Observed humidity trends in dry regions contradict climate models

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BACKGROUND

Why should we care about near surface atmospheric humidity?

(1) Humidity is an important quantity in relation to wildfire[1].

(2) Humidity can provide an indicator of how processes of relevance to the hydroclimate such as evapotranspiration or moisture transports have been evolving.

What do we expect humidity to do?

We expect atmospheric water vapor to rise under warming because a warmer atmosphere can hold more moisture. Whether it will rise at the rate expected from Clausius Clapeyron scaling (~7%/K), maintaining a fixed relative humidity, will depend on whether there is enough water available to satisfy the increased atmospheric demand. Over land, climate models do show slight reductions in relative humidity out to 2100, but they still suggest that water vapor should increase in general[2]. Prior studies have suggested that water vapor has not risen as much in models as observations[3,4,5,6].

Here we compare historical near surface (2m) humidity trends in Earth System Models, with those in Observations and demonstrate a major discrepancy that is closely linked to climatological aridity.

DATASETS

Observation-based humidity and vapor pressure

- ERA5[7], ISD stations[8], HadISDH homogenized station data[9]

Observation-based precipitation

- GPCC[10], GPCC[11], CRUTS[12]

Observation-based near surface air temperature

- ERA5[7] and BEST[13]

Aridity Index

- P/PET from the TerraClim[14] dataset

Model simulations

- CMIP6 historical 1980 to 2014 and SSP5-8.5 to 2020
- CMIP6 AMIP simulations to 1980 to 2014
- LENS2: CESM2 large ensemble[15] (100-mems)
- GOGA2: CESM2 GOGA/AMIP simulations, 1980 - 2020 (10-mems)

We consider trends in annual means from 1980 to 2020 unless stated otherwise.

A CASE STUDY: THE US SOUTHWEST

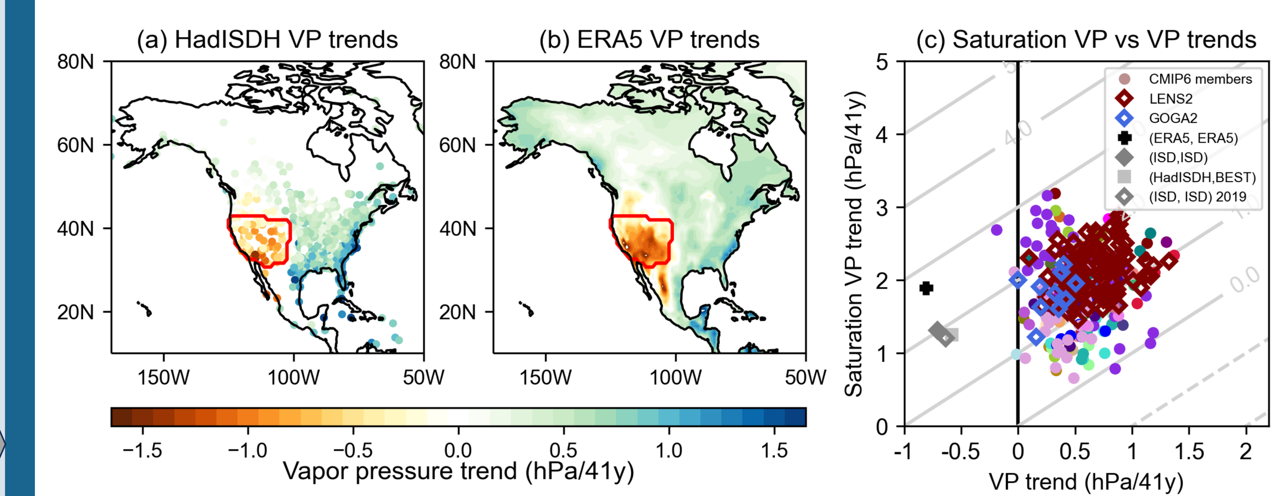


Fig 1: Annual mean trends in from 1980 to 2020 in near surface vapor pressure (VP) in the HadISDH dataset (a) and ERA5 (b). (c) shows area averages over the 6 state region of the Southwest (red outline in a and b) of the trends saturation VP versus actual VP. Gray lines show VPD.

Since 1980 vapor pressure (VP) has declined over the US Southwest. HadISDH and ERA5 agree (Fig 1a,b).

Saturation VP has risen, and the observations lie within the model distribution (Fig 1c)

The decline in VP lies totally outside of the model distribution, even when prescribing observed SSTs (Fig 1c)

While models suggest VP should have increased, the real world has seen a rather steady decline (Fig 2a).

As a result, relative humidty has declined more than in models (Fig 2b).

Vertical profiles of specific humidity (q) trends suggest that the discrepancy is largest near the surface but exists throughout the lower troposphere (Fig 2c).

The discrepancy (in percent of the seasonally varying climatology) is fairly uniform throughout the year (Fig 2d)

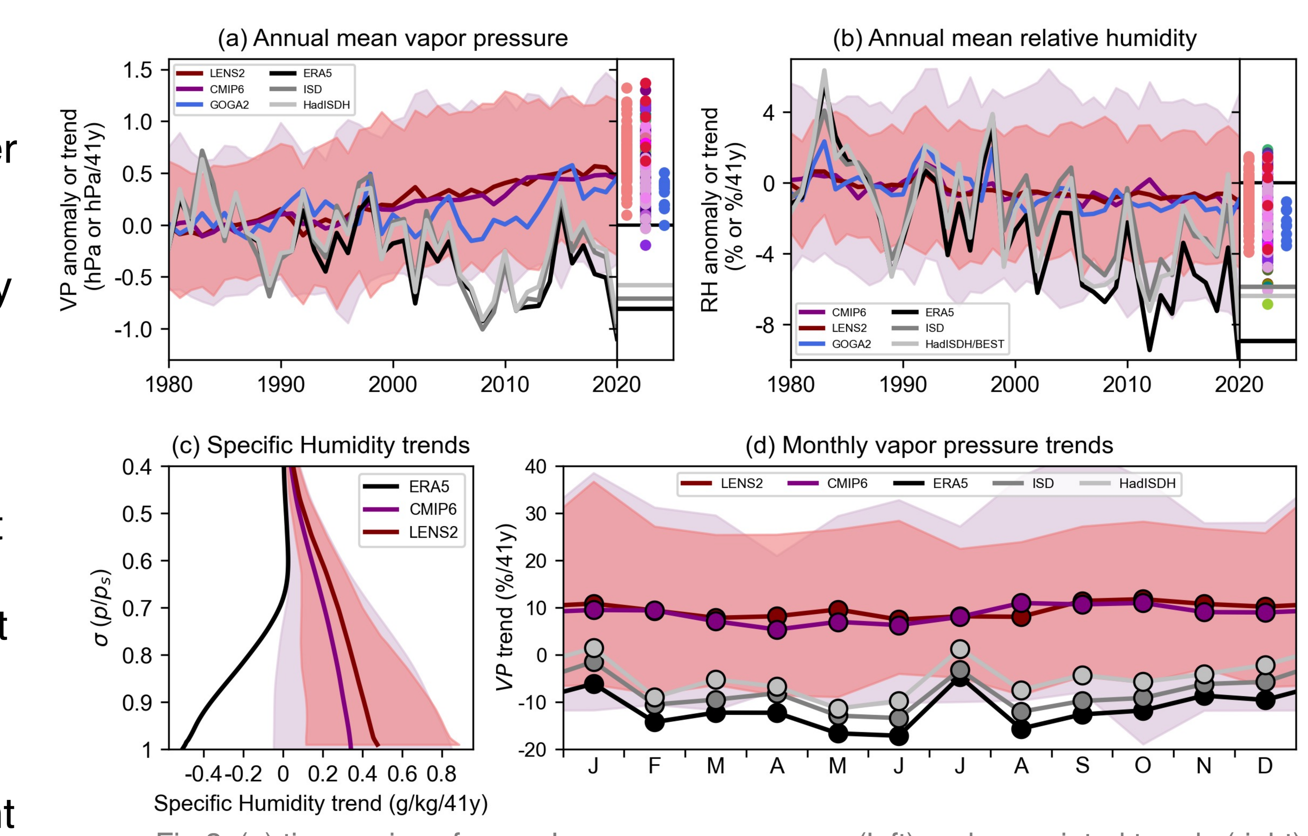


Fig 2: (a) time series of annual mean vapor pressure (left) and associated trends (right). Shaded ranges encompass 95% of the model members. (b) is as (a) but for relative humidity. (c) vertical profiles of specific humidity trends averaged over the Southwest on terrain following sigma coordinates. (d) Trends for each month of the year. Shading shows the minimum to maximum range across model members.

CONNECTIONS TO ARIDITY

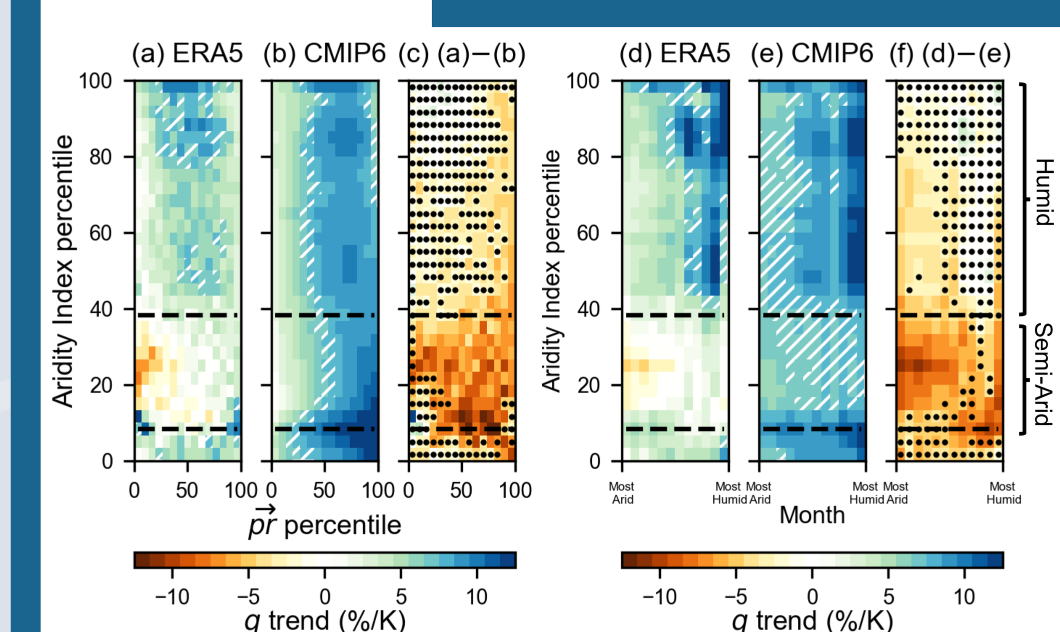


Fig 5: Specific humidity (q) trends normalized by area average temperature trend over land and binned on the y-axis according to the climatological aridity index. (a)-(c) locations within aridity index bins are ordered according to historical trend percentile on the x-axis. (d)-(f) the months of the year are ordered according to climatological monthly aridity on the x-axis. Stippling shows where ERA5 lies within the model distribution, white hatching shows bins that are close to Clausius-Clapeyron Scaling

Binning land regions according to climatological aridity and ordering based on precipitation trends, we can see that the discrepancy occurs primarily in arid/semi-arid regions and occurs regardless of precipitation trends (Fig 5a-c).

Ordering the months of the year according to climatological aridity, we can see the discrepancy also happens in humid regions, but only during the most arid months of the year (Fig 5d-f).

There are close links between where the discrepancy occurs and climatological aridity, both spatially and seasonally

GLOBAL TRENDS

Observed VP trends lie outside of the CMIP distribution in a number of regions (Fig 4c). The discrepancy is even more widespread when accounting for PR trends (Fig 4d). ERA5 shows relatively negative trends compared to CMIP6, mostly in arid/semi-arid regions.

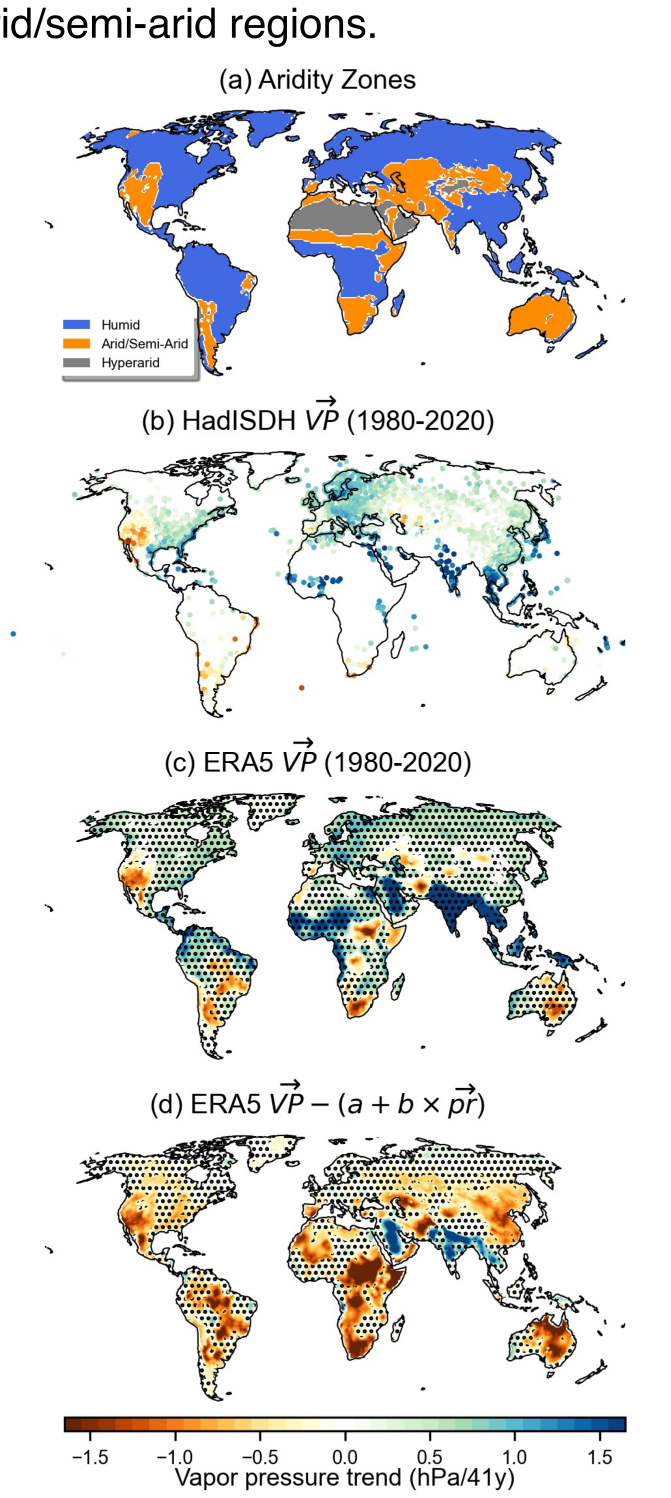
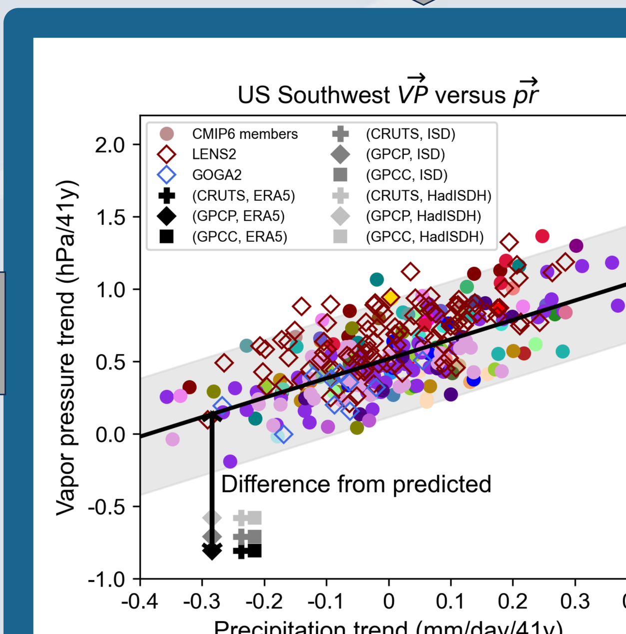


Fig 4: (a) Aridity zones, (b) VP trends in HadISDH, (c) VP trends in ERA5, stippling shows where ERA5 lies within the spread of CMIP6 models. (d) Difference between ERA5 and the trend that would be predicted based on PR trends following the method in the previous box.

ACCOUNTING FOR PRECIPITATION



A substantial precipitation (PR) decline has occurred over the US Southwest since. VP and PR are correlated. While the observed PR trends lie within the model distribution the observed VP trend does not (Fig 3).

Consider the VP trend that would be predicted based on PR using the linear regression across the CMIP6 models $VP^* = a + bPR$. We can consider the difference between the observed VP trend VP^* predicted using observed PR trends ($VP' = VP - VP^*$) and assess whether observed trends lie outside of the +/-2σ range of the residuals of the CMIP6 regression (gray shaded range in Fig 3). In the Southwest it does.

Fig 3: Annual mean 1980 to 2020 trends in VP versus precipitation over the US Southwest

SUMMARY

Over arid/semi-arid regions, observed humidity trends are lower than modelled trends, regardless of precipitation trends (Fig 6). Over arid-semi-arid regions, there has been no rise in specific-humidity on average (Fig 7c), despite rising temperatures (Fig 7a,b). Relative humidity remains fairly constant in the models while it has decreased substantially in observations (Fig 7d).

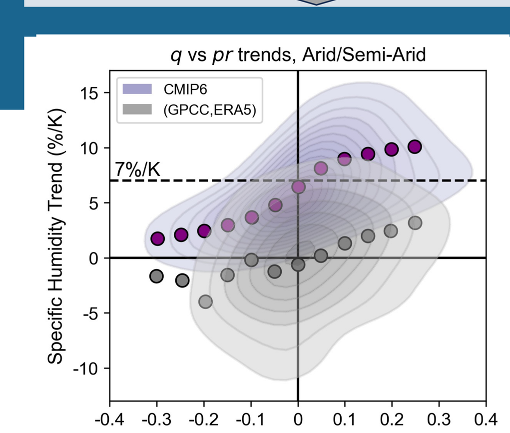


Fig 6: Joint probability distribution of q trends normalized by land average temperature trend versus PR trends for (purple) CMIP6, (gray) Obs. Dots show average over 0.05mm/day PR bins.

Models suggest humidity should have risen at rates close to Clausius Clapeyron scaling over arid/semi-arid regions. This rise has not happened in observations.

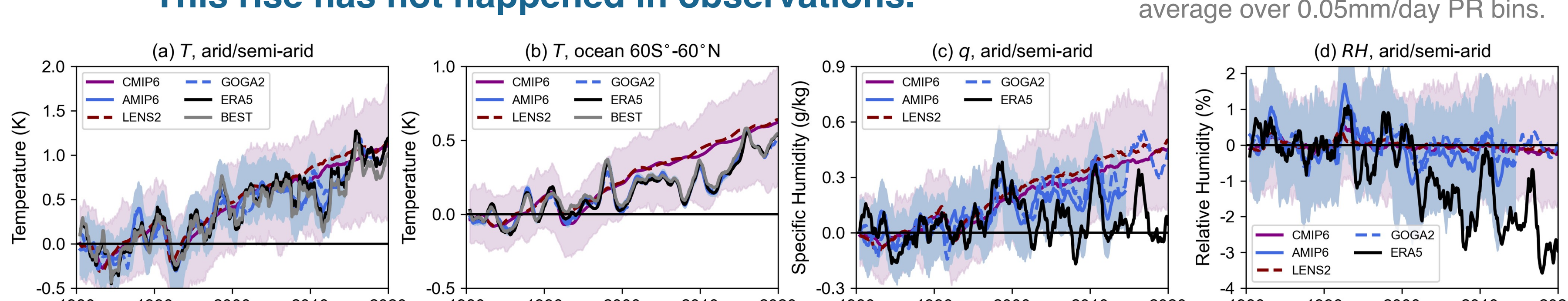


Fig 7: 12 year running mean time series of (a) 2m temperature averaged over arid/semi-arid regions, (b) ocean temperature averaged from 60S-60N, (c) specific humidity and (d) relative humidity averaged over arid/semi-arid regions.

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