Comparisons of EOS MLS Cloud Ice Measurements with ECMWF analyses and GCM Simulations: Initial Results

J.-L. Li[1*], D. E. Waliser[2], J. H. Jiang[2], D. L. Wu[2], W. Read[2], J. W. Waters[2], A. M. Tompkins[3], L. J. Donner[4], J.-D. Chern[5], W.-K. Tao[6], R. Atlas[6], Y. Gu[7], K.N. Liou[7], A. Del Genio[8], M. Khairoutdinov[9], and A. Gettelman[10].

1. SkillStorm/Jet Propulsion Laboratory, Pasadena, CA, USA
2. Jet Propulsion Laboratory, Pasadena, California, USA
3. European Centre for Medium-Range Weather Forecasts, Reading, UK
4. Geophysical Fluid Dynamics Laboratory, Princeton,NJ,, USA
5. GEST/GSFC/NASA, Greenbelt, MD, USA
6. GSFC/NASA, Greenbelt, MD, USA
7. Atmospheric Sciences, UCLA, Los Angeles, CA, USA
8. GISS/NASA, New York, NY, USA
9. Atmospheric Sciences, CSU, Fort Collins, CO, USA
10. National Center of Atmospheric Research, Boulder, CO, USA

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[*]Corresponding author email:jli@jpl.nasa.gov

Abstract. To assess the status of global climate models (GCMs) in simulating upper-tropospheric ice water content (IWC), a new set of IWC measurements from the Earth Observing System's Microwave Limb Sounder (MLS) are used. Comparisons are made with ECMWF analyses and simulations from several GCMs, including two with multi-scale-modeling framework. For January 2005 monthly and daily mean values, the spatial agreement between MLS and ECMWF is quite good, although MLS estimates are higher by a factor of 2-3 over the Western Pacific, tropical Africa and South America. For the GCMs, the model-data agreement is within a factor of 2-4 with larger values of disagreement occurring over Eastern Pacific and Atlantic ITCZs, tropical Africa and South America. The implications arising from sampling and uncertainties in the observations, the modeled values and their comparison are discussed. These initial results demonstrate the potential usefulness of this data set for evaluating GCM performance and guiding development efforts.

1. Introduction

Upper-tropospheric ice clouds that cover large spatial scales and persist in time can strongly influence global climate through their effects on the radiation budget of the earth and the atmosphere [e.g., Starr and Cox 1985; Liou 1986]. The important role of upper troposphere (UT) clouds in our climate system, combined with present-day shortcomings in their representations in General Circulation Models (GCMs), results in one of the major source of uncertainties for climate (e.g., monsoon, El Nino) forecasts and accounts for the principal uncertainty in climate change projections [e.g., Jakob 2003; Waliser et al. 2003; Luo and Rossow 2004]. Although many observations of ice clouds have been made using satellites [e.g., Rossow and Garder 1993] as well as in situ methods [e.g., McFarquhar et al. 1999], our understanding of cloud processes and the vertical distribution of cloud content remains limited, especially for clouds in the UT. For example, ice water content (IWC) has been difficult to adequately characterize from space due to penetration and sensitivity shortcomings in the more often used visible and infrared wavelengths and nadir-viewing geometry. These shortcomings often result in inconsistent definitions between cloud parameterizations and cloud data products that hinder GCM development and validation efforts from making effective use of the observations. The EOS MLS on the Aura satellite platform provides global observations of cloud IWC profiles along with contemporaneous profiles of temperature and water vapor in the UT. These MLS observations offer a new opportunity to study cloud processes, particularly in the UT, which is vital for the evaluation of cloud and convective parameterizations in GCMs. In this paper, we examine the level of agreement between MLS IWC measurements and IWC values from a number of state-of-the-art GCMs as well as from the ECMWF analyses. Summarizing remarks include discussion of uncertainties and expected areas of future research.

2. Observations

The EOS MLS [Waters et al. 1999] onboard the Aura satellite (launched on July 15, 2004) has five radiometers measuring microwave emissions from the Earth's atmosphere to retrieve chemical composition, water vapor, temperature and cloud ice. These retrieved parameters consist of vertical profiles on fixed pressure surfaces having a near-global (82°N-82°S) coverage. The MLS IWCs are derived from cloud induced radiances (CIR) using modeled CIR-IWC relations based on the MLS 240 GHz measurements. The cloud ice data used in this study consists of IWCs between the UT and lower stratosphere (i.e. 316 to 46 hPa). Although the MLS IWC data has yet to be comprehensively validated, the estimated precision for the IWC measurements is approximately 1.2, 1.8, and 3 (mg m^{-3}) at 100, 147, and 215 hPa, respectively. These values account for combined instrument plus algorithm uncertainties associated with a single observation. The IWC data has a vertical resolution of ~3.5 km and a horizontal resolution of ~160 km for a single MLS measurement along an orbital track. The IWC at a given pressure level is a Field-of-View (FOV) averaged value centered at that level. Detailed descriptions of MLS retrieval can be found in [Wu et el. 2005].

Shown in Fig. 1a, is an example of the MLS IWC at 147 hPa for January 2nd 2005 with measurement tracks shown as small black dots and non-zero individual IWC measurements shown as colored dots. The daily and monthly means shown in Fig. 1b and Fig. 2a are computed from the total IWC amounts divided by the total number of measurements (including cloud free conditions) at each 4°× 8° latitude-longitude grid. These figures reveal several areas of deep convective activity over the W. Pacific, Central Equatorial Pacific and Indian Oceans with high IWC values of 2-4 (mg m^{-3}). A series of large values with colored dots are clearly observed over S. America (see track denoted with an A in Fig. 1a) with IWC values up to 10-12 (mg m^{-3}). The IWC values in this region drop to about 4 (mg m^{-3}) after the spatial averaging (Fig. 1b) or spatial and temporal averaging (Fig. 2a). Note that the four tracks with small black dots over S. America have equatorial crossing times of approximately at 0130 LST and 1330 LST.

3. Results

The comparisons focus on IWC at 147 hPa. This level was chosen since there is still considerable IWC at this level, at least in the Tropics, and because there is greater confidence in the MLS retrievals at pressures less than 200 hPa due to the reduced likelihood of liquid and mixed-phase clouds which adversely affect the retrieval. All the model data have been converted from cloud ice mixing ratio (kg kg^{-1}) to IWC (mg m^{-3}) using model temperatures and pressures. In addition, to account for differences in spatial resolution, we regridded all the model datasets to the 4°x 8° latitude-longitude MLS grid.

a. ECMWF analyses

The daily analyses at 00, 06, 12 and 18Z during January 2005 from the ECMWF Integrated Forecasting System (IFS) data assimilation system (DAS) are used. The cloud parameterization used in the system is a fully prognostic cloud scheme [Tiedtke 1993]. Note that the IWC from the MLS measurements are not included in the ECMWF DAS, and so a comparison of the two datasets is meaningful. We have compared daily IWCs for January 2005 and found that on most days, the ECMWF and MLS IWCs are in relatively good agreement, particularly in terms of geographical distribution over the oceans. Over S. America, ECMWF IWC is smaller than the MLS estimates in most cases (not shown). For example, comparing the January 2^{nd} 2005 ECMWF (Fig. 1c) and corresponding MLS IWCs (Fig. 1b) shows that the maxima in IWC are generally well captured by ECMWF over oceans as well as Central Africa, with greater disagreement exhibited over S. America. A comparison of the monthly mean values from MLS (Fig. 2a) and ECMWF (Fig. 2b) at 147 hPa shows very good agreement over most tropical regions, both in terms of magnitude and spatial distribution. The principal areas of disagreement are the peak values over Central Africa, the W. Pacific and S. America that tend to be higher in the MLS estimates than the ECMWF values by about a factor of 2-4, with the largest disagreement over S. America. In addition, there is a discrepancy in the IWC exhibited in the Eastern Pacific and Atlantic ITCZs, with the MLS values exhibiting considerably less IWC than ECMWF.

b. GCM simulations

The GCMs used for this part of the comparison include: the Geophysical Fluid Dynamics Laboratory (GFDL) with the relaxed Arakawa-Schubert (RAS) convection scheme (GFDL-RAS; Moorthi and Suarez 1992), GFDL with Donner convection scheme (GFDL-Donner; Donner et al. 2001), UCLA with Liou's cloud-radiation scheme (UCLA-Liou; Gu et al. 2003), NCAR Community Atmosphere Model V.3 (CAM3), and NASA GISS [Del Genio et al. 2005], respectively. In addition, two GCMs using a MMF are used. These include the NCAR CAM3 developed at CSU (CSUMMF; Khairoutdinov and Randall 2001) and the finite volume MMF (fvMMF) developed at Goddard Space Flight Center (GSFC). The data from the two GFDL GCMs and CAM3 GCM are mean January values taken from multi-year (17~20) simulations with specified observed sea surface temperatures (SSTs). The UCLA and GISS data are based on the mean January, each taken from a 5-year simulation using climatological SSTs. The data from the CSUMMF and fvMMF simulations are based on mean January values that used specified SSTs specific to the years 2003 and 1999, respectively.

Figures 2 and 3 show the mean January IWC values described above from the two MMF simulations and the GCMs, respectively, in terms of maps at 147 hPa. Over the oceans, the IWC distributions from both the MLS and GCMs exhibit a broad maximum over W. Pacific, with, in most cases, a well-defined extension across the Indian Ocean. In addition, nearly all distributions exhibit relative maxima over Central Africa and S. America. One of the greatest disparities is in regards to the depiction of the ITCZs in the Eastern Pacific and Atlantic – in some cases they are quite evident in IWC and in some cases exhibit virtually no IWC. In addition, there also tends to be a sizeable discrepancy over the larger tropical landmasses. In nearly all cases, peak values tend to primarily occur over the W. Pacific and to a lesser extent Central Africa and S. America. In these cases, the overall model-data agreement is within about a factor of 2-4, with the CSU MMF, CAM3 and GFDL-RAS (NASA GISS, UCLA-Liou, GFDL-Donner) models tending to exhibit smaller (larger) values. It is worth pointing out that the main feature that differentiates the GFDL-Donner scheme from the other GCMs is its inclusion of meso-scale dynamic effects. Comparing the IWC contributions from the large-scale (stratiform) ice clouds (Fig. 3e) to the total (Fig. 3f) indicates that for this scheme, about half of the IWC is produced from the parameterized meso-scale contribution.

The comparisons above highlight the present-day uncertainties in modeling IWC in GCMs and illustrate the resulting diversity in their depiction of upper-tropospheric IWC. While there are still reservations associated with the MLS IWC data, they represent some measure of observation-based validation for this quantity which to date has been sorely lacking, particularly on global scales and with some level of vertical discretization. In order to best illustrate the types and level of uncertainty associated with the above comparisons, we discuss in more detail the MLS and modeled IWC values over tropical S. America (~ 5^{o}N-25^{o}S). The uncertainties that need to be considered are: 1) the precision associated with a given MLS observation, 2) the systematic bias associated with the MLS retrievals, 3) the diurnal sub-sampling by the MLS, 4) additional sub-sampling issues by the MLS, and 5) the interannual variability associated with the GCMs. Considering that there are approximately 40-60 individual observations by MLS in a given month in a given 4^{o}x8^{o} grid box, the uncertainty associated with precision gets reduced markedly upon averaging over a given month and even more so when averaging over a larger region. Taking these into account leaves the uncertainty associated with retrieval precision on the order of about 0.1 mg m^{-3} or less. Since there has yet to be a comprehensive validation campaign for MLS IWC, the systematic bias associated with this version of MLS retrievals is not yet known.

In terms of the diurnal cycle, all GCMs resolve and average over the diurnal cycle, and even the ECMWF values are based on the standard 4 observing times of 00, 06, 12 and 18Z. Since Aura's orbit dictates equatorial crossing times of 0130 and 1330 LST (~ 0530 and 1730Z), this means that MLS misses the mid-late afternoon peak in rainfall that occurs over most of S. America (Lin et al. 2000). Taking this into account and presuming that upper-tropospheric IWC exhibits a similar maxima suggests that the MLS may be biased low and thus the discrepancy between models and the MLS values may be even larger in this region if this bias could be properly accounted for. In addition to sub-sampling the diurnal cycle, the MLS, in contrast to the GCMs, measures a subsample of the clouds that occur in a given "box" over a given month. It might be plausible to assume this is unbiased and could be reduced with more spatial and temporal averaging.

Finally, since for the GCMs, we are comparing multi-year averages to the MLS values from January 2005, we need to consider the interannual variability within the GCM simulations. To do so, we have examined the interannual standard deviations for January for four of the multi-year climate simulations (not shown). For these cases, the GCMs exhibit largest interannual variability over the W. Pacific Ocean and Maritime Continent regions (~1-3 mg m^{-3}), with the larger values for the NASA-GISS and GFLD-Donner simulations. In regards to S. America, two of the GCMs show very little interannual variability over this region indicating that their multi-year mean January estimates are roughly representative of any given January suggesting that the discrepancies with MLS for this region for these models do not stem from influences of interannual variability. On the other hand, examination of the standard deviation over the W. Pacific for example in conjunction with the model-data differences suggests caution in drawing too firm of conclusions regarding the differences in this region. It is worth noting that the January 2005 outgoing longwave radiation anomaly over tropical South America is small relative to the interannual standard deviation and thus the MLS observations are not associated with a highly anomalous January (not shown).

4. Discussion

The comparisons presented above are very preliminary given the very early stage of the MLS mission. Given the uncertainties discussed above, the reasons for the inconsistencies between the modeled and MLS IWC values described in this study are not yet clear. Uncertainties associated with interannual variability and MLS sub-sampling (which is apart from the diurnal cycle) can be reduced as the MLS dataset lengthens. In addition, future work will involve sampling the model output in a manner that more closely mimics the MLS measurements, including considerations of the lower detectable limit (e.g., 1.8 mg m^{-3} at 147 hPa) as well as the saturation level (e.g., ~50 mg m^{-3}). This will better account for MLS sub-sampling, including the diurnal cycle. In the meantime, planned validation programs are expected to be carried out to identify and address systematic biases that may be present in the MLS estimates.

Near-term investigations are expected to include a more in-depth analysis of the discrepancies over S. America. As discussed, the model-data and model-model differences are sizeable in this region. Consideration of MLS' sampling of the diurnal cycle indicates the MLS values are likely to be biased low over this region and examination of the role that interannual variability suggests that it may not be accounting for much of the model-data differences over this region. Taken together, the findings suggest that MLS estimates of IWC over S. America may be systematically higher than that depicted by most of the GCMs examined in this study. Our near-term focus is on identifying the potential causes for the differences. Specifically, the effects from aerosols might be important for formation of ice clouds over landmasses that are convectively active and contain pollution and/or aerosol sources [Li et al. 2005]. On the other hand, a systematic low bias in the amount of cumulus convection occurring in the tropical landmass might be responsible for low IWC. The initial results presented here suggest the need for accurate global measurements such as those from EOS MLS and the forthcoming CloudSat [Stephens et al. 2002] in order to obtain a more comprehensive observational data set of cloud-related quantities for use in model evaluation. This is expected to lead to significant improvements in satellite-derived and model-predicted representations of upper-tropospheric clouds, and in turn lead to improvements in our understanding and predictions of cloud-related processes.

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Figures.

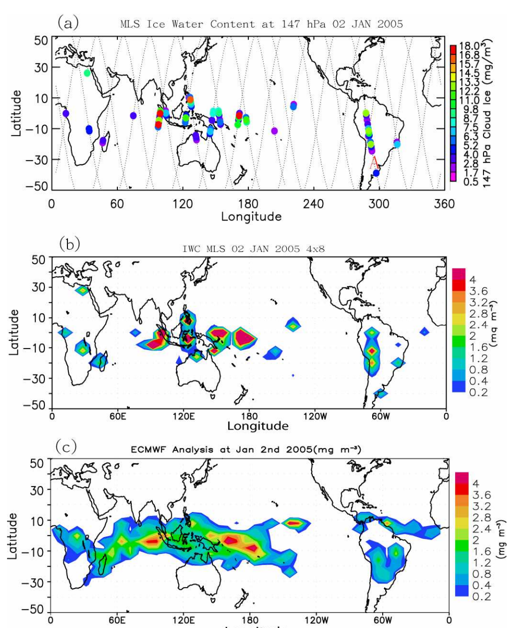

FIG 1. Maps of ice water content (mg m^{-3}) on January 2^{nd} 2005 at 147 hPa from the EOS MLS measurements at (a) footprint spatial scale near 1:30 AM (descending orbit) or 1:30 PM (ascending orbit)

local time, (b) daily averaged with 4^o by 8^o (latitude/longitude) horizontal resolution and (c) the ECMWF analyses averaging at 00z, 06z, 12z and 18z with 4^o by 8^o (latitude/longitude). The estimated precision for the MLS IWC is about 1.8 (mg m^{-3}) at this pressure level.

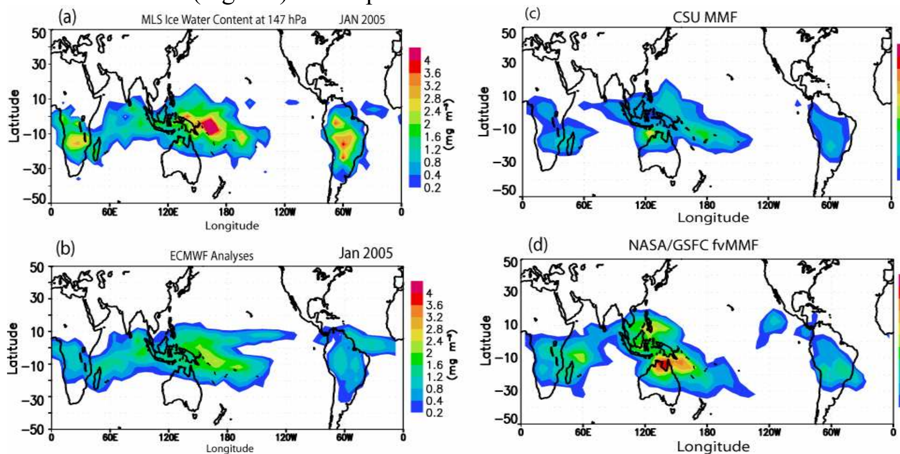

FIG 2. Maps of average ice water content (mg m^{-3}) for January 2005 monthly mean at 147 hPa from the (a) EOS MLS and (b) the ECMWF analyses and single year multi-month simulation from (c) CSU-MMF and (d) NASA fvMMF.

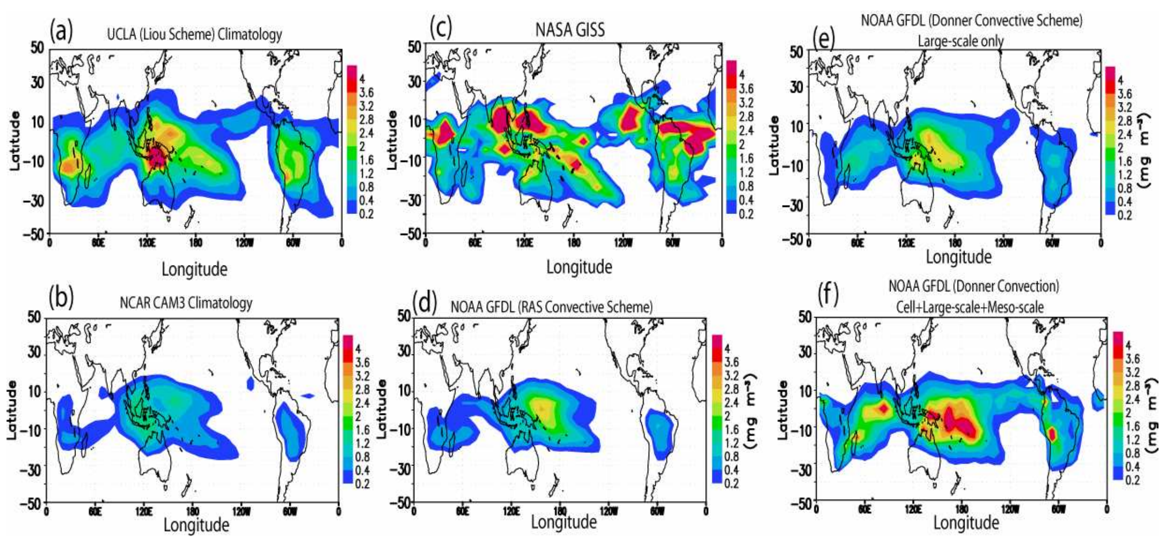

FIG 3. Maps of mean monthly January ice water content (mg m^{-3}) at 147 hPa based on multi-year simulation: (a) 5 years of UCLA-Liou, (b) 10 years of NCAR CAM3, (c) NASA GISS (a single year), (d) 17 years of GFDL-RAS and (e) 17 years of GFDL-Donner (large-scale only) and (f) same as in (e) but with the sum of cells, meso-scale and large-scale contributions.