Anonymous Referee #1
GMDD version Received and published: 17 July 2012

QUESTION: *(1) The authors compare cloud properties to satellite data. It is now widely recognized that for such an evaluation, it is necessary to diagnose cloud properties in the model via a "satellite simulator" (such as the Cloud Feedback Model Intercomparison Project Observational Simulator Package, COSP, http://cfmip.metoffice.com/COSP.html now operational in all general circulation models participating to the 5th Coupled Model Intercomparison Project, CMIP5). The authors should clearly specify whether they have used the COSP diagnostics for the comparison or not (and if not, how they assure comparability).*

Reply: We did not use the COSP simulator in the original simulations described in the manuscript. In fact, at that time, COSP was not fully implemented in GEOS-5 GCM. The comparisons with the satellite data therefore followed the straight comparison used in the pre-COSP era. In the intervening time period, some progress was made in the implementation of COSP in GEOS-5, and although we are not yet fully confident that the implementation operates flawlessly, we have included some results showing the key differences in the COSP simulator versus satellite data in the revised paper. The results come from one-year runs of the CTL and MAC configurations of GEOS-5 GCM; we find one-year simulations are sufficient to assess the impact of applying the ISCCP and MODIS components of the COSP simulator since the interannual variability of zonal cloud fractions and water paths are relatively small as compared to the simulator changes (see Figure 1).

Figure 2 shows comparisons of high, middle, and low cloud fractions with and without the ISCCP simulator. Even though the total cloud fraction fields from the ISSCP and MODIS (not shown) simulator agree well with the model's original total cloud fraction field (top left panel), the other three panels for the high-, mid-, and low-level clouds from the ISCCP simulator exhibit large differences compared to the counterpart model-fields. The simulator successfully accounts for the obscuration of mid and low level clouds by high clouds and yields better agreement between model (MAC simulation) and ISCCP low clouds; however, middle level clouds appear to be overcorrected. On the other hand, high cloud agreement is worse. The CTL clouds appear less affected by the ISCCP simulator than MAC.

Figure 3 shows that the MODIS simulator gives substantially different effective radii for ice and liquid cloud particles, but the biases the overall are not reduced. The ice particles sizes produced by the MODIS simulator are smaller, while the liquid particle sizes are slightly larger. Such biases may be caused by the presence of liquid phase cloud underneath ice clouds that creates low biases for the ice particle size, because the entire cloudy column is assigned to the ice phase, a well known deficiency of the MODIS ice/water separation methodology. Liquid particle sizes are probably larger because of the known sensitivity of the MODIS retrievals to particles near the cloud top. In-cloud ice and liquid water paths generated by MODIS simulator are shown in Figures 4 and 5 respectively and are compared with their MODIS counterparts. We include the simulator results along with the original results in Table 3 of the revised paper (simulator data are shaded gray). These quantities are impossible to diagnose without the MODIS simulator and the associated sub-column generator; only grid mean (i.e., including clear skies) can be created with the original model fields.

Finally, we must point out that recent studies with the COSP simulator have shown some shortcomings that need to be recognized before interpreting the model biases. For example, if the model produces thin high cloud over thick low cloud, the ISCCP simulator will see it as a middle level cloud while the MODIS simulator will see it as a high-topped cloud (Klein et al, 2011); both outcomes misguide the model developers about the actual height of clouds. Conventional output from the model is thus also useful to infer the cloud optical property biases by height.

Extension: *Related comments*

p1393 l20: Is the ISCCP simulator used for the definition of the cloud fractions? What is the overlap assumption used to generate the subgrid-scale variability? If no application of the ISCCP simulator: How are the various satellite issues taken care of in the preparation of the output?

No, the ISCCP simulator was not used in the data analysis in the GMDD manuscript. The satellite data products were used in their original gridded form with spatial degradation/interpolation to the model resolution as appropriate. Please note that some of the satellite data are pre-processed by GMAO as part of their database of satellite validation datasets. GEOS-5 standard post-processing tools generate comparison and difference maps automatically during model runs. Our subsequent application used the default overlap assumption used in the COSP cloud generator, i.e., maximum-random overlap.

p1396 l14: Is the MODIS simulator used? Are these grid-box average values, including clear skies?

The MODIS simulator was not used in the analysis shown in GMDD manuscript. Yes, the grid-average values include clear skies. With the limited/provisional use of the MODIS simulator we can now compare effective particle sizes representative of the entire cloudy column and in-cloud water paths.

(2) A clear explanation of the observational datasets used for evaluation is necessary.

This point is well taken. The revised paper provides a better documentation of the observational datasets used. Basically, we used the datasets in the old fashioned way. The GMAO post-processing tools of model output were already set-up to make many of these comparisons.

Extension: *Related comments*

p1397 l4: SSM/I data has specific deficiencies, e.g. Seethala and Horvath, JGR 2010

Thanks for pointing out this deficiency in the SSM/I data. Clearly, *Seethala and Horvath, (2010)*, point out systematic low bias caused by cloud water and precipitating hydrometeor partitioning above 180 g m^{-2} as the microwave algorithm assigns an increasing portion of the liquid water content of thicker non-precipitating clouds to rain water. We now discuss this bias in the revised manuscript. However, we still believe that the SSM/I LWP is a valuable evaluation dataset. The alternative, MODIS dataset often does not adequately assess the LWP that is topped by ice clouds (the entire cloudy column is assigned to the ice phase). Moreover, the LWP is not directly observed by the MODIS passive measurements, but is rather inferred from combining optical depth and effective radius retrievals assuming a vertically homogeneous cloud, introducing some uncertainty thereby.

p1421 Table 3: It is necessary to specify exactly also here the datasets used, i.e., versions of the datasets. What are resolutions and time periods used for the data?

We have added the appropriate information in the caption of Table 3 in the revised paper.

(3) A more specific explanation on which parts of the cloud parameterization are replaced in the new implementation is necessary (see comment on p1387 l13).

We now discuss all the changes in the cloud parameterization for MAC configuration. Please note that the McRAS-AC scheme has been extensively described in the previous publications. More details are covered concisely in the response to the following question.

p1387 l13: It would be necessary to clarify whether the McRAS covers all types of cloud (stratiform and convective, and for the latter, shallow and deep convective?). l26: LPNC and ICNC need to be defined.

We relate the GEOS-5 implementation to the chronological history of McRAS development. McRAS generates three types of prognostic clouds: i) stratiform or large-scale, ii) moist convective towers topped by anvils that end up as large-scale clouds on the time-scale of an hour, and iii) boundary layer clouds, mostly a by-product of the detraining anvils of dry convective plumes (Stull, 1988); these are discussed extensively in Sud and Walker (2003). The first two cloud types of McRAS (Sud et al., 1999a) namely, stratiform and convective, were transplanted in the GEOS-5 GCM replacing the baseline counterparts, however, the original boundary-layer (BL) clouds of the GEOS-5 GCM were retained; this circumvents issues related to the couplings among the BL cloud-parameterization, PBL-turbulence parameterization, land scheme (catchment model, Koster et al., 2000) in the baseline GEOS-5 GCM. We have revised the paper to better clarify this position. In all clouds the aerosol activation for computing cloud drop number concentration (CDNC) is fully prognostic and is related to cloud scale velocities while the level-by-level precipitation microphysics is carried out prognostically. The vertical velocity is determined by solving the layer-by-layer momentum equation for a convective plume entraining the air mass that could contain cloud particles. The entire convective cloud mass rises with the large-scale vertical velocity (Sud and Walker,1999a). In the aerosol-cloud interaction microphysics (Sud and Lee, 2007), fully prognostic aerosols mass and CDNC were added to the scheme. To obtain cloud plume velocity, the net buoyancy force (a vector sum of all the forces on the cloud) is determined by conservative mixing of mass, momentum, enthalpy fully accounting for entrainment and/or detrainment to obtain the thermal buoyancy of the cloud. The parameterization invokes thermal buoyancy by condensation heating minus the drag force of the in-cloud condensate carried aloft and the precipitation traversing through. In the stratiform clouds, the clouds are assumed to remain within the layer; hence the moist microphysics operates over the entire time step of model physics. All physical processes are prognostic and are outlined in the earlier paper(s) detailing the development of McRAS. We have now defined LPNC=liquid particle number concentration and IPNC=ice particle number concentration.

(4) Assessments as a “reasonably good” comparison between model and observations should be avoided.

Agreed, we now avoid vague statements in the revised GMD manuscript.

(5) It is necessary that the authors explain to which degree and with which objective the two simulations have been tuned.

The CTL runs use the recent version of the GEOS-5 GCM as described by Molod et al. (2012), which outlines some tuning elements and their physical basis. The tuning of McRAS-AC was accomplished by taking the following steps: i) Relating the fall velocity of auto-converted hydrometeors to cloud water amount as described in Sud and Lee (2007); the assumption was necessary to estimate the time available for newly forming precipitating hydrometeors to accrete and collect. It was determined empirically and was made a function of in-cloud water mass. This converted an exponential to a linear relationship. ii) Prescribing the temperature of IN activation for which there are no clear physically based algorithms. According to Khvorostyanov and Curry (2005) theory, deliquescence-freezing nucleation may occur at water supersaturation in the temperature range of -5° to -20°C, but recent cloud chamber experiment data from Kulkarni and Dobbie (2010) showed water supersaturation range of 5-10% for different IN species and that represents -5^0C to -10^0C temperature range. Indeed, our current choice of -8°C, *based on brute force tuning to obtain reasonable pattern of the zonal mean ice clouds*, turns out to fall right in the middle of the Kulkarni and Dobbie (2010) estimates. iii) Using the so-called “Cahalan factor” for cloud inhomogeneity effect on reflected solar radiation. iv) Assuming no time delay in aerosol activation. This can be expected to generate excessive in-clouds CCN, but it is unavoidable because all processes of a GCM assume thermal equilibrium, and v) neglect of giant CCNs (Barahona et al., 2010) that can help to tune the excessive clouds over land. As part of our future plan, we will revisit these tuning elements as well as the aerosol input and CCN activation in the “AC part” of McRAS.

p1389 l6: How are ocean, land surfaces and sea ice represented in the simulations?

Oceans are prescribed from SST analysis (Reynolds et al., 2002); land scheme uses catchment model (Koster et al., 2000), while land ice has 3-layer of interactive ice. Sea ice is prescribed from sea-ice data analysis. For more details, reader may like to refer to Molod et al. (2012) and related earlier GEOS-5 GCM model documentation(s).

l23: How are both model versions tuned? Judging from Table 3, MAC is not so well tuned in terms of global-annual mean TOA net radiation, but both are ok in global-annual mean precip.

Tuning was covered in our response above. The tuning of the baseline GEOS5 GCM has long history and is described by Molod et al. (2012). The cloud part involves adjustment of anvil fraction and prescription of cloud particle sizes. We made no special effort to further tune the TOA fluxes.

Question: I couldn’t tell about which degree, McRAS-AC simulation has been tuned to get realistic cloud radiative effect.

We have highlighted all the elements of tuning in and/or for McRAS-AC in response to Question (5). Fortuitously, the global radiation fluxes turned out are quite good, but certainly better physics and observations derived tuning algorithms can be applied in the future. However, one has to be very careful in tuning a research model, because it is not practical to learn about its biases through experience because often model predictions imply future projections that are impossible to evaluate *a priori*.

p1383 l23: This is an unnecessary discussion. Many of the points are very controversial: (i) "climate prediction" is an ill-defined term in this context, the importance of aerosols for weather prediction still has to be established; (iii) the weekly cycle discussed by Bell et al. and Rosenfeld and Bell is very controversial, (iv) the same is true for the Lau and Kim hypothesis. So I suggest the authors drop this paragraph.

We are aware that some of the papers referenced here are considered controversial by a few individuals/scientists. However, our guiding criterion is that results published in the refereed literature can be referenced. Indeed, in any applied sciences, particularly as complex as climate, controversies are inevitable. In over three decade history of climate research, we are often struck by how so many controversies emerged and how so many, but certainly not all of them, were eventually accepted or resolved through future studies. Presumably, the authors also recognize this because some of their publications have titles with question marks (Rosenfeld and Bell, 2011; Lau and Kim, K. M, 2007). In any event, we need to add a statement in the text to clarify that some of the findings require more studies for full confirmation.

p1384 l6: for constant cloud water path p16: "all GCMs" would be an equally valid statement: in any case cloud microphysical processes are parameterized. l26: Benedetti

It is fixed as suggested.

p1390 l25: Scope and title of Part 2 need to be explained somewhere earlier in the manuscript. Why is this paper not entitled "Part 1" if there is a part 2?

References to Part 2 left over from an earlier version of the manuscript have been removed.

p1398 l3: What does "interactive" mean here exactly? Is it really interactive in the simulation evaluated here? If this is possible, why is it not used by default?

"Interactive" essentially means non-climatological (aerosol) and can change via aerosol chemistry and aerosol sources and sinks including self collection. The reason why it was not used by default is because aerosol sizes and numbers are affected by moist physics. For long interactive runs there is need to extensively validate the realism of the resulting aerosol climatology. While we are proceeding in that direction, at this stage of the McRAS scheme development we chose to concentrate and understand other aspects of the scheme's characteristics and performance.

l24: The MODIS observations show particularly large effective radii compared to other satellite retrievals (e.g., Bréon and Doutriaux-Boucher, IEEE Trans Geosc. Rem. Sens., 2005).

This is true, but it has not yet been conclusively proven that the presumed high bias is an artifact of MODIS retrievals. The POLDER retrievals in the publications mentioned above suffer from coarse spatial resolution and that may be a source cause of the discrepancy. This is an area of active research that explores the possible impacts of satellite measurements on retrievals of cloud horizontal and vertical inhomogeneity, subpixel cloud fraction, 3D radiative transfer, adequate separation of drizzle, and choice of wavelengths for performing the retrievals (e.g., see Zhang and Platnick 2011 and Zhang et al. 2012). Clearly, such discrepancies among MODIS and POLDER retrievals remain unresolved.

l27: r_{eff} depends on the aerosols at most with a cube root dependency.

If the cloud water amount is held constant, the effective drop radius indeed depends on the activated aerosol with a cube root dependency. In McRAS-AC employed in MAC, however, the mass of cloud water increases with increasing number of CCN because smaller cloud particle suppress auto-conversion (as parameterized by Sud and Lee, 2007), which in turn increases the cloud particle effective radius. So the net outcome is complex.

p1399 l13/14: A formulation "reasonably well" should be avoided. Quantitative evaluations are necessary.

Agreed. Our revised manuscript will avoid the use of this terminology.

p1401 l11: (Discussion of definition of CRE): The two equations are equivalent only at instantaneous time steps, it is not possible to get from one to the other for time-averaged quantities. In the observations, in fact, C_tot is always either 0 or 1 at pixel level, and a CRE can be defined only by comparing cloud-free to all-sky situations at one locations. This should be clarified.

In the observations CRE is never defined at the pixel-level because the pixels are assumed to be either entirely clear or overcast; hence, CRE is usually defined as a gridded quantity. The text already clarified that eq. (1b) is not used for CRE diagnostics, only for interpretation of CRE, i.e., to expose the general tendency that with everything else being equal CRE increases with the total cloud fraction of the grid-column. Eq. (1a) used for estimating CRE is averaged the usual way as other model diagnostics, including the all-sky radiative fluxes. See also Oreopoulos et al. (2012).

We thank the reviewer for a thorough and constructive review particularly helping us better realize the need for COSP. As a result, we hope to use COSP routinely in future model simulations.

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Table 3. Global mean MAC and CTL Simulation Fields versus Observations

Periods (left to right)	*OBS: Observed Mean			MAC: Mean/(RMSE)			CTL: Mean/(RMSE)		
Fields (top to bottom)	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN
Precipitation (mm day^{-1})	2.68	2.71	2.68	2.89 (1.54)	3.01 (1.87)	2.92 (1.32)	2.84 (1.58)	3.05 (1.92)	2.89 (1.29)
Total Cloud Fraction (%)	67.0	65.5	66.4	56.7 (17.1)	55.0 (16.6)	55.6 (15.8)	44.3 (25.6)	44.8 (24.8)	44.5 (24.3)
Total Cloud Fraction ISCCP simulator (%)				57.4 (16.8)	56.1 (16.5)	56.9 (14.8)	39.8 (29.5)	41.1 (28.0)	40.6 (27.7)
High Cloud Fraction (%)	21.9	21.9	21.7	21.6 (8.9)	22.4 (9.3)	22.3 (6.6)	22.6 (8.9)	23.2 (9.8)	23.1 (7.6)
High Cloud Fraction ISCCP simulator (%)				26.3 (12.1)	25.7 (11.3)	26.4 (9.9)	23.6 (9.8)	23.6 (10.8)	23.5 (8.2)
Middle Cloud Fraction (%)	19.6	17.7	19.2	21.9 (9.3)	19.2 (7.4)	20.5 (6.7)	9.9 (13.3)	9.9 (10.8)	9.8 (11.5)
Mid Cloud Fraction ISCCP simulator (%)				15.6 (10.3)	14.0 (9.7)	14.8 (9.1)	5.9 (16.9)	6.1 (14.5)	5.8 (15.5)
Low Cloud Fraction (%)	24.9	26.6	25.6	37.0 (21.2)	35.4 (18.5)	35.9 (19.8)	22.0 (13.7)	22.8 (17.4)	22.2 (13.1)
Low Cloud Fraction ISCCP simulator (%)				16.1 (13.3)	16.7 (15.8)	16.3 (13.1)	14.8 (14.9)	15.8 (16.8)	15.4 (14.9)
Cloud Liquid Water Path (grid mean, g m^{-2})	84.3	85.8	84.3	76.6 (40.1)	84.2 (44.9)	79.4 (34.1)	72.9 (26.4)	74.5 (33.2)	72.4 (24.2)
Cloud Liquid Water Path (in-cloud, g m^{-2})	108.7	112.0	107.0	113.4 (67.7)	135.7 (72.9)	129.8 (60.0)	246.2 (212)	264.5 (226)	253.5 (212)
Cloud Total Water Path	89.9	90.5	88.2	92.1	107.0	98.3	77.2	82.4	77.8

(grid mean, g m^{-2})				(51.4)	(65.1)	(41.1)	(59/8)	(57.9)	(48.7)
Cloud Ice Water Path (in-cloud, g m^{-2})	228.8	248.6	243.8	184.6 (150)	214.0 (138)	198.3 (93.1)	242.3 (172)	248.6 (170)	272.9 (137)
Cloud-ice effective Radius (cloud fraction weight, μm)	24.8	25.6	25.2	29.9 (8.8)	28.3 (9.3)	28.6 (7.1)	21.5 (4.5)	21.9 (6.8)	21.6 (4.4)
Cloud-ice effective Radius (MODIS simulator, μm)				21.6 (6.3)	21.7 (7.2)	20.5 (5.7)	21.6 (4.3)	22.0 (4.0)	22.0 (3.6)
Cloud-drop effective Radius (cloud fraction weight, μm)	15.2	16.3	15.6	14.3 (4.2)	14.4 (4.4)	14.0 (3.3)	10.1 (6.1)	10.5 (7.1)	10.3 (6.1)
Cloud-drop effective Radius (MODIS simulator, μm)				16.0 (3.7)	15.8 (3.1)	15.8 (2.5)	10.4 (5.5)	10.7 (6.1)	10.6 (5.9)
Grid Average/In-cloud IPNC (# cm^{-3})				4.1/ 10.6	3.5/ 9.4	4.1/ 10.7			
Grid Average/In-cloud LPNC (# cm^{-3})				35.0/ 68.9	44.5/ 93.1	44.3/ 90.3			
OLR (W m^{-2})	236.9	243.3	239.7	236.0 (8.7)	242.0 (9.8)	238.6 (7.0)	237.4 (10.3)	245.8 (12.1)	241.1 (9.0)
ASW (W m^{-2})	244.5	235.7	240.5	252.2 (18.9)	235.3 (15.5)	243.3 (12.1)	246.7 (17.2)	239.0 (21.7)	243.0 (15.6)
Net TOA Rad. (W m^{-2})	7.6	-7.6	0.83	16.2 (17.5)	-6.6 (12.4)	4.7 (11.1)	9.3 (13.4)	-6.8 (16.3)	2.0 (11.2)
LW TOA CRE (W m^{-2})	25.9	26.3	26.2	24.5 (7.7)	25.4 (7.4)	25.3 (6.0)	21.6 (9.3)	22.2 (10.2)	22.2 (8.3)
SW TOA CRE (W m^{-2})	-51.6	-44.8	-47.3	-45.6 (17.9)	-46.7 (16.2)	-46.3 (12.2)	-50.8 (17.3)	-43.2 (20.9)	-46.4 (15.3)
Net CRE TOA	-25.6	-18.4	-21.1	-21.1	-21.3	-21.1	-27.8	-17.2	-21.7

(W m^{-2})				(16.9)	(14.2)	(11.3)	(18.4)	(21.0)	(15.2)

* Datasets deployed

a) GPCP for Precipitation (Adler et al., 2003)
b) ISCCP for Clouds (Rossow, and Schiffer, 1999)
c) SSM/I for grid mean liquid water path (Weng et al. 1997)
d) MODIS for effective radii, grid mean total water path, and in-cloud liquid/ice water path (Platnick et al., 2003)
e) CERES for TOA Radiation (Loeb et al., 2009)
f) SRB for Surface Radiation (Wilber et al., 2006)

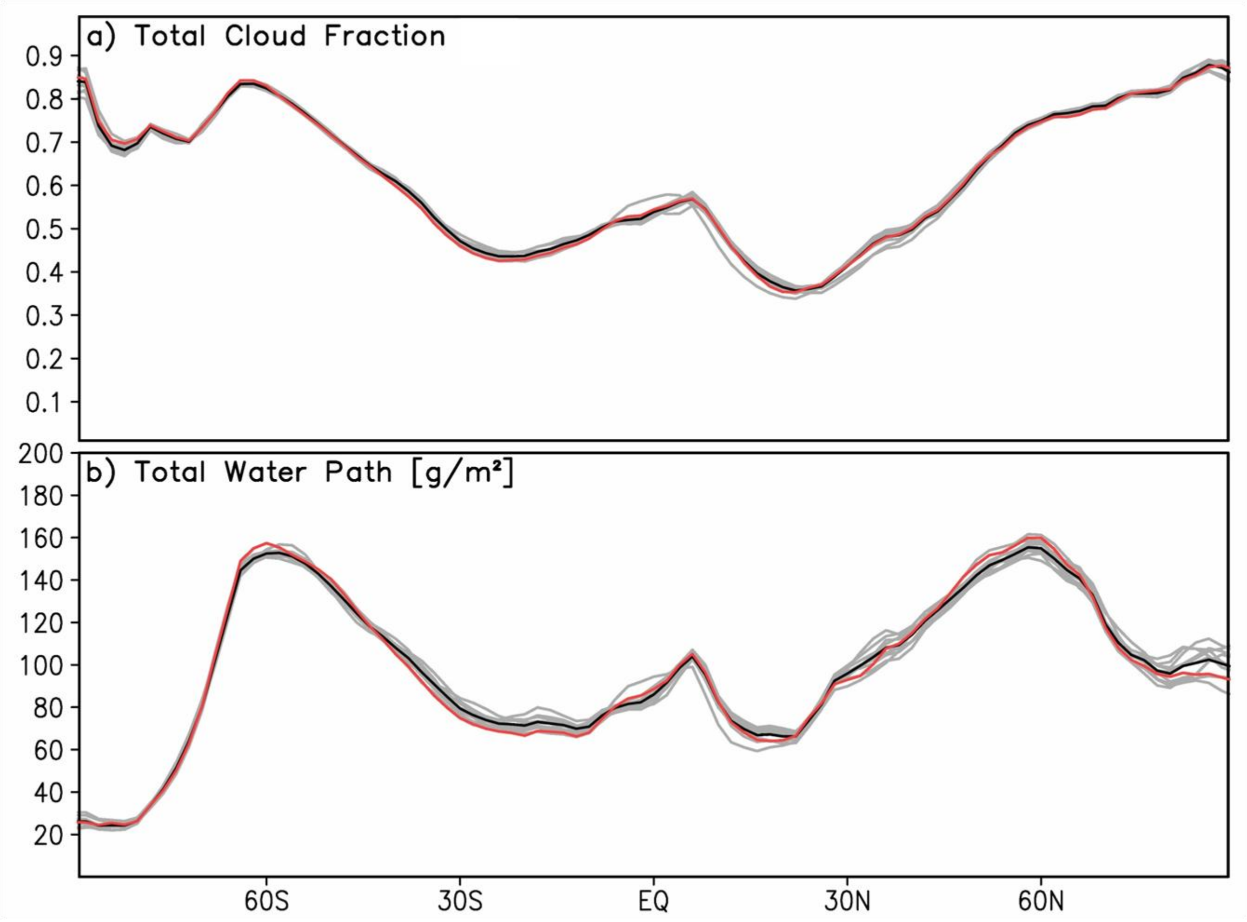

Figure 1: Annual mean of zonally averaged a) total cloud fraction and b) total water path (g m^{-2}). Gray lines are cloud fractions for each of the 10 years (1994 – 2003) of the MAC simulation, black line is for the 10 years mean, and the red line is for a single year (2003).

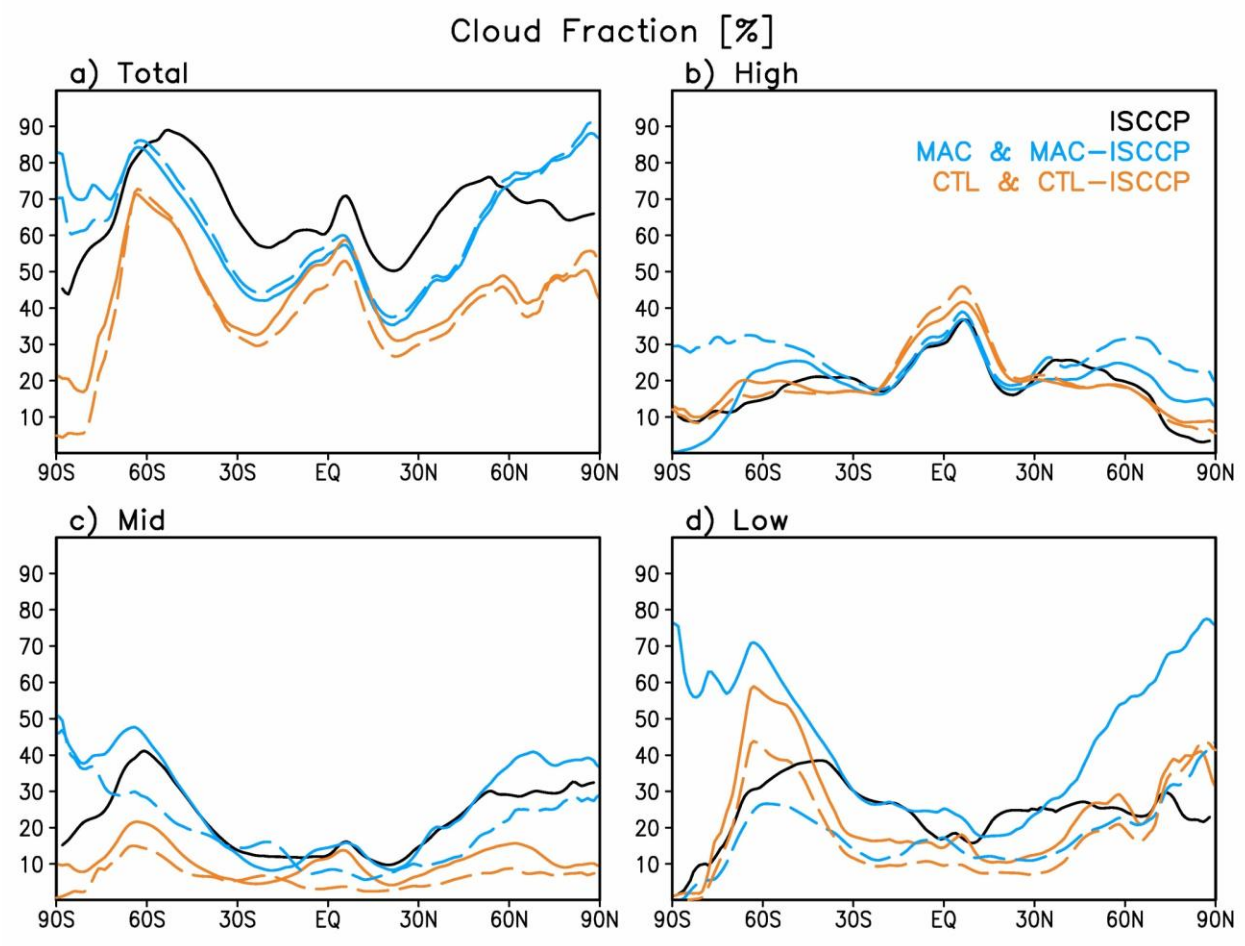

Figure 2: Annual mean zonally averaged cloud fractions for a) total column, b) high, c) mid, and d) low level clouds. Black solid curves correspond to ISCCP data; blue solid (dashed) curves are for raw (ISCCP simulator transformed) MAC experiment outputs. Corresponding orange curves are for the CTL experiment. The cloud fractions are based on maximum/random overlap within and among super-layers as implemented by Chou et al (2001).

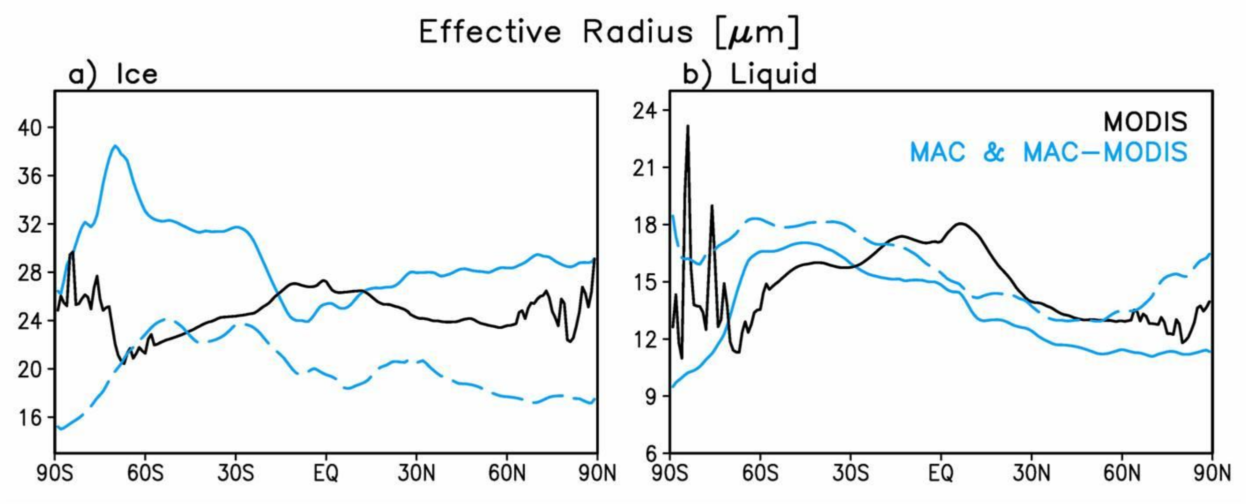

Figure 3: Annual mean effective radius for a) ice and b) liquid clouds: Blue solid line is column average weighted by cloud water content, blue dashed is from the MODIS simulator, and black solid MODIS data.

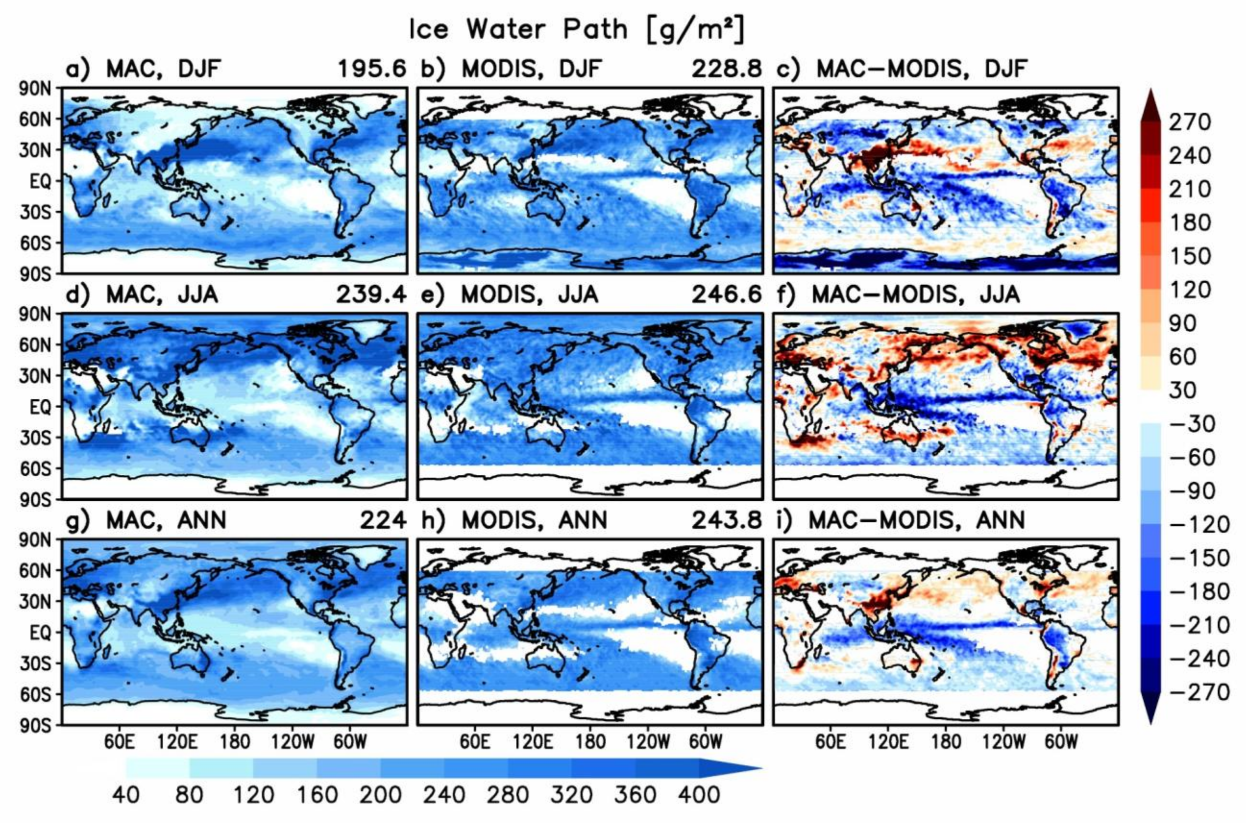

Figure 4: In-cloud ice water path of MAC experiment with MODIS simulator (left column), MODIS IWP (center column), and differences (right column)

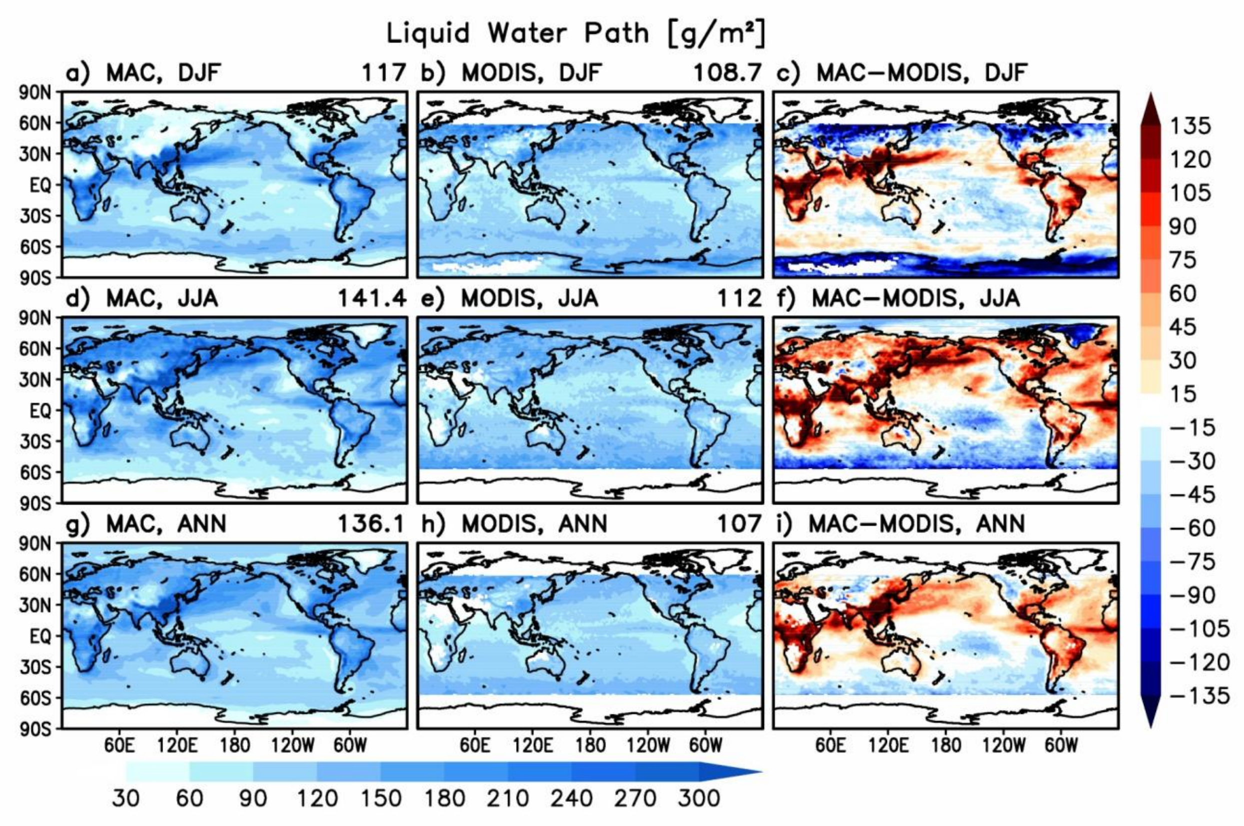

Figure 5: AS Figure 4, but for liquid water path.