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Role of water vapor feedback on the amplitude of season cycle in the global mean surface air temperature

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[1] We have analyzed the seasonal variations of global mean surface air temperature (*SAT*) and surface energy budgets of 17 AR4 models. Considerable differences in the amplitude of seasonal cycle (*A*) in the global mean *SAT* in the pre-industrial control simulations among the models have been traced, to a large degree, to differences in their simulated clear-sky downward longwave radiation ($LW_\downarrow$) and latent heat flux (*LH*). We suggest that water vapor feedback process influence the seasonal changes of *SAT* through its roles on the seasonal variations of $LW_\downarrow$ and *LH*. This implies that the simulated seasonal change of global mean *SAT* might contain a clue about the sensitivity of water vapor feedback and the *A* of in *SAT* thus provides some constraint on climate sensitivity since both are subject to the same feedback process. **Citation:** Wu, Q., D. J. Karoly, and G. R. North (2008), Role of water vapor feedback on the amplitude of season cycle in the global mean surface air temperature, *Geophys. Res. Lett.*, *35*, L08711, doi:10.1029/2008GL033454.

1. Introduction

[2] Several studies have indicated that the seasonal cycle amplitude (*A*) of the global mean surface air temperature (*SAT*) provides a constraint on climate sensitivity since both are examples of externally-forced climate variability, and it has been suggested that both are subject to the same climate feedbacks [*Tsushima et al.*, 2005]. Support for this idea has been found recently in correlations between simulated seasonal cycle amplitudes and sensitivity to eternal forcing in the current GCMs [*Covey et al.*, 2000; *Knutti et al.*, 2006]. *Covey et al.* [2000] find a positive correlation ($r \sim 0.4$) between the hemispherical mean amplitude of the seasonal cycle and the sensitivity of seventeen GCMs to a doubling CO2. Such a correlation is marginally significant at the 90% confidence level. *Knutti et al.* [2006] utilize a neural network to establish a stronger correlation ($r \sim 0.88$) between the simulated seasonal cycle amplitudes and the sensitivity to external forcing in a version of the Third Hadley Centre atmosphere-slab ocean model (HadSM3). Most models with high sensitivities tend to overestimate the seasonal cycle compared to observations.

[3] There is considerable variation of the seasonal cycle amplitude as well as the climate sensitivity in the above studies. *Covey et al.* [2000] conclude that equilibrium climate sensitivity is one of many factors influencing the amplitude of seasonal cycle, but accounts for only $r^2 = 15\%$ of its variance among 17 climate models. Therefore, the seasonal cycle amplitude provides only a weak constraint on the climate sensitivity. This is in contrast to the strong constraint of seasonal cycle amplitude on the climate sensitivity found by *Knutti et al.* [2006] since equilibrium climate sensitivity is an important factor influencing the amplitude of seasonal cycle and accounts for $r^2 = 78\%$ of its variance in the HadSM3 model.

[4] One purpose of this study is re-examine the correlation found by Covey et al. between the amplitude of seasonal cycle and equilibrium climate sensitivity using the new GCM data archived by the PCMDI from 17 GCMs generated for the Fourth Assessment Report of IPCC (AR4). As noted by *Covey et al.* [2000], the spread of seasonal cycle amplitudes in their study is due to in part to differing definitions of SAT. Four of the 17 models in their study simply take the temperature of lowest model layer as SAT, while the other 13 make an extrapolation from the lowest layer temperature. In the new GCM outputs for IPCC AR4, SAT is defined uniformly as a temperature above the surface at 2 m and represents a value that is interpolated between the lowest model level and the surface temperature. In our study, a larger correlation ($r \sim 0.63$) is found between the *A* of global mean *SAT* and climate sensitivity among 17 GCMs.

[5] An understanding of the reasons for the discrepancy of the *A* between models may be gained by examining the factors that influence seasonal changes in the global mean *SAT*. In general, the *A* of global mean *SAT* is affected by seasonally varying forcing of sunlight (including the elliptical orbit) and the asymmetric distribution of land between the Northern and Southern Hemispheres. The rate of heat storage in a thin slab at the surface is the net of the global mean energy fluxes at the surface and can be written as

$$N = SW_\downarrow + SW_\uparrow + LW_\downarrow + LW_\uparrow + LH + SH. \tag{1}$$

Here $SW_\downarrow$ and $SW_\uparrow$ are downward and upward flux densities of solar radiation at the surface, $LW_\downarrow$ and $LW_\uparrow$ are the surface incoming and outgoing terrestrial longwave radiative fluxes, *LH* and *SH* are the turbulent fluxes of latent and sensible heat, *N* is the net surface energy flux. The radiative fluxes can be broken down further, e.g., into clear sky (*CLR*) and cloud forcing (*CF*) components.

[6] The main purpose here is to investigate the possible effects of classical feedback processes on the *A* of global mean *SAT*. Both *Covey et al.* [2000] and *Knutti et al.* [2006] mention that key feedback processes are equally important for both seasonal cycle amplitude and climate sensitivity. Using radiative flux data from the Earth Radiation Budget

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Experiment (ERBE), *Tsushima and Manabe* [2001] found that the influence of cloud feedback upon the annual variation of the global mean *SAT* is quite small. *Hall and Qu* [2006] suggest that snow albedo feedback is the key process, and that there exists a strong correlation between the seasonal cycle and the climate sensitivity of *SAT* in the Northern extratropics. In this study, we focus on the role of water vapor feedback in the annual variation of global mean *SAT*. We speculate that water vapor feedback may be dominant for both the seasonal change and climate sensitivity of global mean *SAT*. As suggested by the Clausius-Clapeyron equation, Northern Hemisphere (where there is more land) summertime specific humidity increases more than that during NH wintertime. Therefore, water vapor is expected to trap more $LW_{\uparrow}$ and thus re-emit more $LW_{\downarrow}$ back to the surface heating the earth's surface and the lower atmosphere in the NH summer months than in the winter months. Figure 1 shows that the annual variation of the simulated global mean *SAT* (Figure 1a) in GFDL_CM2.0 generally follows the $LW_{\downarrow}$ (Figure 1b), which peaks in July approaching 341.0 Wm^{-2}. Therefore, water vapor feedback appears to affect the $LW_{\downarrow}$ in such a way as to enhance the annual variation of global mean *SAT* and thus amplify the *A* of *SAT*.

[7] The range for equilibrium climate sensitivity was estimated by currently used GCMs to a doubling of CO2 to be 1.5 to 4.5°C [*Intergovermental Panel on Climate Change*, 2007]. Some recent studies have shown that the spread of feedbacks might stem from the water vapor feedback [*Colman*, 2003; *Soden and Held*, 2006]. This suggests that inter-model differences in water vapor feedbacks account for some of the differences in the *A* of $LW_{\downarrow}$, and thus is responsible for some of the differences in the *A* of *SAT*. If this happens, there should exist significant correlations between differences in the *A* of global mean *SAT*, differences in the *A* of $LW_{\downarrow}$, and differences in the simulated equilibrium climate sensitivity to a doubling of CO2 of existing GCMs.

[8] Here we investigate such correlations using the fields of *SAT* and surface energy fluxes of the pre-industrial control simulations from 17 AR4 model climates. Although about 23 models are available for the AR4, only these 17 models have the complete time series of longwave radiation flux we need. Table 1 shows the acronyms used for the different models. The second row contains the climate sensitivities to doubling CO2, which were usually estimated from mixed layer models. Additional information on the above 17 models is available at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

2. An Interpretation of the Relationship Between Intermodel Differences of Climate Sensitivity and the *A* of Global Mean *SAT*

[9] Table 1 summarizes the simulated *A* of *SAT*, surface energy fluxes in the pre-industrial control runs of 17 AR4 GCMs. We define the difference between the climatological mean January and climatological mean July global mean value of a field as its seasonal cycle amplitude, the same as used in previous studies [*Covey et al.*, 2000; *Tsushima et al.*, 2005]. As demonstrated by *Covey et al.* [2000], the difference between January and July climatological temperature is an excellent approximation to the amplitude of the full seasonal cycle. Following *Covey et al.* [2000], we calculate the observed value of *A* of the global mean *SAT* from *Legates and Willmott* [1990]. Its value is 3.5K. This value is almost identical to that obtained using the surface temperature of NCEP reanalyses [*Kalnay et al.*, 1996]. Values of *A* for each of the models in this study are given in Table 1. The values range from 2.7K to 4.6K. Table 1 indicates that climate models also exhibit wide ranges of the *A* of components of surface energy fluxes. Table 2 lists the correlations between inter-model differences in the *A* of *SAT* and that of each component of surface energy fluxes on the global mean case. It shows that, at the 95% confidence level, the differences in the *A* of the global mean *SAT* is significantly correlated with that of $LW_{\downarrow}$, $LW_{\uparrow}$ and *LH*. In contrast, differences in the *A* of the global mean *SAT* and that $SW_{\downarrow}$, $SW_{\uparrow}$ and *SH* are not statistically significant at the 95% conference level. Figures 2a and 2c show a scatter diagram of the *A* of *SAT* and the *A* of these $LW_{\downarrow}$ and *LH*.

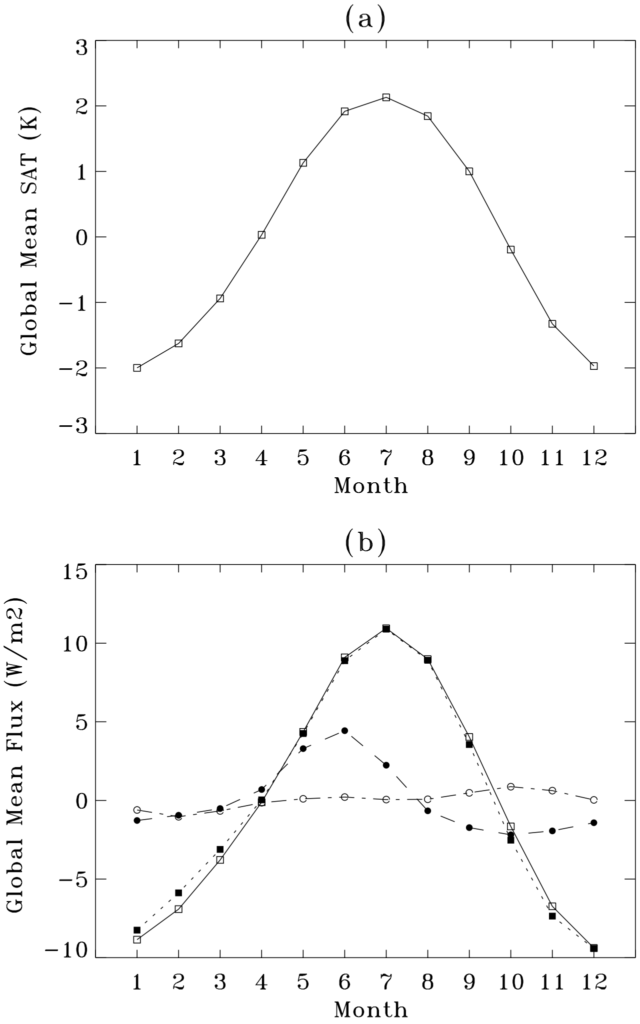

Figure 1. (a) Annual variation of the simulated global mean SAT (K) in GFDL_CM2.0 model. (b) Annual variation of the simulated global mean latent heat flux (*LH*) (dash line), all-sky (solid line), clear-sky (dotted line) surface downwelling longwave radiation ($LW_{\downarrow}$, $LW_{\downarrow\mathrm{CLR}}$) and longwave cloud forcing ($LW_{\downarrow\mathrm{CF}}$) (dot dash line) in GFDL_CM2.0 model.

Table 1. Climate Sensitivity and the Amplitudes of Seasonal Cycle (*A*) of Global Mean *SAT*, Latent Heat Flux, Surface Downwelling Longwave Radiation Fluxes in 17 AR4 Climate Models

	GCMs[a]																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
T_{2x}[b]	2.1	2.1	2.7	2.7	2.9	3.1	3.2	3.2	3.3	3.4	3.4	3.4	3.4	4.0	4.3	4.4	4.4
SAT[c]	2.7	3.3	3.3	3.3	4.1	3.7	4.1	4.1	4.1	3.9	3.5	4.1	4.2	4.0	3.5	4.0	4.6
LH[c]	.3	.3	.5	.6	3.5	2.1	3.7	3.7	4.4	3.1	3.4	2.9	4.1	4.2	4.3	2.5	3.3
$LW_{\downarrow}$[c]	11.7	8.2	14.2	17.0	19.8	16.1	15.6	18.5	18.6	18.0	16.6	19.7	20.1	22.9	20.1	16.0	19.9
$LW_{\downarrow \mathrm{CLR}}$[c]	14.0	10.7	14.6		19.1	16.9	16.5	17.5	19.4	16.8	15.7	20.4	20.3	21.8	19.6	18.3	20.3
$LW_{\downarrow \mathrm{CF}}$[c]	−2.3	−2.5	−0.3		−0.7	−0.8	−0.9	1.0	−0.8	1.2	0.9	−0.7	−0.2	1.1	−0.5	−2.3	−0.4

[a] Acronyms of 17 AR4 models are 1, INM-CM3.0; 2, PCM1.1; 3, CCSM3.0; 4, GISS-AOM; 5, GFDL_CM2.0; 6, CSIRO-Mk3.0; 7, ECHO-G; 8, MRI-CGCM2; 9, UKMO-HadCM3; 10, CGCM3.1 (T47); 11, CGCM3.1 (T63); 12, ECHAM5/MPI; 13, GFDL_CM2.1; 14, MIROC3.2 (m); 15, MIROC3.2 (h); 16, IPSL-CM4; 17, UKMO-HadGEM1. Note that only all-sky $LW_{\downarrow}$ is available for GISS-AOM.

[b] Published sensitivities to doubling CO2 (deg C) for the same models.

[c] The *A* of the global mean *SAT*, the latent heat flux (*LH*), all-sky and clear-sky surface incoming long wave radiative fluxes ($LW_{\downarrow}$, $LW_{\downarrow \mathrm{CLR}}$), and long wave cloud radiative forcing ($LW_{\downarrow \mathrm{CF}}$). The *A* of a field is defined as the difference between the climatological mean January and climatological mean July global mean value.

[10] These $LW_{\uparrow}$ and $LW_{\downarrow}$ are the two largest components of the globally averaged surface energy balance. According to the Stefan-Boltzmann law, it is straightforward that differences in the *A* of global mean *SAT* are significantly correlated with that of $LW_{\uparrow}$. In the model simulations, $LW_{\downarrow}$ has to be determined by comprehensive radiative transfer calculations that take into account the complex radiative characteristics of the atmosphere, and therefore it is very sensitive to deficiencies in their parameterizations. Our results show that there is considerable divergence in the simulated $LW_{\downarrow}$ and that $LW_{\downarrow}$ is an important factor influencing the *A* of *SAT*, accounting for perhaps 45% of variance of global mean *SAT* among 17 AR4 climate models.

[11] Figure 2d shows a scatter diagram of climate sensitivity versus a measure of the *A* of $LW_{\downarrow}$. In this case the correlation coefficients ($r \sim 0.76$) are significant at the 95% confidence level. The wide range of values for *A* of $LW_{\downarrow}$ is explained by the feedback processes that should be related to water vapor feedback and the longwave component of cloud feedback. In Table 2, inter-model differences in equilibrium climate sensitivity and the *A* of the global mean *SAT* is significantly correlated at the 95% confidence level ($r \sim 0.63$). Figure 3 shows a scatter diagram of climate sensitivity versus the *A* of the global mean *SAT*. Figures 2 and 3 confirm the speculation that the feedback processes enhance the seasonal variations of $LW_{\downarrow}$ and thus the strength of the seasonal cycle of *SAT*. This explains why there exists a significant correlation between the equilibrium climate sensitivity of the models to CO_2 doubling and the *A* of global mean *SAT*.

[12] $LW_{\downarrow}$ is composed primarily of longwave emission from the moist boundary layer and the lowest cloud level, and can thus be divided into clear sky and cloud components. At the surface, the cloud radiative forcing can be defined as the difference between the all-sky and clear-sky $LW_{\downarrow}$ values. Table 2 and Figure 2b show that the correlation between differences in the *A* of *SAT* and $LW_{\downarrow}$ in the clear sky are significantly correlated at the 95% confidence level ($r \sim 0.70$). In contrast, no strong relationship exists between inter-model differences in the *A* of global mean *SAT* and that of longwave cloud forcing at the 95% confidence level. These results are consistent with Table 1 in that the simulated seasonal changes of clear-sky $LW_{\downarrow}$ ($LW_{\downarrow \mathrm{CLR}}$) are close to that of all-sky $LW_{\downarrow}$ while the seasonal variations of longwave cloud forcing ($LW_{\downarrow \mathrm{CF}}$) are very small in most GCMs. In addition, Table 2 and Figures 2b and 2e show that the correlation between differences in the *A* of *SAT* and $LW_{\downarrow}$ in the clear sky is almost identical to that in the all sky, and that the correlation between differences in climate sensitivity and in the *A* of $LW_{\downarrow}$ in the clear sky is same as that of in the all sky. Obviously, this suggests that inter-model differences in the *A* of $LW_{\downarrow}$ in the clear sky are strongly influencing differences of seasonal changes of global mean *SAT*, while differences in the longwave component of cloud feedback are of minor importance in accounting for differences of the *A* of *SAT*. We therefore conclude that differences in the simulated *A* of global mean *SAT* are attributable to differences in the seasonal response of clear-sky downward component of the surface longwave radiation caused by the water vapor feedback. This agrees with *Tsushima and Manabe* [2001] on the small influence of the cloud feedback upon the annual variation of the global mean *SAT*. The above results suggest that it is the water vapor feedback that are equally important for both the equilibrium climate sensitivity of the models to CO_2 doubling and the seasonal cycle amplitude of global mean *SAT*.

[13] From Tables 1 and 2 (also Figure 2c), there are considerable differences in the simulated *A* of *LH* and such differences are also significantly correlated with inter-model

Table 2. Correlations Between Intermodel Differences in Equilibrium Climate Sensitivity, the Amplitude of Seasonal Cycle of the Global Mean SAT, and That of the Global Mean Surface Energy Fluxes[a]

	SAT	$LW_{\downarrow}$	$LW_{\uparrow}$	$SW_{\downarrow}$	$SW_{\uparrow}$	*LH*	SH	$LW_{\downarrow \mathrm{CLR}}$	$LW_{\downarrow \mathrm{CF}}$
SAT		**0.69**	**0.76**	0.05	0.44	**0.58**	−0.23	**0.70**	0.38
T_{2x}	**0.63**	**0.76**	**0.72**	0.26	0.47	**0.69**	−0.21	**0.76**	0.35

[a] The correlation is calculated between intermodel differences in sensitivity, the *A* of *SAT* and the *A* of the $LW_{\downarrow}$, $LW_{\uparrow}$, $SW_{\downarrow}$, $SW_{\uparrow}$, *LH*, *SH*, $LW_{\downarrow \mathrm{CLR}}$ and $LW_{\downarrow \mathrm{CF}}$. Correlations significant at the 95% confidence level are bolded. Note that GISS-AOM is not included to calculate correlations of $LW_{\downarrow \mathrm{CLR}}$ and $LW_{\downarrow \mathrm{CF}}$.

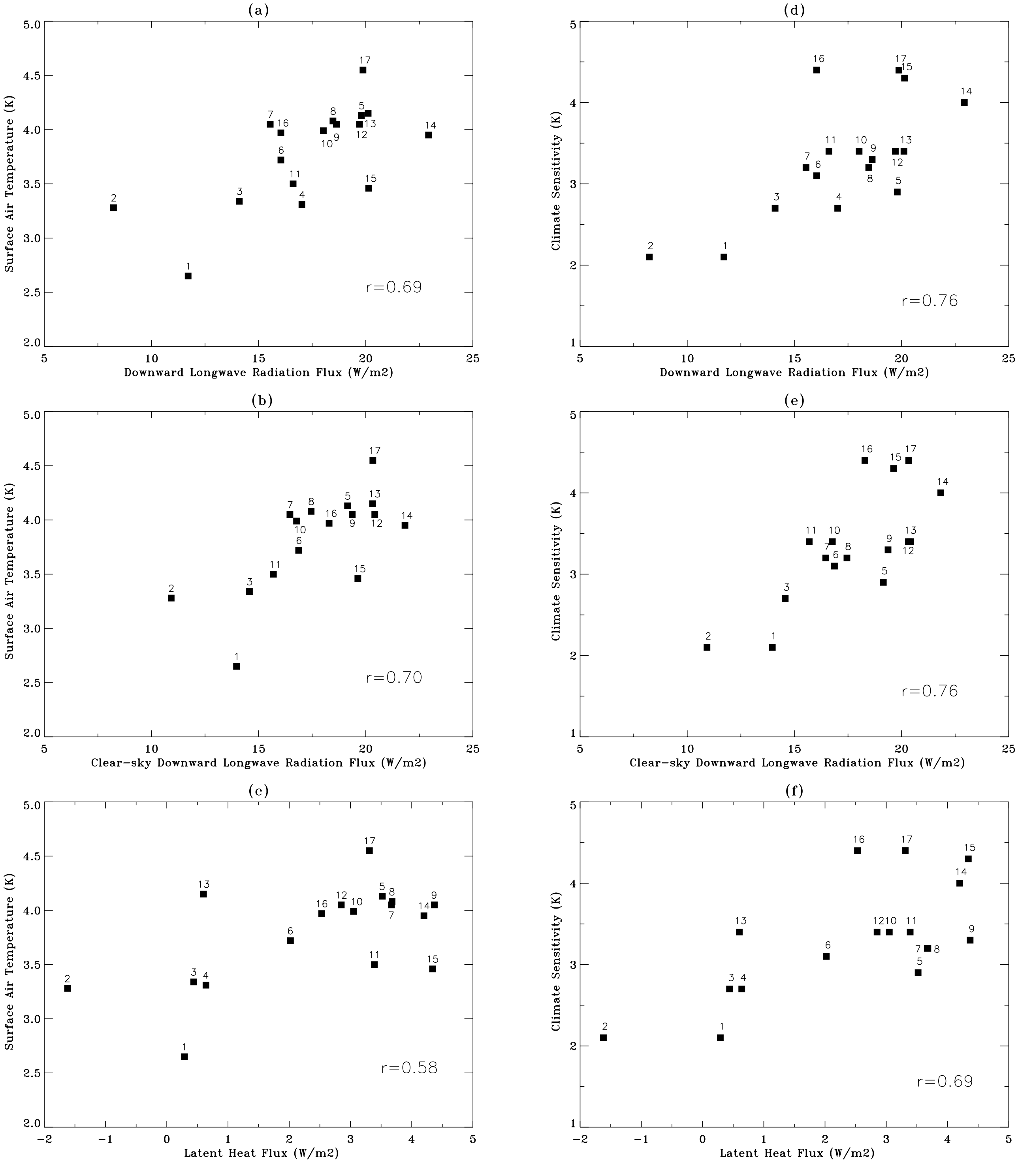

Figure 2. Scatter diagrams of the seasonal cycle amplitude of (a–c) the global mean *SAT* and (d–f) sensitivity of models to doubling CO2 versus the amplitude of seasonal cycle in global mean all-sky, clear-sky surface downwelling longwave radiation ($LW_{\downarrow}$, $LW_{\downarrow\mathrm{CLR}}$) and latent heat flux (*LH*) in AR4 models.

differences in the *A* of *SAT* ($r \sim 0.58$). Such results indicate that *LH* is accounting for 34% of the variance of *A* for the *SAT* among the 17 AR4 climate models. Also, most models with the larger *A* of $LW_{\downarrow}$ tend to simulate the *LH* with larger *A*. Differences in the *A* of $LW_{\downarrow}$ and that of *LH* are significantly correlated at the 95% confidence ($r \sim 0.75$). Such strong interactions among water vapor, $LW_{\downarrow}$ and *LH* can be explained as following. The global mean *SAT* anomalies are associated with water vapor anomalies [*Sun and Held*, 1996]. When more water vapor is present in summertime, the increase in water vapor associated with a warmer climate enhances downward longwave radiation. To maintain surface heat balance, a larger evaporation occurs in summertime, leading to a similar increase in precipitation.

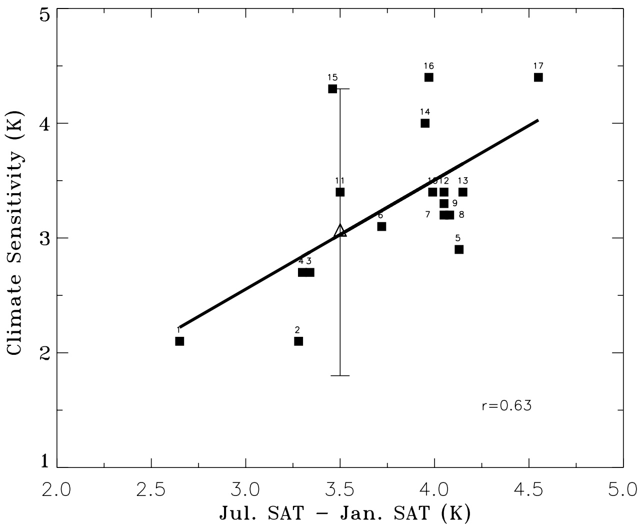

Figure 3. Scatter diagram of the sensitivity of models to doubling CO2 versus the amplitude of seasonal cycle in global mean SAT (defined as the difference the mean SAT of July to that of January) in 17 AR4 models. For the observations the difference is about 3.5K. The correlation between differences in the sensitivity and the *A* was 0.63. A least-squared linear fit is shown as the thick solid line for climate sensitivity as a function of the amplitude of seasonal cycle. The error bar indicates the influence of estimated climate sensitivity from the observations with the 95% confidence interval.

In a time average over thirty days or longer the global mean surface *LH* is obviously proportional to the global mean precipitation. More latent heat released within the troposphere (resulting from the enhanced evaporation) in the summertime warms the troposphere (Figure 1b), thus enhancing troposphere downward longwave radiation emission and amplifying the *A* of $LW_\downarrow$ and *SAT*. Such interactions among seasonal changes of *SAT*, water vapor, the hydrological cycle, *LH* and $LW_\downarrow$ are obviously attributable to water vapor feedback process. The above argument also is consistent with the correlation coefficient between differences in equilibrium climate sensitivity and those of *A* for *LH* ($r \sim 0.69$) are statistically significant at the 95% confidence level in Table 2 and Figure 2f.

3. Concluding Remarks

[14] Using output of 17 AR4 climate models, we reexamine the relationship between intermodel differences in the simulated A of SAT on the global scales and climate sensitivity. The correlation here (about 0.63) is stronger than that from *Covey et al.* [2000], but still much weaker than that from *Knutti et al.* [2006]. We believe that the strength of correlation from *Knutti et al.* [2006] might mainly result from the varying adjustable parameters only in the HadSM3 model, rather than comparing completely different models. We have shown that water vapor feedback is responsible for considerable inter-model differences in the simulated *A* in the global mean *SAT* of 17 AR4 climate models. We saw that inter-model differences in the *A* of global mean *SAT*, $LW_\downarrow$ and *LH* are very tightly linked. This explains why the diversity of the *A* of the simulated global mean *SAT* is significantly correlated to differences in equilibrium climate sensitivities to a doubling of CO_2 at the 95% confidence level. Our results, together with what found by *Covey et al.* [2000], *Hall and Qu* [2006], and *Knutti et al.* [2006], imply similarities between the seasonal cycle and anthropogenic climate change. Therefore, comparison of the simulated amplitude in the seasonal cycle to observations provides a meaningful constraint on simulated feedback strength in climate change. The observed seasonal cycle is consistent with models whose sensitivity to CO2 doubling is around 3.1°C. The 95% confidence interval for this estimate is (1.8°C, 4.3°C). Note that we neglect the influence of anthropogenically and naturally induced climate change on the amplitude of observed seasonal cycle. Our results agree with *Lindzen et al.* [1995] that the seasonal cycle may serve as a surrogate for climate for purposes of evaluating model performance. Our results are also consistent with experiments by *Schneider et al.* [1999] that removal of water vapor feedback in the COLA model produced a reduction in both equilibrium climate sensitivity and the *A* of SAT at high latitude.

[15] Our results suggest that seasonality contain considerable information correlated with climate sensitivity. However, the agreement is far from perfect, indicating that the seasonality considered here contains not all the information needed to predict climate sensitivity successfully. A discrepancy in the magnitudes of the equilibrium climate sensitivities among AR4 models still remains and it may result from the large range of cloud feedback [*Webb et al.*, 2006]. It is a promising strategy to constrain feedbacks combining both seasonality considered in this study and additional information considered by other studies. *Wu and North* [2003] found a significant correlation (about 0.8) between differences in the climate sensitivity and the *A* of variance of the global mean *SAT* anomalies among 13 (older) GCMs. They found that models with small seasonal cycle of variance of the global mean *SAT* tend to have large sensitivities to CO2 doubling. *Tsushima et al.* [2005] find that the information of terrestrial and reflected solar radiation at top of atmosphere obtained from ERBE related to the annual variation of the global mean *SAT* is useful to evaluate the overall feedback of the atmosphere.

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