Diagnostic analysis of atmospheric moisture and clear-sky radiative feedback in the Hadley Centre and Geophysical Fluid Dynamics Laboratory (GFDL) climate models

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[1] The interannual variability of the hydrological cycle is diagnosed from the Hadley Centre and Geophysical Fluid Dynamics Laboratory (GFDL) climate models, both of which are forced by observed sea surface temperatures. The models produce a similar sensitivity of clear-sky outgoing longwave radiation to surface temperature of ~2 W m^{-2} K^{-1}, indicating a consistent and positive clear-sky radiative feedback. However, differences between changes in the temperature lapse-rate and the height dependence of moisture fluctuations suggest that contrasting mechanisms bring about this result. The GFDL model appears to give a weaker water vapor feedback (i.e., changes in specific humidity). This is counteracted by a smaller upper tropospheric temperature response to surface warming, which implies a compensating positive lapse-rate feedback. *INDEX TERMS:* 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 1610 Global Change: Atmosphere (0315, 0325); 1878 Hydrology: Water/energy interactions; *KEYWORDS:* water vapor, temperature lapse-rate, climate model, feedback

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1. Introduction

[2] The response of the surface temperature to an increasing concentration of greenhouse gases in the atmosphere is dependent on feedbacks operating within the climate system. Using a variety of general circulation models, it was estimated that a strongly positive water vapor feedback amplifies greenhouse gas warming by a factor of 1.6 relative to the warming experienced with this feedback disabled and assuming there are no other feedbacks operating in the climate system [e.g., *Houghton et al.*, 1990]. Such model estimates are generally derived using one of two techniques. The first method involves a control integration in which the radiative properties of water vapor are allowed to feed back on the model physics. In conjunction with this an additional experiment is performed whereby the radiative feedback due to changes in water vapor amount is disabled by prescribing climatological specific humidity within the radiative component of the model. Comparing the different temperature responses to a specified forcing allows a direct calculation of the water vapor feedback operating within the model [e.g., *Hall and Manabe*, 1999; *Schneider et al.*, 1999].

[3] The second method diagnoses water vapor feedback from the relationship between the top-of-atmosphere clear-sky outgoing longwave radiation (OLR) and surface temperature (T_s) [e.g., *Cess et al.*, 1990]. In essence, this is the reverse of the first method: Rather than calculate the surface temperature response to a radiative forcing, the second method calculates the radiative response to a specified change in T_s. Method 1 has the advantage of being able to determine precisely, albeit theoretically, the magnitude of the water vapor feedback. Method 2 infers the radiative impact of the water vapor response to a change in T_s and, in fact, accounts for temperature lapse-rate feedback (i.e., changes in the temperature profile) as well as water vapor feedback (i.e., changes in specific humidity). Method 2 may be applied to the observational record and is thereby of

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great importance in validating the processes important in determining the water vapor feedback [e.g., *Slingo et al.*, 2000].

[4] Consistency between model simulations of clear-sky OLR response to T_s may be diagnosed, to first order, by similarities in the clear-sky feedbacks operating in such models. However, such comparisons are unable to identify consistency in or verify the feedback mechanisms between such models. To isolate the clear-sky feedbacks operating within climate models, both the temperature and moisture variability should be analyzed. With the foregoing as the basis the present study seeks to address the following question: Do models with apparently consistent water vapor feedbacks, as diagnosed from the clear-sky OLR dependence on T_s, also show similar temperature and moisture responses to changes in T_s?

[5] In the present study, height-dependent responses of atmospheric temperature and moisture are diagnosed from the Hadley Centre and Geophysical Fluid Dynamics Laboratory (GFDL) climate models, both of which are forced with observed sea surface temperature over the period 1979–1997. These two models have been extensively employed for studying climate variations and changes, including the feedbacks that determine the responses of the climate system on timescales ranging from interannual to multidecadal. They also employ significantly different physical parameterizations and thus provide a test of the consistency in their depiction of physical processes.

[6] While it is essential that all climate models undergo verification regarding climate variation simulations on all timescales, here we investigate one component by analyzing the interannual variability for global and low-latitude means. The latter is particularly crucial as it involves major water vapor–radiative interactions that have impacts for the whole globe [e.g., *Schneider et al.*, 1997]. Analyzing only the global-means can mask fundamental elements of the hydrologic cycle and equator-to-pole climate characteristics. Because the converse also holds, namely the potential importance of water vapor feedback at high latitudes [*Schneider et al.*, 1999], it behooves that both the global and low-latitude means be examined. While it is also desirable to carry out the verification on smaller spatial scales, this is outside the scope of the present analysis.

[7] We first consider, in section 3, the global and low-latitude mean interannual relationships between variables commonly used in the analysis of water vapor feedback [e.g., *Slingo et al.*, 2000], comparing the models with available observations (described in section 2). Subsequently, in section 4, the height dependence of temperature and humidity on changes in T_s that are applicable to the assessment of clear-sky radiative feedback is diagnosed. It is unclear at present whether such height-dependent temperature and moisture variability from observations [e.g., *Sun and Held*, 1996; *Sun et al.*, 2001] or reanalyses [e.g., *Trenberth et al.*, 2001; *Allan et al.*, 2002] or the interannual variations from upper tropospheric water vapor data sets [e.g., *Bates and Jackson*, 2001] are yet of sufficiently robust quality to verify the model relationships. Thus we restrict this section to a diagnostic analysis of the model variability.

2. Models and Data

[8] The two climate models used in the present study are the 19 vertical level Hadley Centre atmospheric model (HadAM3) and the 14 level GFDL R30 model. The second version of the Atmospheric Model Intercomparison Project (AMIP) [see *Gates*, 1992] sea surface temperature and ice fields were used to force HadAM3 (see *Pope et al.* [2000] for model description), providing output over the period 1979 to 1995. Moist and dry convection are parameterized using a mass flux scheme with convective downdrafts. Improvements included in the model are a new land surface scheme and an account of the direct effects of convection on momentum transport. The GFDL model employs a conceptually similar strategy as that followed for the AMIP integrations of the Hadley Centre model and has essentially similar physics as that employed in an earlier version employing a coarser spatial resolution [e.g., *Wetherald et al.*, 1991]. Some aspects of the simulations of the present model's AMIP integrations are discussed by *Soden* [2000].

[9] In addition to the model output, satellite scanning measurements of clear-sky outgoing longwave radiation are utilized from the Earth Radiation Budget Satellite (ERBS) [*Barkstrom et al.*, 1990], which covers the period 1985 to 1989. Also used were observations of column-integrated water vapor from the Scanning Multichannel Microwave Radiometer (SMMR) [*Wentz and Francis*, 1992], the Special Sensor Microwave Imager (SSM/I) [*Wentz*, 1997; *Colton and Poe*, 1999], and the NASA Water Vapor Project data set (NVAP) [*Randel et al.*, 1996], which combines a blend of conventional radiosonde measurements with SSM/I and other satellite data. Observed T_s constitutes a blend of surface air temperature [*Jones et al.*, 1999] and the Hadley Centre Sea-Ice and Sea Surface Temperature data set (HadISST) [*Rayner et al.*, 1998].

3. Interannual Variability

[10] The variability of atmospheric moisture and clear-sky radiative fluxes and their dependence on surface temperature changes are first analyzed in both climate models. The analysis is conducted using global and low-latitude (40°S to 40°N) monthly-means with the 1979–1993 mean seasonal climatology removed, thus concentrating on interannual anomalies. Figure 1 shows the low-latitude mean interannual variability of T_s, column water vapor (CWV), and clear-sky OLR for both models and observations. The dependence of fluxes and moisture on T_s is estimated by performing linear regressions on the time series (Table 1). Statistical significance of each regression is >99%. This was computed from the correlation coefficient and the degrees of freedom, adjusted to account for autocorrelation of the data in accordance with the method of *Yang and Tung* [1998].

[11] Table 1 shows consistency in the clear-sky OLR response to T_s at $\sim$2 W m^{-2} K^{-1} both globally and for low latitudes (values in parentheses). It is similar to the values calculated for a range of climate models when sea surface temperature is uniformly perturbed by ±2 K [*Cess et al.*, 1990] and is significantly less than the no-feedback response [*Slingo et al.*, 2000], therefore constituting a positive clear-sky radiative feedback. The low-latitude sensitivity is in agreement with the value of 1.8 W m^{-2} K^{-1}

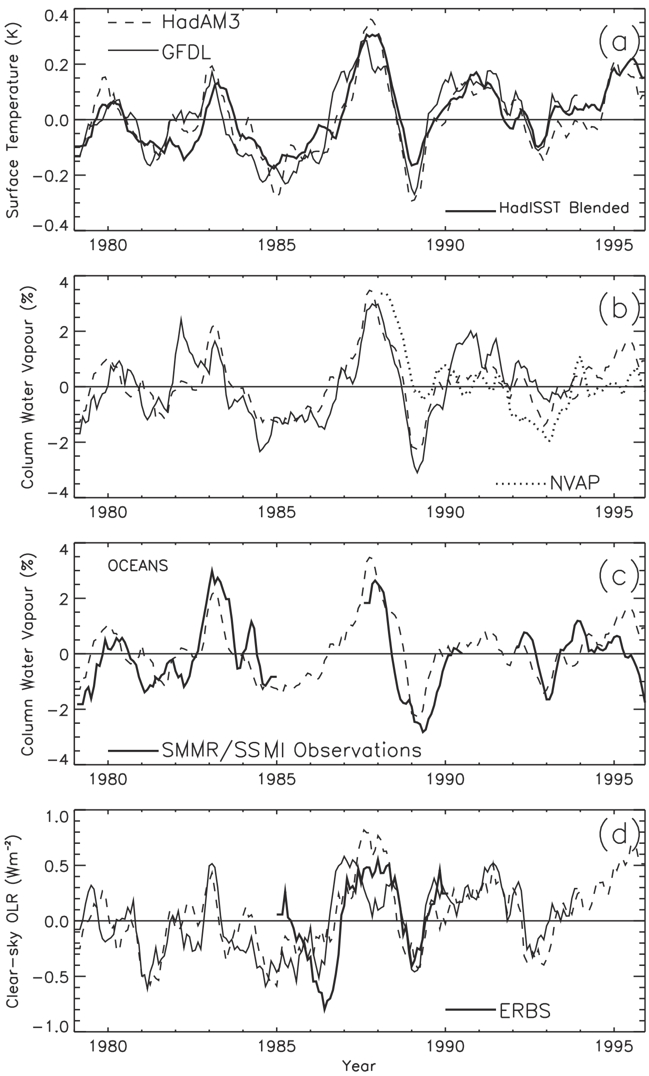

Figure 1. Anomaly time series of the low-latitude mean (40°S to 40°N) interannual variability of (a) surface temperature (K), (b) column-integrated water vapor (%), (c) column water vapor over low-latitude oceans, and (d) clear-sky outgoing longwave radiation (W m^{-2}) for the HadAM3 and GFDL models and observations. A five-month running mean was applied to focus on interannual variability.

(99% significance level), derived from ERBS clear-sky OLR and the blended HadISST surface temperature measurements from 1985 to 1990. The observed clear-sky OLR variability is in reasonable agreement with the simulated variability between 1985 and 1990 (Figure 1d), although the observed decrease during 1985 is not captured.

[12] It is common to use the column-integrated water vapor to provide information on the water vapor feedback [e.g., *Wentz and Schabel*, 2000; *Soden*, 2000]. Consistent with these studies, Figure 1b shows positive CWV anomalies simulated by the models to generally coincide with warm El Niño events (Figure 1a). Figure 1c shows that the simulated CWV variability over the ocean is consistent with values from SMMR and SSM/I (these data will be referred to as observations throughout). Agreement with NVAP values for the low-latitude land and ocean is not as good (Figure 1b); this appears to be mainly due to a systematic drying over land in the NVAP data, which is not apparent in the model simulations. This drying may be related to biases in the radiosonde humidity record due to instrumentation changes [*Ross and Gaffen*, 1998]. Applying the regressions to simulated CWV, significant positive relationships with T_s are computed, consistent with the diagnosed clear-sky longwave radiative feedback. This is consistent with *Wentz and Schabel* [2000], who also show this coupling to apply to the observed decadal trends of T_s and CWV. Rather than providing evidence of positive water vapor feedback in the models, this merely indicates that water vapor in the tropical lower troposphere, which largely determines the CWV parameter, provides a positive feedback consistent with the radiatively diagnosed effect. This is unsurprising given the strong coupling between T_s and lower boundary layer moisture; while models can simulate this coupling [*Soden*, 2000], it is important to assess the temperature and moisture relationships away from the tropical ocean boundary layer where the relationship with T_s is less clear. This is addressed in section 4.

[13] Despite the similar clear-sky OLR response to T_s between the models, the GFDL simulation gives a significantly smaller CWV response to T_s than HadAM3. Because the GFDL model maintains 13% less atmospheric water vapor than the Hadley Centre model, a given absolute change in CWV may lead to a larger radiative response in the GFDL model because of a less saturated longwave radiative spectrum compared with HadAM3. Thus the relative changes in water vapor may provide a more consistent measure of the radiative feedback in both models. However, even when the regressions are applied on the percentage column water vapor anomalies (i.e., normalized with respect to the annual mean CWV), a similar result is produced, indicating a stronger lower tropospheric water vapor feedback operating in HadAM3 compared with the GFDL model.

[14] The clear-sky OLR is dependent not only on moisture variations at low levels, as sampled by CWV, but also by the percentage changes in moisture throughout the

Table 1. Regression Between Global and Low-Latitude Interannual Monthly-Mean Anomalies for the HadAM3 and GFDL Model AMIP Integrations[a]

y	Model	$\frac{dy}{dT_s}$	*r*
OLR	HadAM3	1.9 (2.1) W m^{-2} K^{-1}	0.76 (0.68)
OLR	GFDL	1.9 (2.0) W m^{-2} K^{-1}	0.84 (0.66)
CWV	HadAM3	1.3 (2.0) kg m^{-2} K^{-1}	0.65 (0.76)
CWV	GFDL	0.8 (1.5) kg m^{-2} K^{-1}	0.57 (0.68)
%CWV	HadAM3	5.5 (6.4) %K^{-1}	0.65 (0.76)
%CWV	GFDL	3.6 (5.4) %K^{-1}	0.57 (0.68)
CWA	HadAM3	11.3 (12.9) %K^{-1}	0.70 (0.74)
CWA	GFDL	9.0 (8.8) %K^{-1}	0.66 (0.56)

[a] Numbers in parentheses denote low-latitude values. Definitions are as follows: *y* is the independent variable defined in column 1; *r* is the correlation coefficient; OLR is the interannual anomaly of clear-sky outgoing longwave radiation at the top of the atmosphere; CWV is the interannual anomaly of column-integrated specific humidity; %CWV is the interannual anomaly of column-integrated specific humidity subsequently normalized by the climatological mean value; and CWA is the interannual anomaly of specific humidity normalized by the climatological mean values at each of the model levels and then averaged vertically.

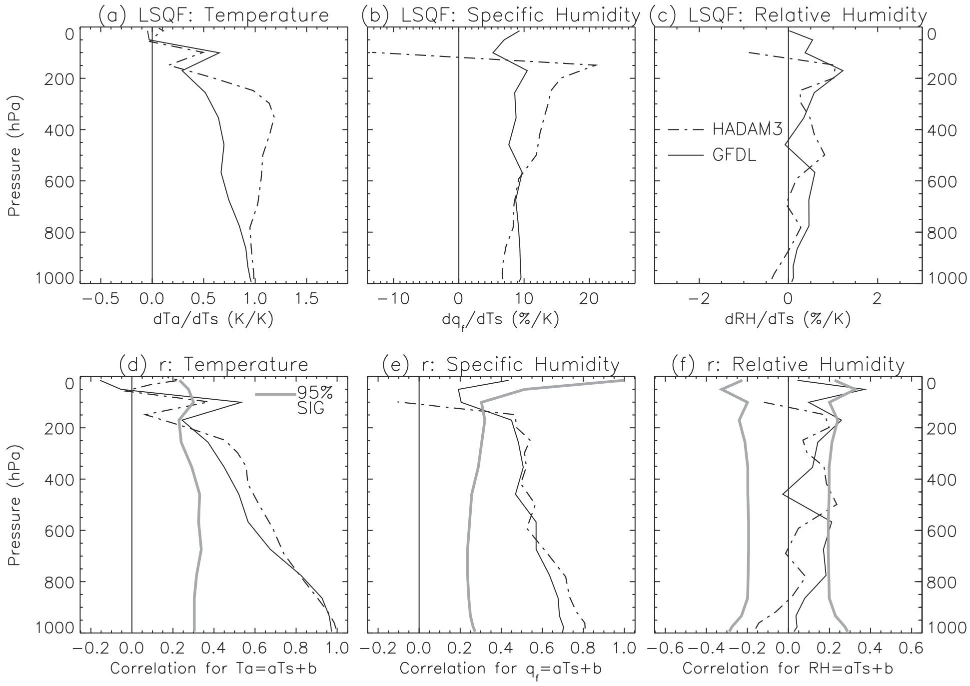

Figure 2. The global-mean height-dependent least squares fit sensitivity of (a) temperature, (b) percentage changes in specific humidity and (c) relative humidity to surface temperature, and (d, e, and f) associated correlations for the HadAM3 and GFDL model AMIP integrations. The 95% confidence level, allowing for autocorrelation of the data, is plotted for the GFDL data in Figures 2d, 2e, and 2f.

atmosphere [*Shine and Sinha*, 1991]. A moisture parameter that sums the percentage moisture changes (i.e., specific humidity anomalies at each vertical level normalized by the mean specific humidity at that level) is of greater relevance to water vapor feedback than CWV. Regressions were repeated on column-integrated percentage water vapor anomalies (CWA) (see *Slingo et al.* [2000] for details). For both models globally and in the tropics CWA increases at the rate of ~10% per Kelvin increase in surface temperature (Table 1). However, the GFDL model again shows a weaker water vapor response than HadAM3, especially in the tropics.

[15] The increases in global-mean CWV with T_s for both models are generally lower than corresponding values given by *Randall et al.* [1992] (~9% K^{-1}), who used results from the climate model integrations described by *Cess et al.* [1990]. This disparity highlights the importance of the nature of sea surface temperature forcing applied, as discussed by *Hall and Manabe* [1999]. In the *Cess et al.* [1990] study, sea surface temperature perturbations are globally uniform and therefore cause temperature and moisture anomalies to propagate to a greater extent in the vertical and horizontal and to be sustained for longer than for the AMIP integrations of the GFDL and HadAM3 models. Therefore simulations with more uniform sea surface temperature perturbations should exhibit a stronger water vapor dependence on T_s than that diagnosed from AMIP simulations and also the observed record when considering a decadal timescale. Also, while this affects the CWV dependence on T_s and therefore the direct water vapor feedback acting at the surface, the clear-sky OLR does not show this difference because of the compensating longwave radiative effects of temperature and moisture anomalies at the top of the atmosphere. Thus despite a similar top-of-atmosphere clear-sky feedback operating in the models, differences in the moisture dependence on T_s beg further analysis of the height-dependent variability of temperature and water vapor and its dependence on the surface temperature in assessing the consistency of water vapor feedback between models.

4. Height-Dependent Regressions

[16] In section 3 we presented columnar variables commonly used in studies of the water vapor feedback and that can easily be compared with observed quantities (e.g., SSM/I). We now build on these comparisons by performing statistical analysis, which is more meaningful with respect to water vapor feedback. Regressions of the spatial mean interannual monthly anomalies of air temperature, fractional specific humidity anomalies, and relative humidity anomalies on T_s were computed globally (Figure 2) and for low latitudes (Figure 3). This is preferred to averaging regressions at each grid point as in Figure 1 of *Hu et al.* [2000] because their method can alias the local temperature and moisture response to changes in T_s due to spatial shifts in convective regimes, which are independent of climate feedbacks [e.g., *Allan et al.*, 1999]. To fully account for the radiatively important perturbations of specific humidity (q) from the mean ($\bar{q}$), the relative changes, $(q - \bar{q})/\bar{q}$ should be measured rather than the absolute magnitude changes $(q - \bar{q})$ [*Shine and Sinha*, 1991]. Arithmetic means are sensitive to absolute changes in q and therefore bias the spatial mean moisture variability to the tropics thus not accounting adequately for the water vapor variability at higher latitudes. Spatial averages of q were therefore com-

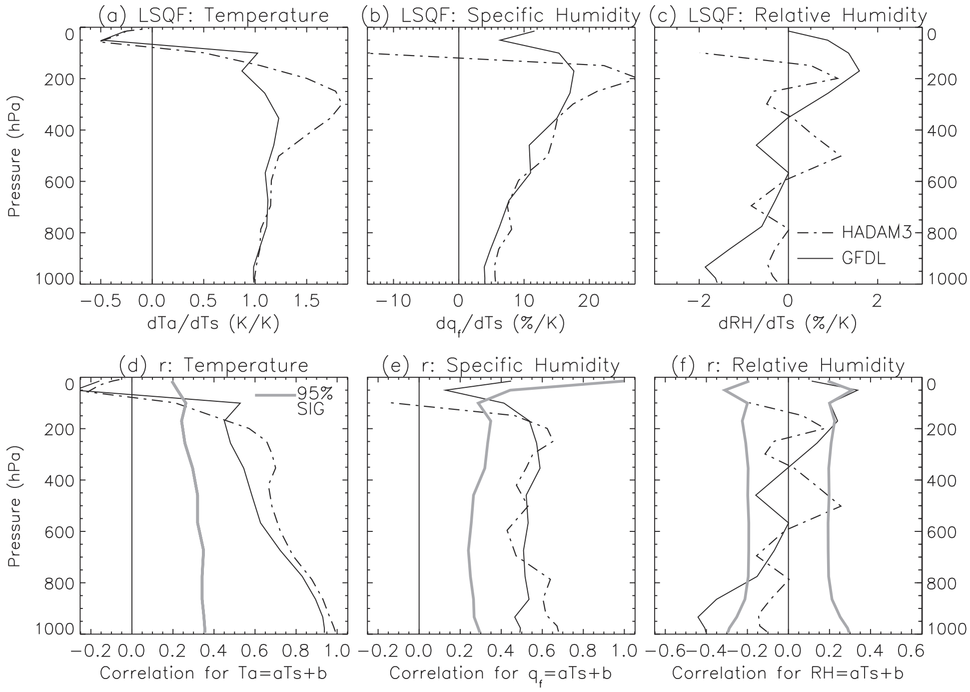

Figure 3. As in Figure 2 but for low latitudes (40°S to 40°N).

puted geometrically, which provides sensitivity to relative changes in q. The main conclusions, however, are unaffected by the different averaging.

[17] Figure 2a shows the global-mean calculated air temperature sensitivity to surface temperature. Correlation coefficients are shown in Figure 2d. The 95% confidence interval is also plotted (thick, gray line) and was calculated using the GFDL data and adjusting for autocorrelation. Correlation is generally positive and significant in the troposphere. A notable finding is the differing atmospheric temperature response to surface temperature between the HadAM3 and GFDL models. Upper tropospheric temperature response to changes in T_s is generally small in the GFDL model compared with HadAM3. This implies a more positive lapse-rate feedback in the GFDL model.

[18] Examining the low-latitude sensitivities (Figure 3a), a maximum sensitivity at 200–300 hPa is evident in HadAM3, while the GFDL upper tropospheric temperature sensitivity to T_s is smaller, consistent with the global comparison. In the lower troposphere the GFDL and HadAM3 sensitivities are similar. This suggests that the smaller global sensitivities of lower tropospheric temperature to T_s in the GFDL model (Figure 2a) are manifest in the extratropics. For both models the global temperature sensitivity to changes in T_s is smaller than in the tropics where convection causes greater efficiency of vertical heat transfer.

[19] There is a similar water vapor response to changes in T_s for the models between the surface and 600 hPa (Figures 2 and 3). At pressures <150 hPa strongly negative correlations in HadAM3 are due to a systematic drying of the stratosphere. Between 150 and 600 hPa, HadAM3 gives a larger moisture response to changes in T_s than the GFDL model, presumably linked to the larger upper tropospheric temperature response to T_s changes in the Hadley Centre model. Conversely, *Sun and Held* [1996] found that while the GFDL model moisture response agreed with tropical radiosonde observations in the boundary layer, this was not the case in the midtroposphere where the model overestimated the moisture increases with surface warming. Correlation between relative humidity (RH) and T_s is generally insignificant for both models (Figures 2f and 3f), although there is significant negative correlation between low-latitude boundary layer humidity and changes in T_s for the GFDL model. From Table 1, Figure 2, and Figure 3 it is apparent that, while there is a smaller moisture response to changes in T_s in the GFDL model compared with HadAM3, there is also a weaker atmospheric temperature response in the GFDL model. Thus a weaker water vapor feedback diagnosed in the GFDL model is compensated by a stronger lapse-rate feedback, resulting in a consistent top-of-atmosphere clear-sky feedback diagnosed from the clear-sky OLR dependence on T_s.

[20] The differing temperature and moisture profile relationships with changes in T_s between the models are symptomatic of the differences in convection schemes used, as discussed in previous studies [e.g., *Ramaswamy and Ramanathan*, 1989; *Hack*, 1994]. The GFDL model employs a simple moist convective adjustment scheme [*Manabe et al.*, 1965], which relaxes the temperature profile to that of a moist adiabat between levels if a grid point is conditionally unstable and saturated with respect to water vapor, immediately precipitating out any water mass condensed in this procedure. It is well known that such schemes produce too cold and dry an upper troposphere [e.g., *Hack*, 1994]; this is indeed the case comparing the GFDL model with HadAM3. One of the reasons for the development of cumulus convective mass flux schemes, such as the one used in HadAM3, was to reduce such biases by more physically accounting for the convective process. The cold bias may be in part attributed to other causes, such as accounting for the solar heating effect of cirrus clouds

[*Ramaswamy and Ramanathan*, 1989]. However, the implementation of a mass flux scheme improves the temperature and moisture profile comparisons with analyses and observations compared with the Manabe scheme [e.g., *Hack*, 1994]. *Hack* [1994] explains this improvement in terms of the explicit vertical eddy heat transport term in mass flux schemes; this effect is not accounted for in adjustment schemes, which instead restore thermodynamic balance by unrealistically removing all the liquid water at low levels by precipitation.

[21] While both types of convection schemes are able to adequately reproduce many aspects of the observed climate [e.g., *Li*, 1996] and the interannual variability as seen in Figure 1 and *Soden* [2000], the differing complexity of physics assumed causes differences in the height-dependent distribution of temperature and water vapor and further causes differences in the temperature and moisture profile response to changes in T_s. This has been demonstrated using both types of convection schemes by *Zhang et al.* [1994], who applied uniform sea surface temperature forcing to versions of an atmospheric model, and by *Hu et al.* [2000], who considered versions of a slab ocean coupled model. Consistent with these findings, the present study suggests a more efficient vertical transport of water vapor and heat into the upper troposphere in HadAM3 causing a stronger dependence of temperature and moisture on changes in T_s compared to the GFDL model. However, this consistency does not signal universality of such conclusions. We have compared here only one moist convection scheme application and one mass flux scheme. Variants of these applied to other models could well yield quantitative aspects that differ from the present results. Also, while the different sensitivity is particularly evident in the low-latitude upper troposphere where the transport of moisture and heat are particularly sensitive to convective processes, differences evident in the global comparison rather than low-latitude analysis may be independent of the convection scheme differences. For example, the global lower tropospheric temperature response differences, not seen in the low-latitude analysis, are more likely due to other differences between the models such as the boundary layer scheme.

5. Discussion

[22] Consistent relationships between the top-of-atmosphere clear-sky radiative fluxes and surface temperatures simulated by a range of climate models have been suggested as evidence that model depiction of the water vapor feedback is robust [e.g., *Cess et al.*, 1990]. The present study shows that while two atmospheric climate models produce similar clear-sky OLR dependence on changes in T_s of $\sim$2 W m^{-2} K^{-1}, this result is the product of compensating water vapor and temperature lapse-rate feedbacks as diagnosed from the height-dependent interannual variability of moisture and temperature. Considering previous work, for example *Zhang et al.* [1994], this is likely related to the convection scheme employed in the GFDL model, which is based on moist convective adjustment as opposed to the mass flux scheme used in HadAM3. A similar conclusion was also reached by *Hu et al.* [2000] using versions of a slab ocean coupled model comparing a mass flux scheme with the simple Manabe formulation. Nevertheless, it is striking that this simplistic formulation reproduces many aspects of the observations of moisture and OLR variation.

[23] Despite the apparently consistent overall clear-sky feedback, the dependence of additional climate feedbacks, such as those involving cloud, on the different temperature and water vapor changes may provide quite different overall climate sensitivity to a given forcing. It would thus seem important to employ the best physically sound parameterizations available in climate models to ensure accuracy in temperature and water vapor changes at all altitudes. It will only be possible to verify such parameterizations in a robust manner when the quality of height-dependent variability from observations [*Sun and Held*, 1996] or reanalyses [*Trenberth et al.*, 2001] is established. It is essential to test both the analyses and also the observations on a continuous basis in order to ensure the reliability of the longtime series and therefore allow meaningful validation of climate model processes such as water vapor and cloud feedbacks. Narrowing the uncertainties in model predictions of future climate change is still dependent on such temporally consistent data sets to provide validation of the simulated water vapor response to increases in surface temperature.

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