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Water Vapour Feedback Observations and Climate Sensitivity

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The response of atmospheric moisture to changes in surface temperature (Ts) determines to a large extent the sensitivity of the climate system to a radiative perturbation. Aside from the indirect influence of moisture changes on cloud feedbacks, a primary component of the direct water vapour feedback (β_{wv}) is encapsulated by,

$$\beta_{wv} \approx \left(\frac{\partial OLRc}{\partial WV}\right)\left(\frac{\partial WV}{\partial Ts}\right), \qquad (1)$$

where *OLRc* is the clear-sky outgoing longwave radiation and *WV* is a generic water vapour variable. An important step in diagnosing water vapour feedback from observations is therefore to establish a relationship between water vapour concentrations and the surface temperature. Although it is only possible to measure dWV/dTs rather than $\partial WV/\partial Ts$, it is possible to reduce this difference by removing the effects of the large scale circulation on the local changes in *WV*. This may be achieved by subsampling dynamical regimes (e.g. Bony *et al.* (1997), Allan *et al.* (2002c)) or by averaging over the large-scale circulation systems (e.g. Allan *et al.* (2002a)).

An important theoretical constraint on the water vapour feedback is the Clausius Clapeyron equation which predicts an approximately exponential increase in water vapour with temperature where relative humidity (*RH*) is conserved (e.g. Raval and Ramanathan (1989)). Wentz and Schabel (2000) demonstrated an observed increase in column integrated water vapour (*CWV*) with *Ts* of about 9% K^{-1}, close to that predicted by the Clausius Clapeyron equation, by analysing trends over the ocean. In Fig. 1a-b both models and satellite observations show excellent agreement in the relationship between *CWV* and *Ts* over a decadal time-scale (see also Soden (2000)) with $dCWV/dTs$ = 3.5 kg m^{-2} (≈ 9% K^{-1}).

Given the strong coupling between ocean surface temperature and boundary layer water vapour, which is the primary determinant of *CWV*, it would be surprising if the relationship between marine *CWV* and *Ts* did not hold. However, *OLRc* is sensitive to humidity changes throughout the troposphere (e.g. Allan *et al.* (1999)) so it is therefore important also to evaluate the free tropospheric moisture changes simulated by models. One possibility is to use reanalyses which assimilate a variety of observations into an atmospheric model and output variables such as the vertical profiles of atmospheric water vapour globally. However, the changing quality of the observational input to reanalyses render the presently available products unsuitable for the analysis of water vapour feedback (Trenberth *et al.* (2001), Allan *et al.* (2002b), Allan *et al.* (2004)).

Because *OLRc* is highly sensitive to humidity throughout the troposphere it is feasible to use $dOLRc/dTs$ as a proxy for β_{wv} (e.g. Raval and Ramanathan (1989), Slingo *et al.* (2000)). Cess *et al.* (1990) demonstrated good agreement between model $dOLRc/dTs$ and interpreted this as consistency in water vapour feedback. Agreement between observed and simulated variations in *OLRc* (Soden (2000), Allan and Slingo (2002)) suggest that the simulated water vapour feedback is realistic. For example, Fig. 1c shows reasonable agreement between observed and model simulated normalised greenhouse trapping, $g_a = 1 - (\sigma Ts^4/OLRc)$, with increased greenhouse trapping during warm events, symptomatic of positive water vapour feedback (Allan *et al.* (2003)). However, as demonstrated in Fig. 1c (dashed line), g_a is also sensitive to forcings such as greenhouse gas concentration changes and volcanic aerosols which may confuse the diagnosis of water vapour feedback from analysing broadband radiative fluxes. In addition to this limitation, similarity in $dOLRc/dTs$ does not necessarily indicate consistency in water vapour feedback. For example, Allan *et al.* (2002a) showed that 2 models with identical forcings produced a similar sensitivity, $dOLRc/dTs \approx 2$ W m^{-2} K^{-1}, but contained rather different temperature and water vapour profile responses to *Ts* over an interannual time-scale. The discrepancy, which was ascribed to differences in the model convection parametrizations, raises questions as how best to diagnose water vapour feedback (see also Held and Soden (2000)) and how the water vapour, temperature lapse rate and cloud feedbacks may interact.

Colman (2003) compared climate feedbacks from a variety of models and found a large compensation between water vapour and temperature lapse rate

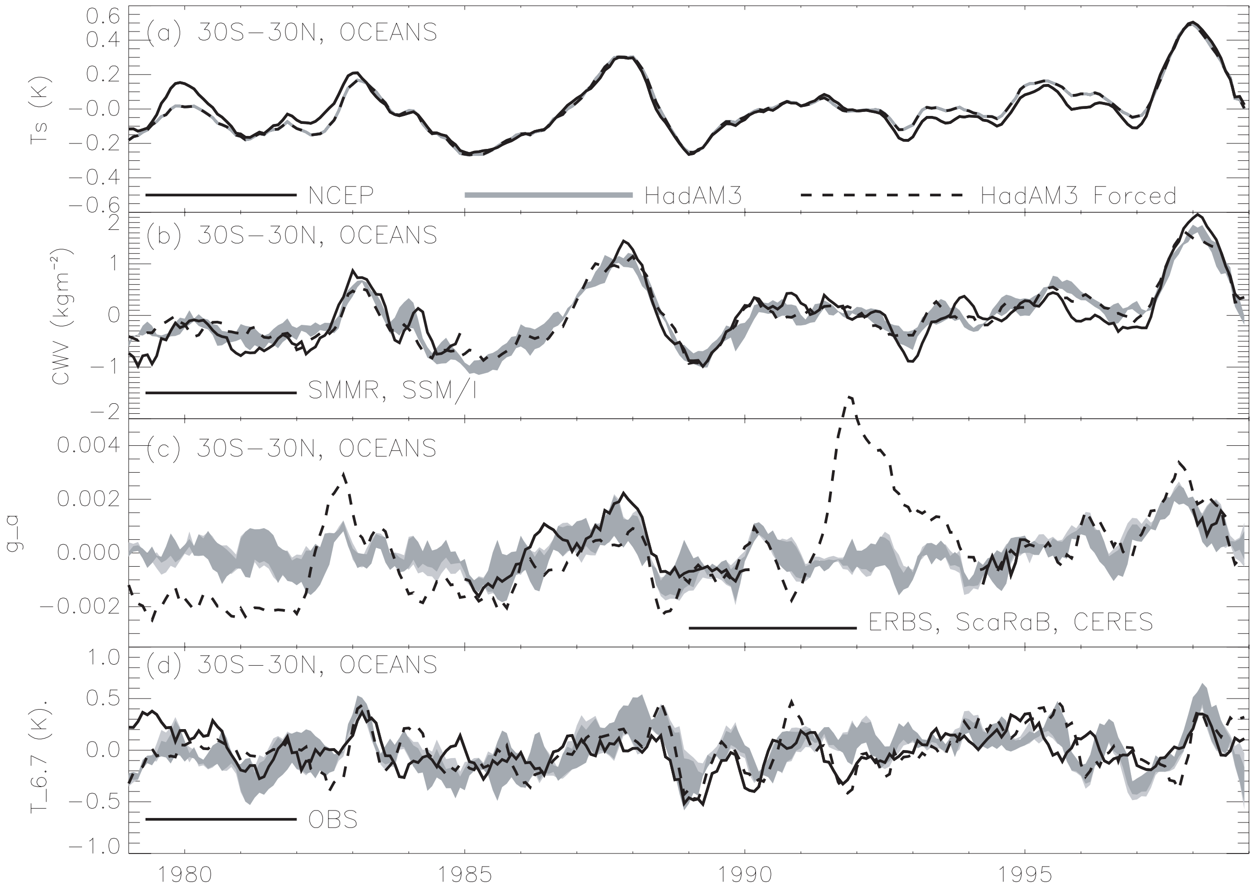

Figure 1. Interannual variations in (a) surface temperature, (b) column integrated water vapour, (c) atmospheric normalised greenhouse trapping and (d) 6.7 μm brightness temperature for sea surface temperature (SST) forced model (shaded), model with all known forcings (dashed) and observations (solid) (from Allan *et al.* (2003).

feedback, consistent with the analysis of Allan *et al.* (2002a). Based on the apparent robust nature of modelled and observed constant relative humidity water vapour feedback feedback (e.g. Ingram (2002), Soden *et al.* (2002)) it seems reasonable to check for departure from this theoretical relationship by measuring the feedback, if any, involving relative humidity. An additional benefit of this approach is the potential applicability to cloud feedbacks given the strong relationship between *RH* and cloudiness (e.g. J. M. Slingo (1980)). Thus it is important to evaluate the sensitivity of *OLRc* to *RH* ($\partial OLRc/\partial RH$) and to diagnose the changes in *RH* in response to *Ts*.

Figure 2 illustrates a technique to estimate $\partial OLRc/\partial RH$ by computing *dOLRc/dUTH* using the results of Allan *et al.* (2003). Here, *dOLRc/dUTH* is calculated at each tropical grid-point from interannual monthly anomalies, plotted as a function of mean *UTH* where *UTH* is estimated from observations *and* simulations of 6.7 μm radiances. The increasingly negative *dOLRc/dUTH* with decreasing humidity is consistent with previous studies (e.g. Spencer and Braswell (1997)) although the model appears to overestimate the magnitude of this sensitivity, especially at low humidities compared with the combined ERBS and HIRS satellite observations. Regardless of the approximate relationship, $dOLRc/dUTH \approx 0.5\%\ K^{-1}$, the departure from a constant relative humidity water vapour feedback appears small on the interannual time-scale because changes in 6.7 μm radiance (or equivalent brightness temperature, $T_{6.7}$) are small and not significantly correlated with *Ts* (Fig. 1d; Allan *et al.* (2003)). Although $T_{6.7}$ does not appear to be directly influenced by additional forcings (see dashed line in Fig. 1d) the relationship between $T_{6.7}$ and *UTH* may not be robust on interannual time-scales where temperature changes may also influence changes $T_{6.7}$ (Allan *et al.* 2003). Therefore, these techniques may need to be further refined. Finally, understanding the links between *Ts*, *RH*, cloudiness and the large-scale dynamics may improve our understanding of climate feedbacks and how they interact with one another (e.g. Hartmann *et al.* (2001)).

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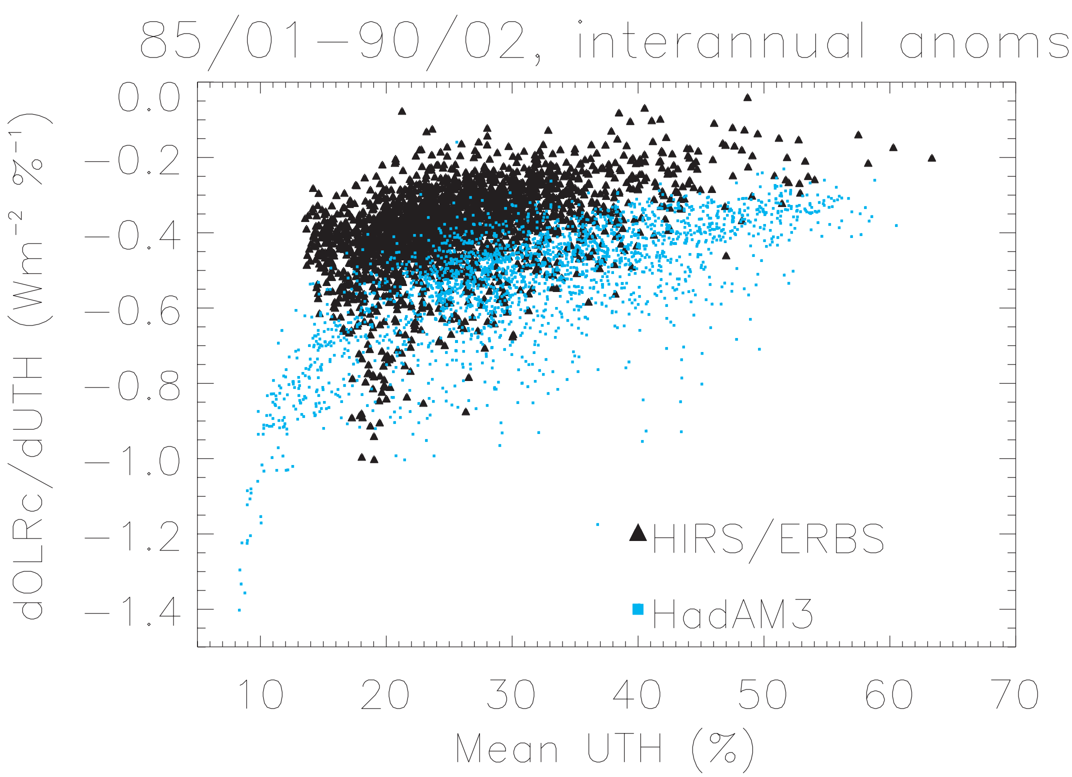

Figure 2. Sensitivity of clear-sky OLR to upper tropospheric humidity (UTH) as a function of mean UTH for the HadAM3 model and satellite observations.

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