Physical mechanisms of tropical climate feedbacks revealed by temperature and moisture trends

Angus Ferraro[1], Hugo Lambert[1], Mat Collins[1] & Georgina Miles[2]

[1]College of Engineering, Mathematics and Physical Sciences, University of Exeter [2]Rutherford Appleton Laboratory, Harwell, Oxford

UNIVERSITY OF EXETER

Find out more: dx.doi.org/10.6084/m9.figshare.1335975
emps.exeter.ac.uk/mathematics/staff/ajf223

Contact: a.j.ferraro@exeter.ac.uk
@angusferraro

- Water vapour and lapse rate feedbacks are not geographically anti-correlated
- Regional pattern of lapse rate feedback is determined by regional pattern of surface temperature change.
- Regional pattern of water vapour feedback is determined by regional pattern of precipitation change.
- When feedbacks are formulated in terms of the precipitation distribution the physically expected anti-correlation is partially recovered.

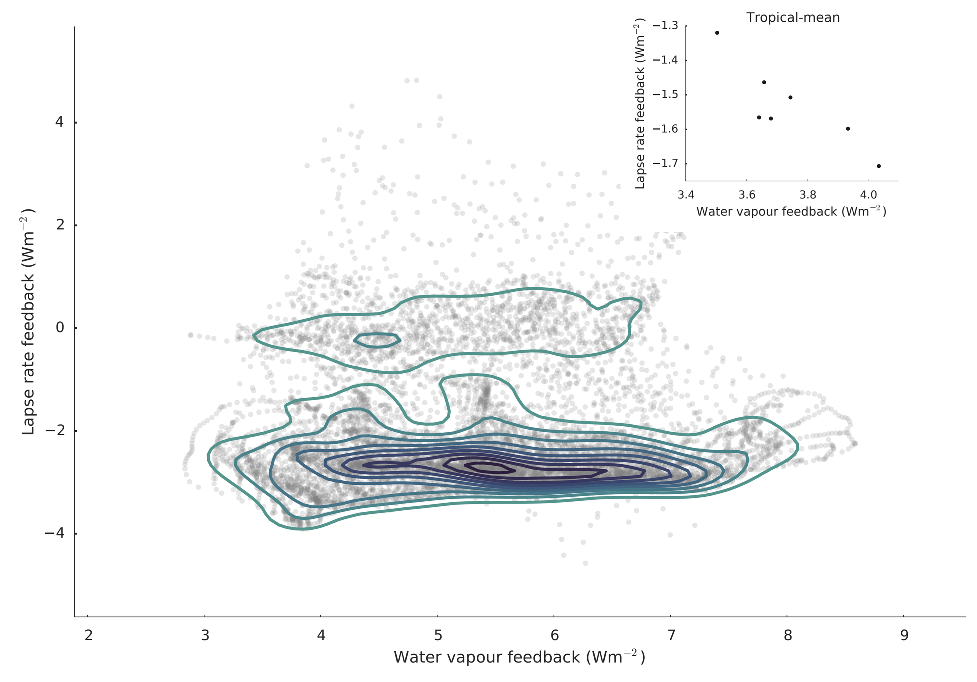

Figure 1. Relating lapse rate and water vapour feedback.
Grid-point radiative flux changes divided by tropical-mean temperature change. (inset) Tropical-mean water vapour and lapse rate feedbacks in 7 CMIP5 climate models.

Increasing specific humidity under surface warming drives a positive water vapour feedback. Faster warming in the troposphere than at the surface drives a negative lapse rate feedback.

Both feedbacks are related to convective processes - convection heats the upper troposphere via condensation and latent heat release, and also transports water vapour from the boundary layer to the upper troposphere. Upper tropospheric water vapour changes have a greater impact on top-of-atmosphere radiative flux than changes lower down.

Tropical-mean water vapour and lapse rate feedbacks are anti-correlated because relative humidity changes are small. There is no such relationship between the regional patterns of these feedbacks. This occurs in spite of the apparent physical link via convection.

Consistent feedback structure in models and observations

Here we use satellite observations as metrics of climate feedbacks.

Lapse rate: tropospheric temperature change relative to surface temperature change. Tropospheric temperature (TTT) is measured by the Microwave Sounding Unit instruments and processed by two different institutes - the University of Alabama Huntsville (UAH) and Remote Sensing Systems.

Water vapour: tropospheric humidity changes. The High Resolution Infrared Sounder Channel 12 (~6.7 microns) brightness temperature (T12) is sensitive to upper-tropospheric relative humidity. Increasing T12 = decreasing relative humidity.

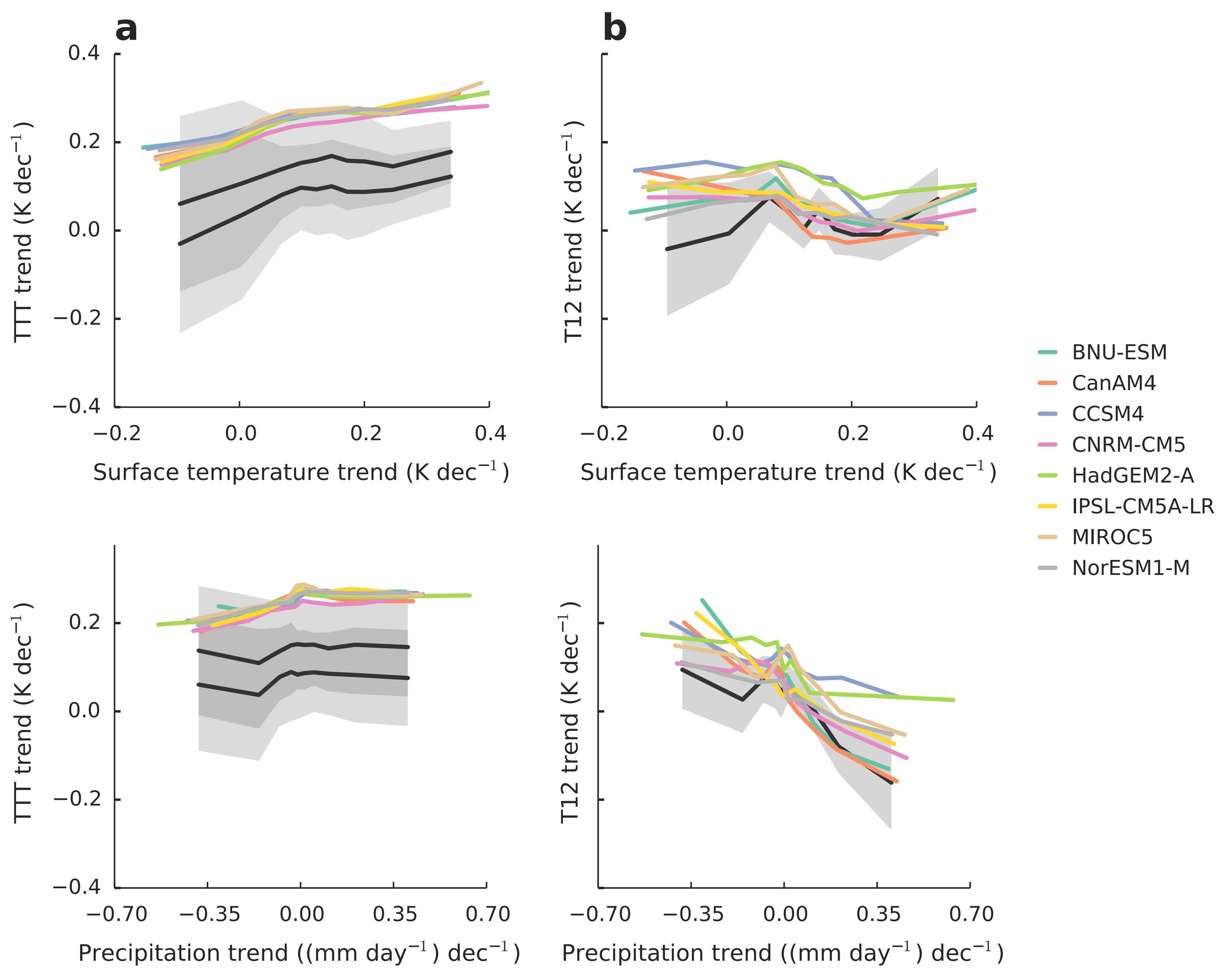

Figure 2. Observed trends against surface temperature and precipitation trends.
Trend in (a) tropospheric temperature TTT and (b) tropospheric relative humidity brightness temperature T12 in deciles of surface temperature trend. Trends are for 1979-2008 using observations (in black) from RSS/UAH for TTT and HIRS for T12. Model simulations are AMIP CMIP5 simulations. 95% confidence intervals for observations are in grey. Confidence intervals for models are omitted for clarity.

Tropospheric temperature trends are much less regionally variable than surface temperature trends (Figure 2a, top). This demonstrates that the regional pattern of the lapse rate feedback is primarily determined by the regional pattern of surface temperature changes.

T12 trends are uncertain, especially in regions of surface cooling (Figure 2b, top). In regions of surface warming, the most negative T12 trends are found in regions of intermediate surface temperature trends. Since decreasing T12 implies increasing upper-tropospheric relative humidity, this means the water vapour feedback is strongest in these regions.

The regional pattern of T12 trends is much more closely related to the regional pattern of precipitation trends (Figure 2b, bottom). This is to be expected: in the tropics precipitation is largely convective, and deep convection also transports water into the upper troposphere.

The relationship between upper-tropospheric humidity and precipitation trends is fairly robust among models and observations. Uncertainties in trend calculation could account for much of the apparent discrepancies.

Lambert & Taylor (2014, doi:10.1002/2014GL061987) showed robust regional patterns of tropical climate feedbacks in climate models.
The results above show that these patterns can also be seen in observable variables, indicating common physical processes among models and observations. But what causes the regional patterns we see? (see right)

Physical causes of regional feedback patterns

Since upper tropospheric humidity trends are strongly related to precipitation trends we apply a new physically-motivated spatial decomposition of the water vapour feedback. We calculate the change in top-of-atmosphere radiative flux in precipitation percentiles rather than geographical coordinates.

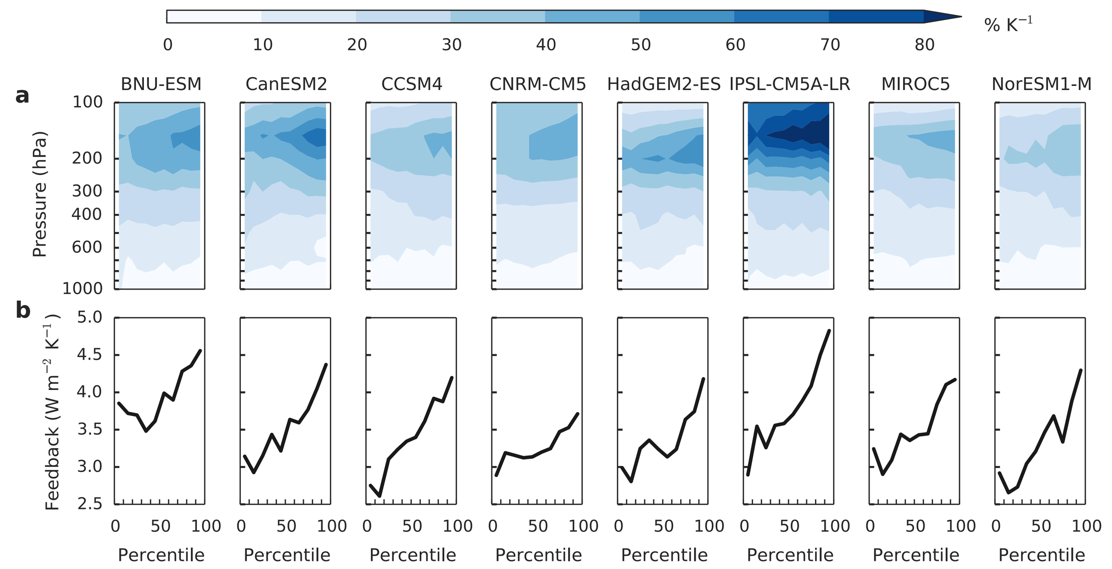

Figure 3. Water vapour feedback in precipitation percentiles.
(a) Specific humidity changes and (b) water vapour feedback in precipitation percentiles. Changes are calculated between the final 30 years of CMIP5 pre-industrial control and abrupt 4xCO2 simulations and normalised by tropical-mean temperature change.

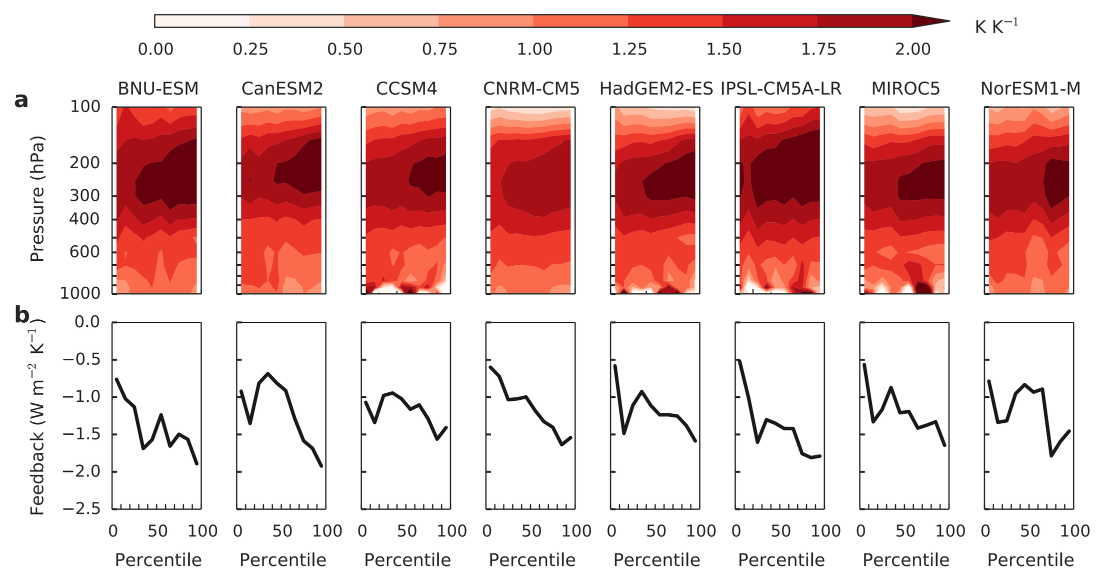

Figure 4. Lapse rate feedback in precipitation percentiles.
(a) Temperature changes and (b) lapse rate feedback in precipitation percentiles. Changes are calculated between the final 30 years of CMIP5 pre-industrial control and abrupt 4xCO2 simulations and normalised by tropical-mean temperature change.

The specific humidity response to surface warming is largest in the upper troposphere - this region is important for determining the strength of the water vapour feedback. Figure 3a shows there is also a strong horizontal gradient in upper-tropospheric humidity change. The greatest increase in specific humidity occurs in the highest precipitation percentiles, i.e. the convective regions of the tropics.

The horizontal gradient in specific humidity change drives the horizontal gradient in the water vapour feedback (Figure 3b).

The lapse rate feedback is determined by upper-tropospheric warming relative to the surface. This warming is also greatest in the convective regions (higher precipitation percentiles). It is commonly assumed horizontal temperature gradients are negligible in the tropics because of the small Coriolis parameter, but here we see an association between the gradient in lapse rate feedback (Figure 4b) and the gradient in upper-tropospheric warming (Figure 4a).

The horizontal gradient in modelled relative humidity changes is much smaller than that in specific humidity changes. This suggests the horizontal gradient in specific humidity changes is to some extent controlled by the same processes that maintain the horizontal gradient in temperature changes. Thus, in precipitation percentiles, we partially recover the expected anti-correlation between water vapour and lapse rate feedbacks.

Funding: NERC PROBEC project NE/K016016/1.
Data: tropospheric temperatures from University of Alabama Huntsville & Remote Sensing Systems, HIRS T12 from the NOAA Climate Data Record, surface temperature from GISTEMP, precipitation from GPCP. Climate model data from CMIP5 AMIP, piControl and abrupt4xCO2 simulations.