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Seasonal variations of upper tropospheric water vapor and high clouds observed from satellites

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Abstract. Multiyear satellite measurements of specific humidity at 215 mbar from the Microwave Limb Sounder aboard the Upper Atmosphere Research Satellite and cloud amount from the International Satellite Cloud Climatology Project have been used to investigate seasonal variations of upper tropospheric water vapor (UTWV), high clouds, and deep convection. The tropical and extratropical UTWV for each hemisphere have maximum values in summer and minimum values in winter because of the moistening effect of the tropical deep convection. The seasonal change of high cloud amount is similar to UTWV in the tropics but very different in the extratropics. Implications of the present results for the water vapor feedback in the climate system are discussed.

1. Introduction

Water vapor plays an important role in regulating the Earth climate system through its greenhouse effect [*Manabe and Wetherald*, 1967; *Ramanathan*, 1981; *Cess et al.*, 1990]. The estimated global warming due to an increase in CO_2 depends critically on representations of the water vapor feedback in climate models used for the estimation. The feedback is sensitive to upper tropospheric water vapor (UTWV) even though UTWV accounts for only a small proportion of total water vapor in the atmosphere. It is generally believed that the water vapor feedback amplifies global warming resulting from an increase in CO_2. This positive feedback is due to stronger convection and more water vapor in the warmer troposphere, including the upper troposphere [*Raval and Ramanathan*, 1989; *Betts*, 1990; *Rind et al.*, 1991; *Soden and Fu*, 1995]. *Lindzen* [1990], however, has proposed a negative water vapor feedback possibly induced by enhanced compensatory subsidence associated with stronger convection.

Another mechanism through which UTWV regulates the climate system is the interaction between UTWV and high clouds. Water vapor and clouds directly interact with each other through condensation and evaporation. There are also indirect and more complicated interactions between water vapor and clouds through the impact on stability and radiative heating. On the other hand, high clouds are largely controlled by deep convection. We can infer deep convection and its relationship to UTWV from high clouds and the relationship between high clouds and UTWV.

Despite the importance of UTWV for the climate system, there is a lack of accurate observations of UTWV [*Starr and Melfi*, 1991; *Elliot and Gaffen*, 1991]. Inadequate knowledge of UTWV, such as the climatology and seasonal and interannual variations, obstructs validation and improvement of physical parameterizations of deep convection and clouds in climate models and casts significant uncertainty on quantitative prediction of the CO_2 warming. Recent progress in retrieving water vapor from satellite measurements [*Schmetz and Turpeinen*, 1988; *Rind et al.*, 1993; *Soden and Bretherton*, 1993; *Read et al.*, 1995] has provided opportunities for better understanding of upper tropospheric water vapor [*Rind et al.*, 1991; *Udelhofen and Hartmann*, 1995; *Soden and Fu*, 1995; *Salathé and Chesters*, 1995; *Chen et al.*, 1996].

In this study we investigate the seasonal variation of upper tropospheric humidity (UTH) and its relation to the variations of deep convection and high clouds using the UTH data recently retrieved from the measurements of the Microwave Limb Sounder (MLS) aboard the Upper Atmosphere Research Satellite (UARS) [*Read et al.*, 1995] and the cloud observations from the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1991]. This kind of research is an important step to clarify the issue of the water vapor feedback, though the feedback in the global warming scenario might be different from that observed in the seasonal variation. Also, the observed relationship between the seasonal variations of deep convection and upper tropospheric water vapor is an important validation of physical parameterizations in climate models.

2. Data Sets

The important feature of the MLS measurement technique for UTH is its ability to observe through cirrus clouds and to determine vertical structure with more than 1300 profiles per day obtained from UARS. *Read et al.* [1995] have given a description of the retrieval technique and initial results of the retrieved UTH. The MLS UTH is available for three layers with thickness of about 3 km and centered at the levels of 316, 215, and 147 mbar. Since the retrieval is best at 215 mbar [*Read et al.*, 1995], this study is focused on the 215 mbar humidity. Comparison with aircraft measurements [*Newell et al.*, 1996] indicates that the MLS UTH is in reasonable agreement with aircraft measurements. A definitive error estimation of the

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MLS data is not available yet. Current investigations by the MLS team at the Jet Propulsion Laboratory suggest that the MLS humidity be too high at 215 mbar by $30-40 \times 10^{-3}$ g kg^{-1} with an uncertainty of 20×10^{-3} g kg^{-1}. Systematic errors would not change results of seasonal variations in a significant way, and using multiyear means minimizes uncertainty due to random errors. We have processed the MLS data for the 5-year period (1992–1996). For each month the retrieved UTH is binned into the boxes with the resolution of 2.5° by 2.5° (the ISCCP data resolution). However, the actual data sampling could be twice as coarse for some latitudes in the tropics, and quite large gaps may exist in regions poleward of 34° because the MLS sampled only those regions during a portion of the month. The 5-year mean monthly humidity field with latitudinal coverage of 80°S–80°N is used to depict the seasonal variation of UTH.

The ISCCP C2 monthly mean data [*Rossow and Schiffer*, 1991] for the period from July 1983 through June 1991 are used in this study. The ISCCP C2 data provide high cloud amount and deep convective cloud amount as well as other quantities. The ISCCP high clouds are those with cloud top pressure $<$440 mbar. The ISCCP deep convective clouds are defined as a subset of high clouds which are optically thick (optical thickness $>$23) for the solar radiation. Thus the ISCCP deep convective clouds represent only those observed during daytime. Because of this, we use high cloud amount instead of deep convective cloud amount in this study. High clouds are generally associated with deep convection, especially in the tropics, even though they occupy larger regions than deep convection or deep convective clouds. The monthly mean high cloud amount at the resolution of 2.5° by 2.5° for the 8 years is averaged to generate the 8-year mean monthly cloud amount for the seasonal variation study.

The time periods of the MLS UTH and the ISCCP high cloud amount are different. However, differences in seasonal variations due to the different temporal coverage should be minimal since we use the multiyear-averaged monthly means for both the MLS and the ISCCP data. The seasonal variations from the 5-year mean MLS UTH and the 8-year mean ISCCP clouds can be interpreted as their climatological seasonal variations.

3. Global Distribution

Plates 1a–1d show the 215-mbar specific humidity for January, April, July, and October. High humidity is mostly confined in low latitudes with maxima found over the continents and the maritime continent. The high-humidity band is associated with the intertropical convergence zone (ITCZ) and migrates between its most southward position in January and its most northward position in July. Except for January, the tropical high-humidity band crosses all longitudes with different latitudinal coverage. In January the eastern equatorial Pacific is relatively dry, and hence the high-humidity band breaks over this region. There are three distinctive features for July. First, the high humidity found over the large Asian summer monsoon region is the largest observed in all months. Second, a local maximum of UTH is found in the eastern equatorial Pacific and Central America. Third, the tropical high UTH extends far northward into eastern Asia and the North Pacific, and the southeastern United States and the western Atlantic. For the extratropics of the Southern Hemisphere (SH) the humidity reaches the highest values in January and the lowest in July (more details in section 4). Similarly, UTH in the Northern Hemisphere (NH) extratropics has its peak in the northern summer and its lowest values in the northern winter.

Plates 1e–1h show the corresponding ISCCP high cloud amount (HCA). Several interesting points emerge from the comparison of UTH with HCA. In low latitudes the maxima of UTH always coexist with the maxima of HCA for all months. This is due to the fact that high UTH and HCA are directly forced by deep convection. However, high UTH stretches into much greater regions than does large HCA. Since high clouds occupy larger regions than deep convection, it is clear that high UTH occurs in regions much wider than deep convection. The spread of high UTH from deep convective regions is due to two mechanisms. The first is the outflow of water (both vapor and condensed water) from the deep convective plume associated with detrainment, subgrid mixing, and large-scale advection. The second is the water source left by the decay of deep convective clouds [*Betts*, 1990]. The relative contributions from the two mechanisms are still unclear and need further studies.

In the extratropics, there is no clear relationship between UTH and HCA, which is consistent with the result of *Soden and Fu* [1995]. For January, HCA is high in the North Pacific and North Atlantic because of the winter storm tracks, while UTH in those regions is not clearly larger than surrounding areas. Furthermore, UTH in those regions reaches the lowest values in the seasonal cycle. This kind of phenomenon is also evident for the SH extratropics. Possible reasons are as follows. The convection in the extratropics does not penetrate high enough to have a significant moistening effect on the humidity of the 3-km layer centered at 215 mbar. Also, the level of 215 mbar in midlatitudes of the winter hemisphere is very likely in the stratosphere. On the other hand, the tropical UTH of both hemispheres has peak values in their local summer seasons. This enables more water vapor to be transported from low latitudes to middle and high latitudes in summer. Also, temperature in the extratropics is significantly higher in summer than in winter, giving a greater water-holding capacity of the atmosphere in summer. The latter two factors might explain why the extratropical UTH is higher in summer. The humidity at 316 mbar shows similar seasonal variations.

4. Zonal Mean

Figure 1 shows the seasonal variations of the zonal-mean UTH and HCA, defined as the deviations of monthly means from their annual means. UTH is highest in January in the SH, while it is highest in July in the NH except for a narrow region around the equator (7°S–5°N), where UTH reaches its peak in April. The seasonal variation of UTH is significant not only in low latitudes but also in middle and high latitudes. The largest difference between January and July, which may be interpreted as the amplitude of the UTH seasonal variation, is about 45% of the annual mean in the SH and about 60% in the NH. The HCA variation in the tropics has the same sign as UTH. The largest HCA differences between January and July are about 160% and 120% of the annual mean in the SH and NH tropics, respectively. In high latitudes, HCA has maxima in winter, while the variation in middle latitudes of both hemispheres is quite small. The HCA variation is unusually large in the SH high latitudes, which might be related to large uncertainties in cloud detection in polar regions due to the significant reduction of contrast in reflectance of solar radiation and tempera-

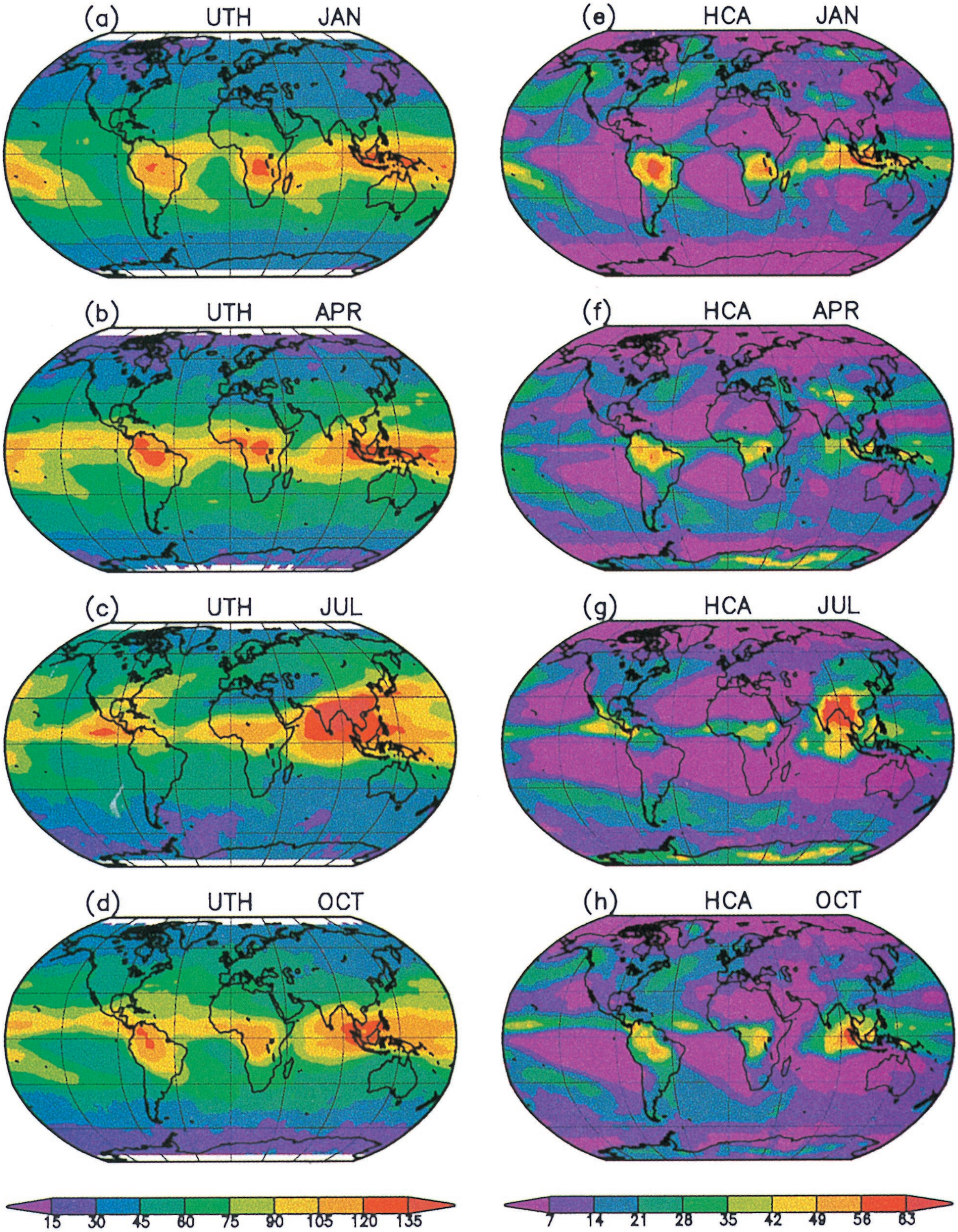

Plate 1. (Plates 1a–1d) Five-year mean monthly specific humidity at 215 mbar from the Microwave Limb Sounder in the unit of 10^{-3} g kg^{-1} and (Plates 1e–1h) 8-year mean monthly high cloud amount from the International Satellite Cloud Climatology Project in percent.

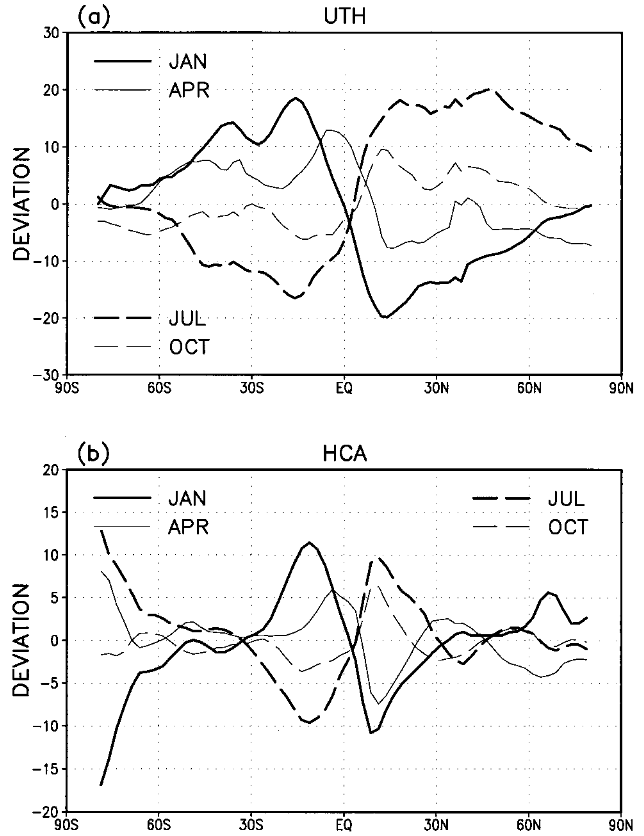

Figure 1. Deviations of monthly means from the annual means for (a) the 215-mbar specific humidity in the unit of 10^{-3} g kg^{-1} and (b) the high cloud amount in percent.

ture between clouds and the surface underneath [*Rossow and Garder*, 1993].

Regarding the relationship between UTH and high clouds, the zonal-mean results are similar to those from the global distribution. In low latitudes, UTH and HCA reach their peak values in summer as a result of deep convection along the ITCZ. For middle and high latitudes the UTH and HCA seasonal variations do not show any clear relationship. The extratropical UTH has highest values in summer because of more water vapor transported from low latitudes and higher summer temperature. The extratropical seasonal variation of UTH is stronger in the NH than in the SH. HCA in the extratropics is largest in winter in high latitudes, while its seasonal change in middle latitudes is small.

5. Concluding Remarks

Our study using the MLS water vapor and ISCCP cloud observations has shown that the tropical deep convection significantly increases the upper tropospheric water vapor in the tropics and the extratropics. The moistening effect of the tropical deep convection on the tropical UTH is realized in regions much greater than deep convection itself. Also, the moistening effect of the tropical deep convection is seen in the extratropics. Both of these indicate a role of large-scale circulation and other factors in determination of UTH.

Satellite observations of water vapor provide important bases for validation of simulations of water vapor and related physical parameterizations in climate models. In addition, humidity observations from satellites are important data resources for humidity assimilation in global data assimilation systems. In the past, however, humidity assimilation has not been given high priority in the development of assimilation systems because of two reasons. First, the development of data assimilation has historically been driven by the requirement to improve medium-range numerical weather prediction. Inclusion of satellite UTH data does not necessarily improve weather forecasts and sometimes even deteriorates them [e.g., *Andersson et al.*, 1991; *McNally and Vesperini*, 1996]. Second, there are difficulties in using satellite humidity observations. One issue is data rejection. Data rejection means the model physics, largely through moist convection, tries to remove humidity changes introduced by satellite data. Data rejection is mainly due to the model humidity forced by model convection being inconsistent with satellite data. More efforts need to be directed to the assimilation of satellite humidity measurements.

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