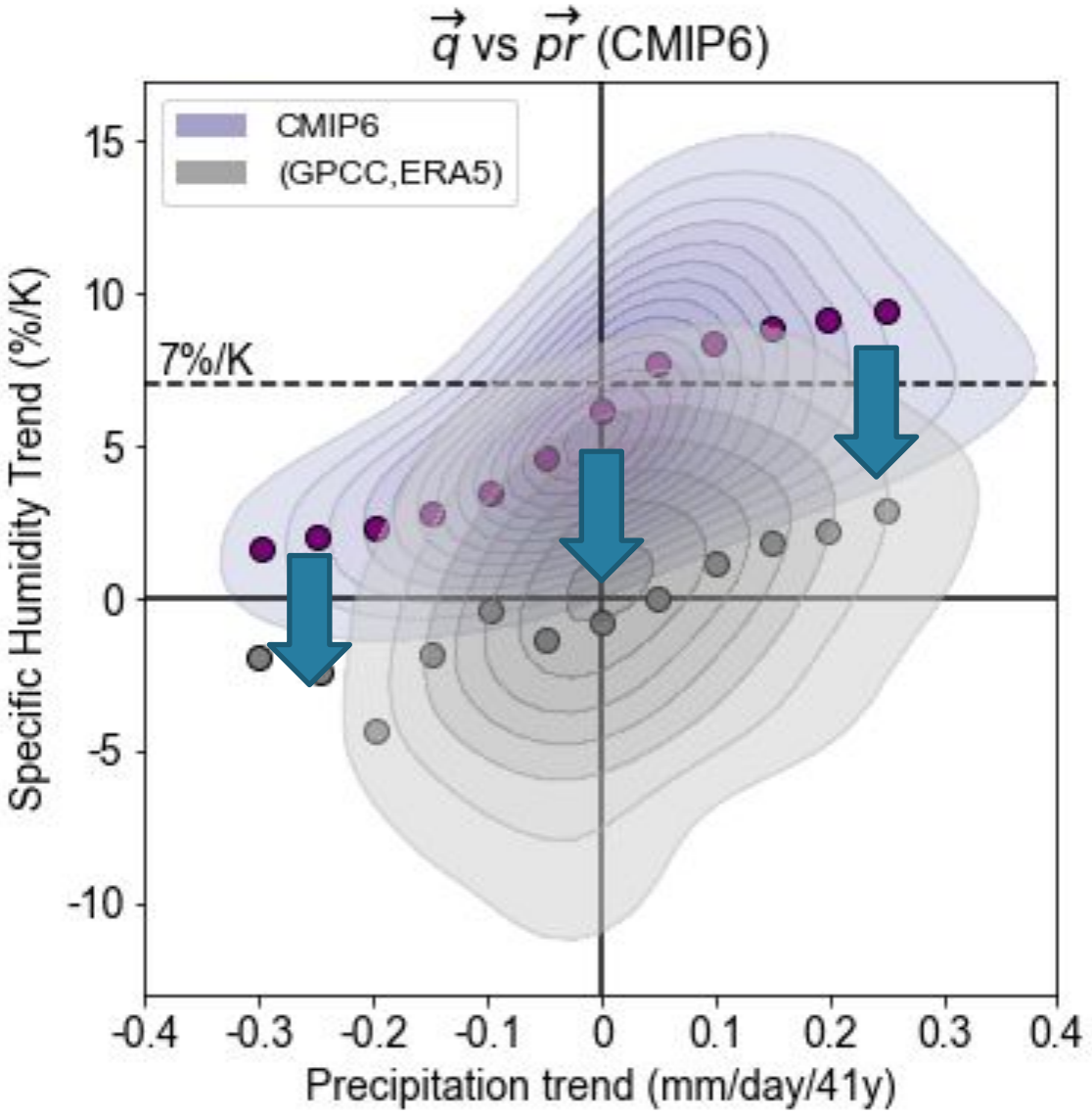
Specific humidity trend (%/K) in arid/semi-arid regions versus precipitation trends



The forced trend in vapor pressure, independent of precipitation, is different in the models

In observations, we don't see the forced, thermodynamic increase in vapor pressure over Arid/Semi-Arid regions that the models suggest should have happened

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



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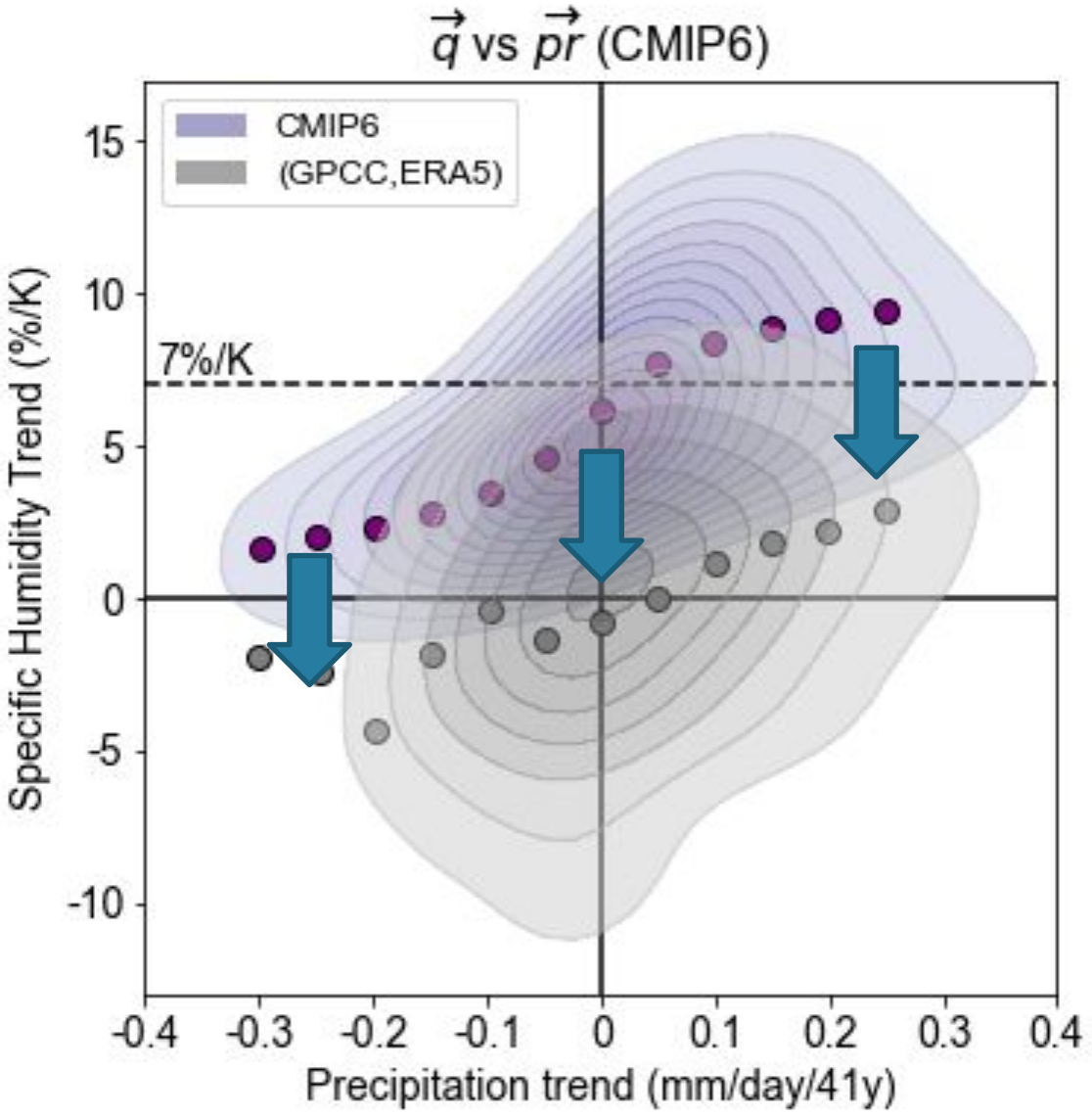
Something is wrong, which could have potentially severe implications for climate projections in Arid/Semi-Arid regions

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



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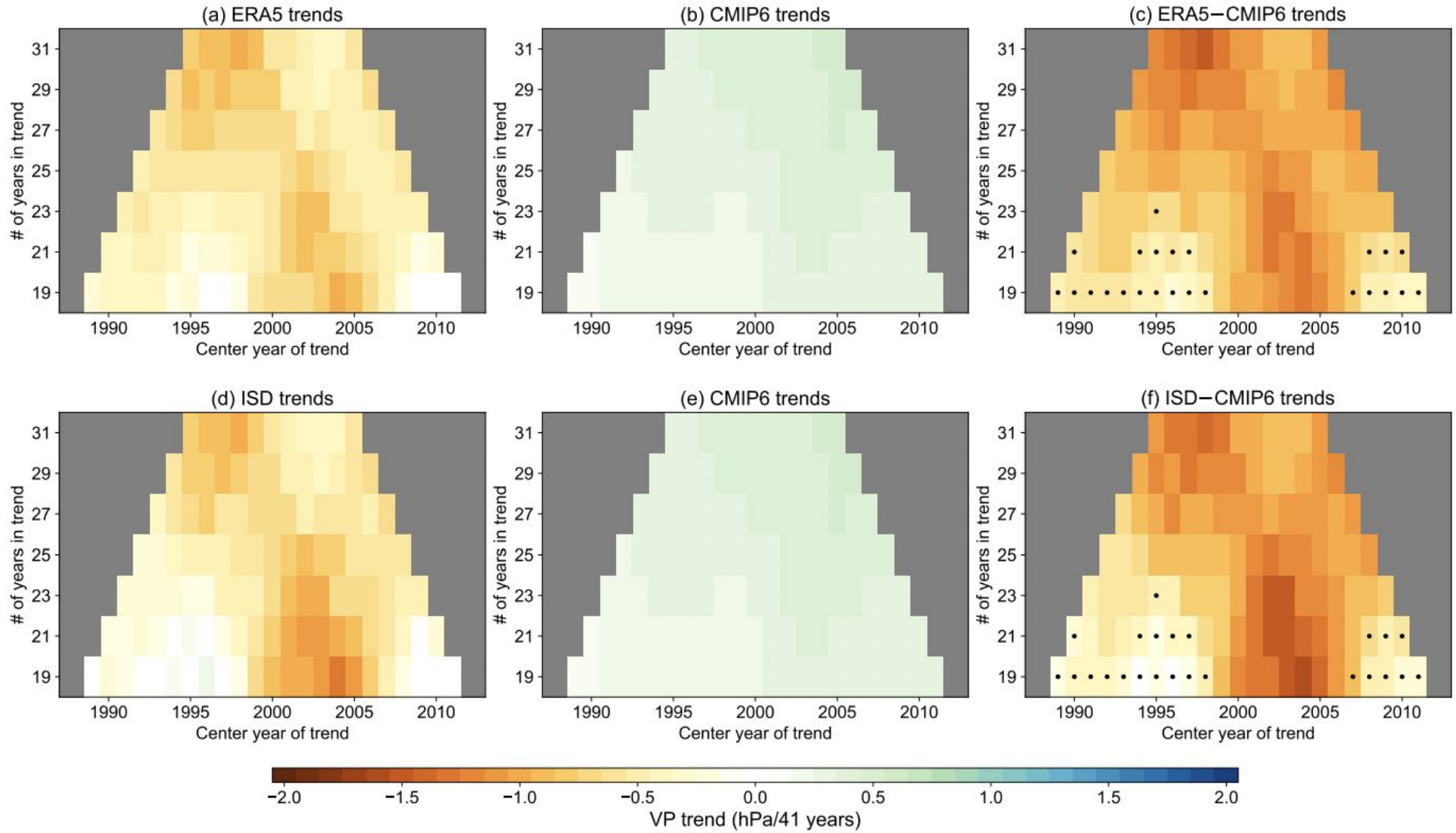
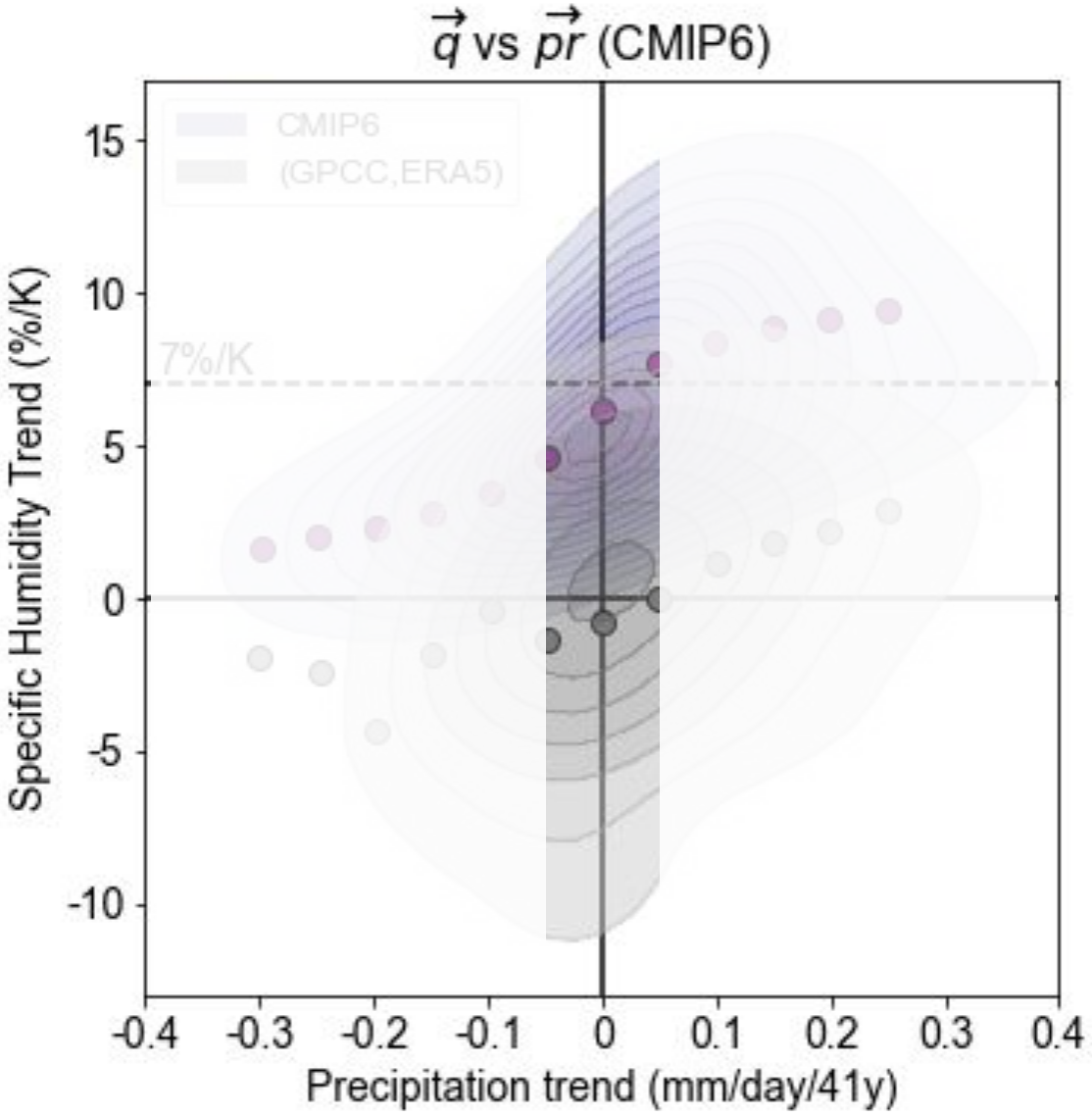
Too much water availability from the land surface?
Has the land surface dried out more in reality?
Plant physiology changes?
A global water vapor transport issue?

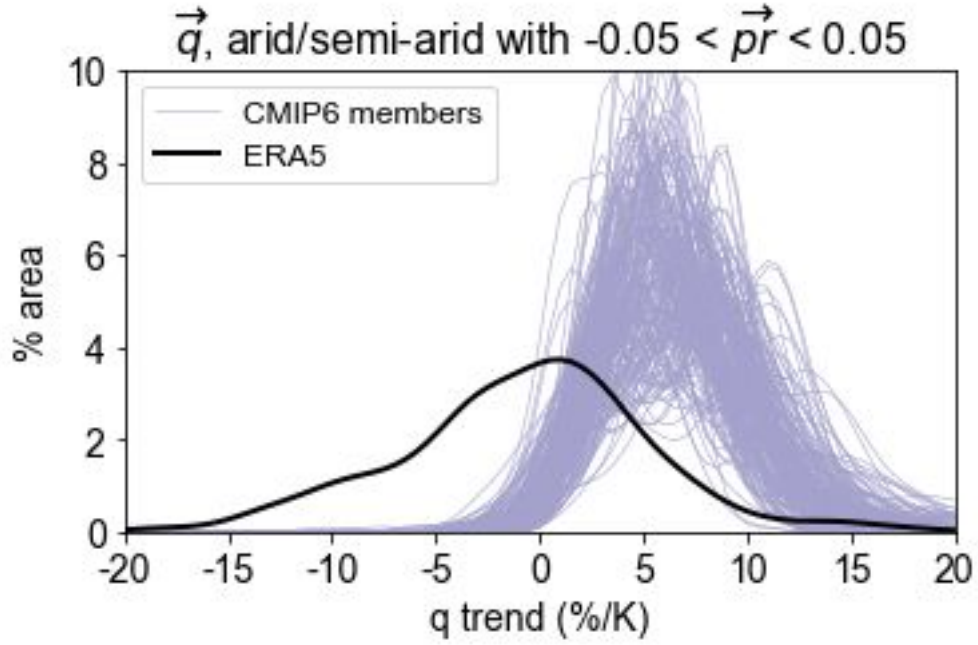
Extra Slides


(a) ERA5 trends
(b) CMIP6 trends
(c) ERA5−CMIP6 trends
(d) ISD trends
(e) CMIP6 trends
(f) ISD−CMIP6 trends
# of years in trend
31
29
27
25
23
21
19
1990
1995
2000
2005
2010
Center year of trend
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
VP trend (hPa/41 years)

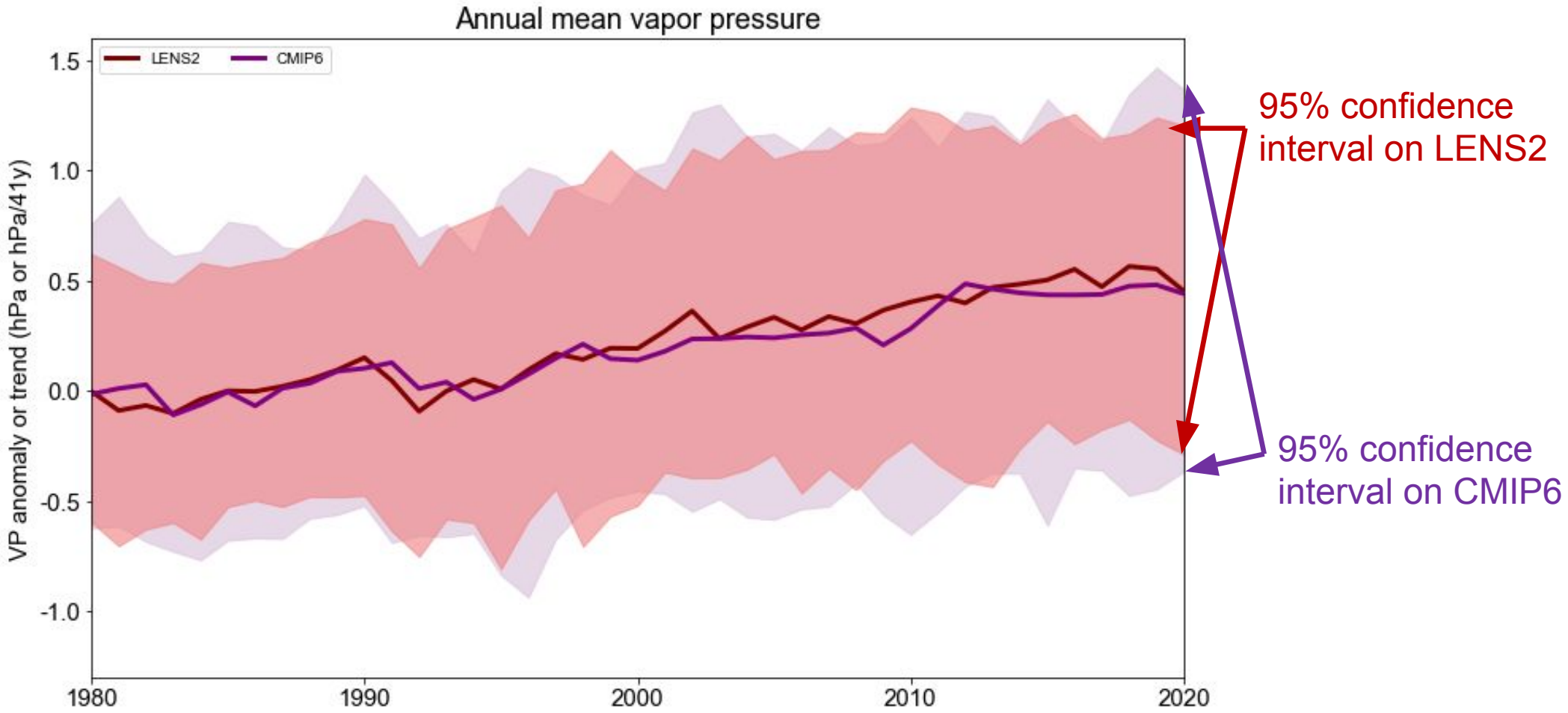
Specific humidity trend (%/K) in arid/semi-arid regions versus precipitation trends



Specific humidity trend pdfs for all model members in the locations with precipitation trends between -0.05 and 0.05 mm/day/41y



Time series of annual mean vapor pressure averaged over the Southwest



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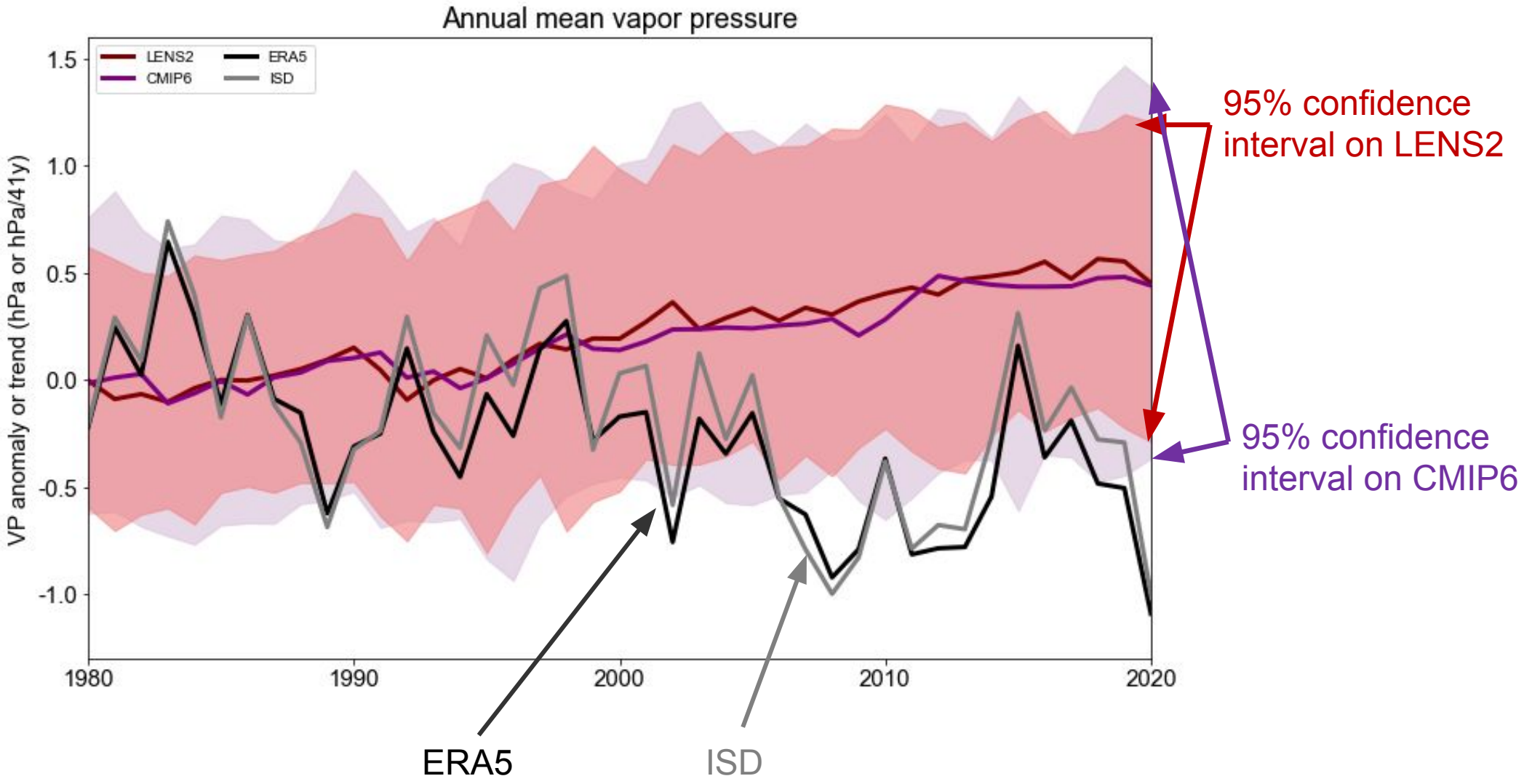
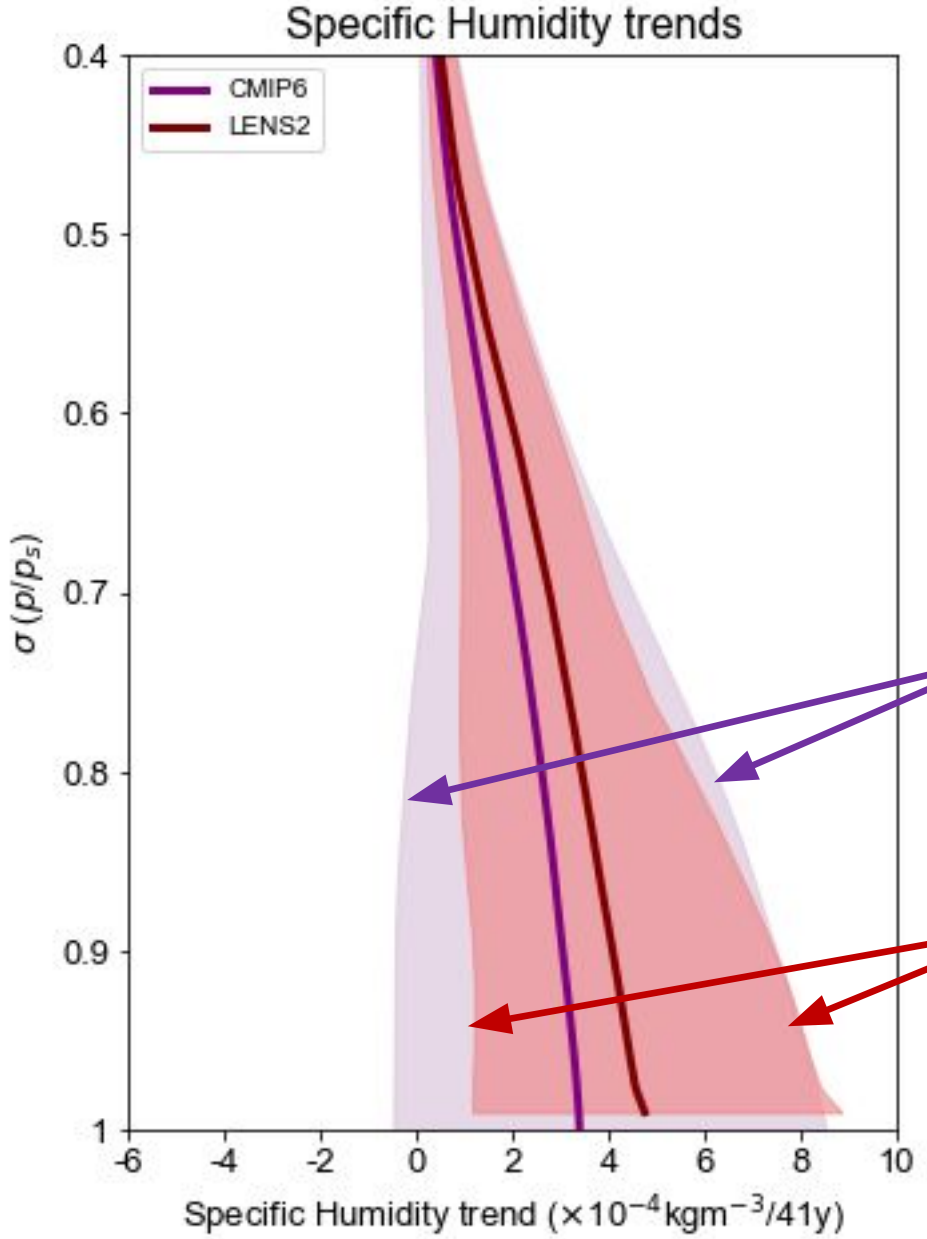


Vertical structure of specific humidity trends

Mid-troposphere

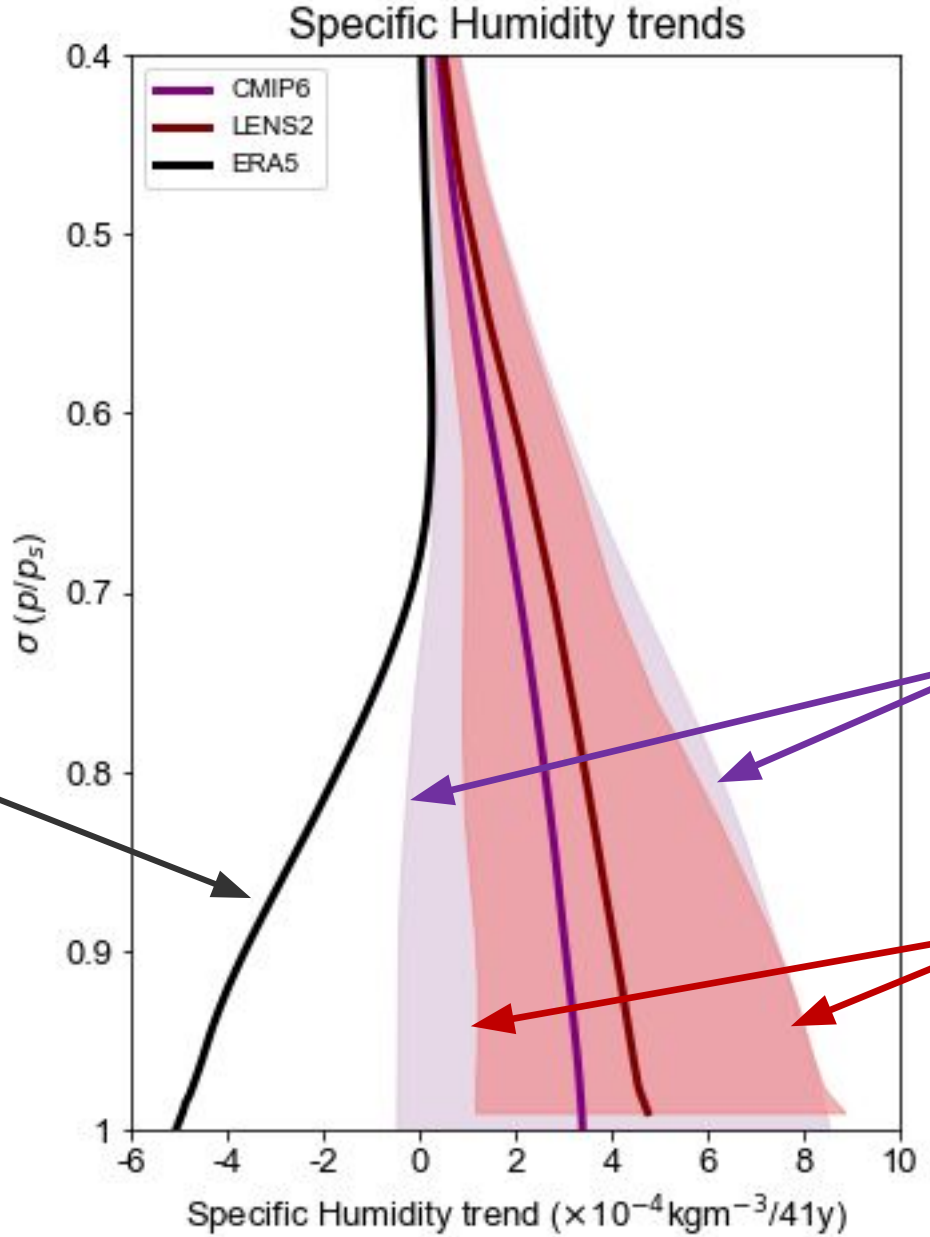
Surface



Min to Max range of CMIP6

Min to Max range of LENS2

Vertical structure of specific humidity trends



Mid-troposphere

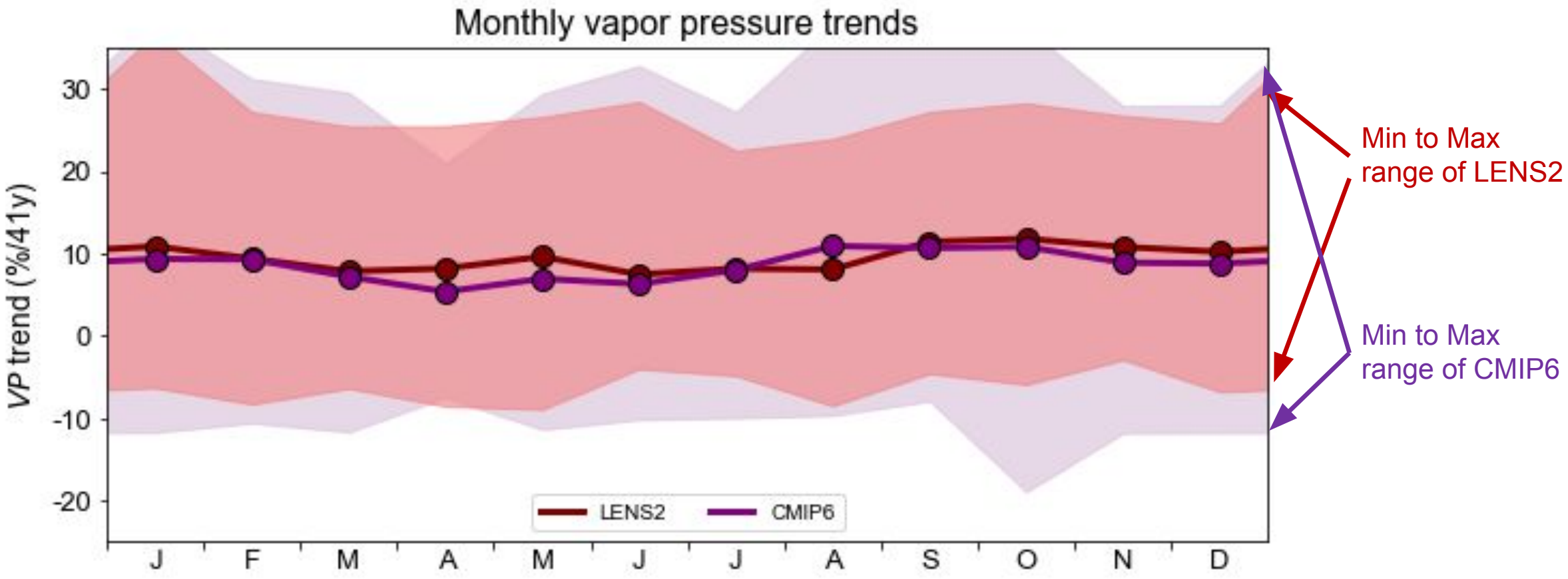
ERA5

Surface

Min to Max range of CMIP6

Min to Max range of LENS2

Seasonality of vapor pressure trend discrepancy



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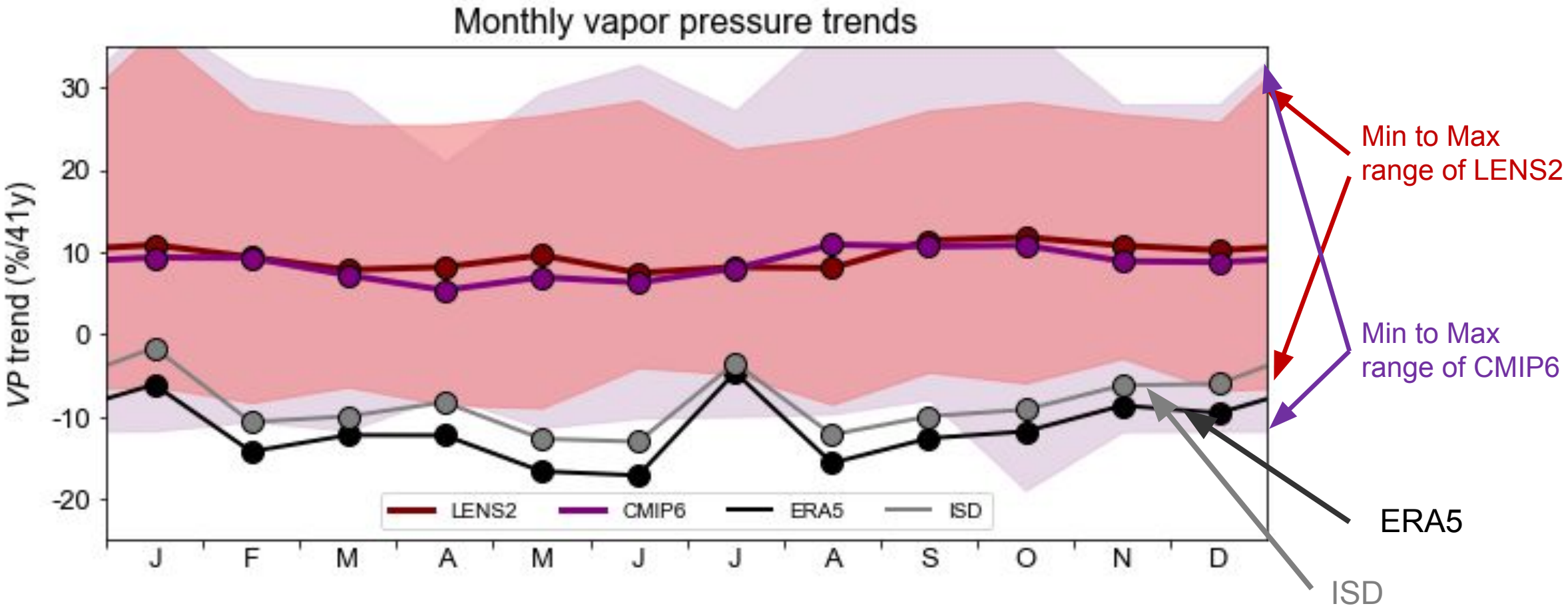

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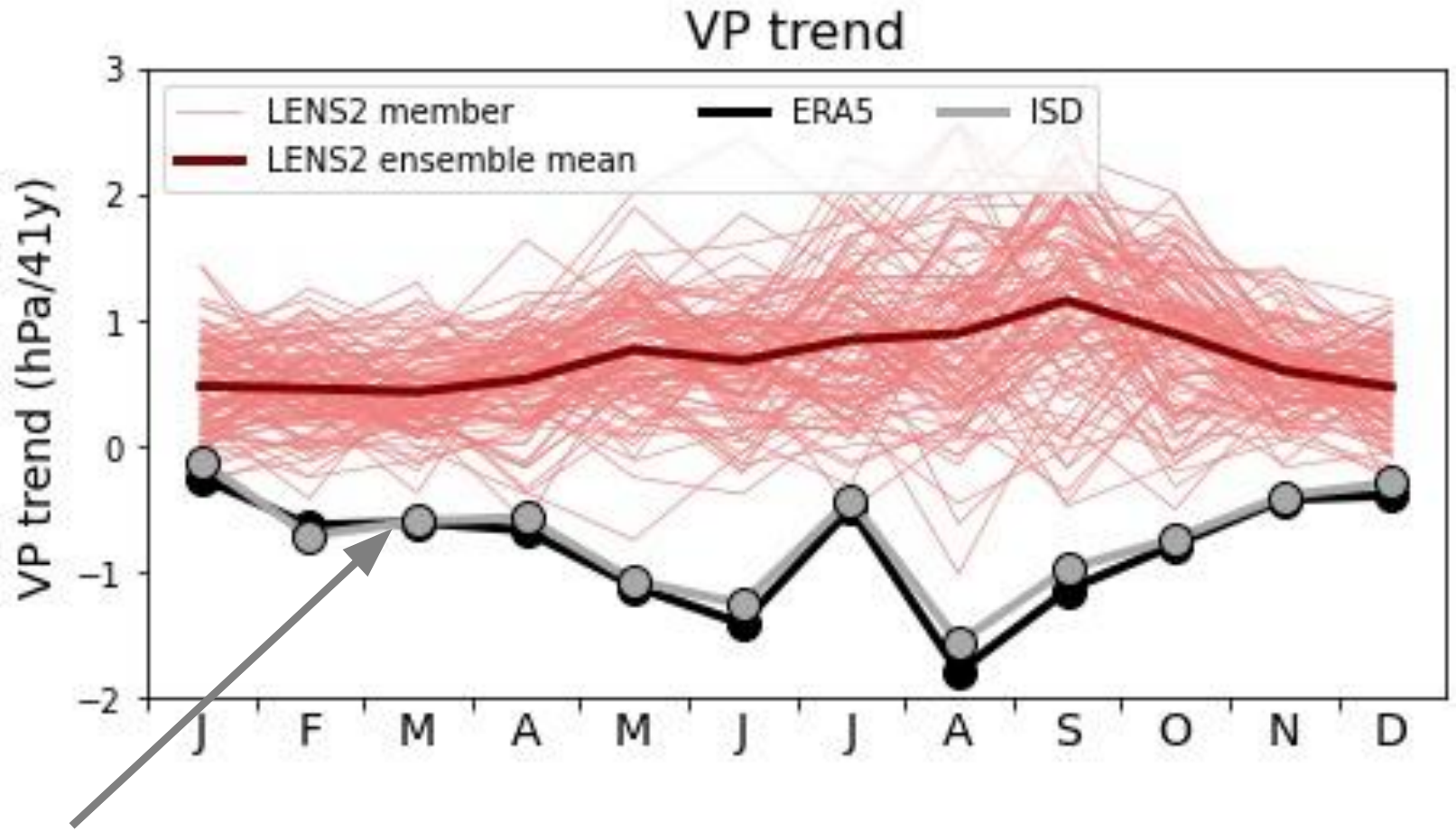
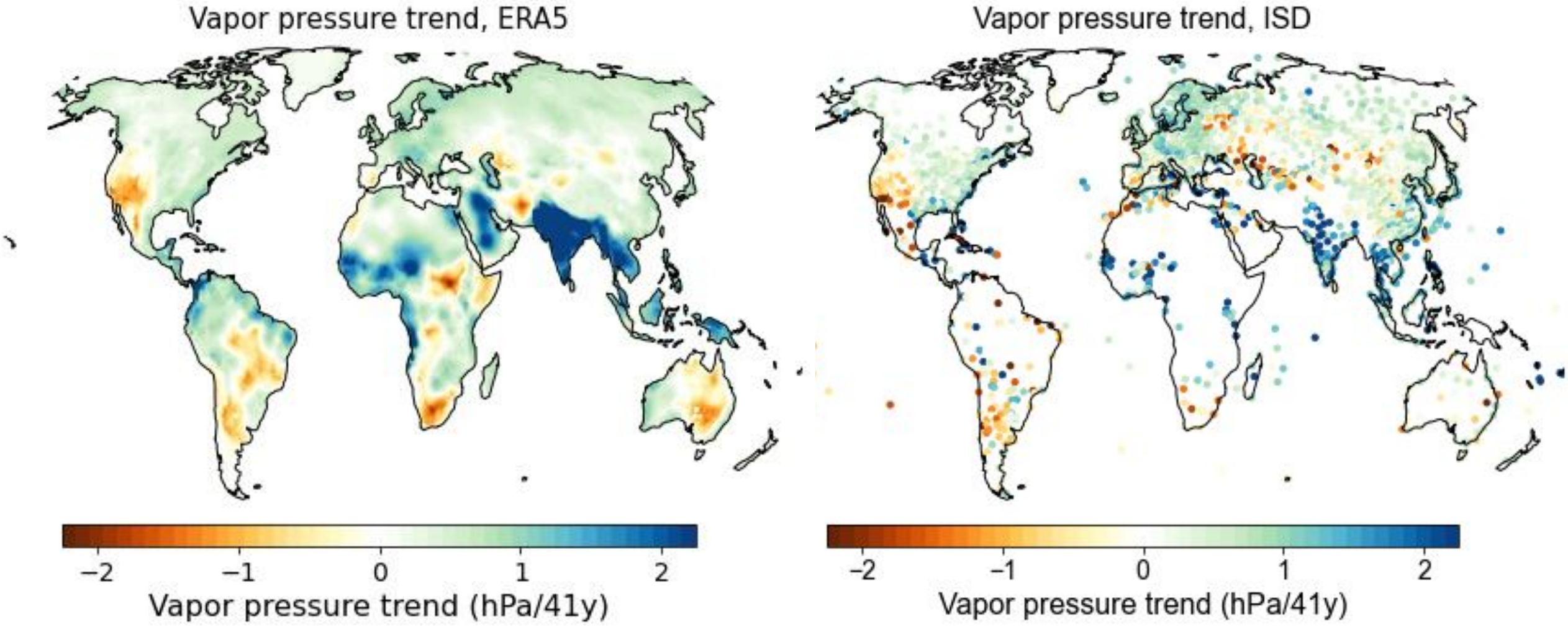


ISD station data

Global vapor pressure trends



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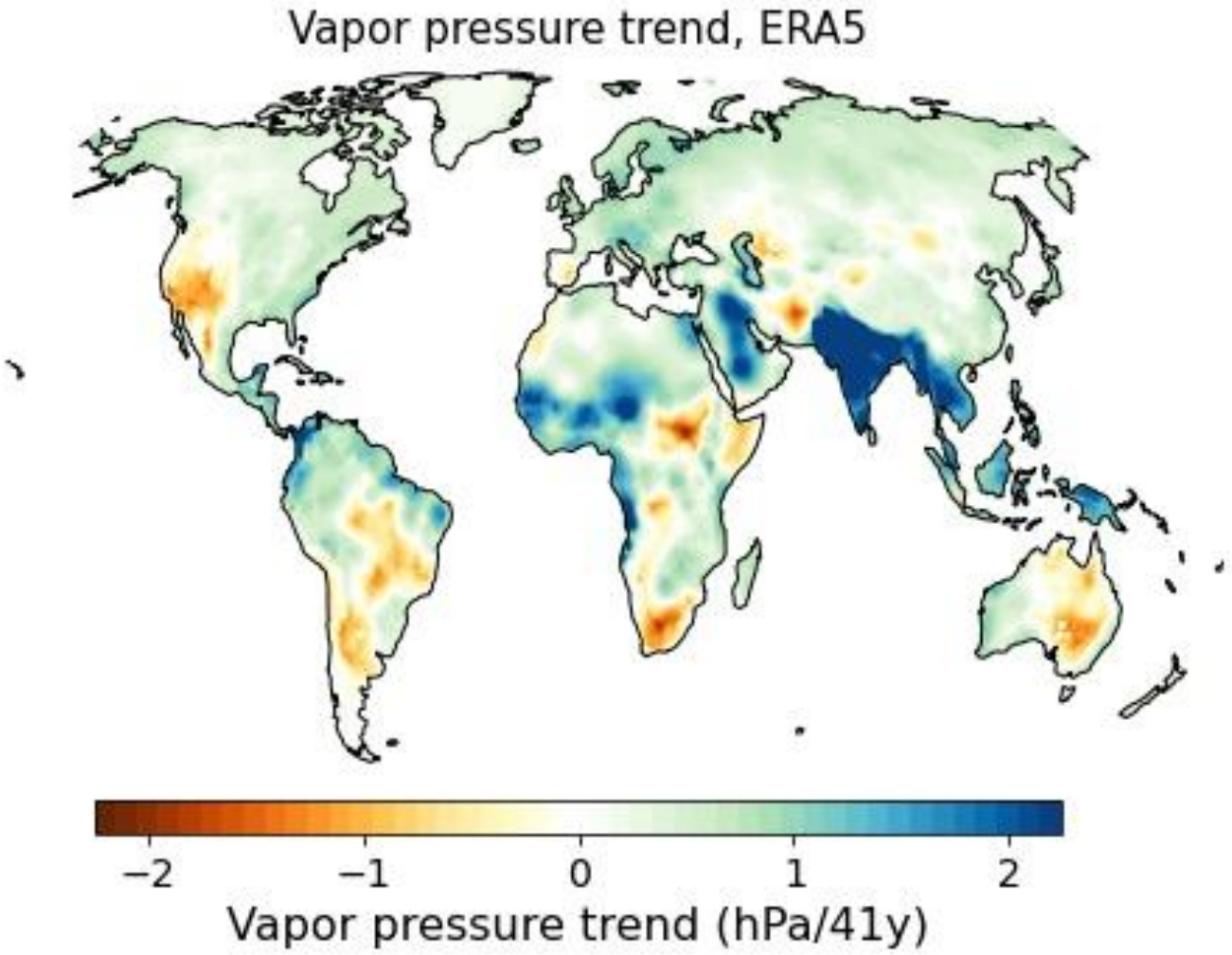

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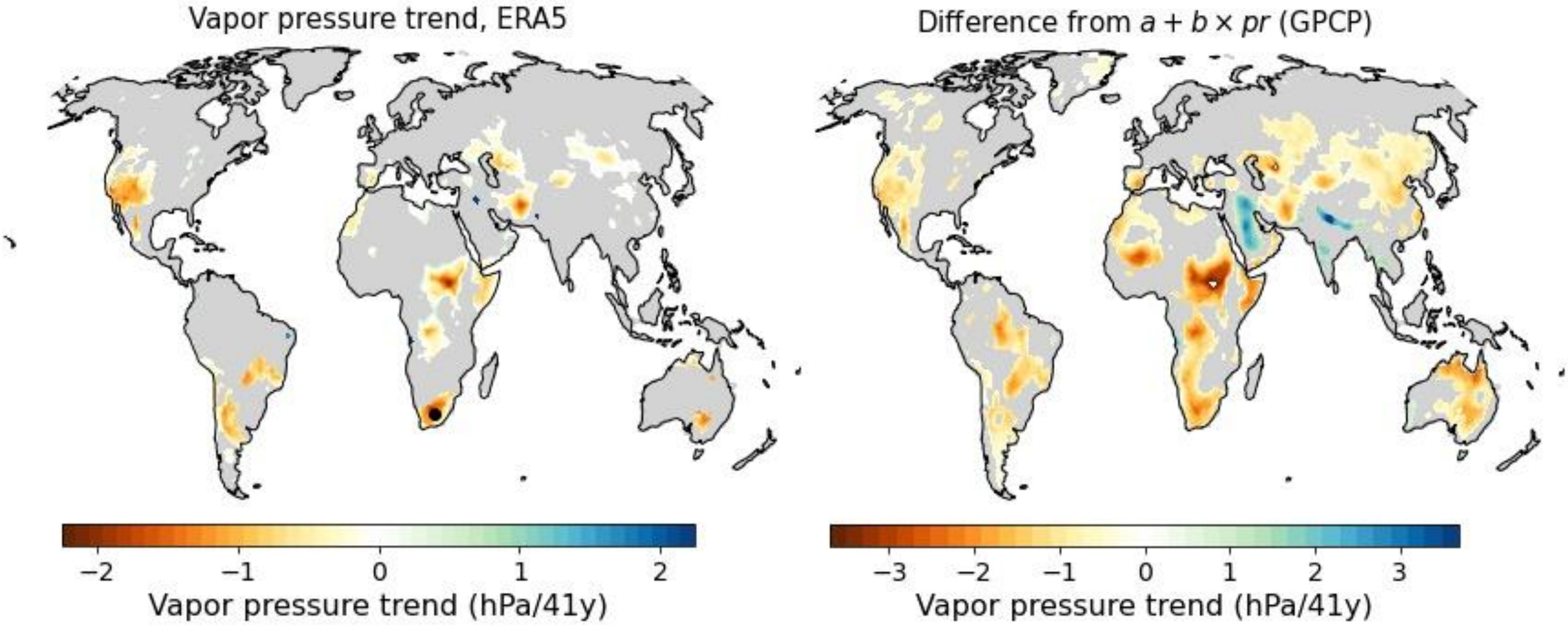
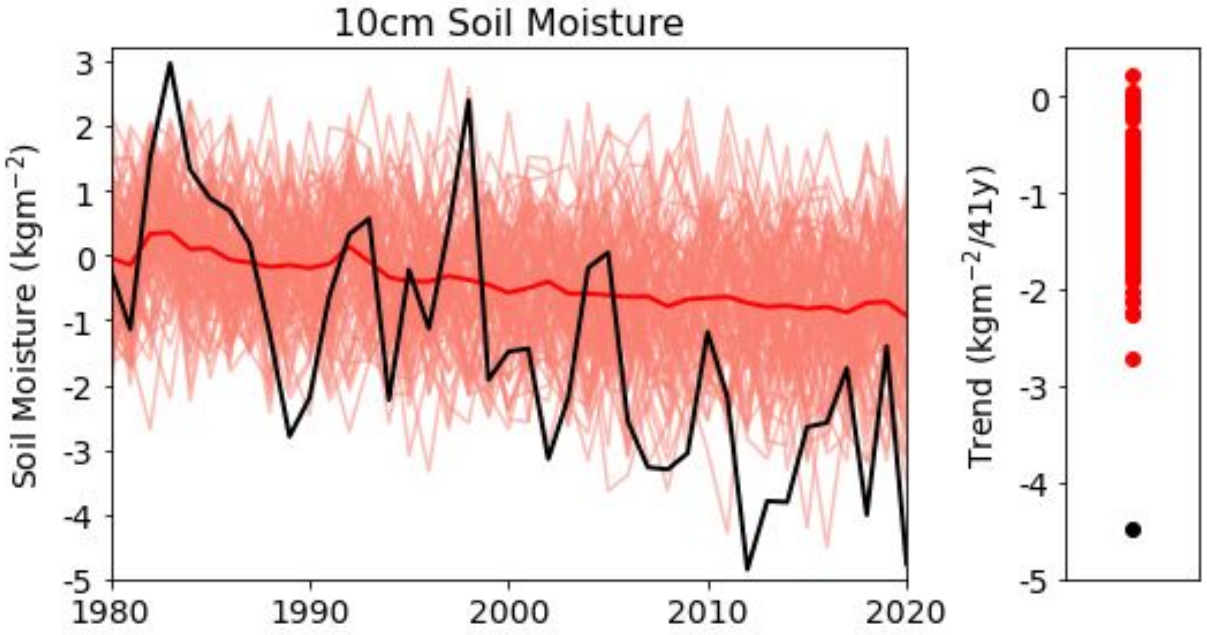


A challenge…

We don’t really have observations of all the other relevant quantities that are needed

While ERA5 produces vapor pressure trends that are consistent with station observations, it has other inconsistencies.

Soil moisture declines more in ERA5 than in the models



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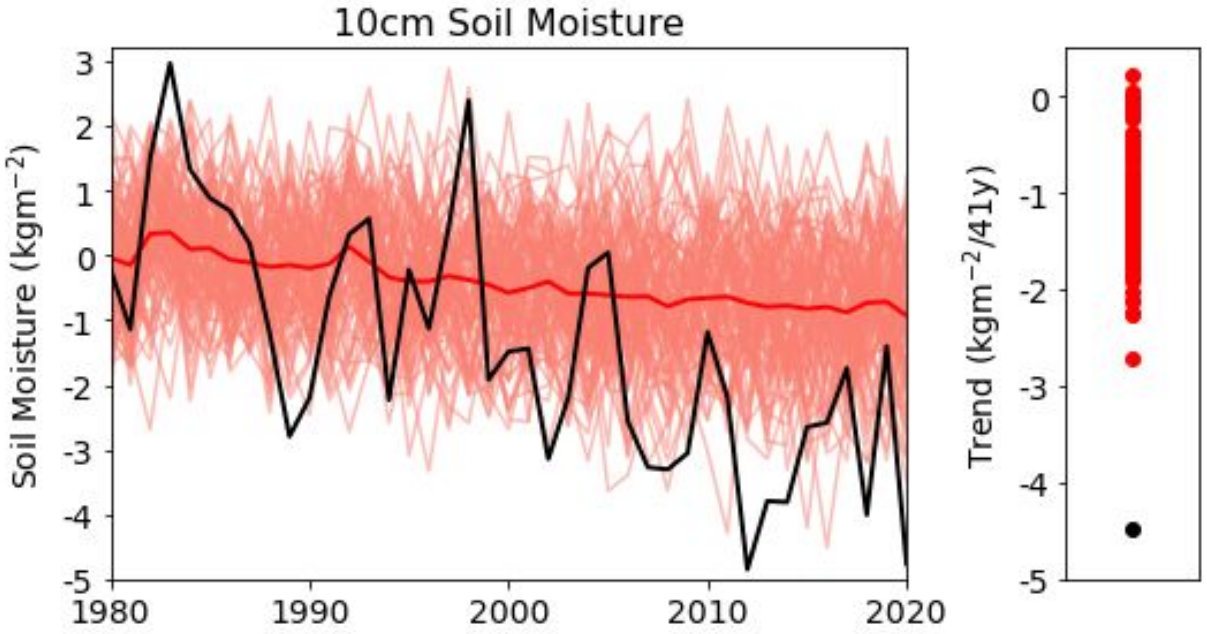
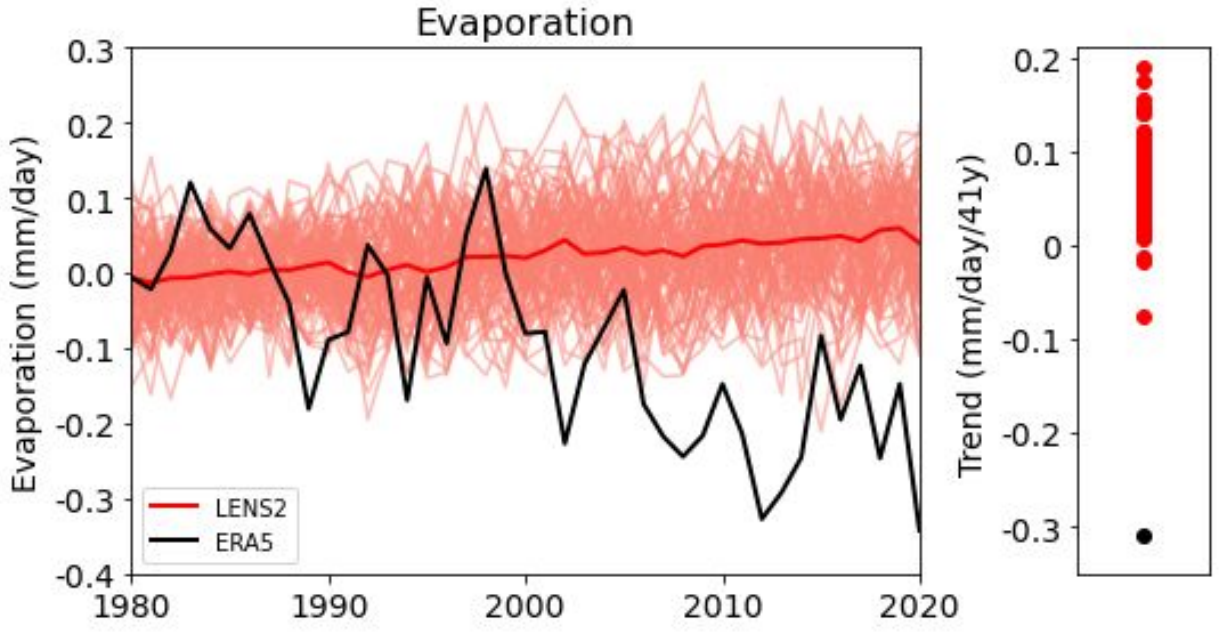


So does evaporation



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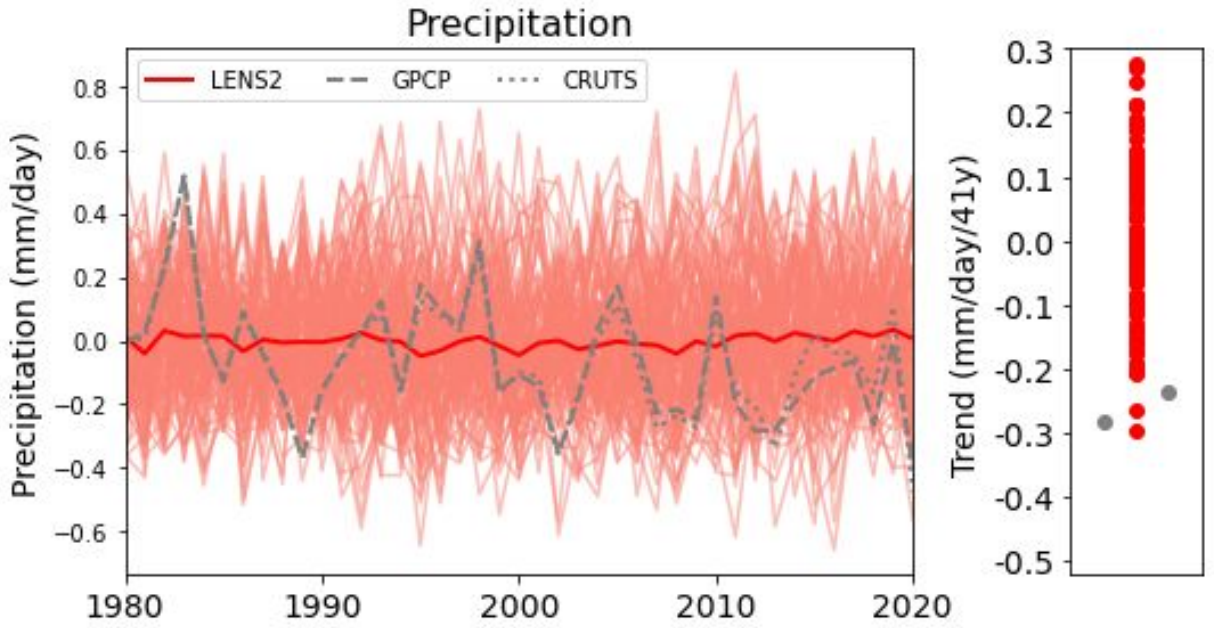

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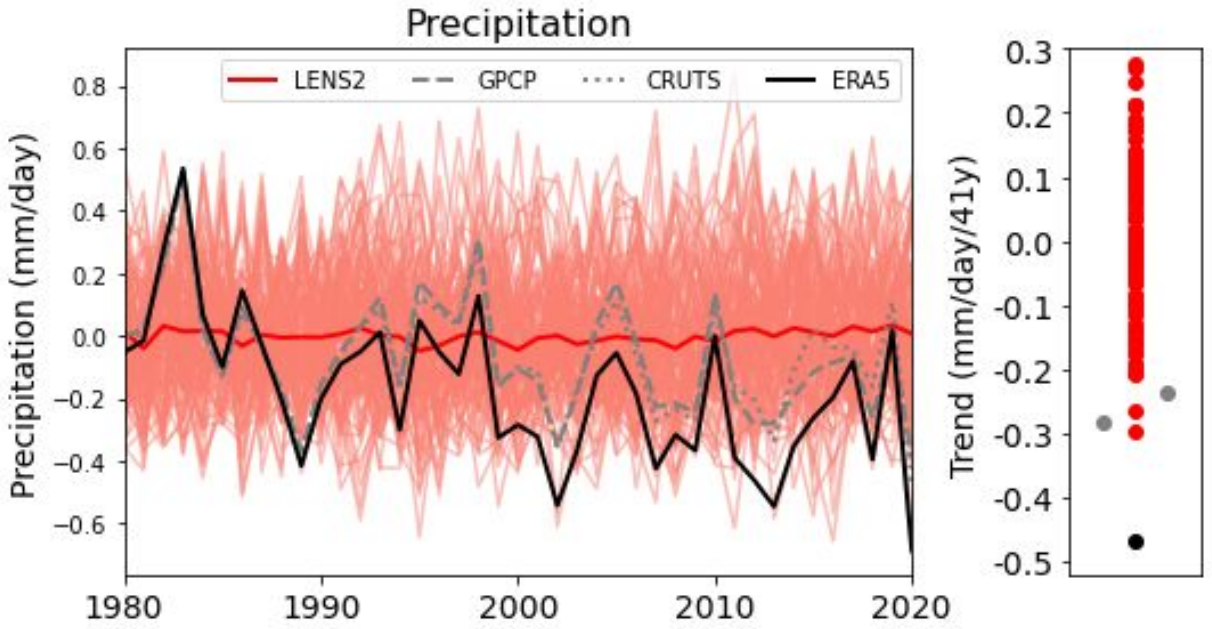
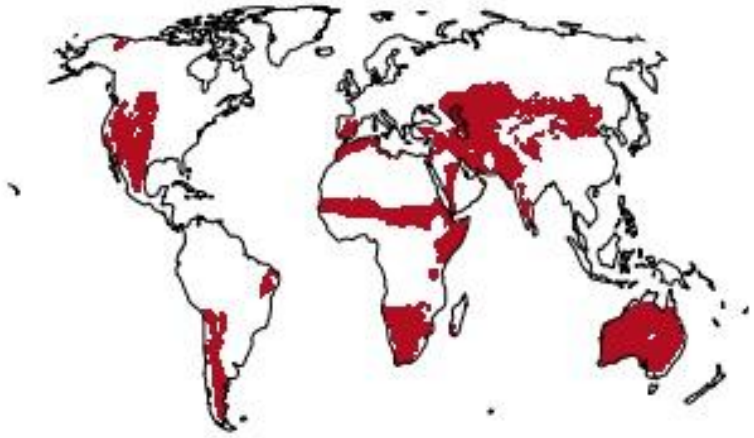


Humid

Aridity Index ≥ 0.5

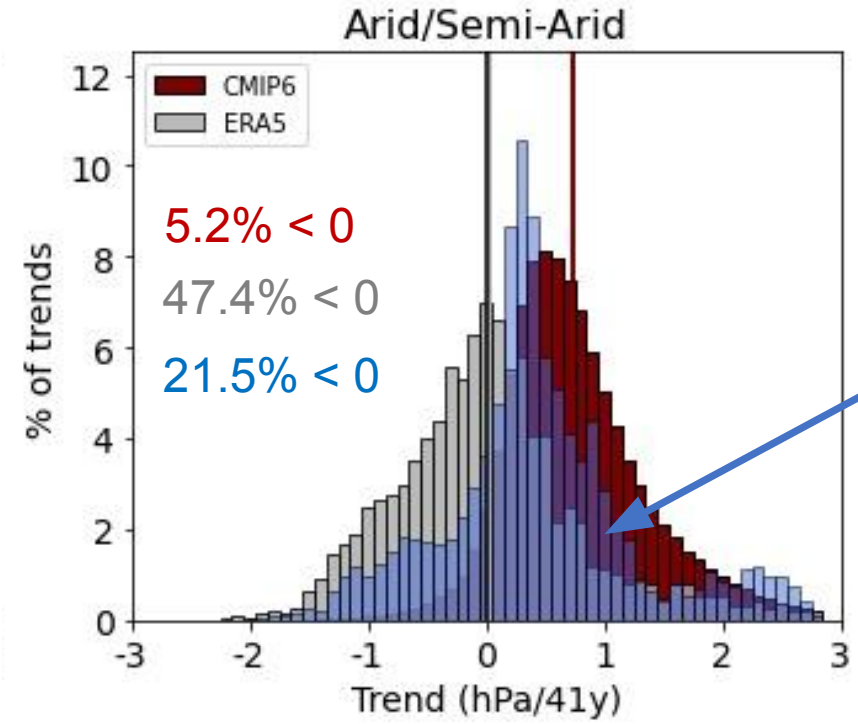
Arid/Semi-Arid



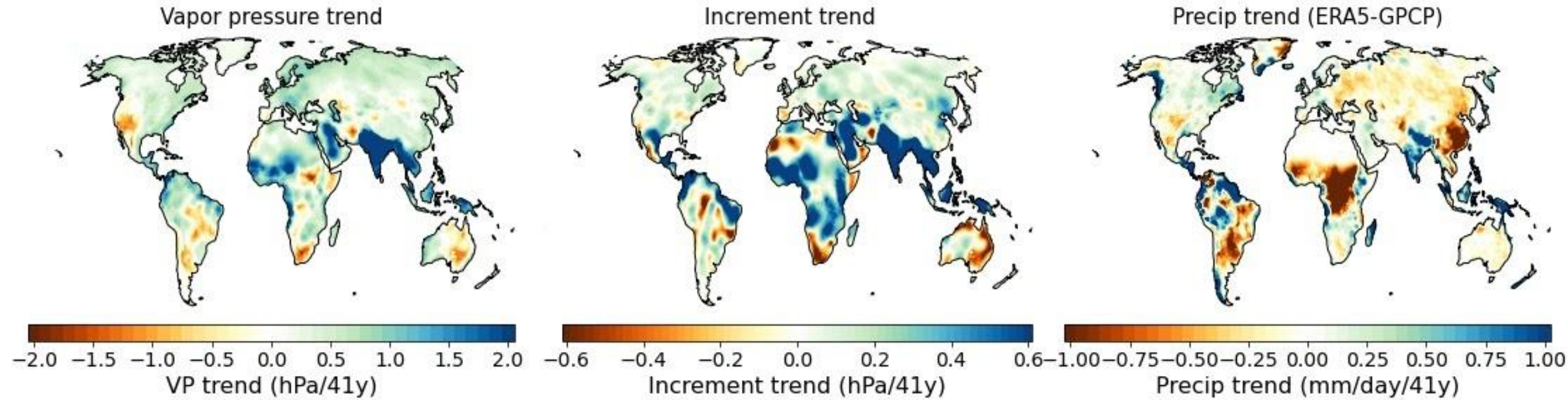
0.05 < Aridity Index < 0.5

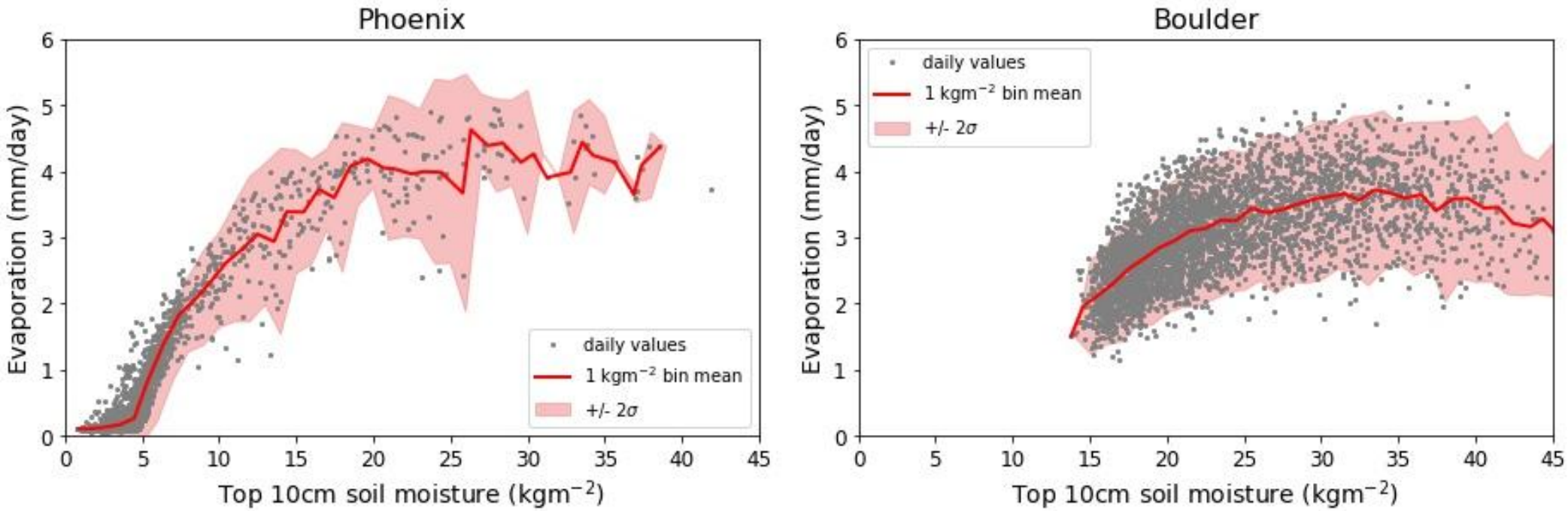
Hyper-arid

Aridity Index ≤ 0.05

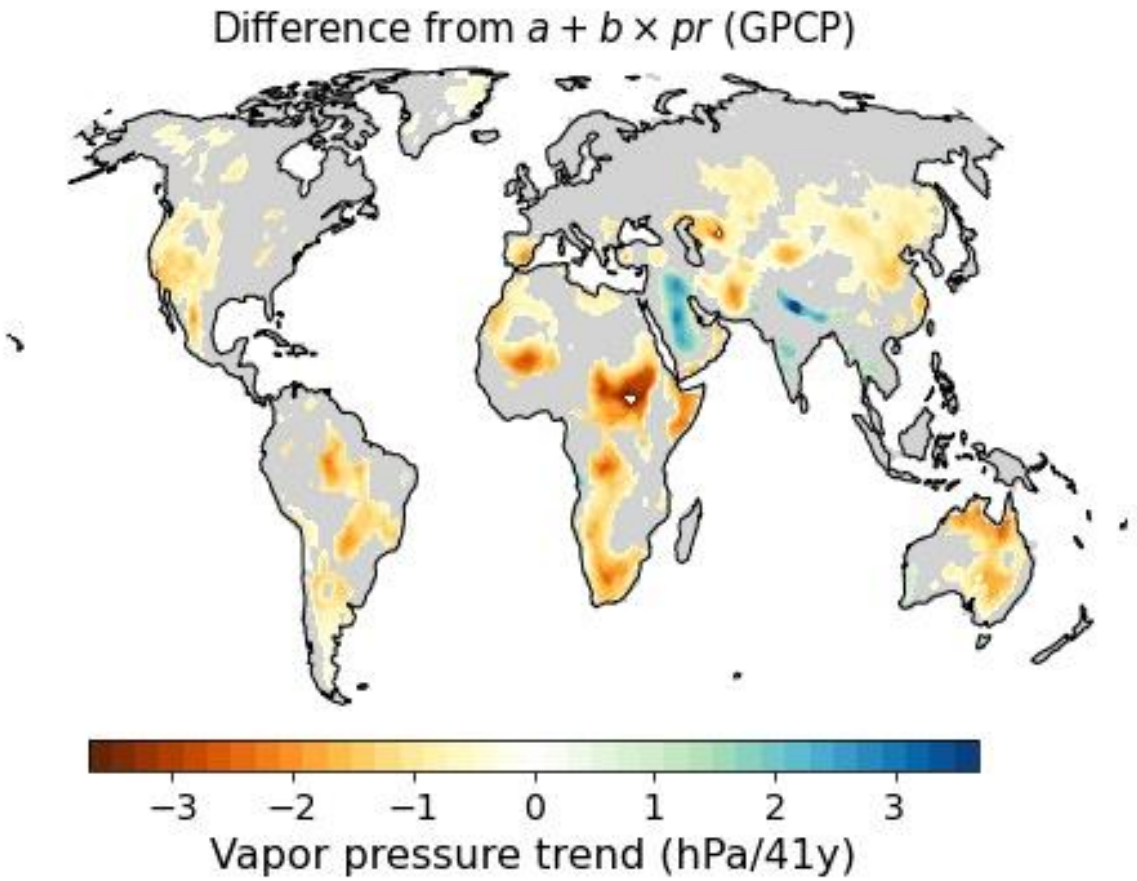


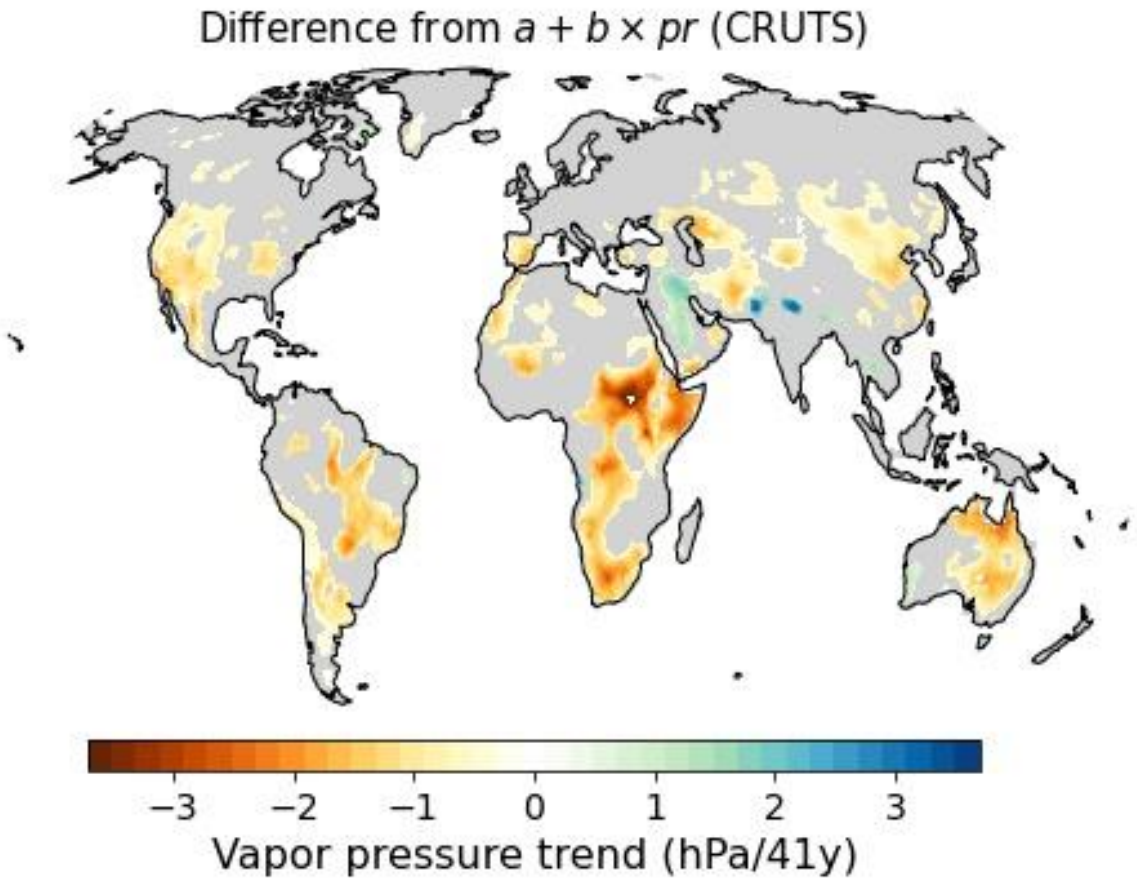
The most extreme CMIP6 member

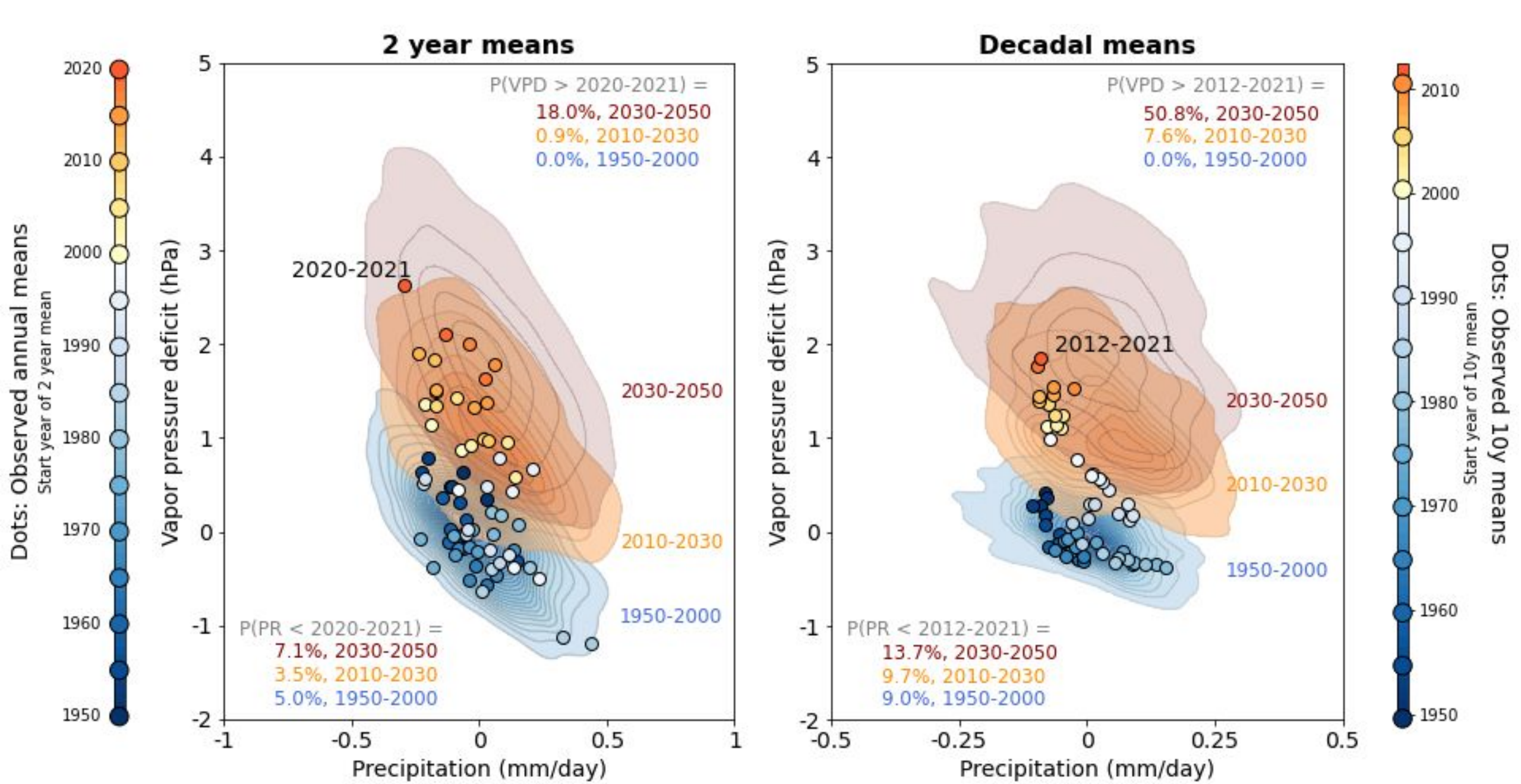

Vapor pressure trend
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0
VP trend (hPa/41y)
Increment trend
−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
Increment trend (hPa/41y)
Precip trend (ERA5-GPCP)
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
Precip trend (mm/day/41y)


Phoenix
Boulder
Evaporation (mm/day)
Top 10cm soil moisture (kgm^{-2})
daily values
1 kgm^{-2} bin mean
+/- 2σ
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45

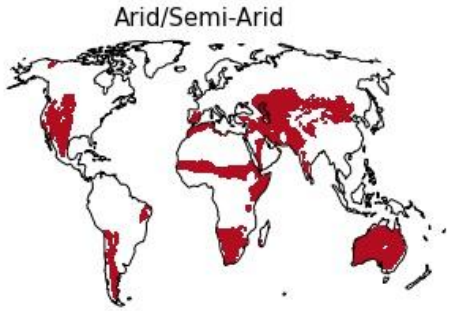
Global vapor pressure trends






2 year means
Decadal means
Dots: Observed annual means
Start year of 2 year mean
Dots: Observed 10y means
Start year of 10y mean
Vapor pressure deficit (hPa)
Precipitation (mm/day)
P(VPD > 2020-2021) =
18.0%, 2030-2050
0.9%, 2010-2030
0.0%, 1950-2000
2020-2021
2030-2050
2010-2030
1950-2000
P(PR < 2020-2021) =
7.1%, 2030-2050
3.5%, 2010-2030
5.0%, 1950-2000
P(VPD > 2012-2021) =
50.8%, 2030-2050
7.6%, 2010-2030
0.0%, 1950-2000
2012-2021
2030-2050
2010-2030
1950-2000
P(PR < 2012-2021) =
13.7%, 2030-2050
9.7%, 2010-2030
9.0%, 1950-2000

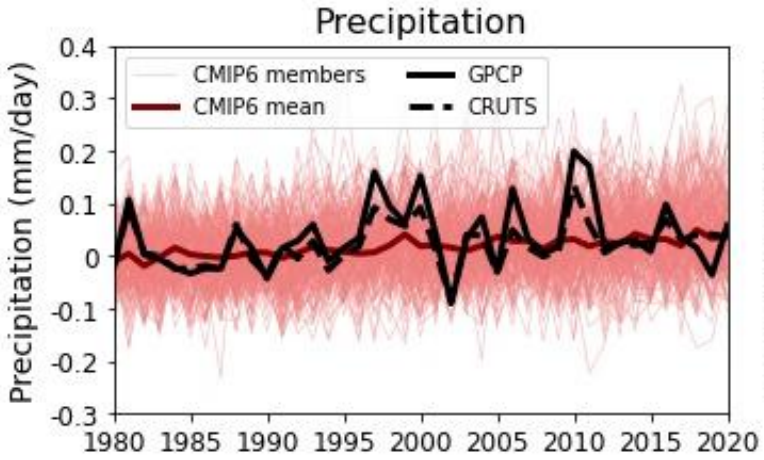
P, E and 10cm Soil Moisture trends at all arid/semi-arid grid points

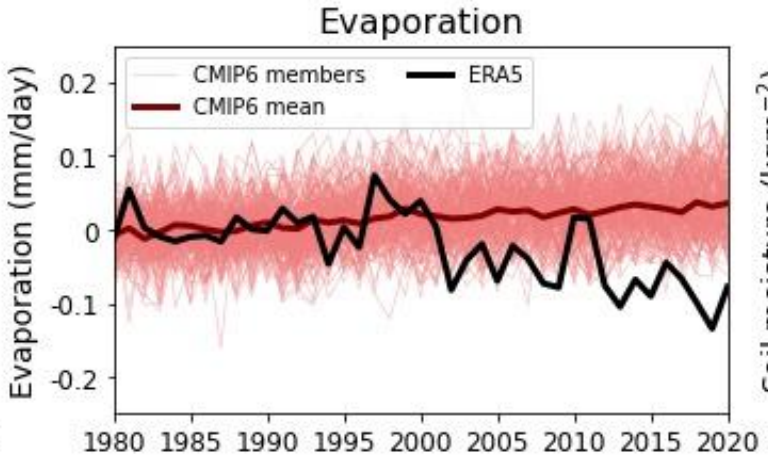


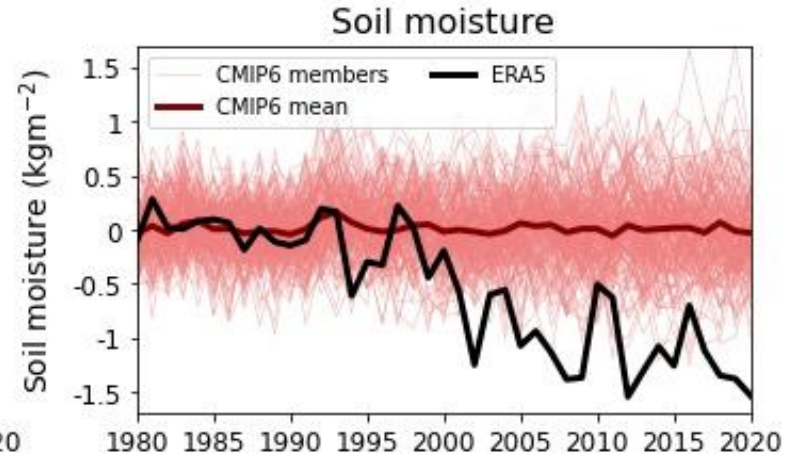
Precipitation

Evaporation

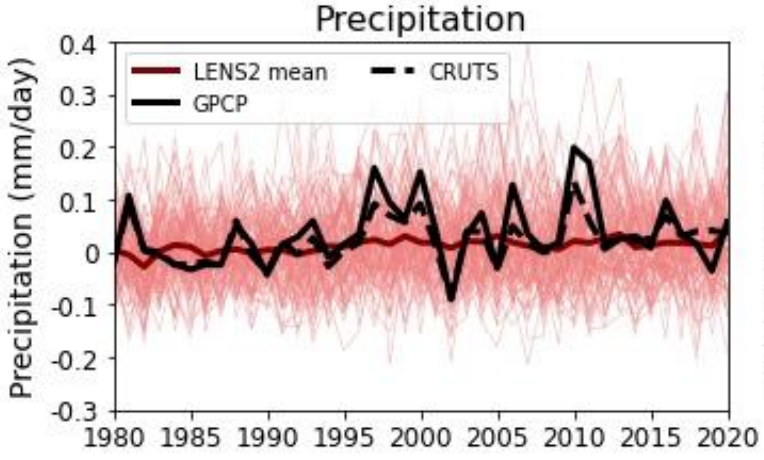
Soil Moisture

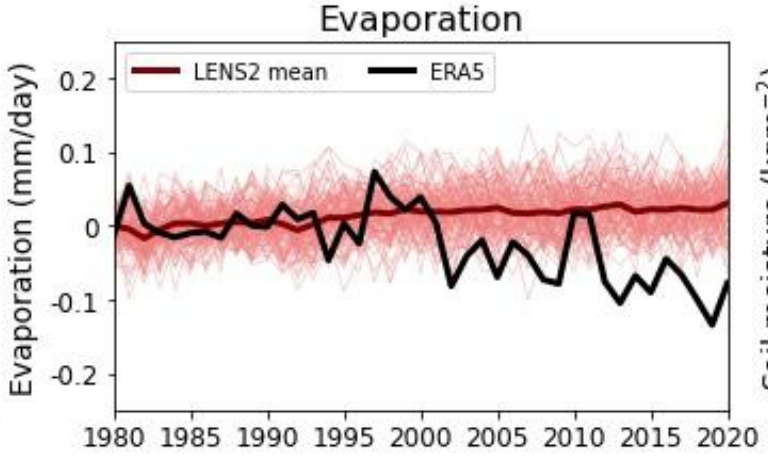


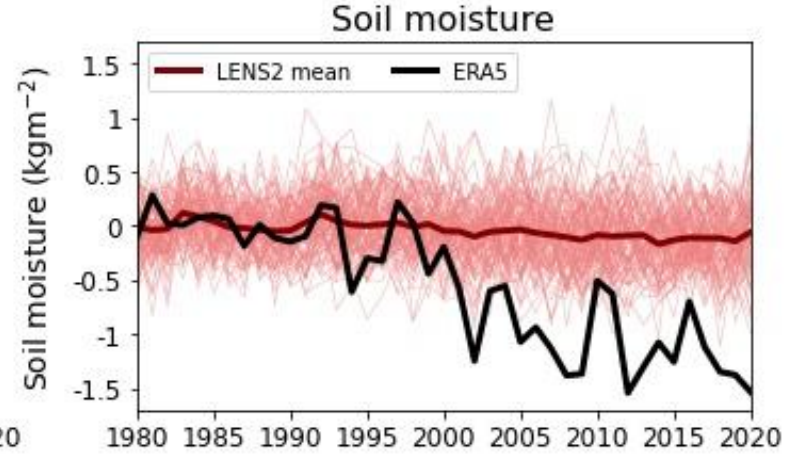




CMIP6







LENS2

GLEAM

GLDAS-NOAH

GLDAS-CLSM

GLDAS-VIC

GLEAM

GLDAS-NOAH

GLDAS-CLSM

GLDAS-VIC

Uses radiation inputs from CERES after 2001, ERA-Interim before that, along with ERA-Interim surface air temperature to calculate potential evapotanspiration (PET)

Relates PET to Evaporation using a stress factor. Stress factor calculated as a function of microwave vegetation optical depth and root zone soil moisture.

Root zone soil moisture is estimated using a soil model with assimilation of microwave surface soil moisture.

GLEAM

GLDAS-NOAH

GLDAS-CLSM

GLDAS-VIC

Offline land models

Combined version 2.0 (1980-2014) with version 2.1 (2000-2020) by adding an offset to ensure the same mean over the period of overlap

2.0 forced with Princeton meteorological forcing, 2.1 forced with NCEP/GPCP

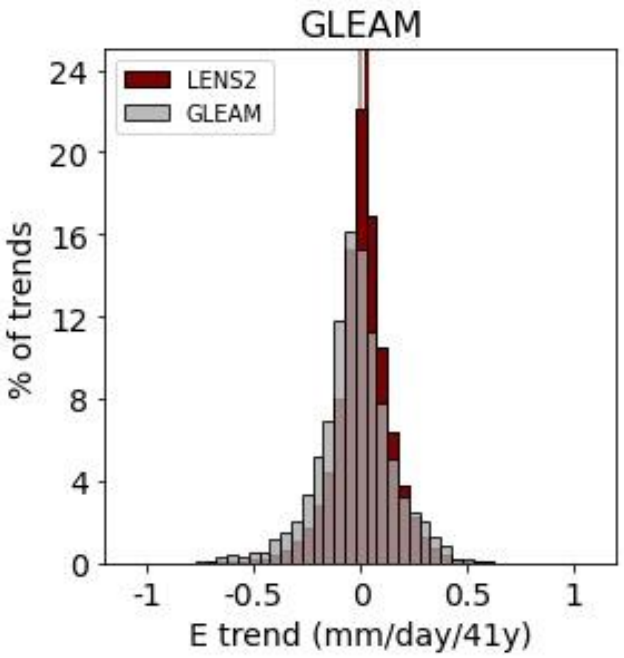
(if the issue is an issue in all land models, we wouldn't expect these land models to produce it)

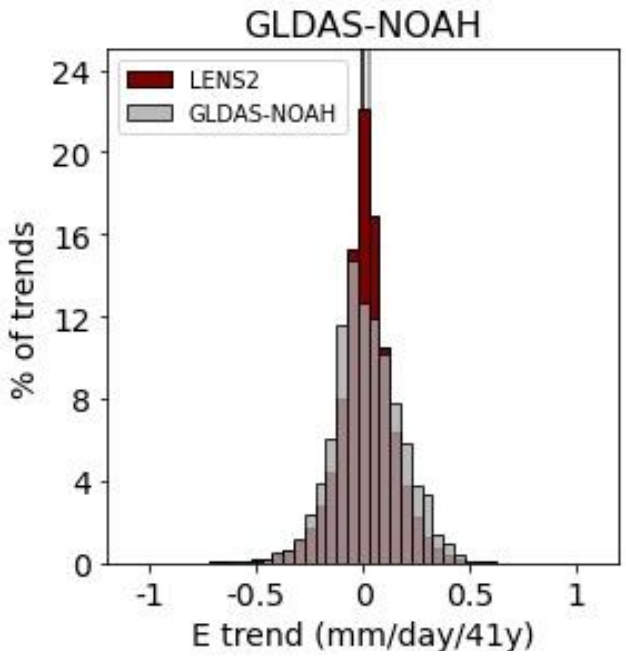
GLEAM

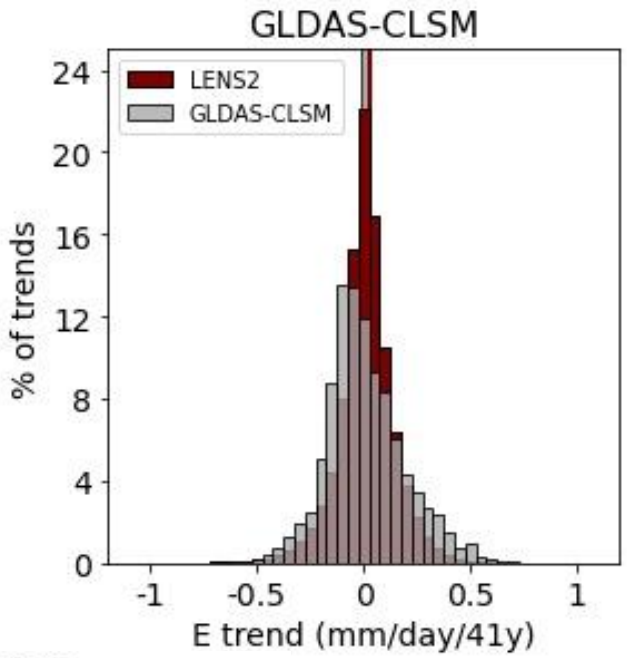
GLDAS-NOAH

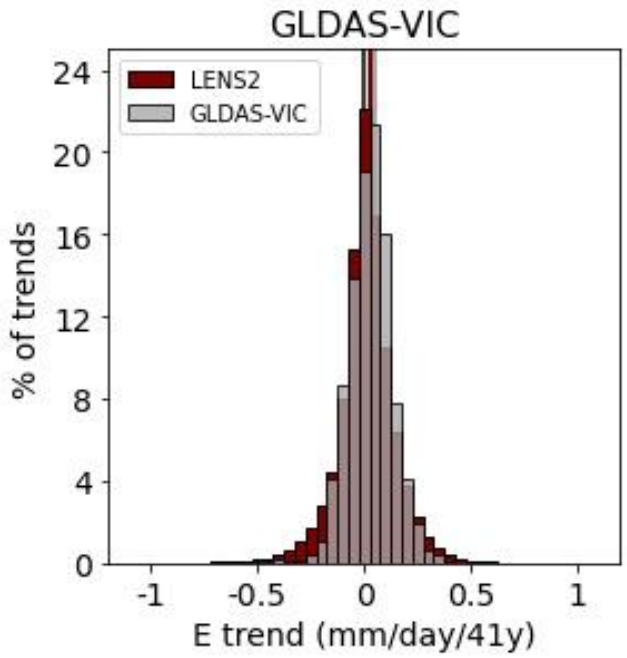
GLDAS-CLSM

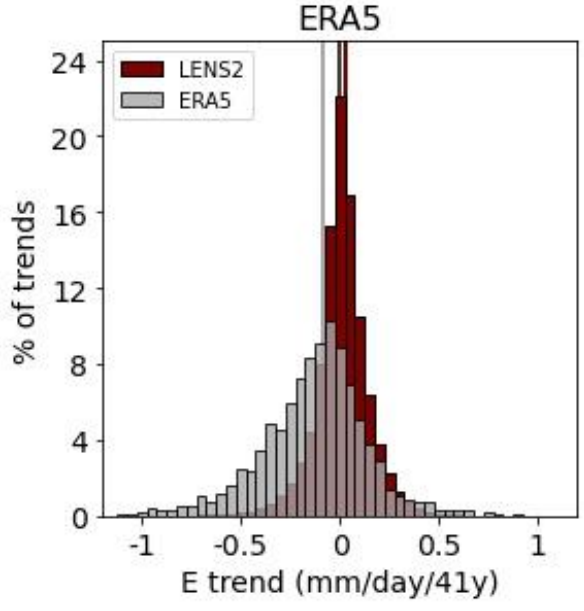
GLDAS-VIC









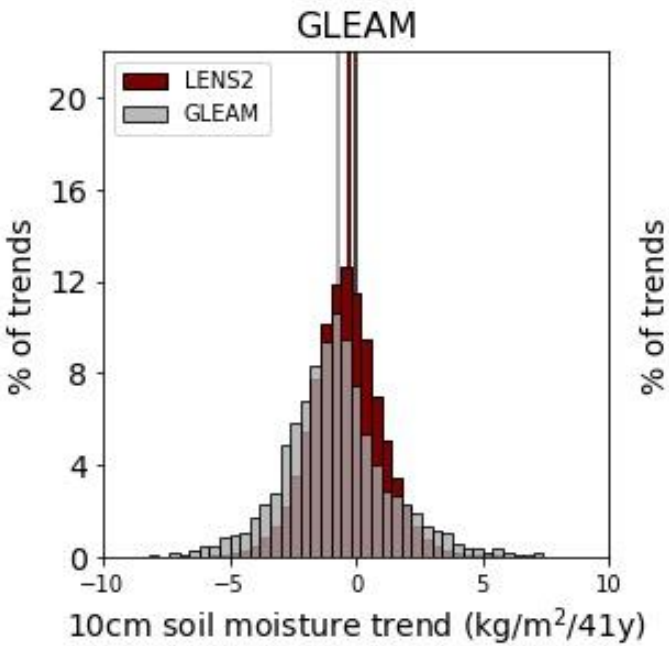


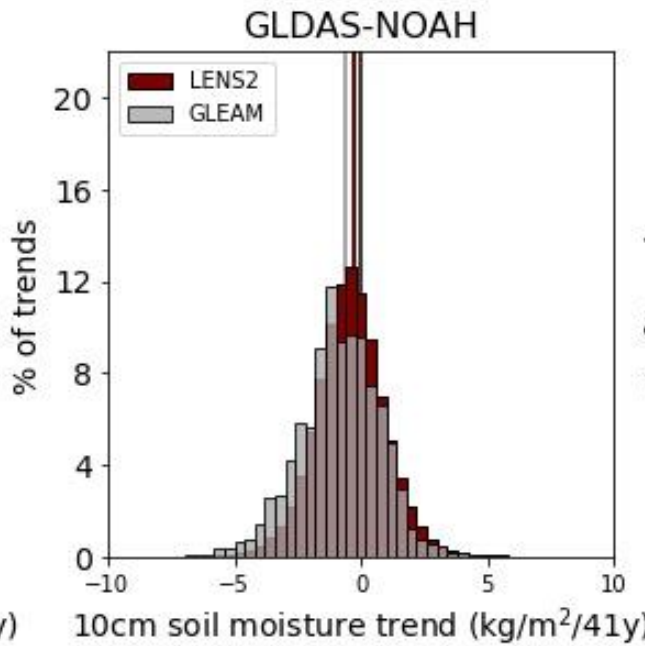
GLEAM

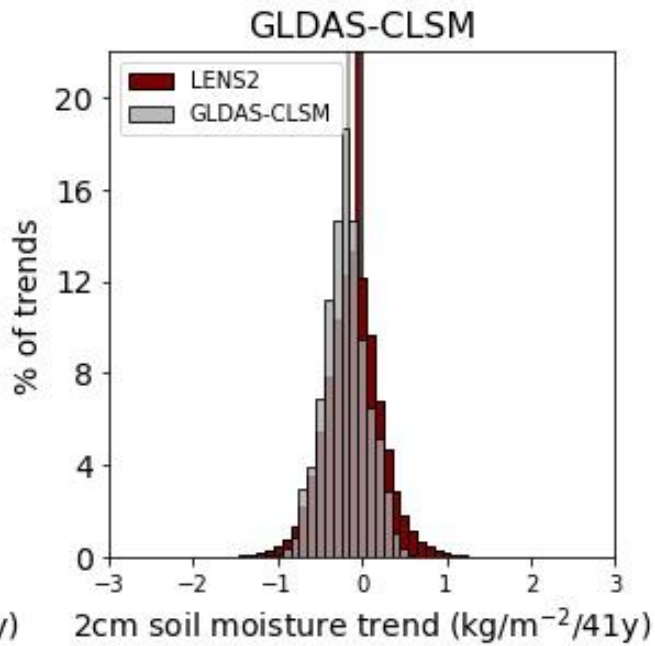
GLDAS-NOAH

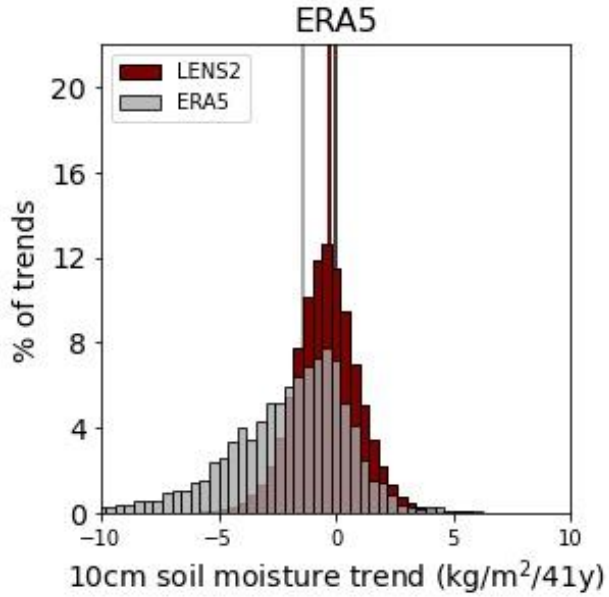
GLDAS-CLSM

GLDAS-VIC



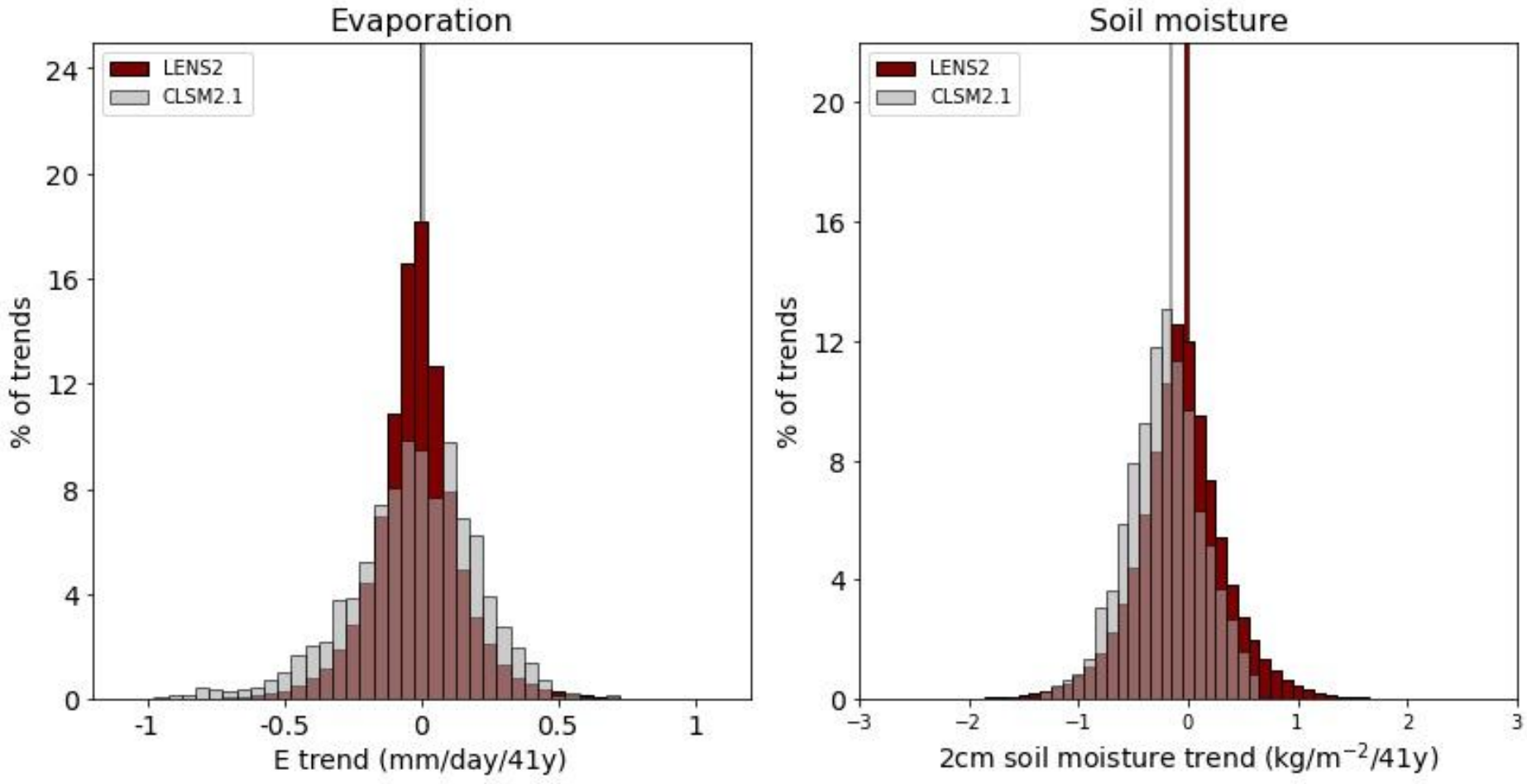






GLDAS-CLSM2.1 versus GLDAS-CLSM2.2

GLDAS-CLSM2.2 runs from Feb 2003 onwards and assimilates GRACE, which provides satellite based estimates of terrestrial water storage. Let's compare GLDAS-CLSM2.1 (with no assimilation) with GLDAS-CLSM2.2 with the GRACE assimilation.



GLDAS-CLSM2.1 versus GLDAS-CLSM2.2

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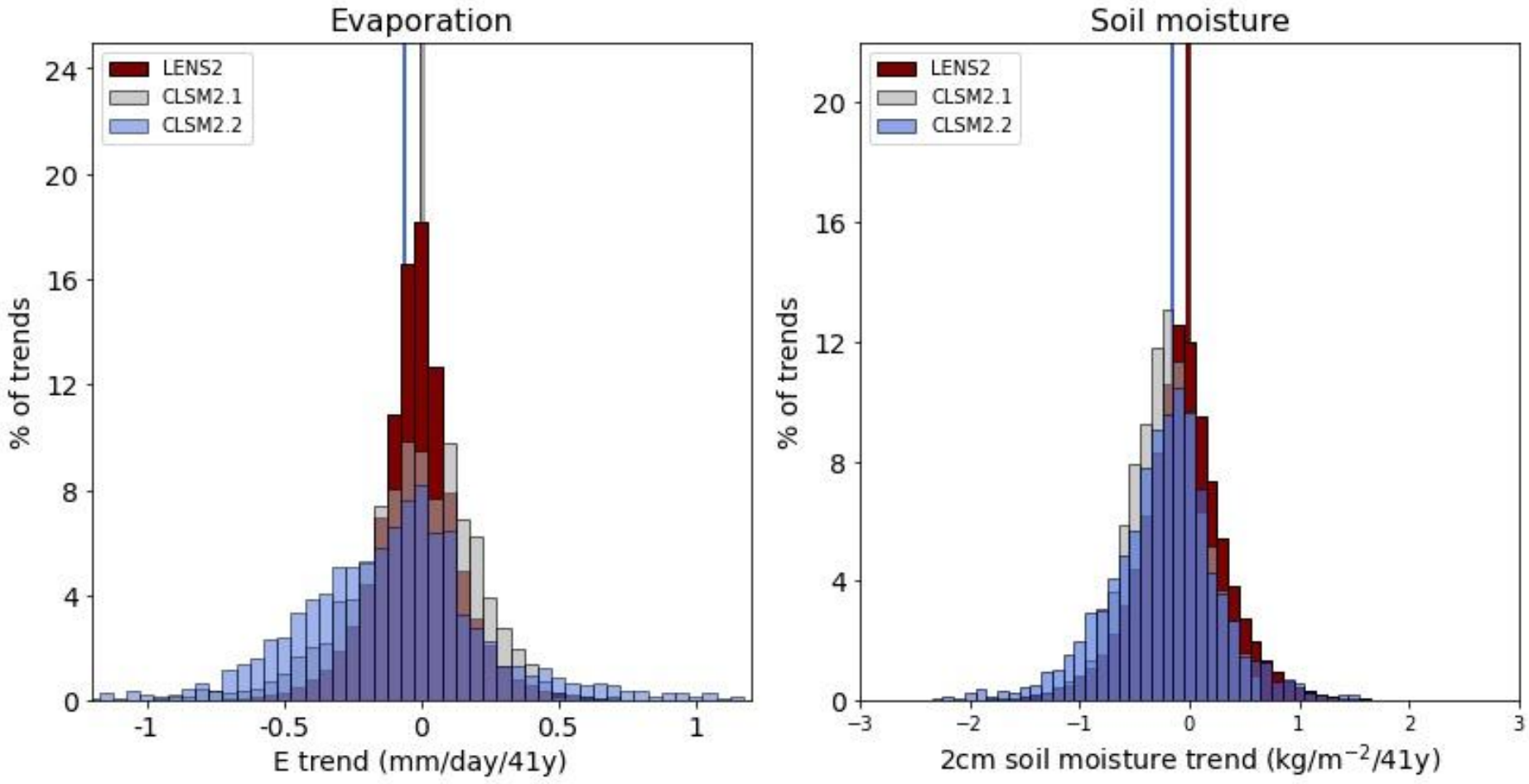
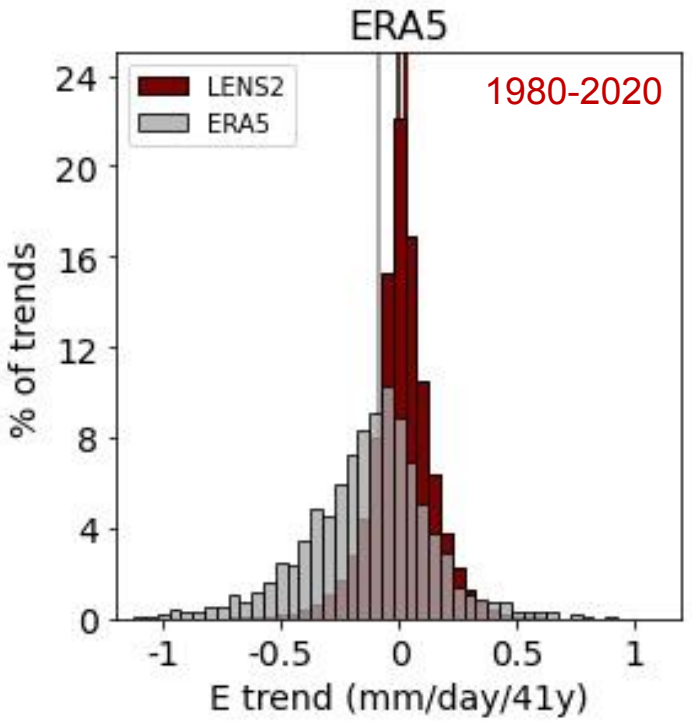


ERA5

Assimilating:

- Satellite measurements of humidity
- Station based humidity measurements
- Scatterometer measurements of soil moisture

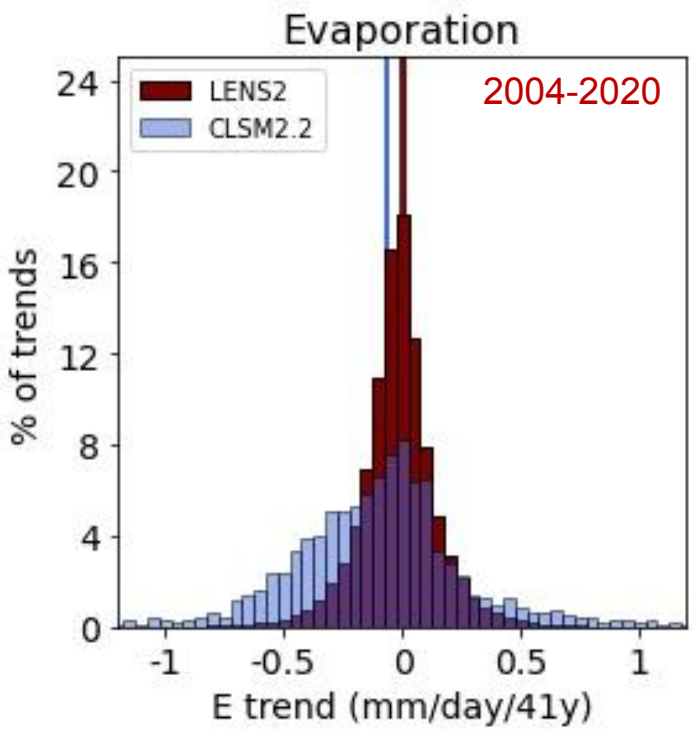


GLDAS-CLSM2.2

Assimilating:

- GRACE estimates of terrestrial water storage

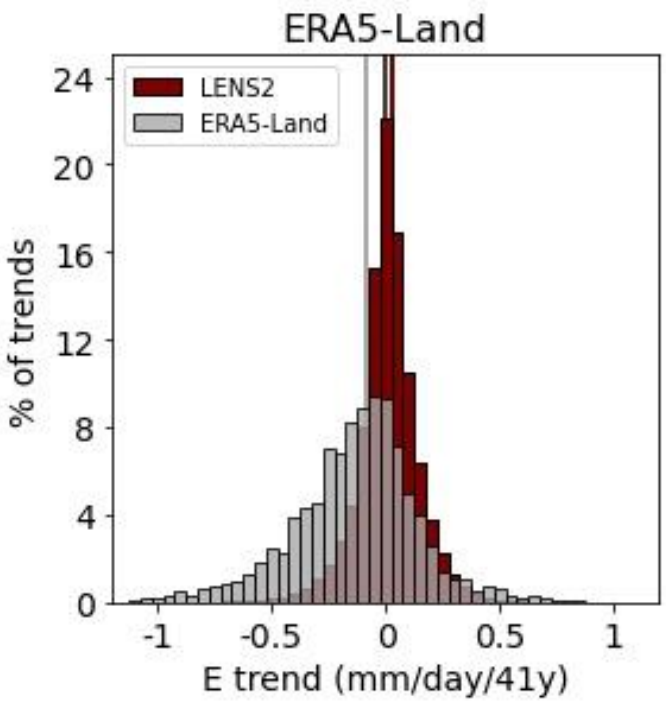
FORCING: ECMWF analyses (versus GPCP for version 2.1)

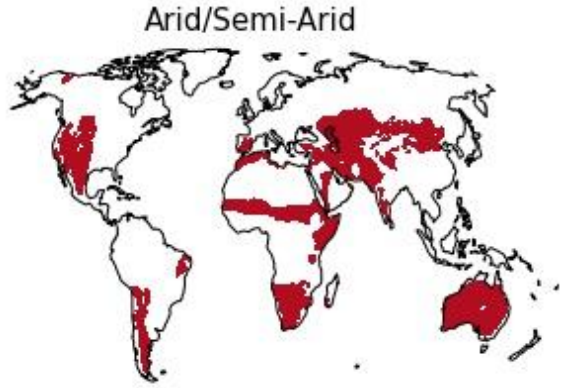
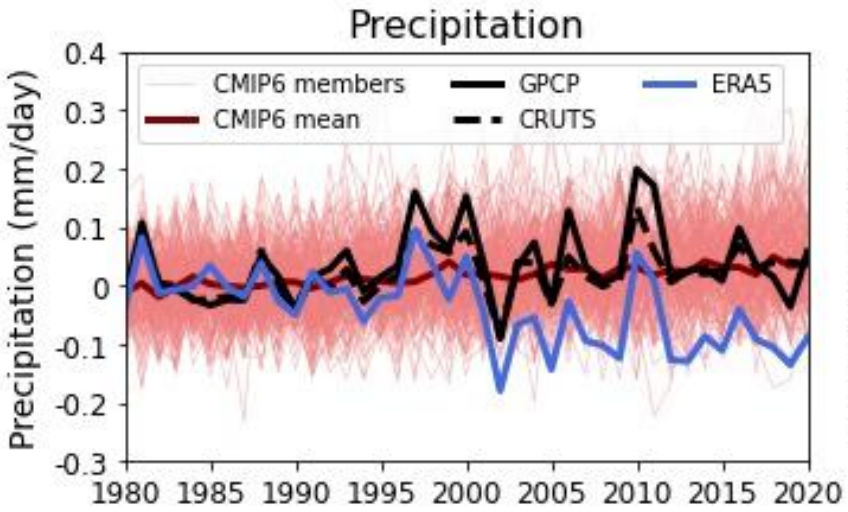
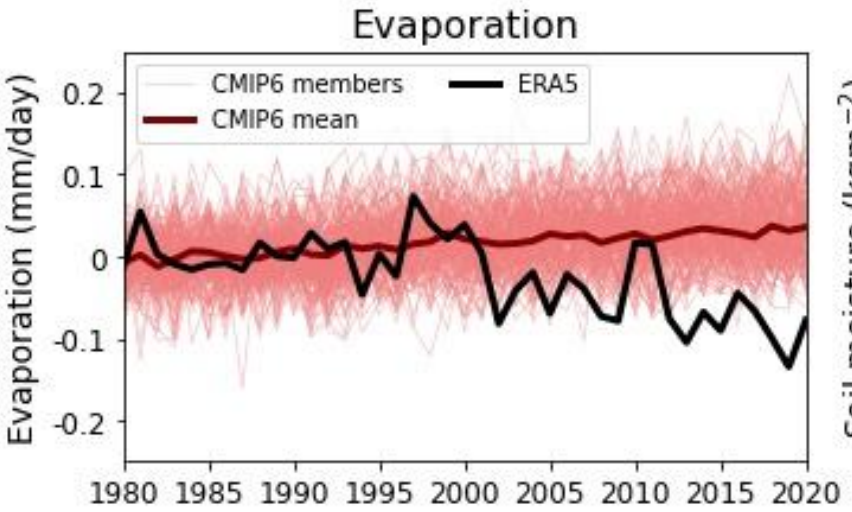
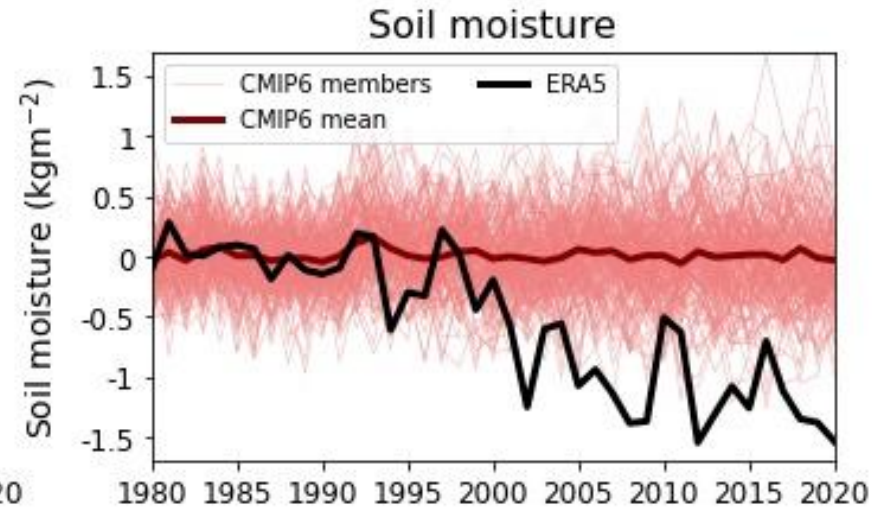


ERA5-Land

NO ASSIMILATION

FORCING: meteorological fields from ERA5 (including precip with no bias correction)



ERA5 has some peculiar precipitation trends

Area weighted averages over arid/semi-arid regions