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Does convectively-detrained cloud ice enhance water vapor feedback?

V. O. John[1] and B. J. Soden[1]

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[1] We demonstrate that coupled Global Climate Models (GCMs) can reproduce observed correlations among ice water path (IWP), upper tropospheric water vapor (UTWV), and sea surface temperature (SST), and that the presence/strength of this correlation has no direct bearing on the strength of water vapor feedback in the model. The models can accurately reproduce a strong positive correlation between IWP and UTWV, a rapid increase of IWP with increasing SST and a 2–3 times increase in the slope of UTWV versus SST for SSTs warmer than ~300 K. We argue that the relative concentrations of IWP to UTWV in both observations and models is too small to significantly influence the observed moistening of the upper troposphere (UT). **Citation:** John, V. O., and B. J. Soden (2006), Does convectively-detrained cloud ice enhance water vapor feedback?, *Geophys. Res. Lett.*, *33*, L20701, doi:10.1029/2006GL027260.

1. Introduction

[2] Atmospheric convection strongly governs the distribution of ice and water vapor in the tropical upper troposphere (UT) and these, in turn, play a key role in regulating climate and its sensitivity to increasing greenhouse gases. Yet despite their importance, the physical processes which determine the outflow of cirrus condensate and the fidelity of their representation in global climate models are not well known. The role of convectively-detrained condensate in modifying the moisture budget of the UT and the potential feedback of this humidification upon the climate system is widely debated. In particular, the partitioning of detrained moisture between vapor and condensate, and the radiative consequences of this moisture remain a poorly constrained problem whose representation is, by all accounts, greatly simplified in current models.

[3] Previous studies have shown that the climate sensitivity in simple radiative convective models is highly dependent upon model assumptions regarding the representation of cloud microphysical processes [*Sun and Lindzen*, 1993; *Renno et al.*, 1994; *Emanuel and Pierrehumbert*, 1996; *Tompkins and Emanuel*, 2000; *Larson and Hartmann*, 2003]. Of particular importance is the convective precipitation efficiency which plays a key role in determining the amount of ice detrained from convective updrafts and whose simplified representation in global climate models (GCMs) has raised concerns about their adequacy for climate change studies.

[4] Underscoring these concerns is the realization that current GCMs differ markedly in their simulation of cloud ice and the response of this ice to global warming. For example, Figure 1 examines the annual, zonal-mean distribution of cirrus cloud cover and ice water path simulated by the coupled ocean-atmosphere models used in the 4th Assessment of the Intergovernmental Panel on Climate Change (IPCC AR4). Despite having very similar distributions of upper tropospheric cloud cover (not shown), the models differ markedly in their simulation of both the climatological ice water path (Figure 1, top), and the response of ice water path to increased CO_2 (Figure 1, bottom). Note that all models shown in Figure 1 lack any explicit dependence of parameterized cloud microphysics upon the climate state – a simplification which likely helps to reduce the model spread.

[5] Because of the difficulty of measuring the relevant cloud microphysical processes, some studies have attempted to infer feedbacks from the observed spatial or temporal relationships between surface temperature, cloud ice and water vapor. *Lindzen et al.* [2001] found that the amount of cirrus generated from convection decreased as the temperature increased. This, they hypothesized, could indicate the presence of a negative feedback in the climate system by which an enhancement in precipitation efficiency reduces the convectively detrained cloud ice thereby drying the UT as the climate warms. However, a growing number of studies [*Salathe and Hartmann*, 1997; *Sherwood*, 1999; *Dessler and Sherwood*, 2000; *Folkins et al.*, 2002; *Soden*, 2004; *Luo and Rossow*, 2004; *Sherwood and Meyer*, 2006] have found that the evaporation of ice does not appear to be an important source of moisture for the UT.

[6] More recently, *Su et al.* [2006] observed a positive relationship between surface temperature, cloud ice and upper tropospheric water vapor. Above 300 K, the amount of cloud ice increased rapidly with surface temperature and the upper tropospheric humidity as well as the greenhouse trapping of outgoing longwave radiation associated it increased rapidly with cloud ice which, they hypothesized, represented an enhanced positive feedback from water vapor about 3 times that implied solely by thermodynamics.

[7] In this study, we compare the observed relationships among IWP, UTWV, and SST with those obtained from climate model simulations used in the IPCC AR4. We find that models accurately reproduce the observed relationships among SST, IWP and UTWV, and their ‘‘enhanced’’ behavior when the SSTs are warmer than ~300 K. Finally, we show that the presence/strength of these spatial correlations have no correlation to the strength of the climate feedback from water vapor simulated in the models.

2. GCM Results

[8] We selected 10 years (1991–2000) of coupled GCM outputs from IPCC AR4 scenario, the simulations of the climate of the twentieth century (20C3M). Table 1 lists models for which the data were readily available for this study (A detailed description of these models can be found online

[1]Division of Meteorology and Physical Oceanography, Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida, USA.

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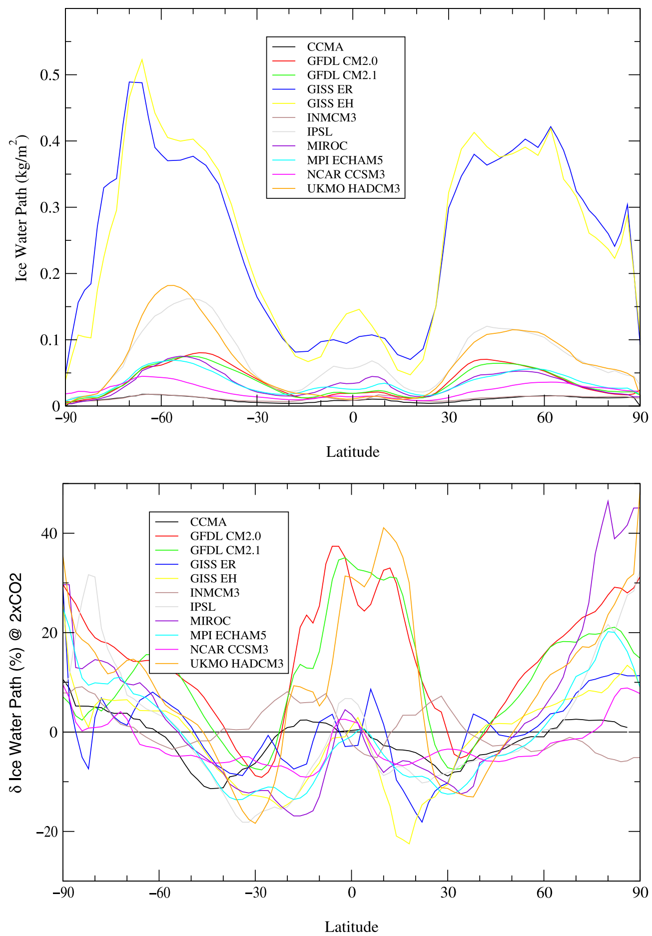

Figure 1. (top) The climatology of zonal annual mean IWP from various climate models in the IPCC AR4 data archive. (bottom) Model predictions of the relative change in zonal annual mean IWP after a CO_2 doubling. Note the large discrepancies between the different models, both in the present mean state and in the predicted response to a changing CO_2 concentration.

at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). Fields of specific humidity, ice water path, atmospheric temperature, and surface skin temperature are used for calculating annual mean UTWV, IWP, and SST. Since the archived model output does not include vertical profiles of cloud ice but only the column-integrated IWP, a direct comparison between UTWV and IWP integrated over the same layers was not possible. Instead, model profiles of specific humidity were used to compute the UTWV for a layer between 500 and 200 hPa, assuming that the ice clouds primarily occur within this layer.

[9] This section discusses relationships among UTWV, IWP, and SST. The analysis is presented in a similar way as by *Su et al.* [2006] using the GCM data and therefore the following discussion is limited to data over tropical (30° S to 30° N) ocean. Nevertheless, we found similar results for tropical land regions also.

2.1. Relationship Between IWP and UTWV

[10] A strong correlation between IWP and UTWV has been noted in previous observational studies [e.g., *Su et al.*, 2006] and is also found in the GCM simulations. Figure 2 shows scatter plots of annual mean ln(UTWV) versus ln(IWP) over tropical ocean for all the models. Most of the models show a very robust relationship between the two quantities (correlation coefficients and linear fit parameters are given in Table 1). All models simulate a strong spatial correlation between IWP and UTWV with correlation coefficient ranging from 0.58 to 0.94 (r, the second column in Table 1) with a mean value of 0.79 ± 0.14. The slope of the linear fit between IWP and UTWV is more variable, ranging from 0.23 to 0.49 (b, the fourth column in Table 1) with a mean value of 0.37 ± 0.09. While the slope of the regression between UTWV and IWP is highly variable from model to model, it is worth noting that for most of the models the strength of the spatial relationships is larger than what was observed from Microwave Limb Sounder (MLS) [*Su et al.*, 2006].

Table 1. Statistics of the Relationships Among IWP, UTWV, and SST[a]

	ln(IWP) Versus ln(UTWV)			ln(IWP) Versus SST			ln(UTWV) Versus SST						
				SST ≥ 300 K			SST < 300 K			SST ≥ 300 K			
Model	r	a	b	r	a	b	r	a	b	r	a	b	λ_{H_2O}
BCCR_BCM2_0	0.94	6.11	0.38	0.00	5.00	0.00	0.61	−23.09	0.10	0.02	5.51	0.01	–
CCCMA_CGCM3_1	0.85	6.46	0.49	0.57	−110.59	0.37	0.50	−9.49	0.09	0.64	−69.46	0.26	–
CNRM_CM3	0.94	6.34	0.38	0.15	−46.93	0.17	0.68	−24.36	0.11	0.35	−44.17	0.17	1.83
CSIRO_MK3_0	0.80	6.41	0.36	0.46	−94.35	0.33	0.65	−21.76	0.10	0.57	−47.83	0.18	–
GFDL_CM2_0	0.61	6.74	0.23	0.41	−125.20	0.43	0.64	−21.86	0.10	0.58	−50.32	0.19	1.87
GFDL_CM2_1	0.66	6.80	0.24	0.43	−128.65	0.44	0.62	−24.51	0.11	0.68	−62.04	0.23	1.97
IAP_FGOALS1_0_G	0.58	6.67	0.45	0.51	−54.07	0.19	0.66	−24.11	0.11	0.73	−41.70	0.16	–
INMCM3_0	0.93	6.52	0.46	0.17	−32.26	0.12	0.53	−20.01	0.09	0.26	−19.11	0.09	1.56
MIROC3_2_MEDRES	0.88	6.21	0.39	0.49	−100.92	0.35	0.71	−30.90	0.13	0.57	−56.89	0.21	1.64
MPI_ECHAM5	0.85	6.57	0.35	0.39	−109.10	0.37	0.37	−9.79	0.06	0.57	−62.56	0.23	1.90
NCAR_CCSM3_0	0.82	6.55	0.45	0.66	−130.35	0.44	0.49	−16.08	0.08	0.79	−95.88	0.34	1.60
UKMO_HADCM3	0.64	6.82	0.24	0.39	−104.96	0.36	0.21	−3.78	0.04	0.68	−60.94	0.23	1.67
GFDL(300−150 hPa)	0.85	4.44	0.30	0.48	−126.34	0.43	0.73	−23.17	0.09	0.59	−48.02	0.18	–
Su et al. [2006]	0.88	5.00	0.22	0.67	−225.10	0.75	0.44	−12.99	0.06	0.65	−55.03	0.20	–

[a]Correlation and fit parameters for different models (column 1) are presented. Columns 2 to 4 represent values for ln(IWP) vs. ln(UTWV), columns 5 to 7 represent values for ln(IWP) vs. SST, Columns 8 to 13 represent values for ln(UTWV) vs. SST, and the last column represent water vapor feedback values, λ_{H_2O}The correlation coefficient is denoted by r. The linear fit is in the form of y = *a* + *b* ∗ x, where *a* is the offset and *b* is the slope. The fit parameters have different units in case of different quantities. In case of ln(IWP) vs. ln(UTWV), *a* and *b* are unit less, where as for all other cases *b* has the unit of K^{-1} and *a* has no units. The water vapor feedback values (λ_{H_2O} in W m^{-2} K^{-1}) are taken from *Soden and Held* [2006].

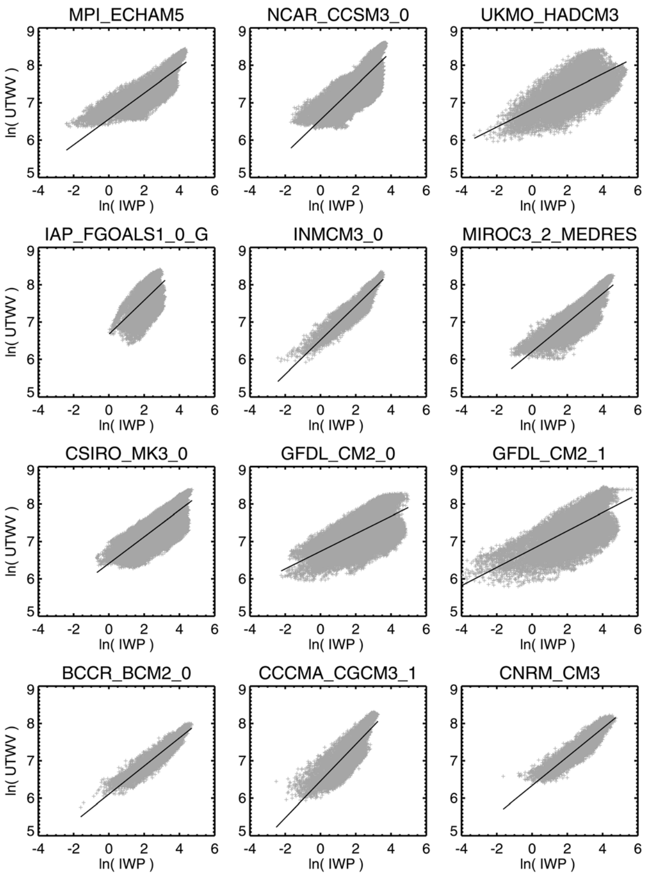

Figure 2. Scatter plots of natural logarithm of upper tropospheric water vapor (UTWV) versus natural logarithm of ice water path (IWP) in the upper troposphere (UT) for all the coupled GCMs. Upper troposphere here is defined as the atmospheric layer between 500 and 200 hPa. Note that IWP was obtained from the IPCC archive where as UTWV was calculated from model parameters. Both UTWV and IWP are expressed in g m^{-2}. A linear fit between the two quantities is shown by the black solid line. Correlations and fit parameters are given in Table 1.

[11] Note that some models, such as the GFDL or NCAR GCMs, show greater scatter and thus a relatively weaker correlation between IWP and UTWV than is observed. We believe the greater scatter likely reflects the aforementioned difference in vertical layers used for computing IWP and UTWV in the models relative to what was used by *Su et al.* [2006]. To investigate this, vertical profiles of ice water content (IWC) were obtained for GFDL_CM2_0 model (data were obtained directly from GFDL) to calculate IWP for a thinner layer of the atmosphere between 300 and 150 hPa. This is closer to the upper tropospheric layers defined by *Su et al.* [2006]. UTWV was then also re-calculated for the same layer of the atmosphere. We denote them as UTWV* and IWP*. Figure 3 a shows the resulting scatter plot of ln(UTWV*) versus ln(IWP*) which now shows a robust relationship. The correlation between IWP* and UTWV* is 0.85 and the linear fit has a slope of 0.3. Thus, the large scatter for some models in Figure 2 is likely due to the fact that IWP available from the IPCC data archive and UTWV are not available for similar layers of the atmosphere.

[12] The strong correlation of IWP* with UTWV* could imply that the evaporation of detrained cloud ice represents an important source of vapor for the UT. However, it can be seen from Figure 3b that there is a large difference in the magnitudes of IWP* and UTWV*. The maximum value of IWP* is only 30 g m^{-2} whereas the maximum of UTWV* is 300 g m^{-2}. This large difference in magnitudes of IWP* and UTWV* is consistent with the observed values given by *Su et al.* [2006], approximately 15 and 250 g m^{-2}, respectively. Thus, in both observations and models the concentrations of IWP are nearly an order of magnitude smaller than those of UTWV. It would thus seem unlikely that IWP could provide a significant source of water for the UT and their strong spatial correlation likely results from the fact that both are generated from convective transport and thus their distributions would be expected to be highly correlated. Similar conclusions have also been obtained from recent observational and modeling investigations [*Luo and Rossow*, 2004; *Sherwood and Meyer*, 2006; *Clement and Soden*, 2005].

2.2. Relationship of IWP and UTWV to SST

[13] Figure 3c shows the relation between IWP* and SST for GFDL_CM2_0 model. An exponential relationship can be seen with IWP* increasing rapidly with SST for SST > ∼300 K. Likewise, the GFDL GCM also simulates a rapid increase in UTWV with SST as the SSTs exceed 300 K. Figure 3d shows a scatter plot of natural logarithm of UTWV* versus SST. One can see two domains - one where the SST < 300 K and the other where SST ≥ 300 K. In both domains ln(UTWV*) and SST follows linear relationship, with the SST ≥ 300 K domain having a steeper slope

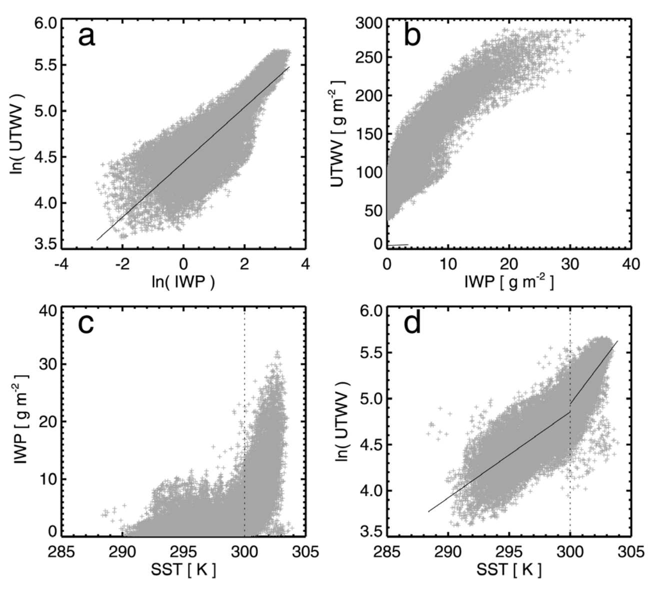

Figure 3. Scatter plots of (a) natural logarithm of UTWV* versus natural logarithm of IWP*, (b) UTWV* versus IWP*, (c) IWP* versus SST, and (d) natural logarithm of UTWV* versus SST for GFDL_CM2_0 model. Correlation and fit parameters are given in the last but one row of Table 1. Note that UTWV* and IWP* are calculated for the atmospheric layer between 300 and 150 hPa. There are two linear fits in Figure 3c: one for data points where SST < 300 K and the other one for data points where SST ≥ 300 K.

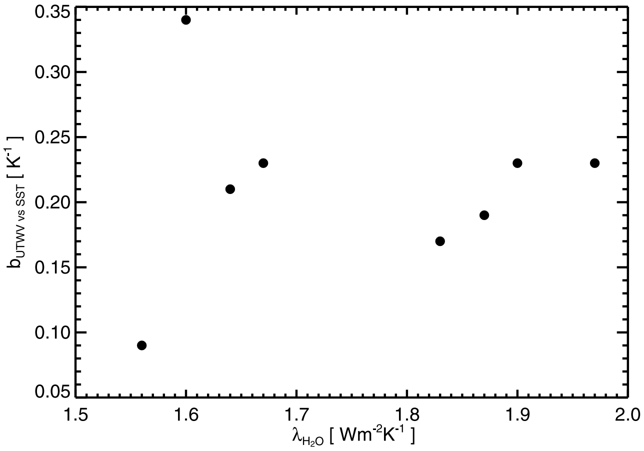

Figure 4. Scatter plot of $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$ for SST $\geq$ 300 K and the water vapor feedback values (λ_{H_2O}) obtained from *Soden and Held* [2006].

(compare columns 10 and 13 in Table 1). This suggests that the amount of water vapor in the UT increases as SST increases, and the rate of this increase accelerates for SSTs greater than 300 K.

[14] This rapid increase in both IWP* and UTWV* is consistent with the observed relationships from MLS noted by *Su et al.* [2006] and was interpreted as evidence of a convectively-induced enhancement of water vapor feedback. *Su et al.* [2006] hypothesize that the detrainment and evaporation of cloud ice could substantially enhance the concentration of water vapor in the UT and, given it's strong correlation to SST, yield a feedback from water vapor that is much larger than what is expected from thermodynamic considerations alone [*Su et al.*, 2006]. However, previous studies have shown that spatial correlations are not necessarily good surrogates for climate feedbacks [*Bony et al.*, 1995]. Consider, for example, the GFDL model which accurately reproduces the rapid increase of IWP* with SST that is cited as evidence of an enhanced feedback. Yet, previous studies have shown this model to have a feedback which is consistent in magnitude with that expected from a constant relative humidity increase in water vapor [*Held and Soden*, 2000; *Soden et al.*, 2005].

[15] The irrelevance of spatial correlations between SST and IWP to the strength of water vapor feedback is further highlighted by considering the other IPCC models. The relationship between SST and IWP is highly variable from model to model. With the exception of one, all exhibit a positive relationship between the warmest SSTs and IWP, however the slope, $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$ (b, the seventh column in Table 1), varies considerably and is somewhat weaker compared to the observed slope. If IWP was a significant contributor to the UTWV budget and if the spatial regressions of $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$ were reflective of the enhancement of water vapor feedback, then one would expect the models to exhibit differing strengths of this feedback in response to global warming.

[16] To investigate this, we compare the slope of $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$ to the strength of water vapor feedback calculated in a recent study by *Soden and Held* [2006] using the same models. Comparison of the $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$ for SST $\geq$ 300 K as a function of the water vapor feedback values (λ_{H_2O}, last column of Table 1) for 8 models (Figure 4) reveals that the strength of water vapor feedback in the models does not depend upon the slope $\frac{\partial \ln(\mathrm{IWP})}{\partial \mathrm{SST}}$. Indeed, *Soden and Held* [2006] found that all models exhibit a robust positive water vapor feedback, consistent with that expected from a constant relative humidity increase in water vapor.

3. Summary and Conclusions

[17] The observed relationships among SST, IWP, and UTWV are compared to those simulated from coupled GCMs to assess the fidelity of their representation in models and investigate whether convectively detrained ice can enhance water vapor feedback. It is found that models can reproduce: (1) a robust, positive correlation between IWP and UTWV, (2) a rapid increase of IWP for SSTs warmer than ~300 K, and (3) a 2–3 times increase in the slope of UTWV versus SST when SST is warmer than ~300 K.

[18] It is further demonstrated that models can accurately reproduce the observed relationship among SST, IWP and UTWV, and still simulate a water vapor feedback which is consistent in strength with that expected from a constant relative humidity moistening of the atmosphere. That is, there is no need for the models to simulate an "enhanced" water vapor feedback in order to reproduce the observed behavior of SST, IWP and UTWV. Moreover, the strength of the spatial correlations between SST and IWP are shown to be uncorrelated to the strength of water vapor feedback simulated by the models in response to global warming. This is consistent with previous studies which suggest that the relative concentrations of IWP to UTWV in both observations and models is too small to significantly influence the observed moistening of the upper troposphere.

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V. O. John and B. J. Soden, Division of Meteorology and Physical Oceanography, Rosenstiel School for Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, FL 33149, USA. (vojohn@rsmas.miami.edu)