Reply to Referee #1

We appreciate the comments and suggestion of the reviewer. The careful inspection of our manuscript gave us the opportunity to improve the quality of our work. The reviewer's comments are addressed below:

1. "This is a fairly limited analysis that supports many previous analysis that have shown that the effective radius derived from two near infrared channels differ. Little new information is presented however the methodology is generally sound…"

We agree with the reviewer that the premise of our manuscript, spatial heterogeneities can bias the satellite cloud retrievals, is not novel. While we properly acknowledge this in our manuscript, we attempt to answer the question whether the MODIS effective radii differences are dominated by the spatial heterogeneities or the cloud vertical structure. Because the cloud microphysical vertical structure is tightly related to the regional/large scale atmospheric processes (see Wood et al., 2011), we use an independent retrieval of LWP for isolating different dynamical patterns. While the use of LWP for studying meteorological processes is new to the remote sensing community, LWP-based analysis have been commonly utilized by the cloud-aerosol interaction community (e.g. McComiskey and Feingold, 2012) to isolate aerosols from cloud dynamical effects. A second point to take into account is that our physical interpretation of the satellite retrievals mostly comes from in-situ observations during VOCALS-REx (Painemal and Zuidema, 2011). Our results for homogeneous clouds are qualitatively consistent with VOCALS-REx in two ways: 1) effective radii are larger at the cloud top (i.e. $r_{e3.8} > r_{e2.1}$), and 2) this pattern is unaffected by LWP, which mostly modulates the magnitude of effective radius. Because we share in part the reviewer's concern about the title, we have replaced "cloud dynamics" by "liquid water path".

We summarize the contribution of our manuscript in the following:

1.We systematically separate the heterogeneity in contribution in terms of cloudy and broken clouds. Although Zhang and Platnick (2011) showed the dual impact of cloud cover and cloud heterogeneities in some selected satellite scenes, the systematic statistical analysis in our manuscript is to our knowledge new.

2. We quantify effective radii differences at scales relevant for climate studies.

3. We provide additional interpretation to the results in Seethala and Horvath (2010) concerning differences between AMSR-E and MODIS in the context of spatial heterogeneities.

4. A link between cloud dynamics and cloud effective radius is also investigated. We understand the concerns of the reviewer regarding this point. We further address this idea below.

2. "Title: 'The impact of' should be changed to 'relationships between' or something along those lines. 'cloud dynamics' definitely needs to be removed. You can't equate microwave LWP retrievals with cloud dynamics."

3 "Line 16: same comment as above

In marine boundary layer clouds, the links between liquid water path (LWP), boundary layer depth, turbulence, and drizzle have been well established (e.g. Wood 2005, Painemal et al., 2013, Terai et al., 2013, among others). In typical marine stratocumulus, deep clouds with high LWP produce strong cloud top radiative cooling, which is the fundamental source of cloud turbulence. In addition, a regional forcing, such as surface convergence, can also produce increase in LWP (e.g. Wood et al., 2009). All of these factors modulate the microphysical structure and determine the transition between purely droplet condensational growth (typical of non-precipitating clouds) to active collision/coalescence, which is the main mechanism for precipitation formation (e.g. Roger and Yau, 1996) The use of LWP as a proxy for cloud dynamics and macrostructure, in the absence of other more specific variables, have, in particular, been used by the cloud-aerosol interactions community (e.g. McComiskey et al., 2009). We, however agree in modifying the title to make more explicit that we are using LWP as a proxy for cloud dynamics. In the latest manuscript, we include the following paragraph:

"For cloudy scenes, when CF > 98%, an LWP-dependent analysis is relevant because one should expect a relationship between LWP, H_σ, and the cloud vertical structure. LWP has been recognized as a cloud macrophysical property (e.g. Wood 2012), as it is the manifestation of different forcing parameters such as: sea surface temperature, divergence, humidity, and atmospheric stability (e.g. Stevens and Brenguier, 2009). LWP and in-cloud turbulence (updrafts) are linked because a LWP increase produces stronger cloud top radiative cooling, which in turn favors the turbulence production. Moreover, increasing LWP associated with boundary layer deepening (e.g. Painemal et al., 2013) should facilitate droplet size condensational growth. All these factors modify the cloud droplet activation and growth, affecting the droplet size, the vertical structure, and drizzle generation. The use of LWP as a proxy for the cloud dynamics has also been applied for isolating the cloud-aerosol interactions from those factors associated with the regional circulation and cloud dynamics (e.g. McComiskey and Feingold, 2012; and references therein)."

4. Line 26: Later in the text you claim that the positive biases are indeed associated with vertical structure. Don't you really have some evidence that both vertical and horizontal structure may play some role and that horizontal structure is most likely more important.

Our interpretation is that when the clouds are homogeneous, a positive difference between the 3.8 and 2.1 μm effective radii agrees better with in-situ observations of cloud effective radius. It is important to emphasize that the interpretation of satellite retrievals requires further knowledge of the cloud structure. This is why we selected the southeast Pacific since this allowed us to take advantage of aircraft microphysical observations during VOCALS Regional Experiment, the most comprehensive field program devoted to the study of marine boundary layer clouds to date. We include a new section explaining some results during VOCALS-REx:

"An advantage of limiting our study to the southeast Pacific Ocean is that we can exploit the improved microphysical understanding gained from the VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment VOCALS Regional Experiment

(Mechoso et al., 2013). Specifically, more than 100 cloud vertical samples over the 19˚S-30˚S and 85˚W-71˚W domain, collected during October-November of 2008, reveal in great detail the cloud microphysical structure of the marine stratocumulus clouds. In-situ observations of westward increases in both r_e and LWP were typical during VOCALS-REx, and connected with a boundary layer deepening and more drizzle occurrence. These zonal changes are qualitatively well reproduced by retrievals using MODIS data (Painemal and Minnis, 2012; Brunke et al., 2010). In terms of the vertical structure, in-situ observations also yield a robust pattern, in which r_e monotonically increases toward the cloud top, regardless of the magnitude of LWP (Figure 5 in Painemal and Zuidema, 2011). Although precipitation can modify the r_e profile, the droplet size tends to peak at the cloud top even for clouds with LWP as large as 250 gm^{-2} (Painemal and Zuidema, 2011). The cloud vertical structure observed during VOCALS-REx has interesting similarities with other field campaigns. For instance, droplet measurements in shallow cumuli collected during the Rain In Cumulus over the Ocean field experiment also evince a maximum r_e near the cloud top (Arabas et al., 2009). The fact that the particle size seems to be unaffected by cloud top entrainment indicates that the mixing is mostly homogeneous, that is, the evaporation time scale is faster than the mixing scale (Lehmann et al., 2009).

In the context of MODIS satellite retrievals, if the source of difference between $r_{e2.1}$ and $r_{e3.8}$ arises exclusively from the cloud vertical inhomogeneity unaccounted for the algorithm, then expectations built upon aircraft observations should be that $r_{e3.8}>r_{e2.1}$, as discussed in Platnick (2000)."

5. Line 97-99: This argument makes no sense to me. The bias in retrieved re is mostly coming from internal pixel heterogeneity (<1km) not external (>1km) pixel heterogeneity. You are better off arguing that heterogeneity at small scales is associated with heterogeneity at larger scales.
We appreciate the reviewer's comment. The internal variability is certainly the cause of the effective radius bias. We are emphasizing now the role of the subpixel variability.

6. Figure 2: Can you use the same data range for 2b and 2c so that the color scales can be compared?
Done

7. Line 140: change 'an' to 'a'
Corrected, thanks

8. Lines 142-144: This is a bit of a stretch and extremely speculative. This physical interpretation just isn't justified or really necessary. Just state that variation in LWP might be associated with variations in cloud dynamics.

See our response to comment 2-3

9. Line 140: Are the results in Figure 3 only from grids with CF > 98%?
Yes. We emphasized this in our latest manuscript.

10. Line 145: AMSR-E LWP is not insensitive to 3D radiative effects [Greenwald, 1997]. This is correct, but it is nearly insensitive to 3D radiative effects for the type of clouds that are the focus of this investigation.

11. Figure 4: The comparison could be better shown as a data density plot. The apparent high bias of MODIS at low values of AMSR-E LWP is simply the result of binning one positive definite variable against another which will always give the impression of biases as one approaches zero. In fact, this particular microwave retrieval is known to have a high bias as MODIS LWP (cloud fraction) tends toward zero.

The main goal of Figure 4 was depicting the geographical heterogeneity increase with LWP, and the possible consequences in MODIS retrievals of LWP. Because the goal of this study is not the comparison between MODIS and AMSR-E LWP, we removed Fig. 4. Instead, We included a new figure 4, where we show a bias transition between coastal and offshore clouds, in order to reinforce the idea that horizontal heterogeneity modulates MODIS LWP, especially far offshore, where clouds tend to possess large LWP. We add the following paragraph:

"Given the westward gradients in Δr_e and H_σ observed in Fig. 1, we analyze further the impact of using $r_{e3.8}$ and $r_{e2.1}$ in the computation of MODIS LWP (Eq. 1), in the context of spatial heterogeneities. Figures 4a and 4b show histograms for the biases between AMSR-E and MODIS LWP, for a 4˚x3˚ coastal (centered at 76.75˚W,23.75˚S) and offshore (centered at 97.75˚W, 23.75˚S) region, respectively. The blue histogram indicates LWP differences calculated using daily $r_{e3.8}$ ($LWP_{3.8}$), whereas its red counterpart makes use of $r_{e2.1}$ ($LWP_{2.1}$). Coastal histograms (Fig. 4a) show a narrow distribution, in part because LWP tends to be small near the coast. In addition, the histograms do not suggest meaningful differences between AMSR-E and MODIS retrievals, whether they are calculated with $LWP_{3.8}$ or $LWP_{2.1}$ (mean biases -7.5 and -5.6 gm^{-2}). In contrast, offshore histograms (Fig. 4b) are broader, with a shift toward larger positive bias for $LWP_{AMSR\text{-}E}$-$LWP_{3.8}$ relative to $LWP_{AMSR\text{-}E}$-$LWP_{2.1}$. The mean AMSR-E/MODIS biases are 9.6 and 1.4 gm^{-2} for $LWP_{3.8}$ and $LWP_{2.1}$, respectively. Interestingly, the differences between Figs. 4a and 4b are accompanied by contrasting changes in $H\sigma$ (Fig. 4c). Coastal and offshore regions yield distinctive values of $H\sigma$, with a distribution mode of 0.15 for coastal clouds (Fig. 4c, gray line), and 0.25 for far offshore clouds (black line). The MODIS LWP and $H\sigma$ relationship is further emphasized in Fig. 4d where mean $H\sigma$ values and the mean differences between $LWP_{3.8}$ and $LWP_{2.1}$ are shown as a function of longitude. The $LWP_{3.8}$-$LWP_{2.1}$ zonal gradients are concomitant with $H\sigma$ increases, indicating a distinctive bias compensation between both r_e's and τ to changes in heterogeneities. We explore this idea in more detail by taking averages of all the binned MODIS variables over the study region (constructed from $LWP_{AMSR\text{-}E}$) as a function of H_σ bins."

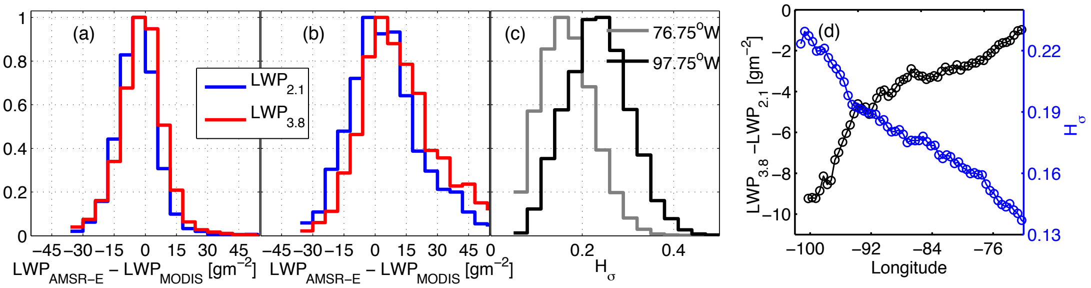

Figure 4: Normalized histograms for the differences between AMSR-E and MODIS LWP for two 4˚x3˚ regions: a) coastal area centered at 76.75˚W, 23.75˚S, and b) offshore area centered at 97.75˚W, 23.75˚S. Red and blue histograms correspond to LWP_{AMSR-E}-$LWP_{3.8}$ and LWP_{AMSR-E}-$LWP_{2.1}$, respectively. c) Normalized $H\sigma$ histograms for the coastal (gray) and offshore (black) regions in Figs. 4a and b. d) Mean westward variation of $H\sigma$ (blue) and $LWP_{3.8}$-$LWP_{2.1}$ along 21.25˚-26.25˚S. Figures are constructed from cloudy scenes only (CF>98%).

12. Line 212-213: This statement needs to be removed. This study deliberately attempts to avoid considering precipitating clouds by imposing a LWP<150 gm-2 data filtering. Therefore, no statement regarding the role of precipitation can be justified.

Precipitation occurrence cannot be fully discarded even for LWP near 150 gm^{-2}. Observations from Cloudsat, MODIS, and aircraft measurements (Kubar et al., 2010, Painemal and Zuidema 2011) indicate that precipitation is likely to occur in clouds with LWP >100 gm^{-2}. Certainly the drizzle associated with LWP< 150 gm^{-2} is smaller than that associated with cumulus clouds. Nevertheless, this can still significantly change the cloud microphysical structure as precipitation is the manifestation of active collision coalescence, with the subsequent cloud effective radius increase.

13. Line 217: 'Spurious' is probably too strong a claim. An association between H_sigma and delta_re is insufficient to claim any causality. It would be better to emphasize that effective radius retrievals should be treated cautiously.

In our recent manuscript we write:

"Finally, while this analysis is only valid for clouds with LWP < 150 gm^{-2}, our results can help by determining the minimum thresholds by which $r_{e3.8}$-$r_{e2.1}$ differences might potentially indicate physical information about the cloud vertical structure. As suggested by Figs. 5a and 3b, we speculate that Δr_e differences in cloudy scenes must at least surpass |- 4.0 µm| (the largest differences for the most heterogeneous scenes) to be plausibly considered as physical rather than biases due to sub-pixel variability. This threshold would imply that, on average, values of $r_{e2.1}$ exceeding 18 µm over oceanic regions (Fig. 3 in Nagao et al. [2013]) along with $r_{e2.1} > (r_{e3.8} + 4$ µm) might be indicative of the actual effect of precipitation on r_e, which would tend to increase droplet size toward the cloud base. "

14. Line 217: Many cumulus have very small LWP. It is enough to just state that

H_sigma is larger in cumulus than stratocumulus.
We modified the text to reflect the recommendation of the reviewer

15. Line 243: Anything like this seems really arbitrary since you haven't actually demonstrated what the true LWP or re is. I think that you put a bit too much trust in the microwave LWP, which may potentially have biases equally as large or larger than those in the optical retrievals.
Following the reviewer's recommendation, we have removed the paragraph from the manuscript.