JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D15, PAGES 20,155–20,163, AUGUST 16, 2000

Simulations of tropical upper tropospheric humidity

A. E. Dessler[1]

Earth System Science Interdisciplinary Center, University of Maryland, College Park

S. C. Sherwood

NASA Goddard Space Flight Center, Greenbelt, MD

Abstract. We present simulations of humidity in the tropical upper troposphere at 215 and 146 hPa made by a model that includes only advection and, whenever relative humidity exceeds 100%, condensation. Despite the simplicity of the model, the simulations agree well with measurements in both convective and nonconvective regions. We see no evidence to suggest that accurate predictions of the humidity in this region are dependent on accurate simulations of microphysical processes or on transport of ice or liquid water. Our results instead suggest that accurate predictions of the humidity primarily require realistic three-dimensional large-scale (greater than a few hundred kilometers) wind fields.

1. Introduction

It is widely agreed that tropical tropospheric humidity is controlled by the interaction of convection, microphysical processes, and advection of ice, liquid water, and water vapor by the large-scale flow [*Emanuel and Pierrehumbert*, 1995; *Sherwood*, 1996a]. Beyond this, however, significant uncertainties in our understanding of tropospheric humidity remain a barrier to making credible predictions about future climate changes [*Intergovernmental Panel on Climate Change (IPCC)*, 1995].

In particular, it is unclear how well general circulation models (GCMs) predict the response of tropospheric humidity to anthropogenic perturbations such as increasing CO_2. At present, GCMs must parameterize convection and microphysical processes owing to speed limitations of modern computers. If detailed representations of these processes are required to accurately determine the humidity distribution in a model, as has been argued [e.g., *Rennó et al.*, 1994; *Emanuel and Zivkovic-Rothman*, 1999], then GCM-based estimates of climate change might be highly inaccurate.

In this paper we investigate the distribution of upper tropospheric humidity (UTH) at 215- and 146-hPa pressure and latitudes between 26°S and 26°N. This region, largely unexplored due to a lack of observations, is crucial for our understanding of the climate due to the strong radiative effect exerted by water vapor there [Shine and Sinha, 1991; Spencer and Braswell, 1997].

2. Data

The ability to study UTH requires a set of accurate measurements of humidity in this region. In this paper we use measurements made by the Microwave Limb Sounder (MLS) [*Barath et al.*, 1993] onboard the Upper Atmosphere Research Satellite (UARS) [*Dessler et al.*, 1998] on the 215- and 146-hPa pressure surfaces. A preliminary version of the data set is described in the literature [*Read et al.*, 1995; *Elson et al.*, 1996] and has shown reasonable agreement with other data sets [*Newell et al.*, 1996]. Because the instrument is a limb sounder, the measurements have a vertical resolution of ~3 km, about half that of nadir sounders [*Soden and Bretherton*, 1993], and can be considered true upper tropospheric measurements. Additionally, the instrument makes measurements in the microwave region of the electromagnetic spectrum. Measurements in this wavelength range take advantage of the reduced sensitivity of microwave radiation to attenuation by cirrus clouds, allowing global monitoring of the concentration of water vapor in the atmosphere under both clear and cloudy conditions.

We will use version 4.90 of the UTH measurements (*W. G. Read et al.*, manuscript in preparation, 1999, hereinafter referred to as R99). The retrieval algorithm uses National Center for Environmental Prediction (NCEP) temperatures and retrieves the abundance of water vapor in relative humidity (RH) units (note that throughout this paper, relative humidity is with respect to ice). Errors in the data set and their implications are discussed later.

In this paper we will be comparing monthly averaged tropical UTH fields derived from MLS measurements with model simulations. We compare monthly averages to minimize random errors and accentuate the systematic differences between the measurements and model. To create the monthly averaged maps, we obtain the MLS measurements over the month and bin and average these data into boxes 4° latitude by 20° longitude. Because the MLS does have some sensitivity to thick cirrus clouds, individual measurements of RH greatly in excess of 100% occur. In order to keep these data from distorting the average, we replace any measurements with RH > 100% with 100% prior to averaging. During the course of the month the MLS makes measurements over the entire range of local times, so the average UTH can be considered 24-hour averages.

3. Model

We compare these tropical UTH measurements with UTH fields simulated by a trajectory model. Our model uses a re-

---

[1] Also at NASA Goddard Space Flight Center, Greenbelt, Maryland

Paper number 2000JD900231.
0148-0227/00/2000JD900231$09.00

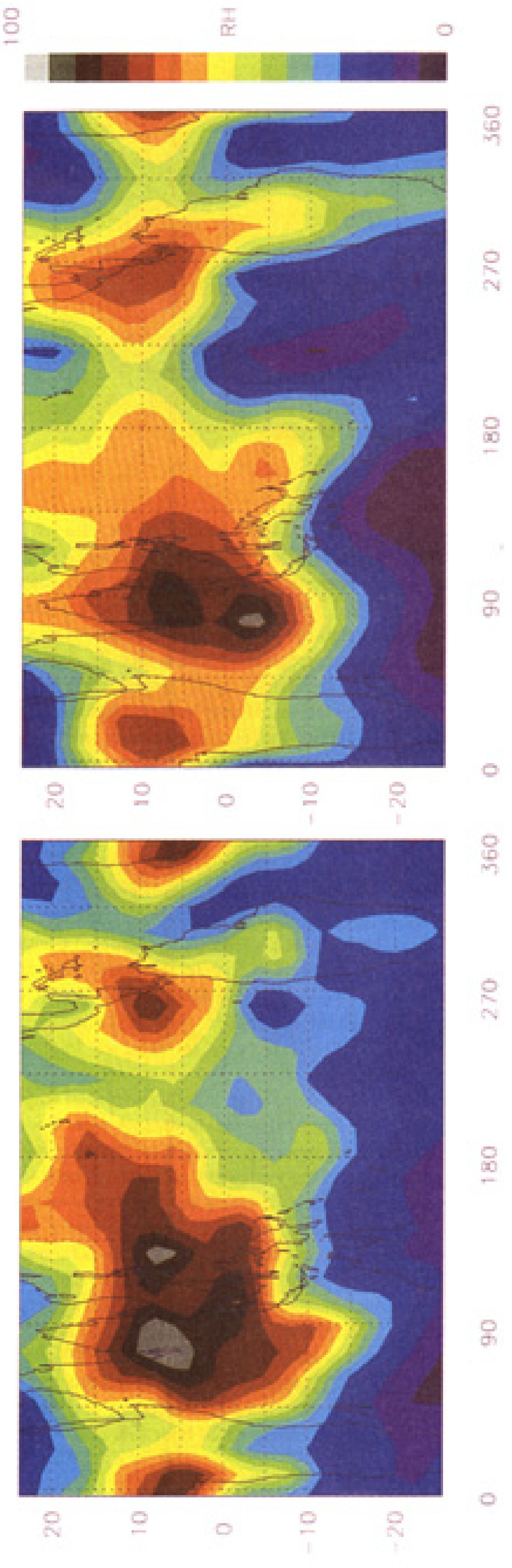

Plate 1. Simulated RH (left) and measured RH (right) for August 1992 on the 215-hPa surface.

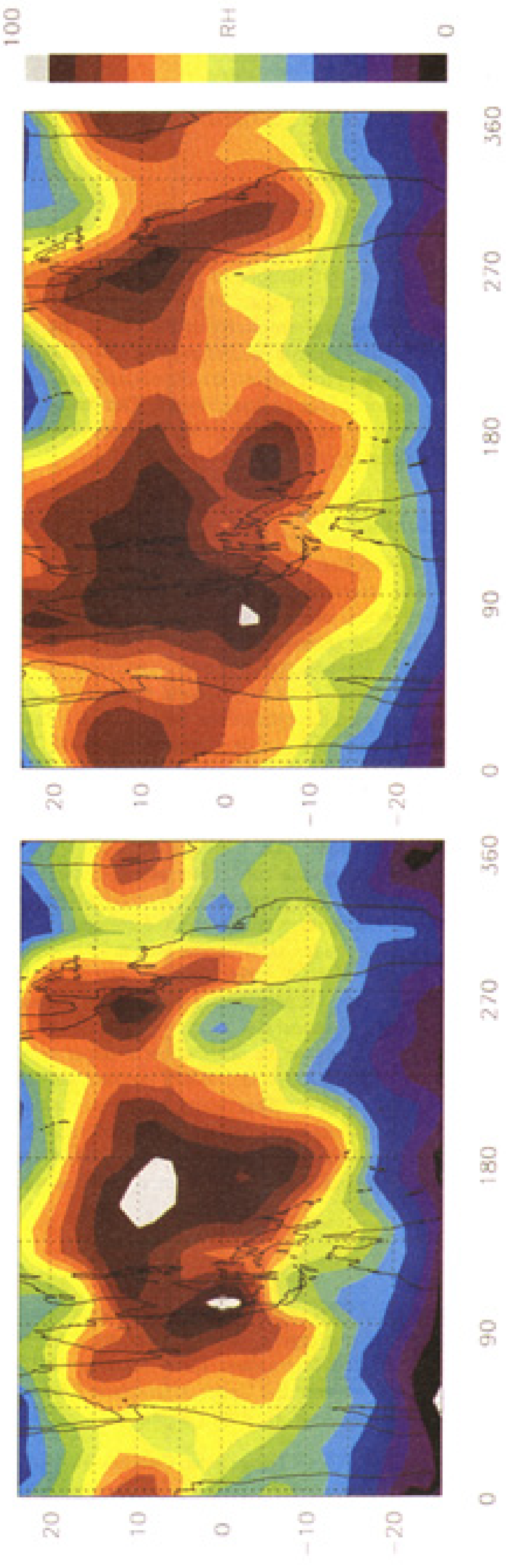

Plate 2. Simulated RH (left) and measured RH (right) for August 1992 on the 146-hPa surface.

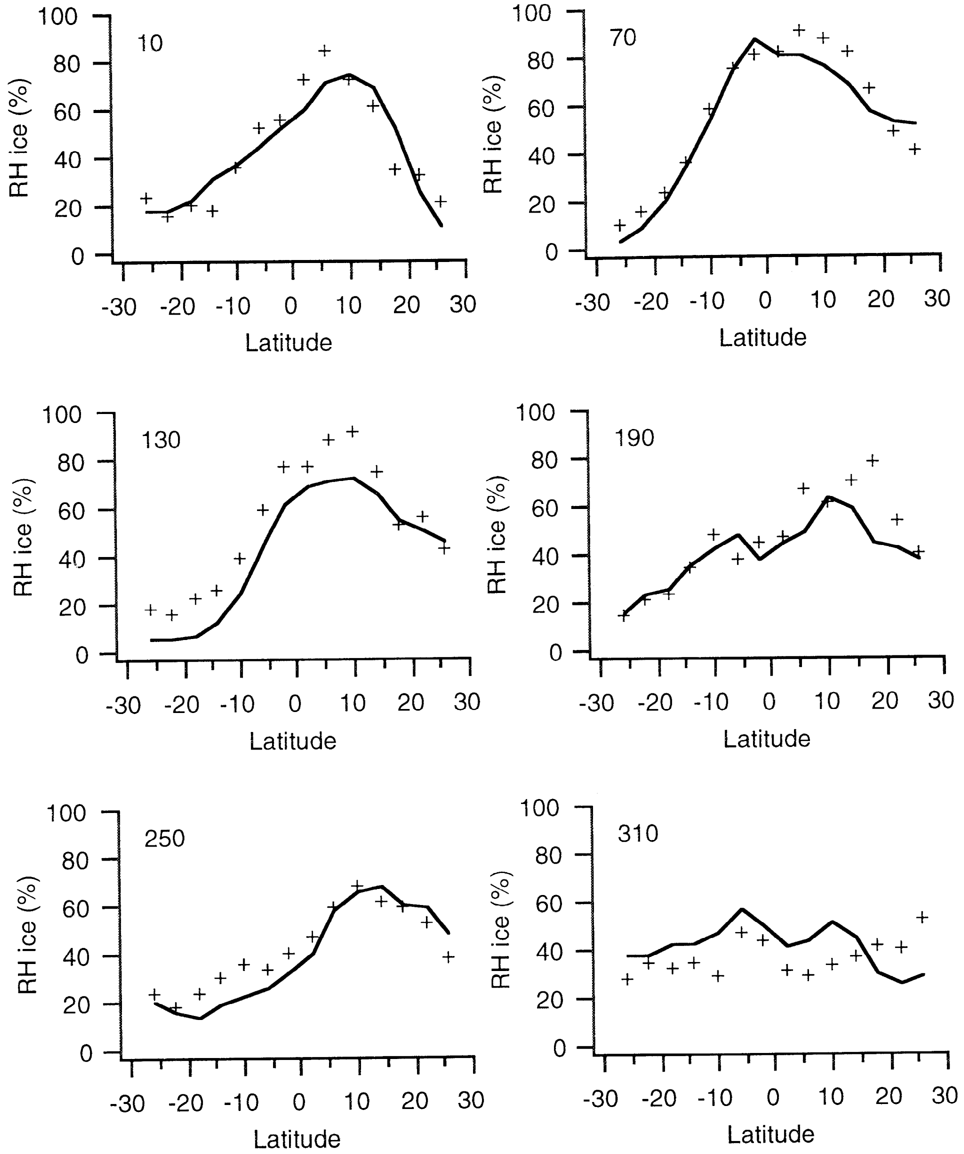

Figure 1. Measured RH (solid lines) and simulated RH (pluses) for August 1992 on the 215-hPa surface versus latitude. The longitude is shown on each plot.

verse-domain filling (RDF) technique [*Sutton et al.*, 1994; *Schoeberl and Newman*, 1995], which has been used previously by other investigators to simulate the distribution of humidity [e.g., *Pierrehumbert*, 1998]. Briefly, to simulate the distribution of humidity on a pressure surface for a given day, we begin with a regular grid of points (4° latitude by 20° longitude resolution) on a pressure surface (either 215 or 146 hPa). Trajectories are initialized at each point at 1200 UT on the day being simulated and are run backwards for 30 days (see *Schoeberl and Sparling* [1995] for more about trajectory calculations).

The water vapor volume mixing ratio (VMR) at the beginning (i.e., the earliest time) of each trajectory is calculated assuming an initial RH of 50% at the beginning temperature and pressure. The water vapor VMR is then carried forward each time step of the trajectory. Anytime the RH of the parcel exceeds 100%, we assume that the water condenses and precipitates in order to maintain a RH of 100%. In other words, the humidity at the final point in the trajectory is set by the minimum saturation VMR along the trajectory. In the few cases where the parcel never achieves saturation, the final RH is set by the initial water vapor VMR of the parcel and the parcel's final pressure and temperature. As we will discuss later, our results are insensitive to the initial RH assumption. Finally, the 1200 UT starting time for the parcels is arbitrary, but calculations using other starting times yield similar results.

To generate a monthly averaged simulation, we run a simulation for each day of the month as described above. The individual daily tropical UTH fields are then averaged together to produce a monthly average field.

The trajectories use the horizontal and vertical wind fields from the NCEP reanalysis [*Kalnay et al.*, 1996]. Integration is accomplished with a fourth-order Runge-Kutta scheme using a time step of 1/100th of a day. The RH is calculated using the

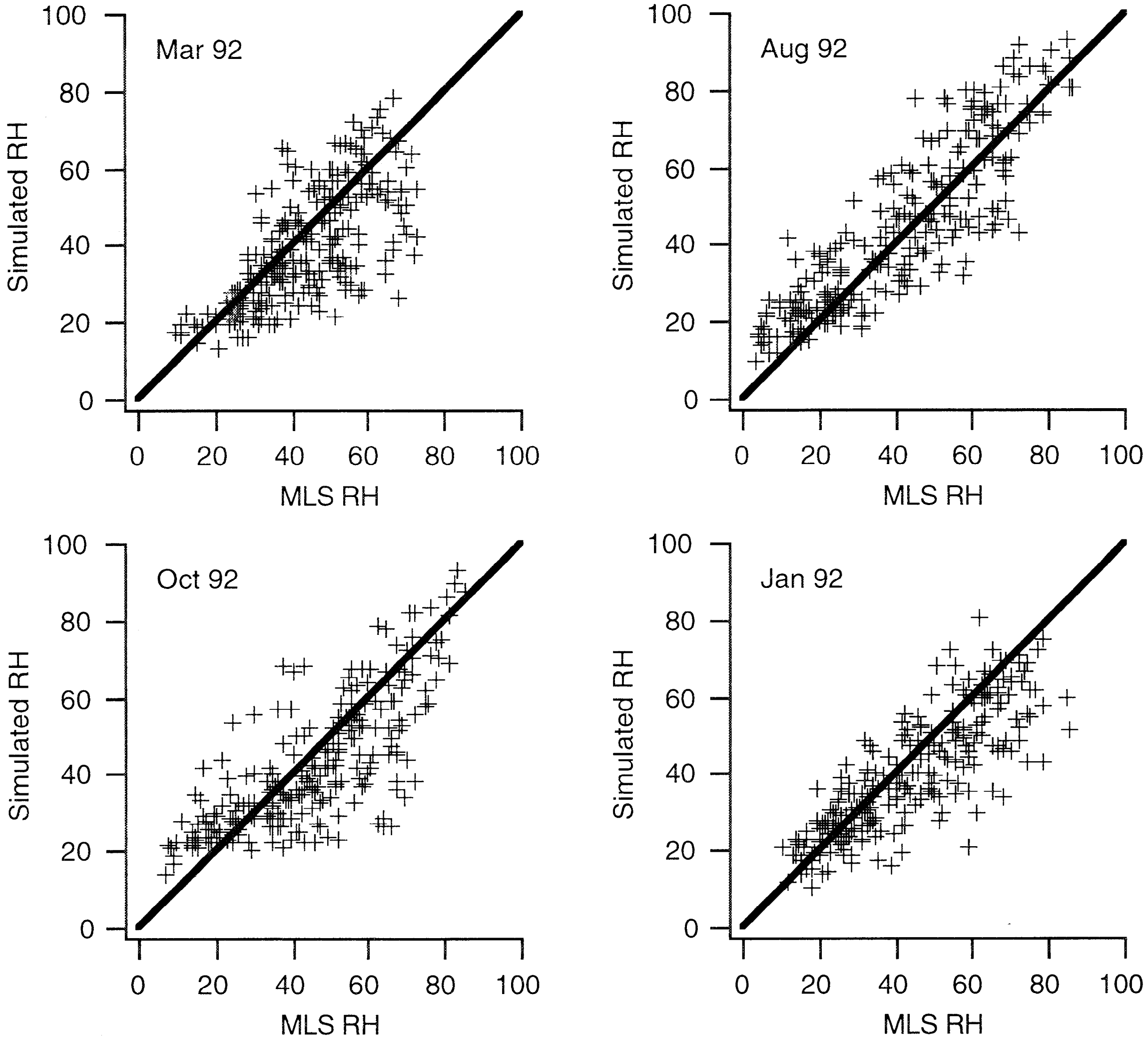

Figure 2. Scatterplot of simulated versus measured RH at 215-hPa simulations for March, August, and October 1992 and January 1993. The lines are 1:1 lines.

accompanying NCEP temperature fields. Note that we do not incorporate convective mass transport in this model. The implications for this will be discussed later.

4. Comparison

4.1. 215 hPa

Plate 1 shows measured and simulated tropical UTH on the 215-hPa surface for August 1992. In general, the agreement between the model and the measurements is good. To better show a quantitative comparison, Figure 1 shows latitudinal slices of RH from Plate 1 at 60° longitude increments, while Figure 2 shows a scatterplot of the RH values from the plots in Plate 1, as well as scatterplots of March 1992, October 1992, and January 1993 simulations.

The simulation for August 1992 is slightly moister overall than the measurements. Other months show both moist and dry biases, with dry biases in the simulations especially prevalent for RHs between 40 and 80%. Considering all of the cases together, the simulation underestimates the measurements by about 2% RH. We cannot not find any consistent pattern to the biases, so we cannot make any general inferences about the mechanisms that regulate UTH from them.

The simulated RH field is insensitive to the RH initial condition. Increasing or decreasing the initial RH by a factor of 2 changes the final predicted monthly averaged RH by only a few percent. This is true because over the 30 days of the simulation, nearly all parcels cool to saturation at some point for any reasonable initial RH. This is a consequence of the fact that parcels increase their RH rapidly as they ascend: a parcel with a RH of 20% at 300 hPa will be saturated by the time it reaches 215 hPa. For these parcels the final RH is not effected by the choice of initial RH (as long as it is high enough for the parcel to saturate). It is only those parcels that do not ascend enough to saturate that are affected by the choice of initial RH. And because there are few of these, their impact on the monthly average is small.

4.2. 146 hPa

Plate 2 and Figures 3 and 4 show measured and simulated tropical UTH on the 146-hPa surface for August 1992. Figure 4 also shows scatterplots of March 1992, October 1992, and January 1993 simulations. As with the 215-hPa comparison, the agreement between the model and the measurements is quite good. There is a tendency for the model to overpredict RH at RH < ~25% and underpredict RH at RH > ~60%. As with the 215-hPa comparison, these differences cannot be explained by uncertainties in the initial RH used in the model.

4.3. Sources of error

Both the 215-hPa and the 146-hPa model simulations tend to overestimate the RH at low RH and to underestimate the RH at high RH. Reasons for this can be broadly divided into four categories: errors in the UTH measurements, missing physical processes in the model, errors in the resolved wind field, and the effects of unresolved motions.

4.3.1. MLS measurement errors. The estimated absolute accuracy of the UTH data set is ±20% and ±30% RH at the 215- and 146-hPa pressure surfaces, respectively (R99). Individual retrievals will contain an additional random error, but because of the large number of points going into the monthly average, we expect the random uncertainty to be small and the overall uncertainty to be dominated by systematic errors. Note that all errors in RH are absolute uncertainties; in other words, 30%±20% corresponds to a range running from 10% to 50%. The quoted uncertainty can explain virtually all of the disagreement between the measurements and the model.

Another uncertainty that would not show up in the error estimates are the assumptions used to extract the dry and wet absorption functions from the in-orbit data (R99). The dry function is obtained by assuming that the lowest radiance values in the upper troposphere correspond to a dry atmosphere with zero RH. Justification for this comes from *Spencer and Braswell* [1997], who report UTH measurements as low as 2% RH. This assumption introduces a dry bias in the UTH measurements at the lowest values, which is consistent with the model-measurement comparisons shown above. The wet function is obtained by assuming that the maximum upper tropospheric radiances correspond to 100% RH. Like the dry assumption, this is not provable purely from data. But one thing that lends some credibility to the assumption is that, like the minimum radiances, maximum radiances also form a well-defined curve, suggesting that a natural limit exists in the data. However, if the "true" maximum RH is different from 100%, as observations of supersaturation suggest, then this assumption would introduce a bias in the data. The bottom line is that depending on what is assumed for the vapor contents in both the dry and wet function determinations, the UTH data could probably be adjusted to agree with the model.

Another uncertainty is the use of the 100% RH cutoff, where any individual MLS measurement of RH > 100% is replaced by 100% before averaging. This is done because RH greater than 100% may be due to cirrus contamination. However, it is now clear that the upper troposphere can be supersaturated, so real measurements of RH > 100% can also occur [*Jensen et al.*, 1999; *Heymsfield et al.*, 1998]. Thus, the effect of replacing all measurements of RH > 100% with 100% RH prior to averaging is to create a low bias in the average tropical UTH values obtained from the MLS. How the neglect of supersaturation effects the agreement between the model and the measurements will be discussed in section 4.3.2.

4.3.2. Missing physical processes in the model. Our model discussed so far (the "standard" model) assumes that when the RH of an air parcel exceeds 100%, it instantaneously loses enough water vapor to keep the RH at 100%. Observations of supersaturated air in the upper troposphere [*Jensen et al.*, 1999; *Heymsfield et al.*, 1998], however, show that condensation does not always occur precisely at 100% RH. To assess the effects of the 100% condensation limit, we ran the model for August 1992 with the assumption that condensation does not occur until the RH reaches 120%, at which point enough water vapor is removed to reduce the RH to 100% (the "supersaturation" model). For a consistent comparison with the measured UTH, where individual measurements of RH > 100% are clipped to 100%, at the final time step of the trajectory, we set the RH of any parcels with RH > 100% to 100%.

In agreement with expectation, allowing supersaturation increases simulated RH throughout the model domain. At 215 hPa, predicted monthly averaged RH increases by ~1% at low RH and 2-3% at high RH. At 146 hPa, predicted RH increases by ~1% at low RH, 3-4% at RH ≈ 70%, and ~1% at high RH. Such slight increases in simulated RH imply that supersaturation is not of primary importance to understanding the distribution of tropical UTH.

It is also possible that our 100% RH cutoff is too high. Strong vertical motions are generally present in both directions near convection. Such motions, however, are represented only in a highly smoothed form in analyzed wind fields of the type used in this paper. The effect of mixing of saturated rising air with dry air in unresolved downdrafts could, however, have the effect of maintaining air, even in convective regions, at subsaturated RHs. To investigate this, we ran the model for August 1992 with the assumption that condensation occurs at RH of 80%, at which point enough water vapor is removed to reduce the RH to 80%. As one would expect, such a change reduces the simulated RH uniformly by a multiplicative factor of 0.8. This worsens the agreement in all months. Thus, we see no evidence to support the use of a lower RH cutoff, although considering the uncertainties in the analysis, we cannot rule it out.

Another assumption in our model is that water is instantly removed from the air mass when RH > 100%; in other words, condensate instantly precipitates from the air mass whenever it forms. To test the importance of this assumption, we ran the model with an alternate assumption that condensate precipitates with a time constant of 1 day (the "delayed precipitation" model). In other words, UTH relaxes back to 100% RH with a first-order time constant of 1 day whenever the RH > 100%. For consistency with the UTH data, at the final time step of the trajectory, we set the RH of any parcels with RH > 100% to 100%.

This "delayed precipitation" assumption is equivalent to transporting ice with the air mass; total water loss is delayed and will require supersaturation be sustained on timescales of a day. Parcels that cool below saturation and then warm again on timescales much shorter than a day will lose little water. This is a crude test of the effects of microphysics, and a time constant of 1 day is consistent with estimated cirrus cloud lifetimes [*Sherwood*, 1999].

Figure 5 shows a comparison between the measurements and the simulations for August 1992. The "delayed precipitation" assumption significantly increases RH throughout the tropical upper troposphere, worsening the agreement between the measurements and the simulations. We conclude that there is no evidence here for a significant contribution to UTH from ice

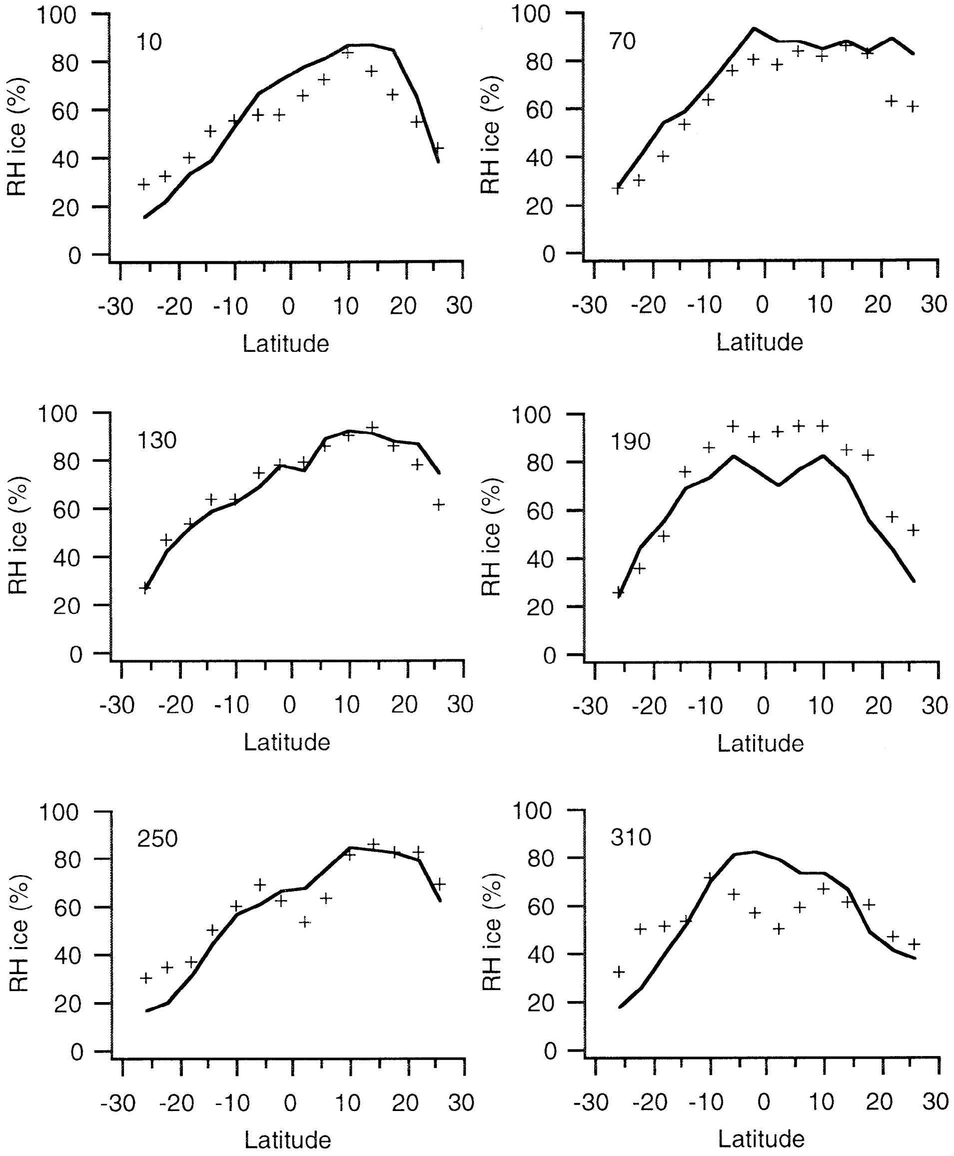

Figure 3. Measured RH (solid lines) and simulated RH (pluses) for August 1992 on the 146-hPa surface versus latitude. The longitude is shown on each plot.

transport. A more detailed analysis using a microphysical model would be helpful for better limiting the effects of ice transport on tropical UTH.

Finally, we note that our "standard" model — instantaneous precipitation at 100% RH — should produce a lower limit of predicted RH. Virtually any process that could be added to the model will tend to impede water loss from an air parcel and thereby increase the predicted RH. Thus, missing processes might explain the underestimate of high RH by the standard model but seem unlikely to account for the overestimate of low RH.

4.3.3. Errors in the meteorological fields.

Errors in the meteorological fields could also be responsible for the disagreements between the simulations and the measurements. Simulations using the GEOS-1 STRAT assimilation (not shown), a stratospheric version of the GEOS-1 (Goddard Earth Observing System) assimilation system [*Schubert et al.*, 1993], begun by the NASA Data Assimilation Office for the Stratospheric Tracers of Atmospheric Transport (STRAT) aircraft mission, are similar to those using NCEP winds. This suggests that when averaged over a month, the wind field in these two assimilation systems are similar. This does not mean that the winds are correct, but it does suggest that if errors in the meteorological fields are responsible, then some aspect of the assimilation system that is common to the NCEP and GEOS assimilations must be responsible.

Besides the winds, errors in the temperature field are potentially important. Biases that leave the gradients in the temperature field unchanged, where a fixed offset is added or subtracted at all grid points, has essentially no effect on the predicted RH. This is true because a fixed offset will change the final temperature as well as the temperature at the minimum saturation point by the same amount, so these changes in RH tend to cancel. These biases would, of course, affect the predicted VMR of water vapor.

Local biases that change the gradients in the temperature field, where one region cools relative to another, can have an important impact on the simulated RH. A detailed analysis of this error source is beyond the scope of this paper.

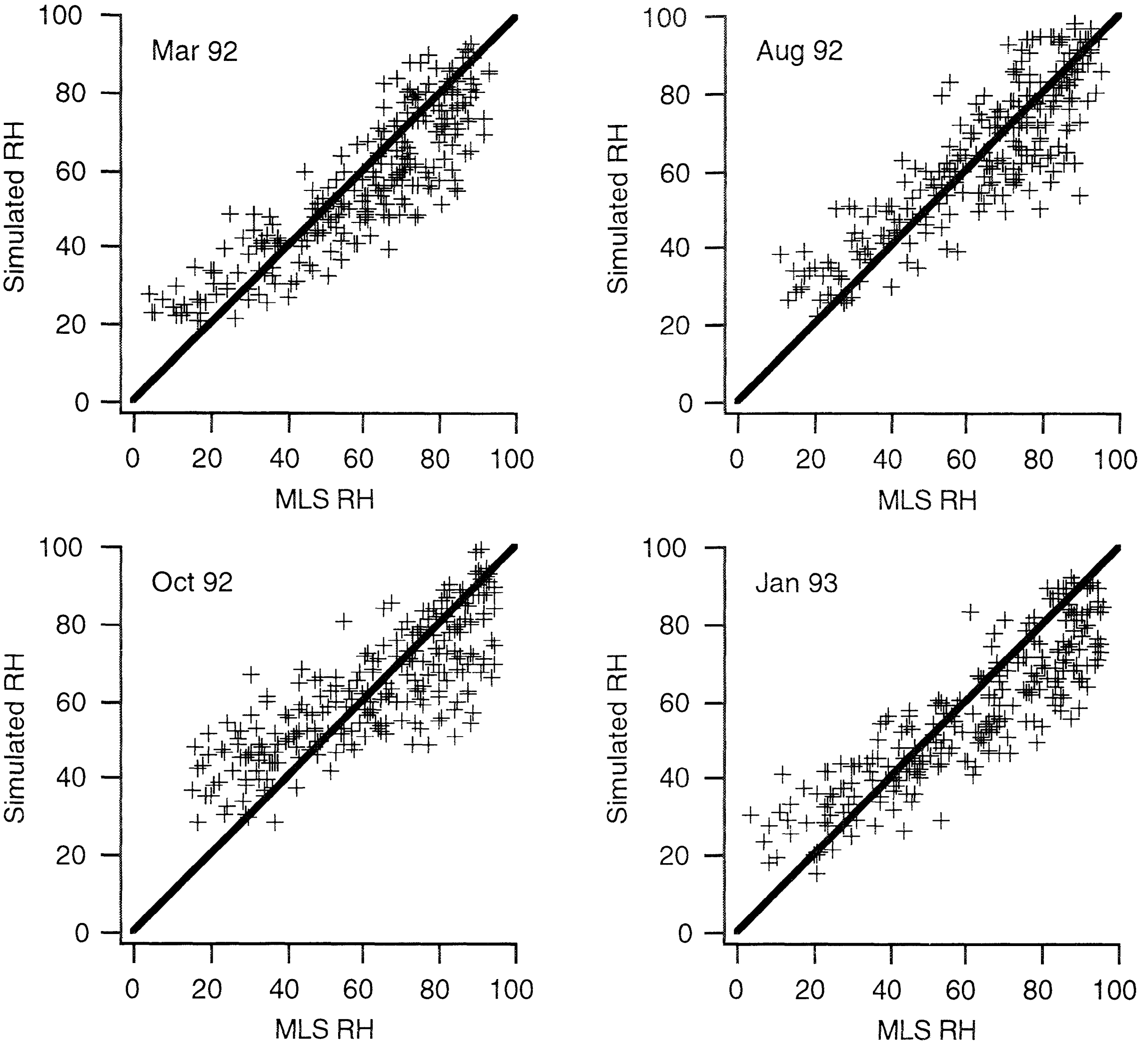

Figure 4. Scatterplot of simulated versus measured RH at 146-hPa simulations for March, August, and October 1992 and January 1993. The lines are 1:1 lines.

4.3.4. Effects of unresolved motions in wind fields.

Finally, convective regions contain small-scale turbulent convection as well as large-scale rising motion (i.e., the Hadley or Walker circulations), both of which transport water within the troposphere. Previous work has shown that the inclusion of convective mass transport in models is required in order to realistically simulate the transport of short-lived species from the lower to the upper troposphere [*Allen et al.*, 1996].

In all of our model runs, we have included only the large-scale wind field and have neglected convective transport. We do this for two reasons. First, convective mass flux is not archived by the NCEP. Second, even if it were archived, it is not clear how to incorporate this quantity in a Lagrangian parcel model.

Since we are doing back trajectories, we only care about the history of air parcels since they were last saturated. Because air in convective areas is evidently near saturation regardless of what kind of drafts it has recently been caught in [e.g., *Sherwood*, 1996b; *Gray et al.*, 1975], the exact history of parcels prior to exit from convective regions is unimportant. The slow, upward mean motion that is captured by the analyzed wind fields in convective areas then becomes a proxy for all the convective processes which have roughly the same result, namely, bringing the air close to saturation. The only hitch is that if the simulated trajectory spends too little time in the convective area, it could fail to reach saturation (e.g., the Bay of Bengal in Plate 2), but the scatterplots show that this does not lead to serious, systematic errors. A more detailed study of the impact of convective mass transport is required to say anything beyond this.

5. Implications for Modeling of the Climate System

Recent satellite observations show that high tropical UTH coincides with deep convection and tracks the seasonal, intraseasonal, and interannual movements of this convection [*Soden and Fu*, 1995; *Sandor et al.*, 1998; *Chen et al.*, 1999]. UTH in these regions is maintained through balance between moistening by detrainment from updrafts and/or large-scale ascent, drying by condensation or freezing of vapor in updrafts, and moistening by reevaporation of detrained hydrometeors and precipitation.

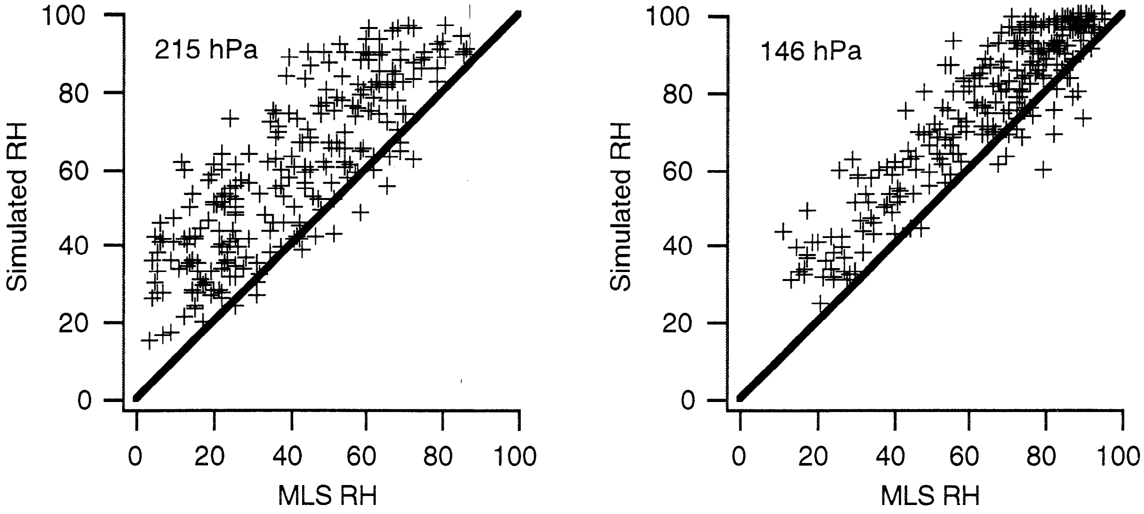

Figure 5. Simulations of August 1992 for 215 hPa and 146 hPa. In these simulations the lifetime of condensate is 1 day with respect to precipitation.

Away from convective regions, so-called "maritime deserts" occur in which humidity levels can be extremely low. It is becoming increasingly clear that humidity in these areas is of great import for the atmospheric greenhouse effect [*Spencer and Braswell*, 1997; *Pierrehumbert*, 1999]. Previous analyses have suggested that moisture levels in these regions are determined to good approximation simply by the character of the free-tropospheric motion field at large scales. *Sherwood* [1996b] was able to reproduce the three-dimensional (3D) moisture field well up to 300 hPa using only motions resolved at the 200-km scale, including only a minor, implicit drying effect due to motions at smaller scales. This result was largely untested above ~300 hPa, although similar conclusions have been reached using trajectory analyses of GOES UTH data, which represents the mean moisture over a broad vertical range between ~500 to ~200 hPa [*Salathe and Hartmann*, 1997; *Salathe and Hartmann*, 2000; *Pierrehumbert and Roca*, 1998].

Our analysis, focusing on 215 and 146 hPa, has extended this conclusion by demonstrating the dominance of advection by the large-scale wind field for determining the distribution of UTH. By now, it is not surprising that this is true in the convectively suppressed, and very dry, regions. What is interesting, and perhaps surprising, is how well the model does even in the convective regions.

This result allows us to put an upper limit on the importance of microphysics and other unresolved physical processes. While we cannot rule out the importance of these processes, the simplest interpretation of our results is that their role is secondary. Sensitivity tests show that the ability of parcels to remain supersaturated would not dramatically alter the monthly averaged humidity distribution. And allowing transport of ice (the delayed precipitation model) worsens agreement with the measurements than the standard model. Consequently, our work provides no evidence to support ice transport as being important for the UTH distribution. *Gettelman et al.* [2000] used an Eulerian model incorporating assumptions similar to our standard model, and found good agreement between their model and measurements at 220 hPa but poor agreement at 150 hPa. They concluded, in disagreement with our analysis, that other physical processes, such as convection, must be important to the overall distribution at 150 hPa.

Though successful, our simple model did consistently underestimate the moisture gradient between moist and dry areas. We have identified several model deficiencies that could easily account for the modest dry biases at high RH, but these deficiencies cannot reasonably account for the moist bias at low RH. Similar problems were encountered by *Sherwood* [1996b], who used an Eulerian approach. He argued that spurious mixing processes were a likely source of excessive vapor in the driest areas. Our approach, however, does not suffer from these mixing processes. Thus the persistence of this problem here suggests instead the existence of some dehydration mechanism, perhaps involving, for example, nonlinear interactions between the unresolved wind field and the physical removal processes. It is also possible that Eulerian and Lagrangian studies make similar errors for different reasons. Since GCMs also overestimate water vapor in dry regions at midtroposphere [*Salathe et al.*, 1995; *Sherwood*, 1996a], the identification of this error is worth pursuing.

6. Conclusions

Our model of upper tropospheric humidity (UTH) of the tropics simulates well the measurements of tropical UTH at 215 and 146 hPa. The model is simple; it contains only advection and, whenever relative humidity exceeds 100%, condensation. Allowing moderate supersaturation has little effect on the simulated tropical UTH, while inclusion of a delayed precipitation feature with an ice-rainout time constant of 1 day produces an unrealistically moist upper troposphere. The latter result suggests that most condensed water precipitates out rapidly. The overall fidelity of the simulations without these modifications was quite good, suggesting that advection alone goes a long way toward explaining the present-day vapor distribution.

Based on this analysis and previous analyses in the midtroposphere, we suggest that three-dimensional general circulation models of climate should be able to simulate the water vapor distribution well, as long as they can correctly simulate the large-scale circulation and temperature structure and can attain suitably moist conditions in convective situations. Detailed microphysics do not appear crucial, unless necessary for simulation of these other aspects of the atmosphere. An important corollary is that models that are able to predict changes in the large-scale circulation and temperature structure correctly under various global change scenarios should also be proficient at predicting changes in tropical UTH.

Acknowledgments. We acknowledge useful suggestions and conversations with Dale Allen, Eugenia Kalnay, Bill Read, Ricky "KOG" Rood, and Mark Schoeberl. This work was supported by NASA grant NAG-11897 to the Univ. of Maryland and a UARS Guest Investigator grant to NASA Goddard Space Flight Center.

References

Allen, D. J., R. B. Rood, A. M. Thompson, and R. D. Hudson, Three-dimensional radon 222 calculations using assimilated meteorological data and a convective mixing algorithm, *J. Geophys. Res., 101,* 6871-6881, 1996.

Barath, F. T., et al., The Upper Atmosphere Research Satellite Microwave Limb Sounder instrument, *J. Geophys. Res., 98,* 10,751-10,762, 1993.

Chen, M. H., R. B. Rood, and W. G. Read, Seasonal variations of upper tropospheric water vapor and high clouds observed from satellites, *J. Geophys. Res., 104,* 6193-6197, 1999.

Dessler, A. E., M. D. Burrage, J.-U. Grooss, J. R. Holton, J. L. Lean, S. T. Massie, M. R. Schoeberl, A. R. Douglass, and C. H. Jackman, Selected science highlights from the first five years of the Upper Atmosphere Research Satellite (UARS) program, *Rev. Geophys., 36,* 183-210, 1998.

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

Emanuel, K. A., and R. T. Pierrehumbert, Microphysical and dynamical control of tropospheric water vapor, in *Clouds, Chemistry, and Climate,* edited by P. J. Crutzen and V. Ramanathan, 17-28, Springer, New York, 1995.

Emanuel, K. A., and M. Zivkovic-Rothman, Development and evaluation of a convective scheme for use in climate models, *J. Atmos. Sci., 56,* 1766-1782, 1999.

Gettelman, A., J. R. Holton, and A. R. Douglass, Simulations of water vapor in the lower stratosphere and upper troposphere, *J. Geophys. Res., 105,* 9003-9023, 2000.

Gray, W. M., E. Ruprecht, and R. Phelps, Relative humidity in tropical weather systems, *Mon. Wea. Rev., 103,* 685-690, 1975.

Heymsfield, A. J., L. M. Miloshevich, C. Twohy, G. Sachse, and S. Oltmans, Upper-tropospheric relative humidity observations and implications for cirrus ice nucleation, *Geophys. Res. Lett., 25,* 1343-1346, 1998.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 1995: The science of climate change, edited by J. T. Houghton, L. G. Meira Filho, B. A. Callender, N. Harris, A. Kattenberg and K. Maskell, 572 pp., Cambridge Univ. Press, New York, 1995.

Jensen, E. J., W. G. Read, J. Merganthaler, B. J. Sandor, L. Pfister, and A. Tabazadeh, High humidities and subvisible cirrus near the tropical tropopause, *Geophys. Res. Lett., 26,* 2347-2350, 1999.

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

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 microwave limb sounder measurements and meteorological analyses, *J. Geophys. Res., 101,* 1931-1941, 1996.

Pierrehumbert, R. T., Lateral mixing as a source of subtropical water vapor, *Geophys. Res. Lett., 25,* 151-154, 1998.

Pierrehumbert, R. T., Subtropical water vapor as a mediator of rapid global climate change, in *Mechanisms of global change at millennial time scales,* edited by P. U. Clark, R. S. Webb and L. D. Keigwin, pp. 339-362, AGU, Washington, DC, 1999.

Pierrehumbert, R. T., and R. Roca, Evidence for control of Atlantic subtropical humidity by large scale advection, *Geophys. Res. Lett., 25,* 4537-4540, 1998.

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.

Rennó, N. O., K. A. Emanuel, and P. H. Stone, Radiative-convective model with an explicit hydrologic cycle. 1. Formulation and sensitivity to model parameters, *J. Geophys. Res., 99,* 14,429-14,441, 1994.

Salathe, E. P., and D. L. Hartmann, A trajectory analysis of tropical upper-tropospheric moisture and convection, *J. Clim., 10,* 2533-2547, 1997.

Salathe, E. P., and D. L. Hartmann, Subsidence and upper-tropospheric drying along trajectories in a general circulation model, *J. Clim., 13,* 257-263, 2000.

Salathe, E. P., D. Chesters, and Y. C. Sud, Evaluation of the upper-tropospheric moisture climatology in a general-circulation model using TOVS radiance observations, *J. Clim., 8,* 2404-2414, 1995.

Sandor, B. J., W. G. Read, J. W. Waters, and K. H. Rosenlof, Seasonal behavior of tropical to midlatitude upper tropospheric water vapor from UARS MLS, *J. Geophys. Res., 103,* 25,935-25,947, 1998.

Schoeberl, M. R., and P. A. Newman, A multiple-level trajectory analysis of vortex filaments, *J. Geophys. Res., 100,* 25,801-25,815, 1995.

Schoeberl, M. R., and L. C. Sparling, Trajectory modelling, in *Diagnostic tools in atmospheric physics,* edited by G. Fiocco and G. Visconti, pp. 289-305, IOS Press, Amsterdam, 1995.

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

Sherwood, S. C., Maintenance of the free-tropospheric tropical water vapor distribution, part I, Clear regime budget, *J. Clim., 9,* 2903-2918, 1996a.

Sherwood, S. C., Maintenance of the free-tropospheric tropical water vapor distribution, part II, Simulation by large-scale advection, *J. Clim., 9,* 2919-2934, 1996b.

Sherwood, S. C., On moistening of the tropical troposphere by cirrus clouds, *J. Geophys. Res., 104,* 11,949-11,960, 1999.

Shine, K. P., and A. Sinha, Sensitivity of the Earth's climate to height-dependent changes in the water vapour mixing ratio, *Nature, 354,* 382-384, 1991.

Soden, B. J., and F. P. Bretherton, Upper tropospheric relative humidity from the 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.

Spencer, R. W., and W. D. Braswell, How dry is the tropical free troposphere? Implications for global warming theory, *Bull. Am. Meteorol. Soc., 78,* 1097-1105, 1997.

Sutton, R. T., H. Maclean, R. Swinbank, A. O'Neill, and F. W. Taylor, High-resolution stratospheric tracer fields estimated from satellite observations using Lagrangian trajectory calculations, *J. Atmos. Sci., 51,* 2995-3005, 1994.

A. E. Dessler, Earth System Science Interdisciplinary Center, 2207 Computer and Space Science Building, University of Maryland, College Park, MD 20742 (dessler@atmos.umd.edu)

S. C. Sherwood, NASA GSFC, Code 916, Greenbelt, MD 20771 (sherwood@zephyr.gsfc.nasa.gov)

(Received September 22, 1999; revised February, 16, 2000;
accepted February, 17, 2000.)