Replies to reviewer 1

The replies are introduced in "italics" below each comment of the reviewer

Comment:

This reviewer has no problem with the principal results, nor with the belief that high aerosol content, other things being equal, may well be responsible for increasing the vigor of deep convection, as indicated by many references cited in this and other papers. However, while including a few caveats toward the end of the paper that aerosols may not be the complete answer, in my opinion this paper is too willing to overlook alternative explanations for the observations. In addition, it is probably too uncritical in accepting the hydrometeor profiles from 2A12, which have many potential shortcomings because of well-known simplifications in their derivation.

The reference cited for 2A12 was published before the launch of TRMM. The most important issue to consider is that even current versions of 2A12 over both land and ocean are attempting a very difficult task in deriving rainfall, an even more difficult task in deriving hydrometeor profiles over water, and an almost impossible task over land. Some appropriate references include Kummerow et al. (2001), Nesbitt et al. (2004), Olson et al. (2006), Fiorino and Smith (2006) and Gopalan et al. (2010). This last paper summarizes the current (unsatisfactory) state of the science in rainfall estimates over land.

Over oceans, the algorithms use a Bayesian retrieval that attempts to match the brightness temperatures observed in 9 channels with forward models that in turn are based upon microphysical profiles from a limited set of cloud resolving models, often simulating specific well-observed case studies from field programs such as GATE and TOGA COARE. As far as I know, none of these cloud model runs come from the regions over or near Mexico that are the subject of this study. Over land, because the brightness temperatures in the low frequency channels include surface-based emission with unknown emissivity that varies with vegetation, soil moisture, etc., the rain and microphysical profiles are entirely empirical, and use only the brightness temperatures at 85 GHz, basically responsive to vertically-integrated ice water content. So there is no significance whatsoever to profiles over land having lots of ice, because there would be no 2A12 rain over land whatsoever without ice! Also, note that the 2A12 rain and profile algorithms treat coastal regions exactly like land regions, so only rainfall well off the coast (> about 50 km) uses the oceanic retrieval schemes. These are difficult problems that the NASA Science Teams are working hard to solve, but they are likely to be a source of frustration for the foreseeable future. Bottom line for this paper: Comparison of land vs. ocean hydrometeor profiles from

2A12 is very uncertain, and most of the significance attributed to small differences between night and day, from month to month, or subregion to subregion, is reading more into the data than can be justified.

Reply:

It is true that the 2A12 TRMM product has deficiencies that are not described in the present version of the paper. The weaknesses of this product will be presented in the revised version of the paper and the profiles of hydrometeors will be interpreted with more caution. Also the recent references for 2A12 TRMM product will be included.

The interpretation based on small differences between the regions will be removed from the paper unless there is additional information based on a dataset different than 2A12 that confirms the interpretation. The largest uncertainties are expected for the continental region; however, the continental profiles are presented only for comparison since the focus of our study are maritime regions.

In addition we would like to clarify that the main conclusions of the paper are not based on the 2A12 TRMM product. The main results of this paper are obtained from the relations between lightning (WWLLN data), surface rainfall (3B42 TRMM product) and AOD (MODIS data). The results are supported by some characteristics of hydrometeor profiles that provide an insight into microphysical processes, but the 2A12 product is not the most important source of information in this study.

Also, the comparison between the continental and maritime precipitation characteristics is primarily based on the number of flashes per rainfall. The 2A12 TRMM product is used to obtain some additional information about differences in precipitation ice and latent heating, but most of the 2A12 data in section 3.2 are interpreted together with WWLLN results and other findings reported in the scientific literature.

Comment:

Turning to the authors' apparent surprise that there is a regime over and near Mexico where lightning increases while rainfall decreases, they could have made more use of a paper of mine (Zipser 1994) that they cited for other reasons. One of the main points of that paper is that for many monsoon regimes around the world, it is common for frequent lightning before and after the rainfall peak, but during the rainfall peak lightning is often much less frequent. A more recent paper (Xu and Zipser, GRL 2012, in press) summarizes this behavior for a number of monsoon regimes around the world, including a marked tendency for intraseasonal variability in which heavy rain periods are "ocean-like" with less lightning, and "break periods" are more continental-like, with reduced rain but increased lightning flash rates. Such behavior has been noted often in the Australian monsoon, and during the TRMM-LBA experiment in Brazil, in which the westerly regime has less lightning and easterly regime more.

Reply:

The paper by Dr. Zipser (1994) indeed presents results for several monsoon regimes around the world. However, none of the regimes presented in that paper exhibits the bimodal precipitation pattern (with a relative minimum between July and August) referred to "mid-summer drought". It is ***during*** *this period of relatively lower precipitation that we observe an increase in lightning. While some of the characteristics of a monsoon regime may be present in the region studied in our paper, there are also significant differences. This southernmost region of North America and Central America has a very narrow land portion (South of 15N) and the summer climatology is dominated by the passage of tropical disturbances, such as easterly waves and mixed Rossby-gravity waves, that modulate the intensity of the Inter-Tropical Convergence Zone. It is not typically considered part of the North American Monsoon (NAM), located further North in Mexico and covering also parts of the SW US (principally Arizona but can also encompass New Mexico) and which exhibits a single peak in precipitation. In that NAM region, we observe that the lightning also exhibits a single peak, as we have already reported in Kucienska et al., 2010 (Cloud-to-ground lightning over Mexico and adjacent oceanic regions: a preliminary climatology using the WWLLN dataset. Ann. Geophys., 28, 2047–2057). In that study both LIS/OTD and WWLLN datasets confirm the single lightning peak in August in the NAM region, coincident with the precipitation peak.*

Moreover, in contrast with Dr. Zipser's assertion that "it is common for frequent lightning before and after the rainfall peak*", the maximum in lightning at the beginning of the rainy season (in May) is NOT observed at the onset of the precipitation period in the NAM region. Both the precipitation and the lightning in the NAM region exhibit a single peak in August and a very clear diurnal cycle (maximum precipitation and lightning over land during the day and both variables peaking over the ocean at night).*

Comment:

The low lightning, heavy rainfall regime noted by the authors in the east Pacific ITCZ is an oceanic archetype, and the authors make an interesting observation that the higher aerosol content in May could be related to an increase in lightning there. One plausible scenario presented by the authors, and by others, that under some circumstances, a cloud in a polluted environment may have more lightning than a cloud in a similar thermodynamic (but clean) environment. But it seems an oversimplification to argue that aerosols are THE most important reason. And it begs the question of whether (for example) pre-monsoon storms are strong because the pre-monsoon environment favors more intense updrafts (which aerosols may make more intense), or whether those storms have more intense updrafts BECAUSE of aerosols. It seems doubtful that all pre-monsoon regimes are also high aerosol regimes, although certainly many of them may be due to end-of-dry season biomass burning.

Reply:

The relative maximum lightning in May is only seen in the eastern Tropical Pacific. We agree that it may be possible that stronger storms develop in the May environment in the area, but unfortunately we do not have a radiosonde site in the region that can confirm larger CAPE during that month. The closest site is Acapulco, located outside the region studied, and that will not have evidence of the intra-seasonal variability observed in the Isthmus of Tehuantepec. The paper by Petersen et al (2003) analyzed the soundings launched by the Ron Brown (at 10N and 95W) during the EPIC project in September-October 2001. They reported the observed variability in relative humidity and temperature during the different phases of easterly waves passing through the ship's location. The anomalies in the relative humidity and temperature (from the surface to about 4km) were about 10 % and less that 1K, respectively. Much larger variability was observed higher in the troposphere. Zuidema et al (2006) using the same dataset pointed out the mid-to-upper level intrusions of drier air, mostly related to the mixing that would lead to the capping and decay of convective clouds. No suggestion was made that this dry layer at mid levels could lead to enhanced updrafts in the observed clouds.

References cited in this reply:

Petersen, W. A., R. Cifelli, D. J. Boccippio, S. A. Rutledge, and C. Fairall, 2003: Convection and easterly wave structures ob- served in the eastern Pacific warm pool during EPIC-2001. J. Atmos. Sci., ***60,*** *1754–1773.*

Zuidema, P., B. Mapes, J. Lin, C. Fairall and G. Wick, 2006: The Interaction of Clouds and Dry Air in the Eastern Tropical Pacific. J Climate, 19, 4531-4544.

Comment:

As for the supercooled cloud water deemed essential for charge separation by the accepted ice-ice-collision non-inductive process, it is quite likely that (other things being equal) stronger updrafts will carry more supercooled cloud water to colder temperatures. There are occasional lightning episodes observed in hurricane eyewalls, and it is difficult to imagine that polluted airmasses survive passage through heavy rainfall and reach the eyewall on all such occasions.

Reply:

We agree with Dr. Zipser that more unstable environment (larger CAPE) and/or sustained large scale forcing that may lead to stronger updrafts, will result in large graupel suspended aloft and contribute to charge separation and lightning regardless of the aerosol loading. We do NOT imply that in ALL cases the enhanced ambient aerosol concentration-microphysics-electrification link will be the only explanation. We only point out that in this study there seems to be a range of aerosol loading that affects precipitation and lightning in a different way. We will carefully word the phrases so that it is clear that we refer to this particular situation and it is not necessarily applicable to all cases of convection.

Comment:

In summary, there are important and interesting observations presented in this paper, which warrant distribution and discussion. Most of the details presented on microphysical retrievals may be beyond the inherent accuracy of the algorithms to resolve. On the positive side, I might encourage the authors to make use of their knowledge of this region to find examples of specific short-term periods with intense oceanic lightning, and analyze those as case studies, employing daily (rather than monthly means) wind analyses and geosynchronous satellite observations. Perhaps some of those intense lightning periods could be attributed to advection of polluted air masses. If so, it would be worthwhile for the authors to comment whether the modestly elevated lightning-rain ratios for some of their summer months are explainable by a few short periods with frequent lightning and reduced rainfall, rather than by a persistent but weaker monthly mean signal.

Reply:

We followed the suggestion of the reviewer and studied daily variability of lightning and AOD. A repeatable pattern of high lightning density registered in May and midsummer (July or August) could be observed in the daily time series. Also a pronounced AOD peak was observed in May and a slight increase in AOD was registered during midsummer. However, daily series of AOD and lightning didn't show a correlation between the magnitudes of both variables. We did some additional investigation on the impact of different ranges of AOD values on lightning density and noticed that the highest values of lightning were observed on days with medium AOD (0.2-0.35).

We will include a couple of additional figures in the revised manuscript (corresponding to numbers 13 and 14) that we describe here. In Figure 13, we present the difference between the average value of lightning registered on days with medium AOD (0.2-0.35) and low AOD (0.05-0.15). The AOD values were derived from the MODIS instrument located on the sun-synchronous Aqua satellite, with overpasses at about 1.30pm *local time. The lightning flashes used to produce the figure were summed between 8am and 5pm local time. The grid resolution is 1 degree. The calculations were done for the year 2009, when the detection efficiency of WWLLN was highest (within the analyzed period: 2005-2009) and the amount of data samples in each AOD range was sufficient to calculate lightning difference for most of grid squares. White squares represent regions where the number of data samples was less than 8 for one or two AOD ranges.*

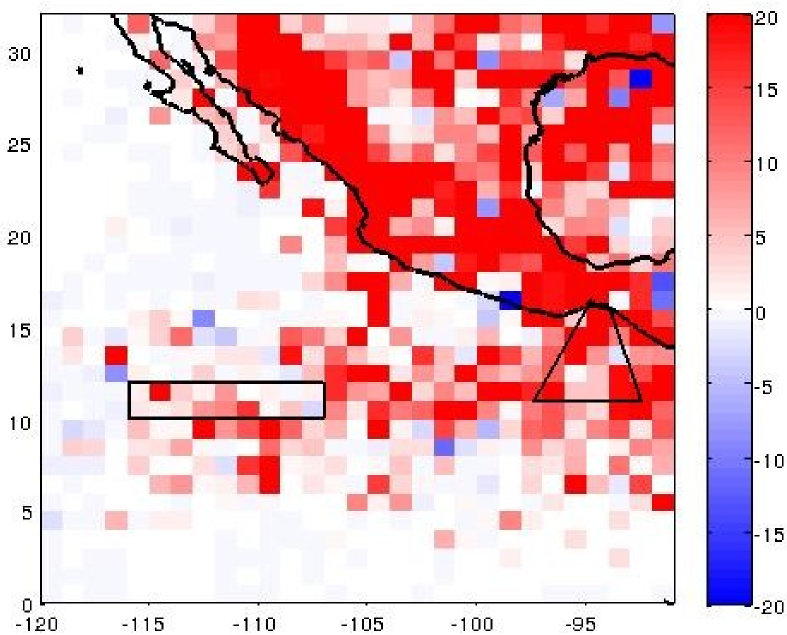

Figure 13. Differences between average numbers of lightning flashes registered during days with medium AOD (0.2-0.35) and low AOD (0.05-0.015)

The results presented in Figure 13 show that there are more lightning flashes recorded on days with medium AOD than on days with low AOD over the Tehuantepec Jet region, Gulf of Mexico, Continental Mexico and some areas of ITCZ. However, the results change drastically when the difference between lightning recorded for high AOD (0.4-1.5) and medium AOD (0.2-0.35) is calculated.

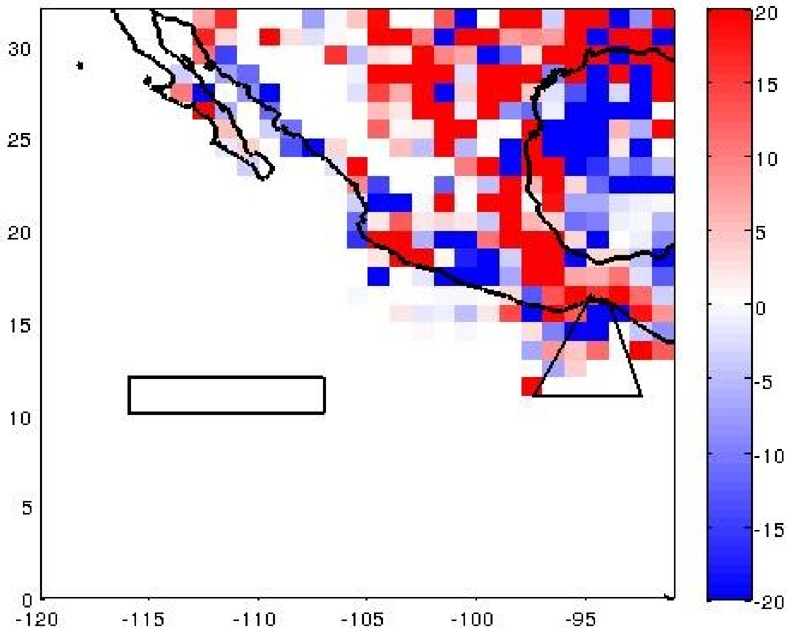

Figure 14. Differences between average numbers of lightning flashes registered during days with high AOD (0.4-1.5) and medium AOD (0.2-0.35)

In contrast with the results in Figure 13, the differences between lightning flashes on days with high and mean AOD (Figure 14), are negative for the Gulf of Tehuantepec, most of the Gulf of Mexico and continental regions of Sierra Madre Occidental, close to Pacific coast. These results indicate that very high values of AOD may decrease lightning and even inhibit it. The results presented in Figures 13 and 14 show that the influence of AOD on lightning depends on ***the range of AOD****. And this fact is the reason why there is no direct correlation between the magnitudes of AOD and lightning in daily time series. Our results are in agreement with the results of Altaratz et al. (2010), who observed that in the regions affected by Amazonian fires, the lightning density increases when AOD increases for AOD values smaller than 0.35 and decreases for AOD larger than 0.4.*

Among the analyzed years, 2007 was the only one that didn't show a lightning peak in May. During most of the days of May, the AOD was much higher than 0.4 and the average AOD in May of 2007 was 0.48, which was the highest value among the analyzed years. These results indicate that very high values of AOD may have suppressed convection and lightning in May 2007.

Moreover, the results shown in Figures 13 and 14 indicate that the increase of both lightning and AOD is not likely driven by the same meteorological conditions, as the relation of proportionality between these two variables is only valid for a limited range of

AOD. These results rather point toward the relation of cause-effect between AOD and lightning density.