Upper tropospheric water vapor from GEOS reanalysis and UARS MLS observation

Minghang Chen and Richard B. Rood

NASA Goddard Space Flight Center, Greenbelt, Maryland

William G. Read

Jet Propulsion Laboratory, Pasadena, California

Abstract. The upper tropospheric water vapor (UTWV) from the reanalysis produced by the Goddard Earth Observing System (GEOS) Data Assimilation System is compared with the retrieved UTWV from the measurements of the Microwave Limb Sounder (MLS) aboard the Upper Atmosphere Research Satellite (UARS). The UTWV from the GEOS reanalysis is in fair agreement with the UTWV retrieved from the UARS MLS observation. Both data sets show high tropical UTWV closely related with the tropical deep convection. There is, however, clear evidence of overestimation of UTWV in the GEOS reanalysis, especially for the summer season (July 1992). The GEOS overestimation is more significant after considering the MLS retrieval bias. The reasons for the GEOS overestimation are discussed. For interannual variations between 1992 and 1993, the reanalysis and the observation consistently show significant changes in UTWV resulting from sea surface temperature anomalies associated with the El Niño-Southern Oscillation phenomenon.

1. Introduction

Water vapor, as the predominant greenhouse gas, plays an important role in regulating the climate system [*Manabe and Wetherald*, 1967; *Ramanathan*, 1981, 1988]. The change of water vapor resulting from an initial climate change can either amplify or reduce the initial climate change, which is referred to as the water vapor feedback. It is generally believed that the water vapor feedback amplifies global warming resulting from increases in trace gases such as CO_2 [e.g., *Manabe and Wetherald*, 1967; *Raval and Ramanathan*, 1989; *Cess*, 1989; *Betts*, 1990; *Rind et al.*, 1991; *Inamdar and Ramanathan*, 1994]. The positive feedback is realized through increases in water vapor in the warmer troposphere, hence stronger greenhouse warming. However, the positive feedback has been questioned by *Lindzen* [1990]. The greenhouse effect of water vapor is sensitive to upper tropospheric water vapor (UTWV) although UTWV accounts for only a small fraction of total column water vapor [e.g., *Udelhofen and Hartmann*, 1995]. Another mechanism through which UTWV regulates the climate system is the interaction of UTWV with high clouds which have a significant impact on radiative heating in the atmosphere and at the surface.

The climatology and variations of UTWV are determined by complicated processes in the climate system, such as transport of water (all phases) by circulation and convection, interaction of water vapor with deep convection and clouds, and subgrid mixing. Because of the lack of observations of UTWV with adequate accuracy [*Starr and Melfi*, 1991; *Elliot and Gaffen*, 1991], understanding of the UTWV climatology and variations is relatively primitive. The limited understanding of UTWV

hinders validation and improvement of physical parameterizations of deep convection and cloud microphysics in general circulation models (GCMs).

Recent progress in retrieving water vapor information from satellite measurements has provided useful data sets for better understanding of UTWV and verification of model simulations [e.g., *Schmetz and Turpeinen*, 1988; *Rind et al.*, 1993; *Soden and Bretherton*, 1993; *Read et al.*, 1995; *Salathé and Chesters*, 1995; *Soden and Fu*, 1995; *Udelhofen and Hartmann*, 1995; *Chen et al.*, 1996; *Elson et al.*, 1996]. Moreover, reanalysis projects with fixed assimilation systems provide unprecedented multiyear data sets for the climate research community [*Schubert et al.*, 1993; *Kalnay et al.*, 1996]. Using a fixed assimilation system for a whole period of a reanalysis avoids any variation induced by changes in an assimilation system. Conventional fields such as winds, temperature, and geopotential height from reanalyses have good accuracy for the troposphere for most regions of the globe and have been widely used for validations of climate simulations. Upper tropospheric humidity from reanalyses, however, has large uncertainty associated with it. The uncertainty results from the lack of reliable humidity observations in the upper troposphere and errors in related physical parameterizations in GCMs used in assimilation systems. In this paper we compare UTWV from the reanalysis produced with version 1 of the Goddard Earth Observing System (GEOS-1) data assimilation system [*Schubert et al.*, 1993] with the recently retrieved UTWV from the measurements of the Microwave Limb Sounder (MLS) aboard the Upper Atmosphere Research Satellite (UARS) [*Read et al.*, 1995]. The comparison serves qualitative validation of UTWV from the reanalysis. Possible reasons for discrepancies between the reanalysis and the satellite estimation are investigated. The investigation is vital for better representation of UTWV in the next version of the GEOS assimilation system.

2. Reanalysis and Satellite Data Sets

2.1. GEOS-1 Reanalysis

The GEOS-1 reanalysis has been produced with the GEOS-1 data assimilation system which consists of the GEOS-1 GCM and a three-dimensional, multivariate optimal interpolation (OI) scheme [*Schubert et al.*, 1993]. The detailed descriptions of the GEOS-1 GCM and the OI scheme can be found in the works of *Takacs et al.* [1994] and *Pfaendtner et al.* [1995], respectively. The GEOS-1 GCM uses version 1 of the Aries/GEOS dynamical core [*Suarez and Takacs*, 1995], which is a second-order energy and potential enstrophy conserving scheme. The turbulence parameterization in the GEOS-1 GCM consists of components which handle vertical diffusion and surface fluxes of heat, moisture, and momentum [*Helfand and Labraga*, 1988]. The relaxed Arakawa-Schubert scheme [*Moorthi and Suarez*, 1992] has been used to parameterize moist convection. The model also includes a parameterization of reevaporation of falling convective rain [*Sud and Molod*, 1988]. The reevaporation scheme accounts for rainfall intensity, drop size distribution, and environmental temperature, pressure, and humidity. Convective and large-scale (layered) clouds are diagnosed according to moist convection and large-scale condensation. The longwave and shortwave radiation schemes closely follow those of *Harshvardhan et al.* [1987]. The cloud extinction coefficient is specified based on the cloud type and temperature.

The OI analysis scheme is a three-dimensional (multivariate in geopotential height and winds, univariate in mixing ratio) statistical objective analysis scheme [*Pfaendtner et al.*, 1995]. It employs a damped cosine function for the horizontal correlation of the model prediction error. The multivariate surface analysis scheme over the oceans adopts an Ekman balance for the pressure-wind analysis. All grid point analyses are conducted using up to 75 nearby observations within a circular data selection cylinder of 1600 km radius. Observational data for the surface analysis are from reports of land stations, ships, and buoys. The upper air analysis of height and winds incorporates data from rawinsondes, dropwindsondes, aircraft winds, cloud-tracked winds, and thicknesses from the TIROS operational vertical sounder (TOVS) produced by the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS). The upper air moisture analysis uses only rawinsonde observations.

The assimilation system uses the GEOS-1 GCM with horizontal resolution of 2° latitude by 2.5° longitude and 20 sigma levels and the OI analysis with the same horizontal resolution but with 14 pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, and 20 mbar) and sea level. The moisture analysis, however, is performed only at the lowest six levels (300 mbar and below). Therefore the moisture above 300 mbar is determined by the assimilating model with constraints imposed by moisture observations at lower levels and observations of other quantities through the atmosphere. The comparison of the reanalysis with the corresponding model simulation shows large differences in humidity between the reanalysis and the model simulation even at levels above 300 mbar [*Takacs and Suarez*, 1996].

2.2. UARS MLS Water Vapor

The UARS MLS, which has been in operation since September 1991, gives a new capacity for global UTWV observa-

tions [*Read et al.*, 1995]. The MLS is sensitive to UTWV when the field of view (FOV) of its ClO spectral band is scanned down through the troposphere. The important feature of the MLS measurement technique for UTWV is its ability to observe through cirrus clouds and to determine vertical structure with more than 1300 profiles per day obtained from UARS. The vertical resolution is limited by the instrument FOV, which has 3.0-km half-power gain width, and the best sensitivity to water vapor occurs in a vertical band where the abundance is around 150 ppmv, corresponding to height of about 12 km in low latitudes and 7 km in high latitudes. The MLS humidity is available for three layers with the 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], our comparison is focused on the 215 mbar humidity. *Newell et al.* [1996] have compared the MLS water vapor with aircraft measurements of UTWV and found that they are in fairly good agreement (see their Table 1 for details). A definitive error estimation of the 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}.

Each month of the retrieved MLS humidity is binned into the boxes with the GEOS-1 resolution (2° by 2.5°). 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 only sampled those regions during a portion of the month. Thus the present study is limited to regions between 35°S and 35°N. In the GEOS-1 reanalysis the nearest level to the 215 mbar level is 200 mbar. We compare the GEOS-1 200 mbar specific humidity directly with the MLS 215 mbar specific humidity, thereby avoiding vertical interpolation, because of the vertical resolution of both data sets being too coarse for meaningful interpolation.

3. Results

Plates 1a and 1b show the UARS MLS and GEOS-1 specific humidity for January 1992. The reanalysis is generally in agreement with the observation with respect to both distribution and magnitude. Large humidity values are found along the Intertropical Convergence Zone (ITCZ) with maxima over deep convective regions. The largest humidity in the GEOS-1 reanalysis is located in the central equatorial Pacific, which results from the eastward shift of strong deep convection associated with the sea surface temperature (SST) anomaly of the El Niño event [*Kousky*, 1993]. The eastward shift of the deep convection is also evident in the MLS humidity even though it is not so distinct as in the GEOS-1 reanalysis. The strong gradients from high tropical UTWV to low subtropical UTWV are consistent in the reanalysis and the observation.

Plate 1c shows the humidity differences between the GEOS-1 reanalysis and the MLS observation. The most striking discrepancy is found in Central America, where large specific humidity exists in GEOS-1 but not in the MLS. The discrepancy is attributed to the problem of the representation of deep convection in the GEOS-1 reanalysis. This problem is also evident in the fields of precipitation and cloud radiative forcing [*Molod et al.*, 1996]. Other regions with the overestimation of the GEOS-1 UTWV are the southern Indian Ocean, the southern central Pacific, and the region to the east of the Philippines with a northward bulge in the GEOS-1 humidity distribution. The GEOS-1 overestimation of UTWV is also
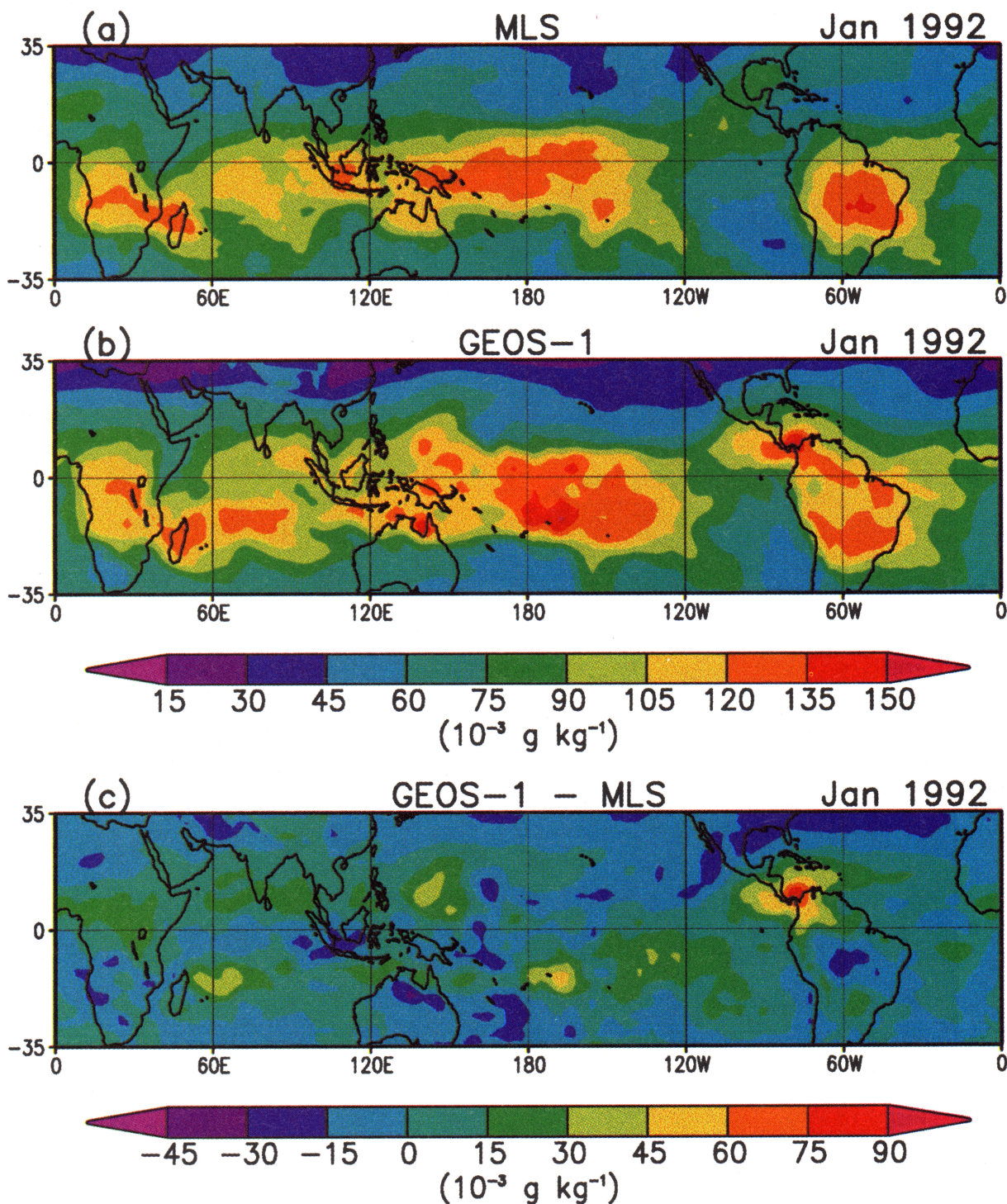
Plate 1. Specific humidity for January 1992 from (a) the UARS Microwave Limb Sounder (MLS) and (b) the GEOS-1 reanalysis, and (c) their differences (GEOS-1 minus MLS).

related to the issue of calculation of saturation humidity with respect to liquid or ice when temperature is well below 0°C. In GEOS-1 saturation humidity is calculated with respect to liquid regardless of temperature. This issue will be discussed below. The overestimation is more significant after considering the wet bias of the MLS specific humidity discussed in the previous section. Perhaps due to the relatively coarse horizontal resolution in the MLS, the GEOS-1 UTWV has more small-scale features in the tropics than the MLS counterpart.

The specific humidity for July 1992 is shown in Plate 2. There are larger differences between the reanalysis and the retrieval than the January case. First, the GEOS-1 specific humidity is greater than the MLS along the ITCZ. Second, the regions with high humidity are much wider in GEOS-1 than in the MLS, especially in the western and central tropical Pacific, the Gulf of Mexico, the Caribbean, and the tropical Indian Ocean. These two factors account for large positive differences shown in Plate 2c. Again, they are related to the issue of
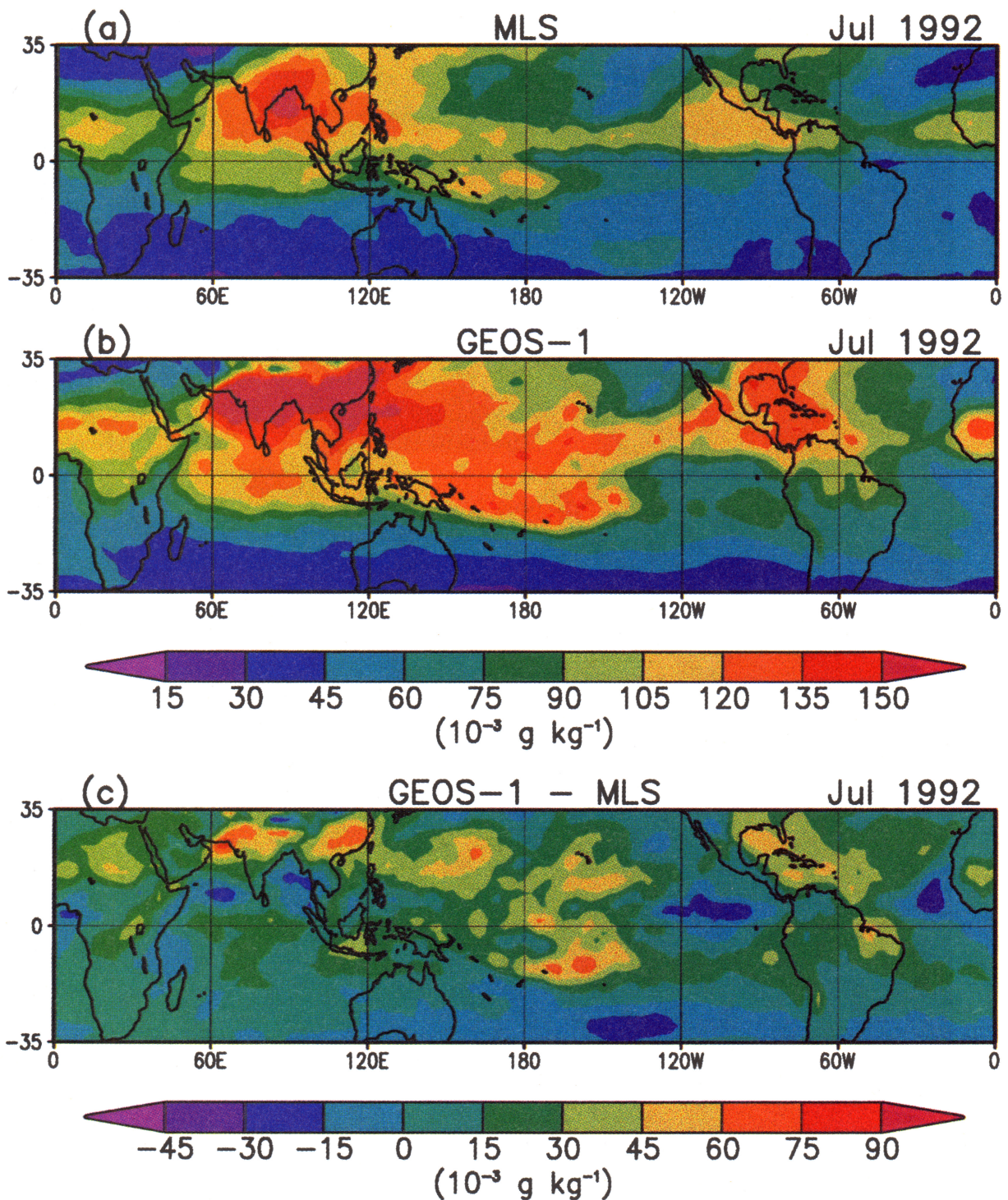
Plate 2. Specific humidity for July 1992 from (a) the UARS MLS and (b) the GEOS-1 reanalysis, and (c) their differences (GEOS-1 minus MLS).

calculation of saturation humidity with respect to liquid regardless of temperature in GEOS-1 and the problem of the GEOS-1 simulation of tropical deep convection. Examination of convective precipitation and deep convective clouds from the GEOS-1 reanalysis reveals that deep convection in the reanalysis occupies wider regions than that inferred from available satellite data sets. This problem arises because the GEOS-1 GCM is not able to accommodate the instability associated with observational data used in the assimilation, i.e.,

the moist convective parameterization in the GEOS-1 model constantly overadjusts the tropical atmosphere [*Molod et al.*, 1996].

The calculation of saturation humidity with respect to ice or liquid in the upper troposphere has an enormous impact on UTWV. As mentioned above, saturation humidity in GEOS-1 is calculated with respect to liquid regardless of temperature. For the typical 200 mbar tropical temperature around −50°C, the ratio of saturation humidity with respect to liquid to that
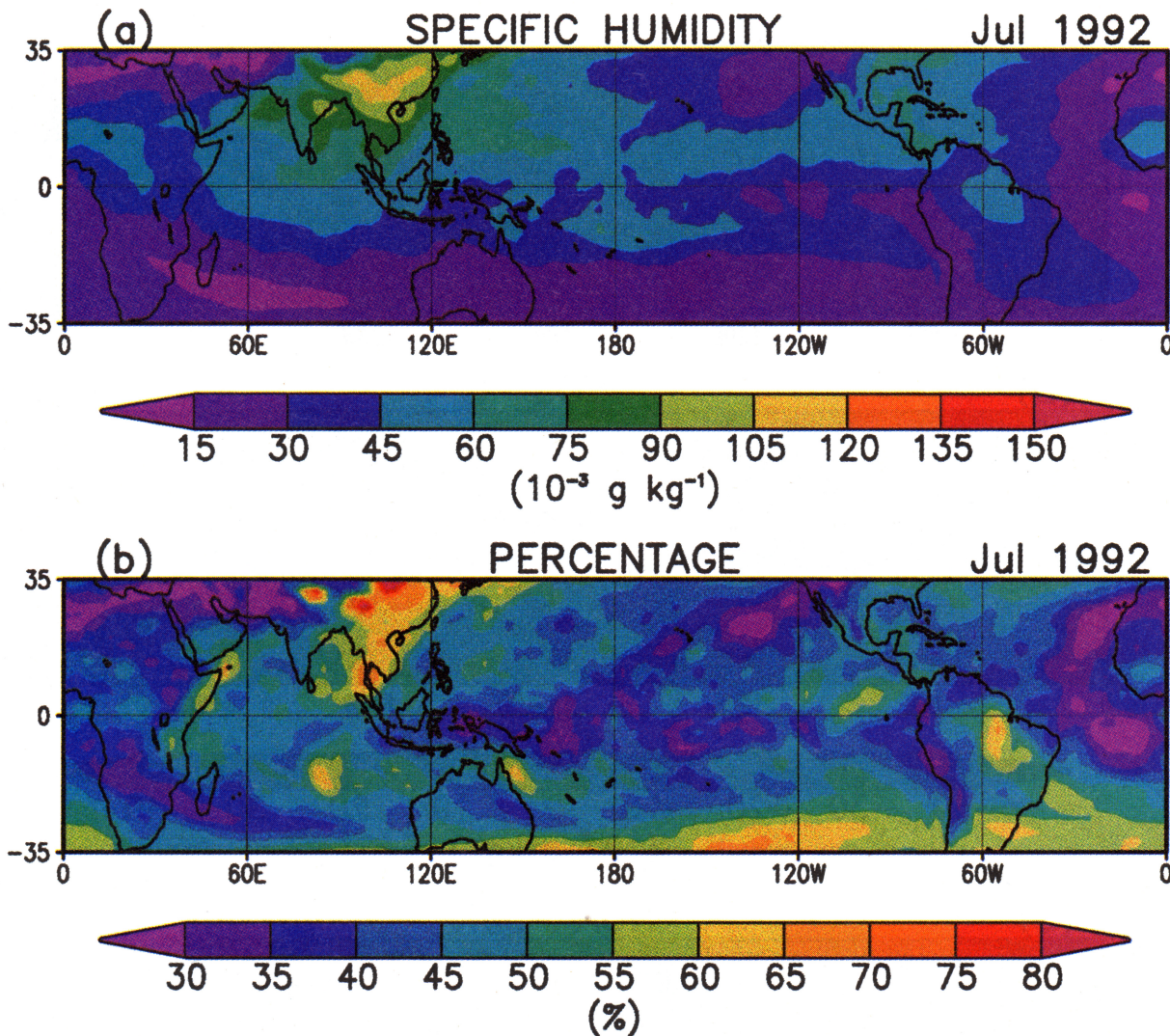
Plate 3. (a) Specific humidity for July 1992 from an experiment using the GEOS assimilation system with saturation humidity calculated with respect to ice when temperature is well below 0°C and (b) percentage of the new specific humidity relative to the GEOS-1 reanalysis (Plate 3a divided by Plate 2b).

with respect to ice is about 1.5. Using the GEOS assimilation system, we have carried out an assimilation experiment with saturation humidity calculated with respect to ice when temperature is well below 0°C. In this assimilation experiment, saturation humidity is calculated with respect to ice when temperature is below −40°C, and a combination of those computed with respect to liquid and ice is used for temperature between 0° and −40°C. Plate 3a shows the new July 1992 GEOS specific humidity at 200 mbar from the experiment. The new humidity is considerably less than the GEOS-1 reanalysis humidity (Plate 2b) and also less than the MLS humidity (Plate 2a). However, the extensive spatial coverage of relatively high humidity in the western Pacific and the wide region from Central America to the southeastern United States and the western Atlantic is similar in Plates 3a and 2b. This suggests a similar problem of deep convection simulation in this experiment, since high UTWV is directly controlled by deep convection. Plate 3b shows the new specific humidity in the percentage of the GEOS-1 reanalysis humidity. The new humidity is about 70–80% of the GEOS-1 reanalysis in southeastern Asia where

the largest humidity exists in July. In other areas the percentage varies from 30 to 70%.

It is interesting to see that the lowest percentage in Plate 3b (less than 35%) is mostly found in dry regions such as the Sahara, southern Africa, the eastern Atlantic, and the eastern subtropical Pacific. This means that the drying effect of using saturation humidity with respect to ice instead of liquid is most significant, in terms of the percentage, over dry regions. The result is unexpected since relative humidity over those dry regions are far less than saturation even with respect to ice. It could be related to the complicated (nonlinear) nature of moisture transport from moist regions to dry regions.

It has been shown that seasonal variations of UTWV are largely controlled by changes of tropical deep convection associated with the seasonal migration of the ITCZ. A similar relationship is expected to exist between interannual variations of UTWV and tropical deep convection. Interannual variations are particularly large during an El Niño event. Plate 4a shows the variations in the January UTWV between 1992 and 1993 from the MLS. The variations are forced mainly by the SST
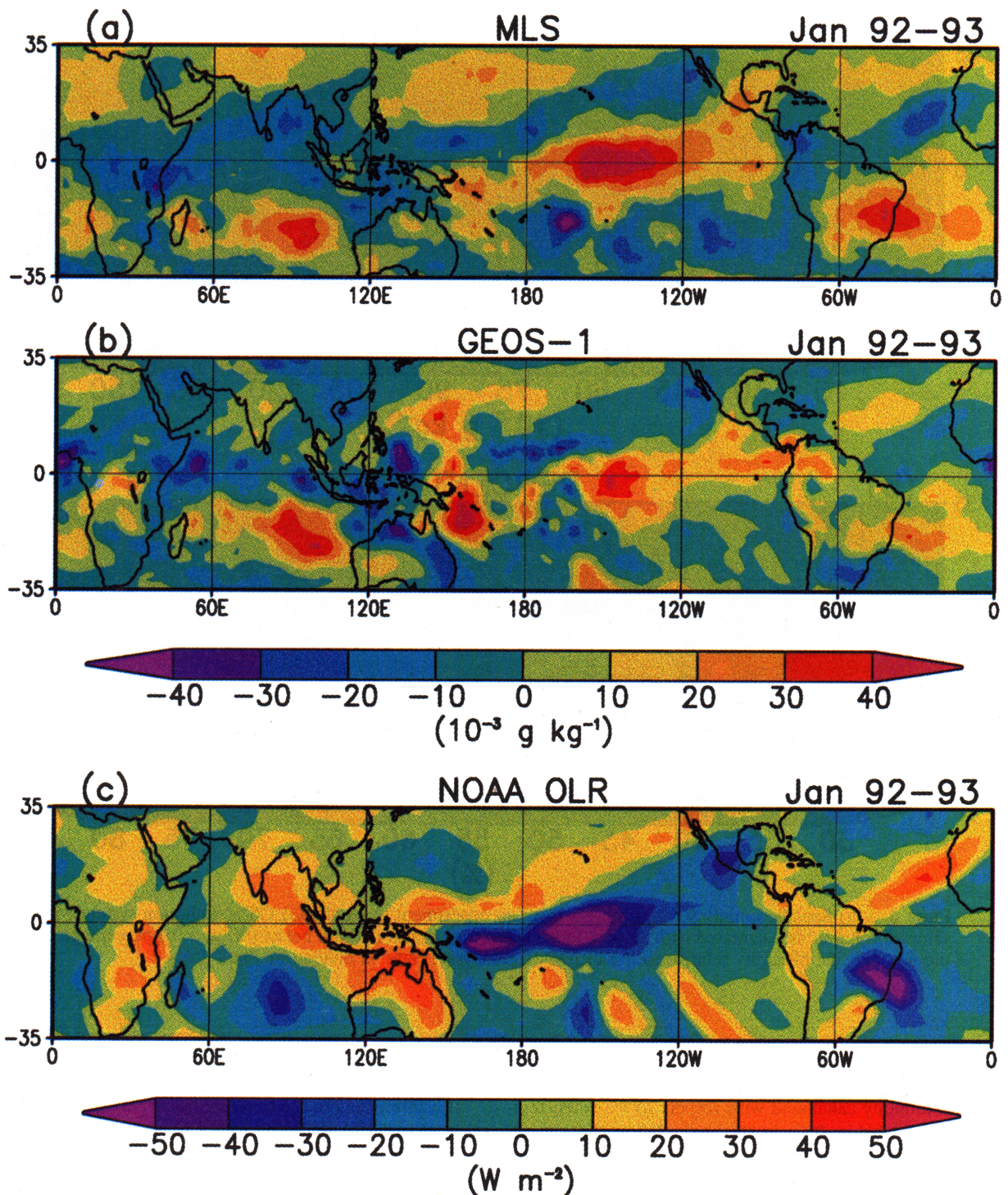
Plate 4. Variations in the specific humidity between January 1992 and January 1993 (1992 minus 1993) from (a) the UARS MLS and (b) the GEOS-1 reanalysis, and (c) corresponding changes in outgoing longwave radiation from the NOAA outgoing longwave radiation.

anomalies during the prolonged El Niño event. The positive SST anomalies in the central and eastern equatorial Pacific for January 1992 are much stronger than those for January 1993, even though both months were in the warm phase of the El Niño event [*Kousky*, 1993; *Bell and Basist*, 1994]. The MLS UTWV has large positive changes in the central equatorial Pacific, eastern Brazil and its immediate oceanic region, and the subtropical Indian Ocean. The maximum change over the

central equatorial Pacific is about 50% of the corresponding humidity for January 1993; that is, the January humidity for 1992 is one and half times as large as that for 1993. The positive differences result from strongly enhanced deep convection in the areas, which can be inferred from the changes in outgoing longwave radiation (OLR) observed from the NOAA polar orbiting satellites [*Gruber and Krueger*, 1984]. Plate 4c shows the OLR differences between the two months. The large

positive humidity differences are remarkably correlated with the negative OLR changes. The negative changes in the MLS humidity are also correlated with the positive differences in OLR.

Plate 4b shows the interannual variations of the GEOS-1 UTWV. Generally, the GEOS-1 variations are consistent with the MLS variations. The largest positive change in the central equatorial Pacific, however, is weaker in GEOS-1. Also, the positive change in eastern Brazil and its immediate oceanic region is weaker, while the positive change to the east of New Guinea is stronger in the GEOS-1 reanalysis.

4. Concluding Remarks

The UTWV in low latitudes from the GEOS-1 reanalysis is in reasonable agreement with the UTWV retrieved from the UARS MLS observation. Both data sets show high UTWV closely related with the tropical deep convection. There is, however, clear evidence of overestimation of UTWV in the GEOS-1 reanalysis, especially for July 1992. The GEOS-1 overestimation is more significant after considering the MLS wet bias. The GEOS-1 overestimation is caused by the two problems in the GEOS-1 assimilation system. The first is the calculation of saturation humidity with respect to liquid regardless of temperature. The second is that the tropical deep convection is too strong and occupies too wide regions in the reanalysis. These two issues need to be addressed adequately in order to have better representation of UTWV in the next version of the GEOS assimilation system.

For interannual variations the reanalysis and the observation show significant changes in the tropical UTWV resulting from the SST anomalies associated with an El Niño event. The GEOS-1 variations are consistent with the MLS variations, though for several regions the GEOS-1 variations are weaker than the MLS. The variations in UTWV are consistent with changes in tropical deep convection inferred from the NOAA OLR.

M. Chen et al. (Seasonal variations of upper tropospheric water vapor and high clouds observed from satellites, submitted to *J. Geophys. Res.*, 1998) have used the MLS UTWV data and the cloud amount data from the International Satellite Cloud Climatology Project [*Schiffer and Rossow*, 1983] to study the impact of deep convection on the seasonal variations of UTWV. They have found that the tropical deep convection significantly increases the upper tropospheric water vapor in the tropics and the extratropics. The study is an important step toward clarifying the water vapor feedback, though the feedback in the global warming scenario might be different from that in the seasonal variation. The observed relationship between deep convection and UTWV is an important resource for validations of physical parameterizations in climate models. The GEOS-1 reanalysis data indicate a similar moistening effect of the tropical deep convection on UTWV in both the tropics and the extratropics.

References

Bell, G. D., and A. N. Basist, The global climate of December 1992–February 1993, I, Warm ENSO conditions continue in the tropical Pacific; California drought abates, *J. Clim.*, 7, 1581–1605, 1994.

Betts, A. K., Greenhouse warming and the tropical water budget, *Bull. Am. Meteorol. Soc.*, 71, 1464–1465, 1990.

Cess, R. D., Gauging water-vapour feedback, *Nature*, 342, 736–737, 1989.

Chen, C.-T., E. Roeckner, and B. J. Soden, A comparison of satellite observations and model simulations of column-integrated moisture and upper-tropospheric humidity, *J. Clim.*, 9, 1561–1585, 1996.

Elliot, W. P., and D. J. Gaffen, On the utility of radiosonde humidity archives for climate studies, *Bull. Am. Meteorol. Soc.*, 65, 1507–1520, 1991.

Elson, L. S., W. G. Read, and J. W. Waters, Space-time variations in water vapor as observed by the UARS Microwave Limb Sounder, *J. Geophys. Res.*, 101, 9001–9015, 1996.

Gruber, A., and A. F. Krueger, The status of the NOAA outgoing longwave radiation data set, *Bull. Am. Meteorol. Soc.*, 65, 958–962, 1984.

Harshvardhan, R. Davies, D. A. Randall, and T. G. Corsetti, A fast radiation parameterization for atmospheric circulation models, *J. Geophys. Res.*, 92, 1009–1016, 1987.

Helfand, H. M., and J. C. Labraga, Design of a non-singular level 2.5 second-order closure model for the prediction of atmospheric turbulence, *J. Atmos. Sci.*, 45, 113–132, 1988.

Inamdar, A. K., and V. Ramanathan, Physics of greenhouse effect and convection in warm oceans, *J. Clim.*, 7, 715–731, 1994.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 77, 437–471, 1996.

Kousky, V. E., The global climate of December 1991–February 1992: Mature-phase warm (ENSO) episode conditions develop, *J. Clim.*, 6, 1639–1655, 1993.

Lindzen, R. S., Some coolness concerning global warming, *Bull. Am. Meteorol. Soc.*, 71, 288–299, 1990.

Manabe, S., and R. T. Wetherald, Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *J. Atmos. Sci.*, 24, 241–259, 1967.

Molod, A., H. M. Helfand, and L. L. Takacs, The climate of the GEOS-1 GCM and its impact on the GEOS-1 data assimilation system, *J. Clim.*, 9, 764–785, 1996.

Moorthi, S., and M. J. Suarez, Relaxed Arakawa-Schubert: A parameterization of moist convection for general circulation models, *Mon. Weather Rev.*, 120, 978–1002, 1992.

Newell, R. E., Y. Zhu, E. V. Browell, S. Ismail, W. G. Read, J. W. Waters, K. K. Kelly, and S. C. Liu, Upper tropospheric water vapor and cirrus: Comparison of DC-8 observations, preliminary UARS MLS measurements and meteorological analysis, *J. Geophys. Res.*, 101, 1931–1941, 1996.

Pfaendtner, J., S. Bloom, D. Lamich, M. Seablom, M. Sienkiewicz, J. Stobie, and A. daSilva, Documentation of the Goddard Earth Observing System (GEOS) data assimilation system—Version 1, *NASA Tech. Memo. 104606*, vol. 4, 44 pp., 1995.

Ramanathan, V., The role of ocean-atmospheric interactions in the CO_2 climate problem, *J. Atmos. Sci.*, 38, 918–930, 1981.

Ramanathan, V., The greenhouse theory of climate change: A test by an inadvertent global experiment, *Science*, 240, 293–299, 1988.

Raval, A., and V. Ramanathan, Observational determination of the greenhouse effect, *Nature*, 342, 758–761, 1989.

Read, W. G., J. W. Waters, D. A. Flower, L. Froidevaux, R. F. Jarnot, D. L. Hartmann, R. S. Harwood, and R. B. Rood, Upper tropospheric water vapor from UARS MLS, *Bull. Am. Meteorol. Soc.*, 76, 2381–2389, 1995.

Rind, D., E.-W. Chiou, W. Chu, J. Larsen, S. Oltmans, J. Lerner, M. P. McCormick, and L. McMaster, Positive water vapour feedback in climate models confirmed by satellite data, *Nature*, 349, 500–503, 1991.

Rind, D., E.-W. Chiou, W. Chu, S. Oltmans, J. Lerner, J. Larsen, M. P. McCormick, and L. McMaster, Overview of the Stratospheric Aerosol and Gas Experiment II water vapor observations: Method, validation, and data characteristics, *J. Geophys. Res.*, 98, 4835–4856, 1993.

Salathé, E. P., and D. Chesters, Variability of moisture in the upper troposphere as inferred from TOVS satellite observations and the ECMWF model analyses in 1989, *J. Clim.*, 8, 120–132, 1995.

Schiffer, R. A., and W. B. Rossow, The International Satellite Cloud Climate Project (ISCCP): The first project of the World Climate Research Program, *Bull. Am. Meteorol. Soc.*, 64, 779–784, 1983.

Schmetz, J., and O. M. Turpeinen, Estimation of the upper tropo-

spheric relative humidity field from METEOSAT water vapor image data, *J. Appl. Meteorol.*, *27*, 889–899, 1988.

Schubert, S. D., R. B. Rood, and J. Pfaendtner, An assimilated dataset for Earth science applications, *Bull. Am. Meteorol. Soc.*, *74*, 2331–2342, 1993.

Soden, B. J., and F. P. Bretherton, Upper tropospheric relative humidity from GOES 6.7 μm channel: Method and climatology for July 1987, *J. Geophys. Res.*, *98*, 16,669–16,688, 1993.

Soden, B. J., and R. Fu, A satellite analysis of deep convection, upper-tropospheric humidity, and the greenhouse effect, *J. Clim.*, *8*, 2333–2351, 1995.

Starr, D. O'C., S. H. Melfi, The role of water vapor in climate: A strategic research plan for the proposed GEWEX water vapor project (GVaP), *NASA Conf. Publ. 3120*, 50 pp., 1991.

Suarez, M. J., and L. L. Takacs, Documentation of the Aries/GEOS dynamical core: Version 2, *NASA Tech. Memo. 104606*, vol. 5, 45 pp., 1995.

Sud, Y. C., and A. Molod, The roles of dry convection, cloud-radiation feedback processes and the influence of recent improvements in the parameterization of convection in the GLA GCM, *Mon. Wea. Rev.*, *116*, 2366–2387, 1988.

Takacs, L. L., A. Molod, and T. Wang, Documentation of the Goddard Earth Observing System (GEOS) general circulation model—Version 1, *NASA Tech. Memo. 104606*, vol. 1, 100 pp., 1994.

Takacs, L. L., and M. J. Suarez, Dynamical aspects of climate simulations using the GEOS general circulation model, *NASA Tech. Memo. 104606*, vol. 10, 56 pp., 1996.

Udelhofen, P. M., and D. L. Hartmann, Influence of tropical cloud systems on the relative humidity in the upper troposphere, *J. Geophys. Res.*, *100*, 7423–7440, 1995.

M. Chen (corresponding author) and R. B. Rood, NASA Goddard Space Flight Center, Code 910.3, Greenbelt, MD 20771. (e-mail: mchen@dao.gsfc.nasa.gov)

W. G. Read, Jet Propulsion Laboratory, Pasadena, CA 91109-8099.