The Global Hydrological Cycle and Atmospheric Shortwave Absorption in Climate Models under CO₂ Forcing

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ABSTRACT

The spread among the predictions by climate models for the strengthening of the global hydrological cycle [i.e., the global mean surface latent heat flux (LH), or, equivalently, precipitation] at a given level of CO₂-induced global warming is of the same magnitude as the intermodel mean. By comparing several climate models from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) database under idealized CO₂ forcings, it is shown that differences in the increase in global atmospheric shortwave heating (SWabs) induced by clear-sky absorption, presumably by water vapor, partly explains this spread. The increases in SWabs and LH present similar spreads across models but are anti-correlated, so the sum SWabs + LH increases more robustly than either alone. This is consistent with a recently proposed theory (Takahashi) that predicts that this sum (or, equivalently, the net longwave divergence minus the surface sensible heat flux) is constrained by energy conservation and robust longwave physics.

The intermodel scatter in SWabs changes is explained neither by differences in the radiative transfer models nor in intermodel differences in global water vapor content change, but perhaps by more subtle aspects of the changes in the water vapor distribution. Nevertheless, the fact that the radiative transfer models generally underestimate the increase in SWabs relative to the corresponding line-by-line calculation for a given change in water vapor content suggests that the climate models might be overestimating the rate of increase in the global hydrological cycle with global warming.

1. Introduction

Comprehensive climate models predict that the global hydrological cycle [or, equivalently, the global mean surface latent heat flux (LH) and precipitation] will increase at a significantly smaller (fractional) rate than atmospheric water vapor content with global warming (Mitchell et al. 1989; Allen and Ingram 2002; Held and Soden 2006). It has been argued that this smaller rate is set by energetic (i.e., radiative) considerations rather than by moist processes (Mitchell et al. 1989; Allen and Ingram 2002). Climate models predict a rate of change in LH of around 2% degree⁻¹ warming (Held and Soden 2006). However, values from individual models can differ by a factor of 5 (e.g., Fig. 2b in Held and Soden 2006). Understanding what determines the mean change in LH and the scatter around it is important for evaluating both climate models and observational estimates. In this study we address the intermodel differences by analyzing available model results and using an approach based on energy conservation, outlined next.

The global mean equilibrium energy budget for the atmosphere is

\[ \text{LH} + \text{SH} + \text{SW}_{\text{abs}} = \text{LW}_{\text{div}} \]  

where the terms (from left to right) represent surface latent and sensible heat (SH) fluxes, shortwave radiation absorbed by the atmosphere, and net atmospheric longwave (LW) flux divergence. This equation is expected to be approximately valid even if the ocean is not in equilibrium with an external radiative forcing, resulting from the relatively small heat capacity of the atmosphere. Under a perturbation in greenhouse gases, the change in the LW fluxes could be taken as a first approximation to consist of a radiative forcing (i.e., the direct effect of the perturbation in composition) and a response that scales with the temperature change (e.g., Allen and Ingram 2002). The latter is physically justified to some extent by the temperature dependence of the Planck blackbody emission function and the observation that assuming fixed relative humidity, which implies that...
water vapor is mainly a function of temperature, provides a good approximation to the water vapor feedback in climate models (Soden and Held 2006). An approximate model could be made for LH by using this LW model and ignoring changes in SH and SWabs (Allen and Ingram 2002), but there is no physical justification for doing the latter a priori. Furthermore, surface sensible heat and longwave radiative fluxes depend on the temperature difference between the surface and the surface air ($\delta T$), which is an additional degree of freedom that will not necessarily scale with global warming. An idealized physical model (Takahashi 2009) suggests that the necessary additional constraint can be provided by considering the energy budget for the atmospheric layer above the cloud-base level. In this idealized model, the change in SWabs above the cloud-base level. In this idealized model, the change in SWabs + LH is approximately determined by the changes in the longwave flux divergence in the layer above cloud base (LWacb), which does not depend on the changes in $\delta T$ and is, therefore, more robustly constrained by longwave physics.

The results from the present study indicate that the changes in SWabs + LH (or, equivalently, LWabs − SH) and, therefore, LWacb (Takahashi 2009), are robust functions of the changes in global temperature and in CO2 concentrations across different models and experiments, but the rates of change in SWabs alone are not, and this results in the scatter in the change in LH. A recent study by Lambert and Webb (2008, hereafter LW08) suggests that the net clear-sky radiative cooling is the robust process that constrains the increase in LH. The present study considers a larger set of climate models and determines that the change in radiative cooling does closely resemble the change in LH, but that the change in SWabs + LH is more robust than either.

In the next section we describe the data used and the methodology, in section 3 we describe the results and their analysis, and finally we present a discussion and main conclusions.

2. Data and methods

We analyze the output of eight climate models from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) database (Meehl et al. 2007; Table 1). Three experiments were considered in which CO2 concentrations were increased and the other radiatively active species (except for water vapor) were held fixed: one in which the climate models had an slab-ocean model and the CO2 concentration was instantly doubled (denoted $2 \times \text{CO}_2$ in the WCRP CMIP3 database), and two others with full-ocean general circulation models in which the CO2 concentration was increased at a rate of 1% yr$^{-1}$ until doubling and quadrupling and then was held constant (1pctto2x and 1pctto4x, respectively). Additionally, a 20-yr four-member ensemble run with Geophysical Fluid Dynamics Laboratory Climate Model version 2.1 (GFDL CM2.1) under instantaneous doubling of CO2 concentrations was considered (denoted $2 \times \text{CO}_2$).

The analysis was performed on the global and multi-year mean perturbations (indicated with $\Delta$) from the transient data in these experiments relative to the mean of the corresponding control runs. The data considered were surface air temperature perturbations ($\Delta T$) and the perturbations in the terms in the atmospheric energy budget (1), computed from surface and top-of-the-atmosphere energy fluxes. It should be noted that although LWacb is frequently mentioned in reference to the theory of Takahashi (2009), no calculation is explicitly made using fluxes at cloud base.

The analysis was made only for those periods during the runs in which the CO2 concentrations are constant in time (i.e., for all time, after year 70, and after year 140 for the $2 \times \text{CO}_2/2 \times \text{CO}_2c$, 1pctto2x, and 1pctto4x runs, respectively). Because the radiative forcing of CO2 is approximately linear on the logarithm of the concentrations, the forcing for the 1pctto4x run is twice as much as in the other two runs. We take advantage of this by dividing the perturbation data of the 1pctto4x run by a factor of 2, which approximately yields the equivalent of a run in which the CO2 concentration is increased by 0.5% yr$^{-1}$ until doubling, except for possible nonlinear effects that might arise from the larger forcing (Hansen et al. 2005).

To reduce the impact of high-frequency unforced internal climate variability in the analysis, the data were subjected to time averaging before the analysis. The 30- and 20-yr means were considered for the 1pctto2x and 1pctto4x runs, respectively, while, for $2 \times \text{CO}_2$ the means were annual for years 1–5, biennial for years 6–10, pentadal for years 11–20, and last, the mean for the rest of the run. The latter averaging was done to yield approximately uniform spacing in global surface air temperature perturbations ($\Delta T$), considering that the slab models equilibrate within 20 yr.

A linear relationship was assumed between $\Delta T$ and the perturbation in a generic energy budget term $X$,

$$\Delta X \approx \left(\frac{\partial X}{\partial T}\right) \Delta T + F_X ;$$

the coefficients $\partial X/\partial T$ and $F_X$ were determined by least squares regression and 95% confidence intervals for the fit are given. The slope parameter $\partial X/\partial T$ is a measure of the response of the climate system mediated by $\Delta T$, while the intercept $F_X$ represents a direct forcing by the change in the CO2 concentrations (i.e., not directly
<table>
<thead>
<tr>
<th>Id</th>
<th>Climate model (WCRP CMIP3 identification)</th>
<th>Run</th>
<th>$\Delta LH / \partial T$ (W m$^{-2}$ K$^{-1}$)</th>
<th>$F_{1, LH}$ (W m$^{-2}$)</th>
<th>$(\Delta LH + \Delta SW_{abs}) / \partial T$ (W m$^{-2}$ K$^{-1}$)</th>
<th>$F_{1, LH + SW_{abs}}$ (W m$^{-2}$)</th>
<th>$\Delta LW_{div} / \partial T$ (W m$^{-2}$ K$^{-1}$)</th>
<th>$F_{1, LW_{div}}$ (W m$^{-2}$)</th>
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<td>3.27 ± 0.35</td>
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<td></td>
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<td>2.92 ± 0.44</td>
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<td>2.56 ± 0.51</td>
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<td>2.51 ± 0.18</td>
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<td>All runs</td>
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<td>0.42 ± 0.92</td>
<td>0.43 ± 0.89</td>
<td>0.62</td>
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<td>1.64 ± 0.08</td>
<td>-1.15 ± 0.17</td>
<td>2.28 ± 0.09</td>
<td>-0.17 ± 0.19</td>
<td>1.94 ± 0.05</td>
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<td>All runs</td>
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<td>2.78 ± 0.10</td>
<td>-2.30 ± 0.23</td>
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Table 1. Estimated linear fit parameters with 95% standard errors of $\Delta LH$, $\Delta(LH + SW_{abs})$, and $\Delta LW_{div}$ against $\Delta T$ for the different WCRP CMIP3 models and runs considered and multimodel estimates, excluding the GFDL CM2.1 2xCO2 run (see text for details).
related to $\Delta T$). This approach was initially proposed by Gregory et al. (2004) in the context of climate sensitivity and forcing and has also been recently used in the context of the global hydrological cycle by LW08.

Under the assumption that there is a “true” linear process (2) that underlies all of the climate models, so that the data from each of the latter results from this single process plus random model-dependent effects, then the slope and intercept coefficients estimated for each of the climate models and the corresponding error estimates can be optimally combined\(^1\) to estimate the parameters $A$ of the linear process according to

$$\hat{A} = \bar{\sigma}^2_A \sum_i \frac{A_i}{\bar{\sigma}^2_{A_i}}, \quad (3)$$

where $A_i$ is the coefficient estimated for the climate model $i$ with estimated error $\sigma_{A_i}$, and $\hat{A}$ is the multimodel optimal estimate. The estimated error for (3) is given by

$$\bar{\sigma} = \left( \sum_i \sigma^2_{A_i} \right)^{-1/2}. \quad (4)$$

Also, a multimodel multirun ensemble dataset was set up for the energy budget terms by linearly interpolating the individual data onto common values of $\Delta T$. The mean and standard deviation were calculated for those values of $\Delta T$ for which at least seven models/runs had data and the linear model (2) was also fit to the mean.

Additional data from a standard case run with stand-alone versions of the radiative transfer schemes used in the CMIP3 models considered from the Radiative Transfer Model Intercomparison Project (RTMIP; Collins et al. 2006a) were also compared to the climate model data.

### 3. Results and analysis

In Fig. 1a we show $\Delta LH$ plotted against the change in global mean surface air temperature ($\Delta T$) for all climate models and runs. The linear model (2) with a single set of coefficients is a reasonable representation of the overall behavior of the climate models, although significant scatter exists across them. The standard deviation with respect to the multimodel/multirun ensemble mean averages to 0.71 W m$^{-2}$ in this case. The estimated slope and forcing coefficients for this ensemble mean are 2.1 W m$^{-2}$ K$^{-1}$ and 1.8 W m$^{-2}$, respectively, which is consistent with the results of LW08. These values are also consistent with the corresponding optimal combination of the estimates for each model and run (Table 1), although the scatter across models is significant (standard deviations of 0.4 W m$^{-2}$ K$^{-1}$ and 0.8 W m$^{-2}$, respectively).

The net radiative cooling [$\Delta (LW_{\text{div}} - SW_{\text{abs}})$; see Fig. 1b, Table 1] has a similar behavior to $\Delta LH$, which is indicative of the relatively small magnitude of $\Delta SH$ (not shown), so that their scatter across models and runs are also similar. On the other hand, the longwave cooling ($\Delta LW_{\text{div}}$; Fig. 1c) is more robust than either (the standard deviation with respect to the multimodel/multirun ensemble mean is 75% of the value for $\Delta LH$). This indicates that the shortwave heating is a source of scatter rather than a robust feature across models. Indeed, as predicted by theory (Takahashi 2009), the quantity $\Delta (LH + SW_{\text{abs}})$ (Fig. 1d) shows an even smaller scatter (68% of that of $\Delta LH$), which indicates that the scatter in $\Delta LH$ and in $\Delta SW_{\text{abs}}$ are anticorrelated.

The differences in scatter indicated above and visually evident in Fig. 1 are not reflected in the linear fit coefficients estimated for the various climate models/runs (Table 1). A reason for this is illustrated in Fig. 2, in which $\Delta LH$ and $\Delta (LH + SW_{\text{abs}})$ for the different runs are plotted against $\Delta T$ for four representative climate models. Although in general the data from different runs tend to cluster around the same lines for each model, the linear fits for each run can have significantly different coefficients. An interesting case is the National Center for Atmospheric Research (NCAR) Community Climate System Model, version 3.0 (CCSM3.0; Fig. 1d), for which the $\Delta LH$ in the three runs can be clearly seen to lie on well-separated, approximately parallel lines, whereas the $\Delta (LH + SW_{\text{abs}})$ data lie on the same line. This is clear evidence that $\Delta (LH + SW_{\text{abs}})$ is better constrained by the longwave physics than $\Delta LH$ alone in this model.

The GFDL CM2.1 data (Fig. 2b) are particularly illuminating for understanding the different fit parameters between runs, because they also include the $2 \times CO_2$ data, corresponding to the ensemble mean of the full-model 20-yr run in which the $CO_2$ concentration is instantly doubled (as with the $2 \times CO_2$ run, except that the model has full-ocean dynamics, as in 1pctto2x). The linear fits for both $\Delta LH$ and $\Delta (LH + SW_{\text{abs}})$ are rather well constrained from the data for each of the runs, but the corresponding lines are well differentiated (Fig. 2b, Table 1). During the early period when $\Delta T$ is small, the $2 \times CO_2$ data start close to the slab model $2 \times CO_2$ run, but, as $\Delta T$ increases, it diverges toward the 1pctto2x results, along which the climate then converges back toward the $2 \times CO_2$ run at higher values of $\Delta T$. This nonlinear behavior has been previously observed in the radiative fluxes at the top of the atmosphere (Forster and Taylor 2006; Williams et al. 2008; Winton et al. 2009, manuscript submitted to J. Climate, hereafter WTH) and is particularly strong in the GFDL models (Forster and Taylor 2006; WTH). In those studies, the nonlinearity is found to emerge from the action of another degree of

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\(^1\) This is done by minimizing the cost function $\sum_i (A_i - \hat{A})^2/\sigma^2_i$. 

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freedom in addition to $\Delta T$ associated with the way the ocean heat uptake in the full climate model affects the warming and cloud distribution (Williams et al. 2008; WTH). To the extent that this effect is small, the full-model climate trajectories will stay close to those of the slab model, but the fit of a linear model to a limited portion of the full-model runs could lead to misleading results. Consistent with this interpretation, the results of the optimal combination of the fit coefficients obtained for the $2 \times CO_2$ run (with no ocean dynamics) are similar to the ones that correspond to the multimodel/multirun ensemble (Table 1), even though the larger range in $\Delta T$ in the former was not included and, therefore, cannot dominate the fit in the latter. Therefore, we believe that the optimal combination of the $2 \times CO_2$ runs and the multimodel/multirun ensemble will provide a more reliable depiction of the robust behavior common to all models and runs, which does not include the nonlinearities that are apparently associated with the dynamical aspects of ocean adjustment.

As previously mentioned, the smaller scatter in $\Delta (LH + SW_{abs})$ compared to $\Delta LH$ for given values of $\Delta T$ implies an antivertical between $\Delta LH$ and $\Delta SW_{abs}$. This can be seen in Fig. 3c, in which the linear fits (Table 1) have been used to estimate the values of $\Delta LH$ and $\Delta SW_{abs}$ at the value $\Delta T = 2 K$, which is approximately the value for which there is the most nearby data and, therefore, the errors associated with extrapolation would be least severe. In this figure, we show that there is indeed an antivertical between the two quantities (with a linear correlation coefficient of $-0.66$) and the fitted linear relation is close to the expected one of $-1$. On the other hand, very little correlation is found if the analysis is done with the linear fit coefficients themselves (Figs. 3a,b), as expected from the previous discussion of the errors that can be made with limited data.

The forcing components for LH and for $(LH + SW_{abs})$ are indistinguishable in the multimodel/multirun ensemble (Table 1), consistent with $SW_{abs}$ being directly controlled by water vapor (and, hence, by temperature and
not by CO₂ concentrations) through the physics of radiative transfer. As a result of this, after the CO₂ concentration is changed but before any warming takes place, ΔLH alone has to balance the associated forcing. Although the doubling of CO₂ does have an effect on SWabs, it is about an order of magnitude smaller than the effect of the associated change in water vapor (Collins et al. 2006a).

On the other hand, the effect of clouds on ΔSW_{abs} cannot be dismissed a priori. However, the scatter in ΔSW_{abs} is well explained by the clear-sky component (Fig. 4), indicating that clouds are not an important source of scatter. There is also no significant relation between ΔSW_{abs} and the clear-sky upward shortwave flux at the surface (not shown), which indicates that surface albedo changes are also unimportant. This suggests that the scatter in ΔSW_{abs} is controlled by water vapor but, while ΔSW_{abs} can differ by a factor of 3 across models, the changes in global mean water vapor content are robust (Held and Soden 2006) and the associated scatter cannot explain the differences in ΔSW_{abs}.

Another possible source for the scatter in ΔSW_{abs} is differences among radiative transfer codes, as found in the RTMIP project, in which stand-alone versions of a variety of these codes subjected to exactly the same change in water vapor (a uniform 20% increase for an idealized profile) resulted in different values of ΔSW_{abs} (Collins et al. 2006a). However, the NCAR CCSM3.0 model spans the full range of the scatter in ΔSW_{abs} (Fig. 4c) despite having the same radiative transfer code in all runs. Furthermore, the scatter in the RTMIP ΔSW_{abs} data mentioned above is not correlated with the scatter in the corresponding WCRP CMIP3 data (not shown).
The previous analysis suggests that the scatter in $\Delta SW_{\text{abs}}$ across models and runs is perhaps associated with subtler aspects of the water vapor changes, particularly on the details of the spatial distribution of the

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**Fig. 3.** (a) Slope and (b) intercept parameters for the linear regression with $\Delta T$ of $\Delta LH$ and $\Delta SW_{\text{abs}}$ plotted against each other. (c) Estimates for $\Delta LH$ and $\Delta SW_{\text{abs}}$ at $\Delta T = 2$ K using the linear regression fits (Table 1). Models are identified by the numbers in Table 1 and are shown for the 2 $\times$ CO$_2$ (o), 1pctto2x ($\Delta$), and 1pctto4x (□) runs. The solid lines represent the case in which the two variables plotted add up to the value corresponding to the linear fit to the multimodel/multi-run ensemble mean $\Delta (LH + SW_{\text{abs}})$. The dashed line in (c) is the linear fit between the variables plotted.

**Fig. 4.** As in Fig. 3, but for clear- and full-sky $\Delta SW_{\text{abs}}$. Solid lines are 1:1 lines, which are included as reference.

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The previous analysis suggests that the scatter in $\Delta SW_{\text{abs}}$ across models and runs is perhaps associated with subtler aspects of the water vapor changes, particularly on the details of the spatial distribution of the
changes in moisture in the models. For instance, in the GFDL CM2.1 model, the changes in shortwave absorption are concentrated in the tropics above the 500-hPa level (not shown), which suggests that small absolute changes in upper-troposphere moisture content have a significant effect on $SW_{abs}$. This is something that could be tested with the radiative kernel approach (Held and Soden 2000; Soden et al. 2008).

An aspect in Fig. 4 that is worth noting is that although both of the linear fit coefficients for the full- and clear-sky $SW_{abs}$ are well correlated (reflecting a direct physical link), the slope coefficient for the clear sky is systematically higher than for the full sky by around 0.1 W m$^{-2}$ K$^{-1}$ (Fig. 4a), which results in smaller values in $\Delta SW_{abs}$ at $\Delta T = 2$ K for the full sky relative to the clear sky by about 20% (Fig. 4c). This is unlikely to be related to changes in clouds with warming, because this is not a robust feature across models (e.g., Bony and Dufresne 2005), but might be related to the basic-state reflection of incoming shortwave radiation by high clouds, which reduces both the basic-state absorption and the increase in this absorption for a given change in water vapor. On the other hand, this would be expected to result in a proportional reduction rather than the uniform one seen in Fig. 4a, so this is probably not the full explanation.

4. Discussion and conclusions

The results of this study support the theoretical prediction that the change in the sum of the surface latent heat flux and atmospheric shortwave absorption (or, equivalently, the net longwave divergence minus the surface sensible heat flux) should vary with CO$_2$-induced global warming more robustly than any other combination of the terms in the energy budget of the atmosphere, because these combinations are proxies for the longwave flux divergence above cloud base, which is determined by longwave physics more robustly than the total atmosphere longwave flux divergence (Takahashi 2009). The results of this study indicate that $\Delta (LH + SW_{abs})$ varies at a rate of around 3.0 W m$^{-2}$ K$^{-1}$ with $\Delta T$ and that doubling CO$_2$ has a direct effect (i.e., “forcing”) of around $-1.8$ W m$^{-2}$.

Despite the fact that clear-sky water vapor changes appear to determine the changes in $\Delta SW_{abs}$, the understanding of what the important aspects of the former are is low. It is only recently that climate models are converging toward producing realistic (sufficiently strong) present-day tropospheric clear-sky shortwave absorption (Wild et al. 2006). Although the physics behind this absorption are well understood from first principles, subtle deficiencies in the depiction of the spectroscopic properties of water vapor have substantial consequences for the clear-sky absorption of shortwave radiation (e.g., Collins et al. 2006b). Furthermore, the convergence in present-day absorption does not necessarily translate to the climate change case and, as shown by Collins et al. (2006a), there are relatively large intermodel discrepancies in the changes in clear-sky surface shortwave flux associated with water vapor that could lead to a systematic error in all models. Specifically, the increase in $SW_{abs}$ associated with an idealized change in water vapor is underestimated by almost all climate models relative to the corresponding line-by-line calculation, which implies that the models are potentially overestimating the increase in LH associated with global warming. On the other hand, the physics that are relevant to the results of the present study are apparently not those of the interaction between the shortwave radiation and water vapor, but rather the processes that control the spatial aspects of the changes in water vapor that lead to differences in the global mean absorption of shortwave radiation by the atmosphere, which are even less well understood.

Considering that $\Delta (LH + SW_{abs})$ varies with $\Delta T$ at a rate of at most around 4 W m$^{-2}$ K$^{-1}$ in the models analyzed and because water vapor increases with global warming (e.g., Held and Soden 2000), so it is unlikely that $SW_{abs}$ would decrease with increasing $T$, the upper bound for the increase in LH per degree global warming in the climate models could be estimated to be around 4 W m$^{-2}$ K$^{-1}$ or 5% K$^{-1}$, which is lower than the Clausius–Clapeyron scaling (around 7% K$^{-1}$) that is followed by the total water vapor content. For LH to increase following the Clausius–Clapeyron scaling (e.g., Wentz et al. 2007), climate models would need to produce a $\partial (LH + SW_{abs})/\partial T$ about 100% higher than they currently do, assuming that $\partial SW_{abs}/\partial T$ is represented correctly. This seems unlikely to occur in future models in the light of the theory of Takahashi (2009), according to which LH + SW$_{abs}$ is a proxy for the longwave flux divergence above cloud base, which depends on relatively well-established longwave physics. It is possible, however, that cloud longwave effects could be systematically underestimated by the models. Perhaps a way in which such effects could lead to an enhanced $\partial (LH + SW_{abs})/\partial T$ is by having low clouds strongly increase with $\Delta T$ [opposite to what most models predict; see Bony and Dufresne (2005)], so that the longwave emission toward the surface is enhanced. However, this would also lead to an opposing enhancement of the absorption of the radiation from the surface, so it seems unlikely that the net flux at cloud base could be sufficiently increased by this process.

It is interesting to consider the implications of having $\Delta SW_{abs}$ relatively unconstrained by the present state of knowledge, with the exception that we expect it to increase with increasing $\Delta T$. In particular, this means that $\Delta LH$ does not even have to be positive. For instance, we
can make an extreme thought experiment in which instead of shortwave absorption by water vapor being dominated by a few almost-saturated bands in the near-infrared, we have it associated with unsaturated weaker and wider bands, but resulting in the same present-day absorption. Then we could expect this absorption to change proportionally to water vapor and, therefore, to increase according to the Clausius–Clapeyron relation. Taking a midtropospheric value of 10% K$^{-1}$ for this relation and a present-day shortwave absorption of 70 W m$^{-2}$ K$^{-1}$ (Kiehl and Trenberth 1997), then the increase would be at a rate of around 4 W m$^{-2}$ K$^{-1}$. Thus, subtracting this from the ensemble value of 3 W m$^{-2}$ K$^{-1}$, which is attributable to longwave physics, would imply that latent heat flux would have to decrease by around 4 W m$^{-2}$ K$^{-1}$ as the climate warms. Although this is a hypothetical scenario that does not agree with the present understanding of the physics of shortwave absorption, it highlights the need for further study into the issue if the changes in the global hydrological cycle are to be quantitatively understood.

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