Impact of lower-tropospheric mixing on global mean precipitation and near-surface relative humidity in climate models

Christopher R. Terai[1]*, Yuxin Shen[1], Jacob Hendrickson[1]

1 Dep. of Earth System Science, UC-Irvine, CA   *email: rterai@uci.edu

Global mean precipitation rate, evaporation, and sensible heat flux in climate models

Bias and spread in CMIP5 global mean precipitation rate

FIG 1

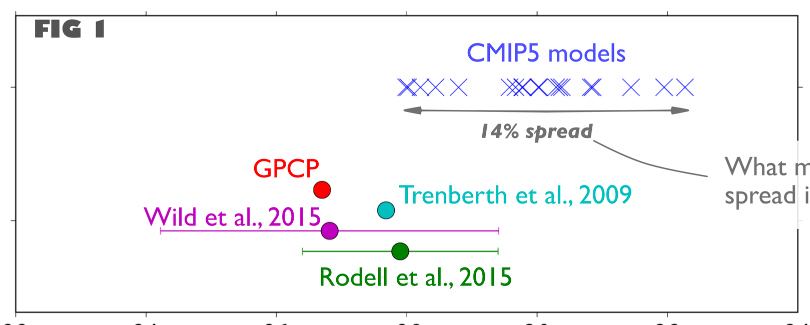


Figure 1: Global mean precipitation in fifteen CMIP5 models (blue crosses), from GPCP satellite estimate (red), and from three published observational estimates.

The global mean precipitation rate in CMIP5 models driven by the same observed sea-surface temperatures and forcing agents disagree with observational estimates (~10%) and with each other (14%) (Fig. 1).

Q: What is behind the difference in the global mean precipitation rate?

Unsurprisingly, most of the precipitation differences exist over the Tropical rain bands (Fig 2).

We can understand the spread in terms of the difference in **surface evaporation** rates over Tropical oceans (Fig 3).

FIG 2 Difference in *P* between top 5 and bottom 5 models

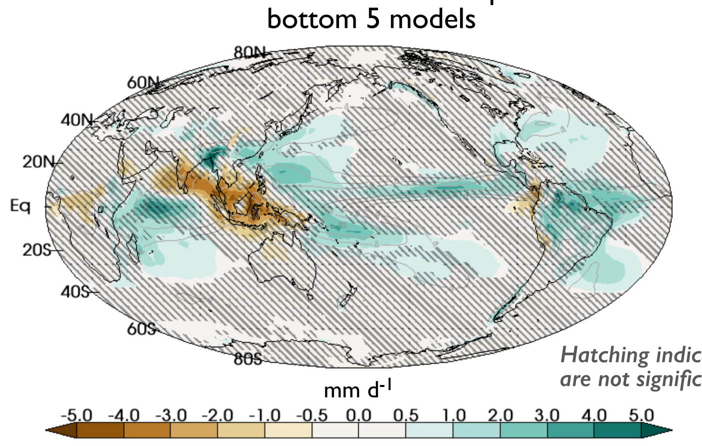


FIG 3 Difference in *E* between top 5 and bottom 5 models

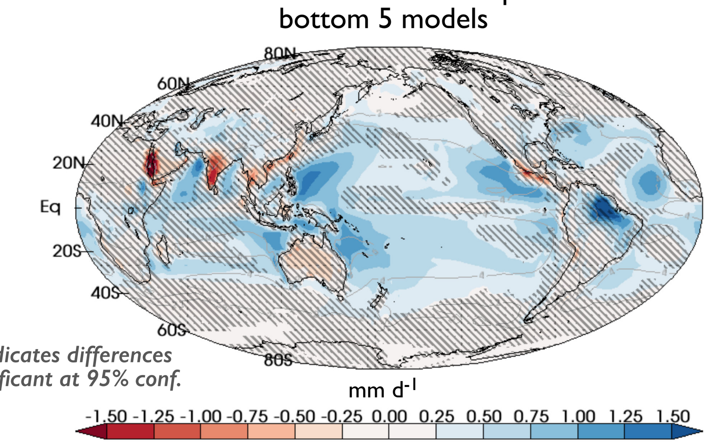


FIG 4 Difference in sensible heat flux between top 5 and bottom 5 models

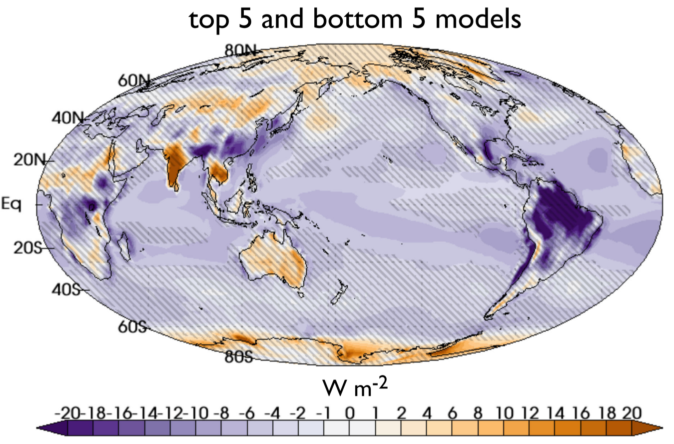


Figure 2 (top left): Map of difference in precipitation rate between models with most global mean precip (top 5) and those with least global mean precip (bottom 5). Contours indicate MMM precipitation rate.
Figure 3 (top right): Map of difference in evaporation rate between top 5 and bottom 5 models.
Figure 4 (bottom left): Map of difference in sensible heat flux between top 5 and bottom 5 models.

Models that rain more in the global mean have **weaker sensible heat flux**, with significant differences over the Tropical oceans.

This and a reduced longwave warming at the surface (not shown)compensate for a higher latent heat flux.

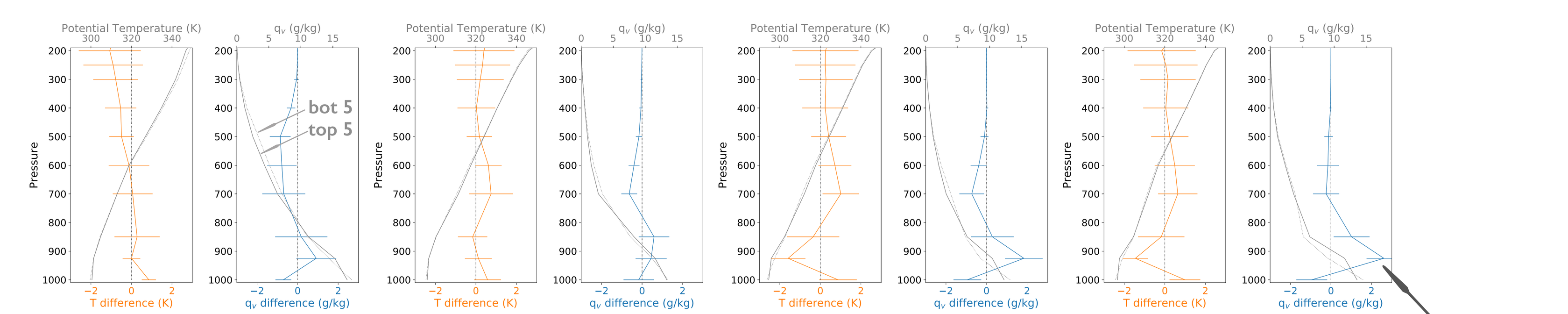
Experiment & Models

15 models from the Atmospheric Model Intercomparison Project (AMIP) experiment of the Fifth Coupled Model Intercomparison Project (CMIP5) are analyzed. The models and the global mean precipitation in each are shown on the right.

In this subset, the atmospheric water budget closes (<3%) and data pertaining to the model's temperature, humidity, and circulation fields are available.

Climate model	Modeling center	Global mean precip rate
ACCESS1-0, ACCESS1-3	CSIRO and Bureau of Meteorology, Australia	3.08 mm d-1, 3.19 mm d-1
CanAM4	Canadian Centre for Climate Modelling and Analysis	2.79 mm d-1
CCSM4, CESM1-CAM5	National Center for Atmospheric Research	2.95 mm d-1, 3.03 mm d-1
CNRM-CM5	National Centre for Meteorological Research	3.03 mm d-1
GFDL-CM3	US Dept. of Commerce/ NOAA GFDL	3.03 mm d-1
GISS-E2-R	Goddard Institute for Space Studies	3.14 mm d-1
IPSL-CM5A-LR, IPSL-CM5B-LR	Institut Pierre Simon Laplace	2.80 mm d-1, 2.84 mm d-1
HadGEM2-A	Hadley Centre for Climate Prediction and Research/Met Office	3.08 mm d-1
MIROC5	The University of Tokyo, National Institute for Environmental Studies, and JAMSTEC	3.23 mm d-1
MPI-ESM-LR, MPI-ESM-MR	Max Planck Institute for Meteorology	2.84 mm d-1, 3.00 mm d-1
NorESM1-M	Norwegian Climate Centre	2.87 mm d-1

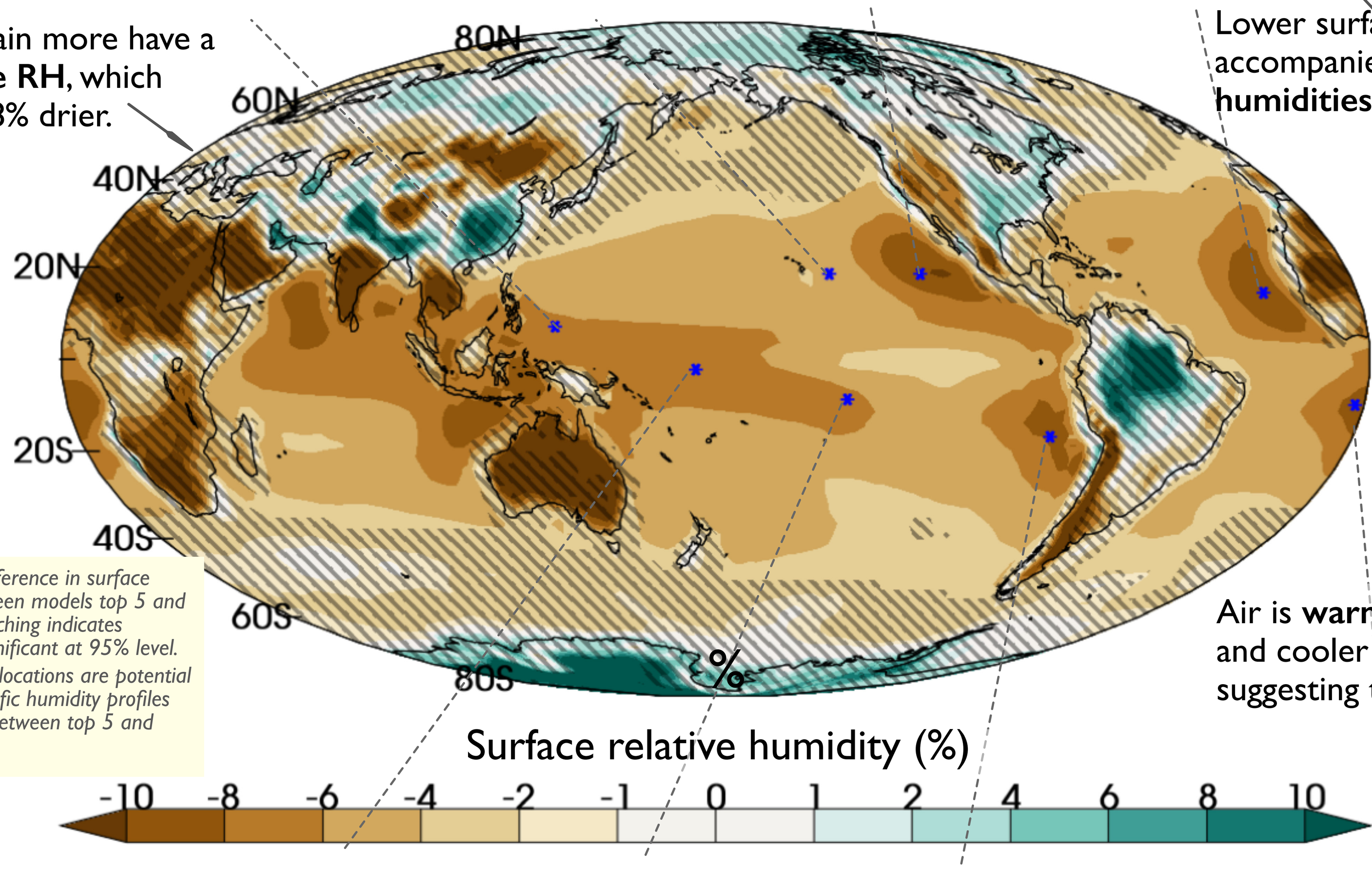
Differences in surface RH and thermodynamic profiles suggest role of vertical mixing



Models that rain more have a **lower surface RH**, which can be up to 8% drier.

Lower surface humidities are accompanied by **elevated humidities at 925hPa.**

FIG 5



Air is **warmer at the surface** and cooler at 925hPa, suggesting the role of mixing.

Figure 5: Map of difference in surface relative humidity between models top 5 and bottom 5 models. Hatching indicates differences are not significant at 95% level. Also shown at specific locations are potential temperature and specific humidity profiles and their differences between top 5 and bottom 5 models.

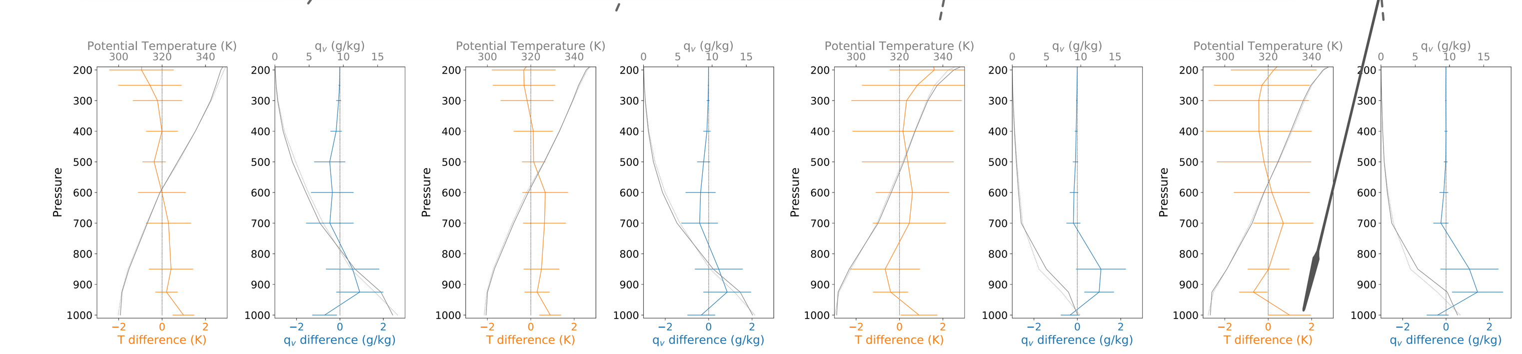


FIG 6 Difference in $\Delta q_{v(1000\text{-}925hPa)}$ between top 5 and bottom 5 models

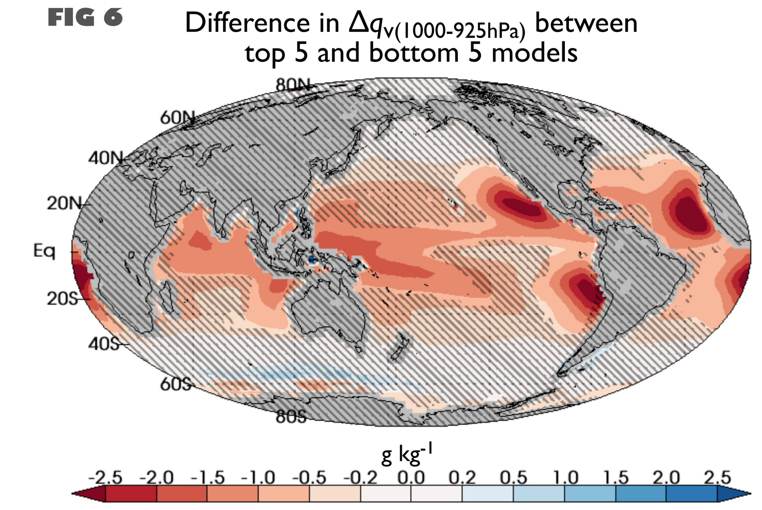


Figure 6 (top): Map of difference in vertical humidity gradient q(1000hPa - 925 hPa) between top 5 and bottom 5 models.
Figure 7 (bottom left): Global mean precipitation plotted against each model's surface RH over Tropical oceans.
Figure 8 (bottom right): Global mean precipitation plotted against each model's vertical humidity gradient over the Tropical subsidence oceans.

Models that rain more in the global mean have a **weaker humidity gradient between 925hPa and 1000hPa,** which suggests a moister boundary layer top or a deeper boundary layer.

Hypothesized mechanism
Increased vertical mixing in models that rain more leads to lower humidities at the surface, driving stronger evaporation.

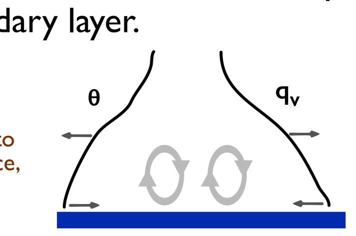


FIG 7

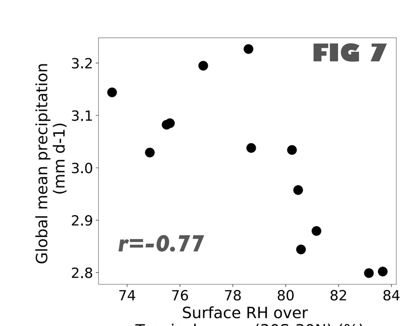
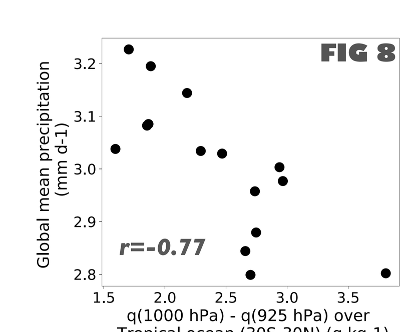


FIG 8



Surface relative humidity over the tropical oceans explain up to 59% of the spread in global mean precipitation rate.

Mechanistically, the surface humidity appear to be largely explained by how efficiently model processes tend to redistribute the evaporated humidity up into the lower parts of the troposphere.

References & Acknowledgments

Hourdin F, et al (2015) Air moisture control on ocean surface temperature, hidden key to the warm bias enigma. Geophys Res Lett, 42, 10885 - 10893, doi:10.1002/2015GL066764
Rodell M, et al (2015) The observed state of the water cycle in the early twenty-first century. J Clim 28(21):8289–8318. doi:10.1175/jcli-d-14-00555.1
Trenberth KE, Smith L, Qian T, Dai A, Fasullo J (2007) Estimates of the global water budget and its annual cycle using observational and model data. J Hydrometeorol 8(4):758–769. doi:10.1175/jhm600.1
Wild M, et al. (2015) The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. Clim Dyn 44(11):33933429. doi:10.1007/s00382-014-2430-z

This work was supported by NASA Grant 80NSSC18K0756.

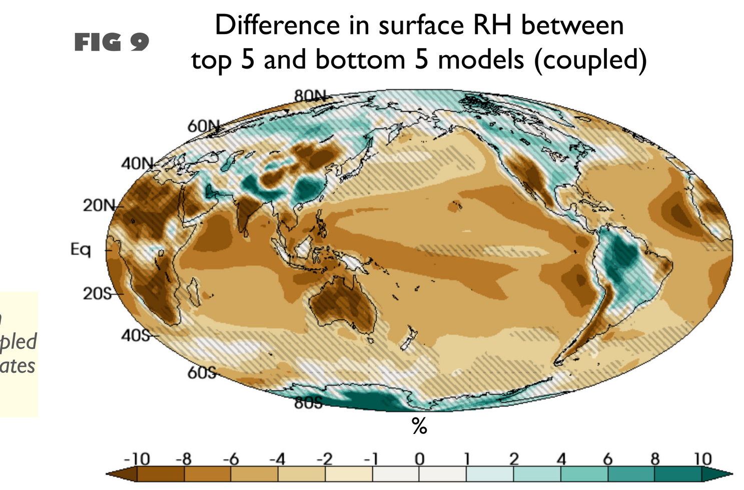
The US Department of Energy's (DOE) Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure for CMIP5 in partnership with the Global Organization for Earth System Science Portals. The model output can be obtained from the Earth System Grid Federation.

Do the differences in AMIP translate to coupled simulations?

A: **Yes**, if we group the models by their global mean precipitation in AMIP simulations and plot differences in surface RH, we get a similar picture as in Fig 5.

Figure 9: Map of difference in surface relative humidity in between models top 5 and bottom 5 models. Surface RH are taken from coupled historical simulations for the time period 1980-2000. Hatching indicates differences are not significant at 95% level.

FIG 9 Difference in surface RH between top 5 and bottom 5 models (coupled)

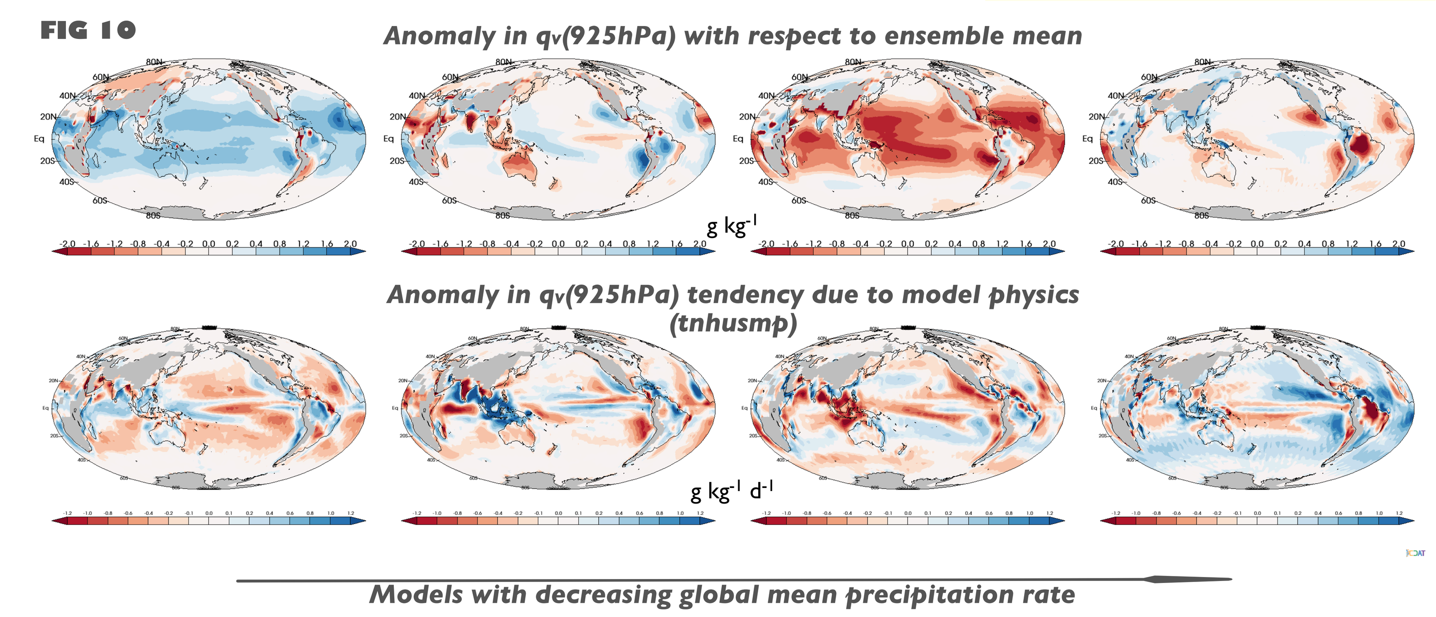


Can model physics tendencies help predict the vertical gradient in humidity?

A: **No.** Based on the subset of climate models provided model physics tendencies of humidity at different levels, we expected to find more positive humidity tendencies in models with higher 925 hPa humidities but found the opposite response.

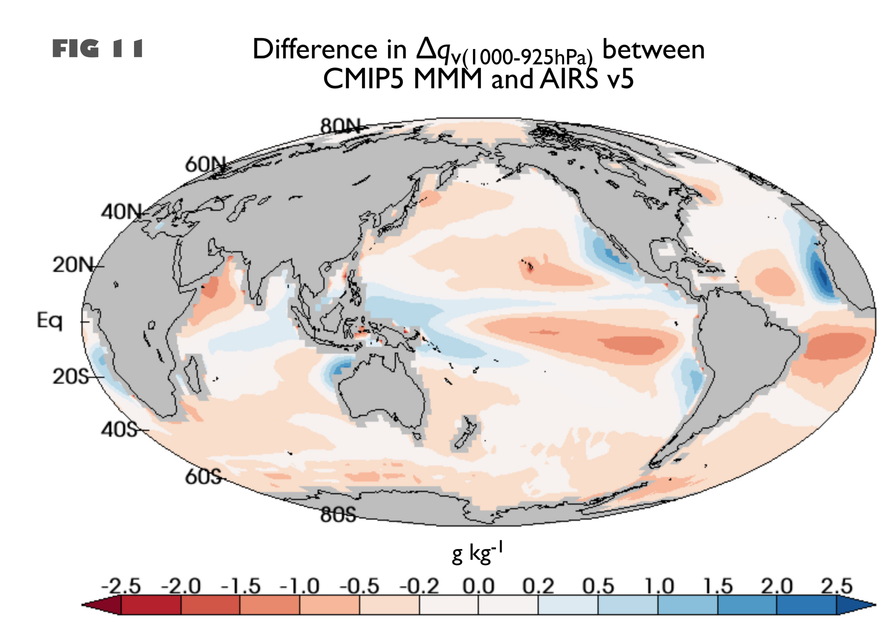
Figure 10: (top row) Maps of anomaly in 925hPa specific humidity relative to an ensemble mean of models with humidity tendencies. (bottom row) Maps of anomaly in specific humidity tendencies from model physics at 925hPa with respect to ensemble mean.

FIG 10



What do satellite retrievals suggest?

FIG 11 Difference in $\Delta q_{v(1000\text{-}925hPa)}$ between CMIP5 MMM and AIRS v5



A: Over trade wind regions of the Tropical oceans, models have too weak of a humidity gradient.

But the over the stratocumulus regions, and TWP where we see the largest intermodel differences, AIRS suggest that models tend to overestimate the gradient.

Q: Are our satellite retrievals accurate and precise enough to detect these differences?

Figure 11: Map of the difference in $\Delta q_{v(1000\text{-}925hPa)}$ (vertical humidity gradient between 1000hPa and 925hPa) between the CMIP5 multimodel mean and AIRS v5.

Summary and questions

Climate model disagree on the global mean precipitation rate and much of the difference manifests itself in the evaporation over tropical and subtropical oceans.

What drives more evaporation? Surface RH tends to be lower by up to 8% in 'wet' models, and regions of lower RH coincide with regions where the vertical gradient in humidity is weaker.

The coincidence of weaker temperature gradient suggest the strength of vertical mixing controls the vertical humidity gradient and the surface relative humidity.

Differences in surface humidity seen in AMIP simulations also occur in coupled simulations, similar to findings from Hourdin et al (2015) who were interested in SST biases.

Satellite retrievals from AIRS suggest a stronger gradient, over trade wind regions, but a weaker gradient where intermodel differences are largest. Does this go against our expectations?