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LONGWAVE CLOUD RADIATIVE FORCING DEPENDING ON THE DIFFERENT DEFINITION OF CLEAR SKY: UPPER TROPOSPHERIC WATER VAPOR CLIMATOLOGY

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1. INTRODUCTION

The ERBE method measures fluxes that would occur without clouds which are referred to as 'clear-sky flux' since they are composed of clear-sky pixels. On the other hand, in the climate models cloud amounts are forcefully set to zero at each time when the clear-sky flux calculation is needed. Since clouds develop only under favorable dynamic and thermodynamic conditions, the atmospheric state only for cloud-free area within a grid box should not in general be the same as the grid mean normally used for the clear-sky flux calculation in the model approach. Therefore atmospheric conditions representing the ERBE clear sky fluxes should not be equal to those in the radiosonde measurements or model outputs because atmospheric profiles of temperature and moisture also change when the clear-sky atmosphere turns into the cloudy condition. Assuming that cloud area in a given cloudy total sky is more humid than the remaining clear-sky area, it can be expected that the composite of satellite-estimated cloud-free scenes (i.e., clear-sky radiation flux) represents a drier atmosphere than the mean total sky which is equivalent to the clear-sky condition of model approach.

The potential drier bias of satellite-estimated cloud radiative forcing (CRF) has been examined; direct comparison of model-estimated clear-sky longwave fluxes with ERBE estimates had been made using either radiosonde observations (Collins and Inamdar, 1995) or reanalysis products (Slingo et al., 1998). Common finding in those studies is that ERBE clear-sky longwave fluxes are systematically higher up to 10-15 Wm^{-2} over the tropical humid areas where deep convections are prevalent (and thus higher ERBE CRF). Consistent with the higher ERBE clear-sky longwave fluxes over the humid region, the recent study of Allan and Ringer (2003) showed that ERBE clear-sky flux is biased up to 15 Wm^{-2} over the convectively active regions.

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In this study we provide evidence that upper tropospheric water vapor (UTW) changes occurred during the cloudy sky (or total sky) formation is the main cause inducing the discrepancies between the ERBE clear-sky longwave flux and model-calculated clear-sky longwave flux over the tropics. In doing so, we generate the clear-sky UTW climatology which likely corresponds to the ERBE clear-sky condition by relating UTWs retrieved from Special Sensor for Microwave (SSM/T-2) to International Satellite Cloud Climatology Project (ISCCP) cloud data. Then longwave radiation fluxes with two clear-sky UTW fields are estimated and consequences of their difference in the climate studies are discussed.

2. DATA DESCRIPTION

The so called UTW, i.e., water vapor amount in the layer between 200 mb and 500 mb was retrieved from the microwave measurements by SSM/T-2 onboard the DMSP satellite by applying a statistical-physical algorithm developed by Sohn et al. (2003). The water vapor profile can be inferred from the SSM/T-2 instrument aboard Defense Meteorological Satellite Program (DMSP) satellites since the sensor carries three channels around the 183 GHz strong water vapor absorption band. The algorithm of Sohn et al. (2003) is based on the physical relaxation utilizing statistical covariance information to provide initial guess profiles and to constrain the updating step in the relaxation process. The validation against radiosonde observations shows UTW retrievals exhibiting an rms error of 0.68 kg m^{-2} with integrated water vapor (IWC) biases below 5% for upper tropospheric layers 700-500 mb and 500-200 mb. Pentad mean UTW data for six summer months (JJA: June, July and August) of 1997 and 1998, and six winter months (DJF: December, January, and February) of 1997 and 1998 were produced for this analysis. The pentad means were constructed in the 2.5° x 2.5° grid format being consistent with ISCCP cloud data.

Relating clouds to water vapor in the upper troposphere, the ISCCP cloud data are employed. We use ISCCP C1 data set which provides various retrieved and calculated parameters with a spatial resolution of 2.5° x 2.5° grid and with a 3-hour sampling.

3. DETERMINATION OF CLEAR-SKY UTW

3.1 Satellite clear-sky UTW

Instead of explicitly determining clear-sky scenes from larger SSM/T-2 foot prints about 50 km at the nadir we rather use cloud information in conjunction with SSM/T-2 derived UTW data in order to determine the clear-sky UTW when cloud disappears. It has been suggested that high clouds can be used as a surrogate for the upper tropospheric water vapor because it is fed by detrained hydrometeors from cumulus towers. However, in this study, to account for the water vapor distribution under cloud-free conditions, we employ a regression scheme that uses vertically stratified clouds.

Introducing low (A_l), middle (A_m), and high (A_h) cloud amount and relating to UTW, the following regression equation can be formulated:

$$UTW = a + b_1 A_l + b_2 A_m + b_3 A_h \quad (1)$$

where *a* is the interception point and *b*'s are regression coefficients. Eq. (1) can be further expressed as a following equation:

$$UTW = UTW_{clr} + \frac{\partial UTW}{\partial A_l} A_l + \frac{\partial UTW}{\partial A_m} A_m + \frac{\partial UTW}{\partial A_h} A_h \quad (2)$$

where UTW_{clr} is then clear-sky UTW. Thus, from a multiple linear regression relating multi-level cloud distribution to UTW, clear-sky UTW can be obtained when $A_l = A_m = A_h = 0$. Since UTW_{clr} is the water vapor amount within the upper tropospheric layer when cloud is absent at a given location and ERBE-type clear-sky fluxes are from cloud-free scenes, UTW_{clr} is likely similar to the UTW distribution that EBRE clear-sky can hold. Because of that we refer UTW_{clr} to as 'satellite clear-sky UTW'.

3.2 Model clear-sky UTW

In the climate model, cloud amounts are forcefully set to zero at each integration time while holding thermodynamic variables when the clear-sky flux calculation is needed. Therefore the model-calculated clear-sky should have an UTW equal to the measured mean UTW whose term is located in the left-hand side of Eq. (2). Because of the equivalent quantities, the measured UTW is now referred to as 'model clear-sky UTW'. Therefore the difference between the model clear-sky UTW and satellite clear-sky UTW can be interpreted as the intrinsic quantity in disagreement between the satellite and model approaches because of different definition of the clear sky. Furthermore, it is possible to interpret the ERBE LW CRF as longwave fluxes not only induced by cloud optical properties but also contributed by water vapor changes associated with cloud development.

4. CLEAR-SKY UTW FIELDS

Regression coefficients of Eq. (1) were determined at each 2.5°x2.5° grid point from 36 pentad means of UTW and cloud amounts for JJA and DJF. In order to examine how well UTW is predicted by vertically stratified clouds (here low, middle, and high clouds), explained variances for JJA and DJF periods are given in Fig. 1. During the summer explained variances higher than 0.4 are found in tropical convective areas such as Asian summer monsoon region, Western Pacific warm fool area, and the ITCZ extending from the Western Pacific to the East Pacific. Since the UTW is supplied mainly through the evaporation of hydrometeors from high-level clouds over the convective area, relatively high values of explained variance can be expected over the convectively active regions. In contrast relatively smaller explained variances are noted over the north and south flanks of the convective areas, implying that correlation between cloud and UTW is weak over the dominant descending regions in which the moisture variation is mainly controlled by horizontal advection of water vapor associated with large-scale circulation (Pierrehumbert and Roca, 1998).

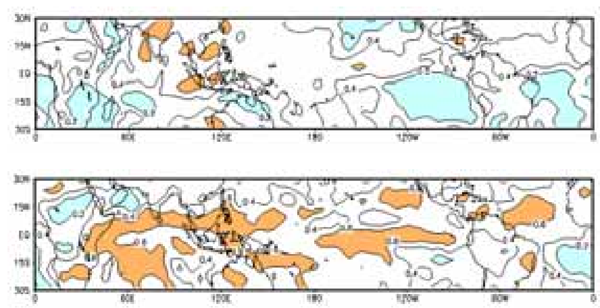

Figure 1: Geographical distribution of explained variances of UTW by vertically stratified ISCCP clouds for (a) the summer of 1997/1998, and (b) the winter of 1997/1998

Same interpretation can be applied for the DJF period. However, in comparison to the JJA period, the DJF period shows higher explained variances over the most of the tropics except North African and Arabian dry regions and cold oceanic regions over the Southeast Pacific and the South Atlantic off South Africa. These lower explained variance regions also appear to be in the descending branch of the Hadley-type circulation.

Although we discussed how well UTWs are related with vertically stratified clouds in terms of explained variances, it is interesting to examine the accuracy of predicted UTW from clouds. In doing so, UTWs for JJA and DJF periods are predicted from corresponding means of low, middle, and high cloud amounts on seasonal time scale by applying the obtained regression coefficients. Results are given in Fig. 2 with UTWs retrieved from SSM/T-2 measurements. In Fig. 2 each data point represents the six-month mean UTW at a given 2.5°x2.5° grid point. The good agreement between measured and predicted UTWs strongly suggests that the water vapor amount in the tropical upper troposphere is closely related to the presence of clouds at least in the seasonal time scale although variations seem larger in the pentad time scale as indicated in the explained variance map of Fig. 1.

In order to examine the different clear-sky UTWs employed in satellite method and model approach, satellite clear-sky UTW, model clear-sky UTW (or measured UTW), and their difference for the JJA of 1997-1998 (i.e., 6 month mean) are presented in Fig. 3. The shaded areas in Fig. 3 represents UTWs greater than 2, 3, and 1 kg m^{-2} for satellite clear-sky UTW, model clear-sky UTW, and the difference field, respectively. In the satellite clear-sky UTW field (top panel), local maximum areas are found over the convectively active regions such as Asian summer monsoon region and the area extending from the equatorial eastern Pacific to Colombia. Higher clear-sky UTW values over the convective areas are not surprising if it is considered that clear-sky area near the cloud edge is significantly influenced by the outflow of moist air from cumulus tower or evaporation of dissipating clouds near the convection cell. Udelhofen and Hartmann (1995) showed that high relative humidity in the upper tropospheric layer is confined to within 500 km from the cloud edge. Thus, the clear-sky composite from cloud-free pixels should hold relatively moister conditions in the convective area because clear areas between cloud clusters or near convective clouds are likely moist.

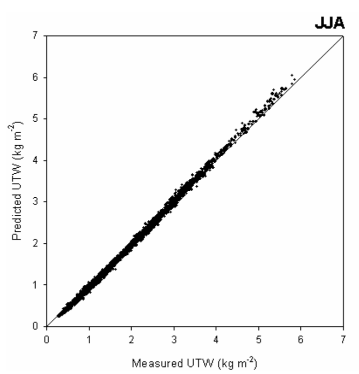

Figure 2: Scatterplot of measured vs. predicted UTWs for the summer of 1997/1998.

Since the model clear-sky UTW contains cloud influence on moisture profile and air is saturated within clouds it is obvious to find that the model clear-sky (or measured) UTW field for JJA given in the middle panel of Fig. 3 shows maximum areas over the convectively active regions. As clearly indicated in the difference map (bottom panel), model clear-sky UTW is wetter by 1 kg m^{-2} over the most of Asian monsoon region, western Pacific, Central Africa, and equatorial eastern Pacific - Central America area. The increased humdity is apparently due to the cloud formation as explained in Eq. (2).

During the DJF period of 1997 and 1998, the maximum regions of satellite clear-sky UTW and model clear-sky UTW are found in the Maritime Continent to the central Pacific, and in rain forest areas of South Africa and South America, due to the shift of convective zone associated with the seasonal change -- see Fig. 4. However, UTW magnitudes seem smaller than shown during the summer. Due to the shift of deep convection zone, the difference map (bottom panel) shows the increased UTW for the model clear sky greater than 1 kg m^{-2} over the most of tropical latitudes between 10°N and 20°S.

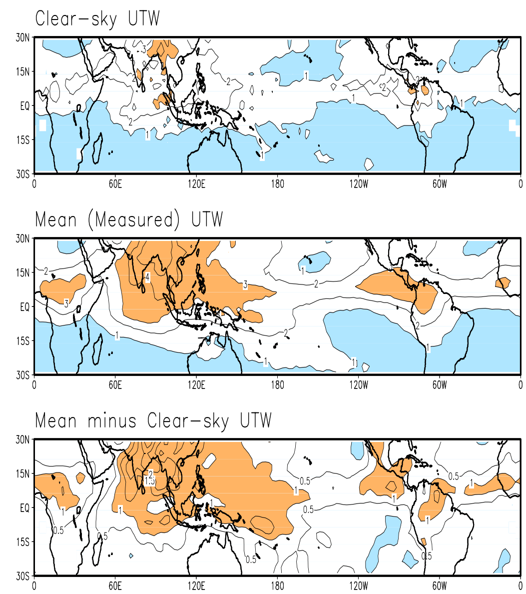

Figure 3: Geographical distributions of clear-sky UTW (top), measured mean UTW (middle), and mean minus clear-sky UTW (bottom) for the summer of 1997/1998.

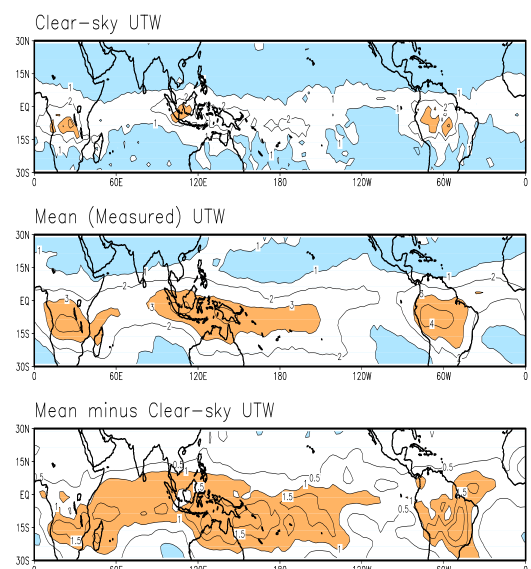

Figure 4: Same as Fig. 3 except for the winter of 1997/1998.

5. CONTRIBUTION OF CLEAR-SKY UTW DIFFERENCE TO THE CRF

The main objective of this study is to explain the discrepancies found between satellite-estimated and model-calculated clear-sky longwave flux (and this LW CRF) from the perspective of different UTW fields which are intrinsically induced by different definition of clear sky flux by satellite method and model approach. For that objective we calculated the clear-sky outgoing longwave radiation (OLR) with two different clear-sky UTW fields obtained in this study as inputs to constrain the humidity profile. For the clear-sky OLR calculation we first constructed the mean atmospheric conditions for the JJA and DJF using National Centers for Environmental Prediction (NCEP) reanalysis data for two year periods of 1997/1998. The TOA flux was then calculated using a radiative transfer model with humidity profiles in which the precipitable water between 200 mb and 500 mb equal to the assigned UTW, while the lower tropospheric humidity below 500 mb is kept at the mean atmospheric conditions from NCEP data. Two sets of clear-sky OLR were calculated depending on clear-sky UTW, and a difference field is presented to diagnose the LW CRF caused by different clear-sky definition.

OLR differences due to the UTW difference between satellite method and model approach of Figs. 3 and 4 are presented in Fig. 5. As expected it is clearly noted that OLR fluxes determined from satellite method are always larger than those from model simulation because of drier condition at least in the tropical region under study. The difference magnitudes larger than 8 W m^{-2} are found most of convectively active regions. Since the CRF is determined by subtracting the measured OLR from the clear-sky OLR, higher clear-sky fluxes found in the satellite approach manifest that satellite determined CRF should also be larger than that can be obtained from model simulations. It is because, as noted in the UTW difference field, upper tropospheric water vapor is highly correlated with cloud development. Therefore satellite estimated CRF includes radiation perturbation not only due to the cloud optical properties, but also due to the water vapor changes caused by the cloudy-sky formation.

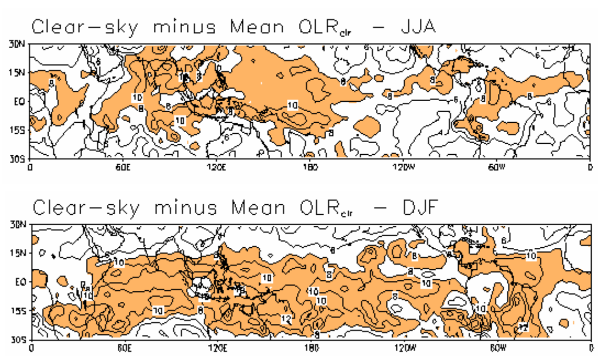

Figure 5: Clear-sky flux difference between satellite method and model approach.

6. SUMMARY AND DISCUSSION

We tried to explain why there exist discrepancies between satellite-estimated clear-sky longwave fluxes and fluxes calculated from model reanalysis data with a radiative transfer model. Considering that the latter approach is the way of climate model calculation in which clear-sky fluxes are usually determined diagnostically in the radiation scheme by setting cloud zero, this study was indeed the comparison of clear-sky longwave fluxes between satellite method and model approach (and thus intercomparison of LW CRF). We argued that the direct comparison may not be valid unless two methods carry the same clear-sky water vapor climatology.

For this argument, we constructed two sets of clear-sky UTW fields which may be seen by satellite method and climate model approach. OLR fluxes calculated using NCEP reanalysis plus two sets of UTW field were compared. It is evident that the discrepancy is largely due to intrinsic differences in clear-sky UTW between two methods. Satellite method put clear-sky fluxes toward in a higher side by selecting and composing only cloud-free pixels which are likely direr than in near-by cloud area while model approach uses the mean atmospheric condition by only removing cloud parameters from the total-sky condition. It was found that there is a significant difference between two clear-sky UTW fields. In the satellite method, clear-sky composition effectively adds the LW contribution by UTW changes associated with the cloudy-sky formation to the CRF. On the other hand, LW contribution by UTW changes is included in the clear-sky flux in the model approach. Because of the different definition of clear-sky UTW, the largest discrepancies up to about 12 Wm^{-2} between satellite estimate and model simulation occur over convectively active tropical regions.

7. ACKNOWLEDGEMENTS

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