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Interactive Comment

Interactive comment on "How small is a small cloud?" *by* I. Koren et al.

I. Koren et al.

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We would like to thank the referees for their important comments and suggestions that hopefully have made this paper clearer.

We will address here the two referees' comments and the short comment by Jane Hurley one by one (referee comment first and then the reply):

Referee #1 Minor comments: 1) I believe that MODIS uses more than a threshold method identify clear pixels. It uses spatial variability of radiances. If the variability is large, it does not use as clear pixel. If small clouds are uniformly distributed (i.e. statistically spatially uniform), this method does not help identifying cloud contaminations. But the authors did not address if this spatial variability test reduces the cloud contamination. In other words, how often are clouds spatially uniformly distributed? It is not the size of cloud alone affecting cloud contaminations. Because of this, 0.8 W mˆ-2 error might be over estimated.

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The reviewer is right, the MODIS cloud masking for the aerosol product is based on local variability (Martins, J.V. et al. GRL 2002). This method was proven to be suitable for the MODIS resolution. It was shown that for 500m to 1km resolution the variability (measured as the local standard deviation) of clouds is higher than of most types of aerosol and background. However this phenomenon does not hold in higher resolutions. We first tried to separate clouds from ocean-background by means of variability but when the pixel resolution scale is comparable to the scale of structures in the ocean (waves and ocean color changes in high spatial resolution) the signal due to small-cloud structure or edges is comparable to the background variability. We could not use it for the first 3 resolutions (30m, 60m, 120m) and because we wanted criteria for cloud detection that were unaffected by resolution, we used reflectance thresholds. However, when comparing theoretically the changes in the standard deviation (used in MODIS as a measure of local variability) and the average reflectance due to the presence of a sub-pixel cloud the results are similar. In other words, when reducing the resolution of an area with one pixel cloud surrounded by background pixels to half, the contrast between the lower resolution pixel that contain the cloud pixel and the background was reduced to 25% of the initial contrast. Similarly, the n by n standard deviation (3 by 3 in MODIS) of the new pixel will be 25% of that for the fine resolution. It was shown that the local variability method works better in cases with high aerosol loading for resolutions of 500-1000m. For such data it avoids classifying aerosols as clouds. In clean cloud fields with high probability of small sub-pixel clouds the methods are comparable. But as the reviewer suggests, in cases where the local variability is more invariant to scale degradation we may be overestimating the apparent contribution of small (sub-pixel) clouds. We have added to the text (in section 4. Summary and Conclusions): " 4) The apparent direct aerosol forcing due to classifying cloud pixels as cloud-free in the sparse cumulus fields is on the order of -0.8 Wmˆ-2 (with an error of 0.2 Wmˆ-2) for the cloud field area. In reality the actual enhanced apparent forcing depends on the way clouds are detected in the algorithm. The specific MODIS errors in apparent direct aerosol forcing may be somewhat smaller than what is reported here

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due to the fact that clouds are detected by means of thresholds on the local variability in reflectance (Martins et al., 2002) rather than thresholds on the reflectance itself. Although we expect that the local variability of sub-pixel clouds will change similarly to the reflectance, cloud detection depends strongly on the thresholds (in reflectance or variability) and there may be cases where the variability method detects traces of sub-pixel clouds that the reflectance threshold will not."

2) In fact, if this spatial variability test is included and if the objective of the paper is to estimate the effect of cloud contaminations in aerosol retrieval, the question becomes how large a cloud free area is instead of how small a small cloud is. Can we find cloud free areas larger than 1 km exist? If so (I believe they do), and if MODIS can find them, which I do not know, the aerosol radiative aerosol forcing can be properly estimated. If screening works, because it screens aerosols close to clouds, which might have a larger radiative effect, it might be underestimated. So I suggest that the authors either focus on the question indicated by the manuscript title and drop the part arguing the effect on the aerosol forcing or add a further analysis of the size of clear areas.

It is shown in the paper that when we degrade the resolution, the cloud fraction increases (fig 2). Still, because these cloud fields are sparse (˜0.2 in Landsat resolution and ˜0.4 in MODIS), there are enough pixels classified as cloud free at any resolution to retrieve aerosols. The MODIS aerosol over ocean algorithm requires only 20 cloud free pixels out of a possible 400 to make an aerosol-retrieval. One of the major problems of cloud and aerosol forcing estimations is the need to separate them. As the reviewer suggests, aerosol forcing in the vicinity of clouds (within a cloud field) may be significantly higher due to changes in the aerosol properties and the extra illumination from the size of the clouds. Therefore, retrieving the true aerosol forcing contribution in the cloud field is important. In the paper we do two things: first, we show (using high resolution data) how important small clouds are (in area and radiative flux contribution) and then, given the importance of these clouds, we show how lower resolution data inherently can not deal with such cloud fields correctly (with regards to both aerosol

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and cloud properties). We think that such an observation reflects a real problem in the way aerosol and clouds are retrieved presently. Certainly, there are details that are not addressed in this paper such as the portion of the so-called cloud-free area within the cloud field that would have been retrieved by the MODIS aerosol algorithm. As the reviewer suggests, it would have been interesting to examine how many pixels labeled as cloud-free exist within the cloud field. Since we have analyzed sparse cloud fields, there are enough pixels labeled as cloud-free to meet the MODIS 20 pixels criterion and to perform retrieval for most of the "cloud-free" area. We tested the 5 cases of this study and all of the MODIS AOD 10km by 10km pixels had much more than the minimum of 20 pixels defined as cloud free. We have added to the text (section 3. results): "Since small cumulus cloud fields are sparse, there are enough pixels labeled as cloud-free to meet the minimum amount of pixels per 10 km area to retrieve aerosols on most of the "cloud-free" area. We tested the 5 cases of this study and found that all of the MODIS AOD 10 km by 10 km pixel arrays had many more pixels than the minimum number, defined as cloud free."

Referee #2 Minor points: 1. Abstract: "When changing the resolution from 30 m to 1 km (Landsat to MODIS) the average "cloud-free" reflectance at 1.65 micron increases more than 25%, the cloud reflectance decreases by half, and the cloud coverage doubles, resulting in an important impact on climate forcing estimations." I find the use of relative changes somewhat confusing, and would suggest to additionally quote absolute changes: the increase of cloud-free reflectance should be pretty independent of e.g. the surface albedo, at least to first order. However, changes of surface albedo will strongly modify the cloud-free reflectance, and cause large differences in the relative numbers. Similar arguments can probably be made for cloud reflectance/cover.

We agree with the reviewer that the absolute values are more important, so we have changed the relevant text as follows (in the abstract) : " When changing the resolution from 30 m to 1 km (Landsat to MODIS) the average cloud-free; reflectance at 1.65 μm increases from 0.0095 to 0.0115 ($>$ 20 %), the cloud reflectance decreases from 0.13

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to 0.066 (˜50%), and the cloud coverage doubles, resulting in an important impact on climate forcing estimations. The apparent aerosol forcing is on the order of 0.5 to 1 Wmˆ-2 per cloud field."

2. Introduction: "when changing pixel size from 10 km to 100 km": please clarify whether is this area (then units of kmˆ2), or some effective diameter?

(Introduction): Changed to " when changing pixel size from 100 kmˆ2 to 10000 kmˆ2 (Krijger et al., 2006)."

3. Current operational cloud masks (e.g. MODIS) do not only use absolute thresholds in reflectance, but also thermal channels and spatial variability thresholds. How are the conclusions of the paper affected by the choice of cloud masking algorithm?

The reviewer is right, the MODIS-cloud-product cloud masking uses tests in few channels in the VIS IR and thermal to detect all possible clouds. Moreover, the MODIS-aerosol-product cloud masking is using thresholds on local variability of reflectance and not on the reflectance itself. The overall effect on the cloud and aerosol properties will depend on the type of clouds, and their spatial distribution and location. For this study we chose the idealized case of marine clouds far from glint with low aerosol loading to demonstrate the concept. Specifically for the cases of sparse low cumulus clouds we do not expect the thermal gradient to be significant and to contribute to cloud detection; also in high resolution the local variability test fails (the variability of the background is comparable to the variability of small weak clouds at such scales). For clarity we have added to the text (in section 4. Summary and Conclusions): " 4) The apparent direct aerosol forcing due to classifying cloud pixels as cloud-free in the sparse cumulus fields is on the order of -0.8 Wmˆ-2 (with an error of 0.2 Wmˆ-2) for the cloud field area. In reality the actual enhanced apparent forcing depends on the way clouds are detected in the algorithm. The specific MODIS errors in apparent direct aerosol forcing may be somewhat smaller than what is reported here due to the fact that clouds are detected by means of thresholds on the local variability in reflectance

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(Martins et al., 2002) rather than thresholds on the reflectance itself. Although we expect that the local variability of sub-pixel clouds will change similarly to the reflectance, cloud detection depends strongly on the thresholds (in reflectance or variability) and there may be cases where the variability method detects traces of sub-pixel clouds that the reflectance threshold will not."

Please also see our response to a similar comment by reviewer one.

4. As additional quantitative estimate of the impact, consider adding SW cloud radiative forcing to the cloud-covered parts of the image, to complement the cloud-free "aerosol radiative forcing". Or is this simply the aerosol radiative forcing multiplied by -1?

Will be answered together with the next point:

5. Eq. 1, and prior statement: "the nadir reflectance observed by ETM+ is a good surrogate for the radiative energy reflected back to space. "In other words, the authors assume that the anisotropy of individual pixels does not change with resolution, and TOA albedo and reflectance are directly related. However, using the Independent Pixel approximation as conceptual model to understand the resolution reduction, the anisotropy is expected to change non-linearly, due to changes of anisotropy with cloud properties (thin clouds have a more inhomogeneous radiation field than thick clouds). This point should be at least discussed. (see e.g. Kato, S., L. M. Hinkelman, and A. Cheng (2006), Estimate of satellite-derived cloud optical thickness and effective radius errors and their effect on computed domain-averaged irradiances, J. Geophys. Res., 111, D17201, doi:10.1029/2005JD006668.) Overall, the difference between directional and hemispheric radiances/reflectances should be discussed more explicitly.

The fact that albedo and nadir reflectance are indeed related is conveyed by the fact that we were able to use the two-stream expression of Bohren for albedo to fit the nadir reflectance (eq. B2) for values of optical thickness below 20. Admittedly, this was for plane-parallel DISORT calculation. But exactly because of the difficulties the reviewer mentions and the fundamental difference between directional and hemi-

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spheric reflectances we did not attempt to estimate errors in cloud radiative forcing due to degradation in detector resolution and the resulting spreading and thinning of the clouds. For aerosols, we related the background reflectance change to an AOD change and extrapolated to an aerosol radiative forcing change based on previous results. For clouds we cannot do so, and we therefore only quote the impact of resolution degradation in terms of nadir reflectance change (which should no be viewed as an albedo change). We now make this point more clearly. Note that the consequences of spatial resolution degradation as described in the paper ensure that the albedo of what is perceived as cloud will decrease, even if this change cannot be easily quantified (i.e., without applying a cloud retrieval algorithm). Due to the non-linear relationship between the apparent reduction (increase) in cloud optical thickness (aerosol optical thickness) when resolution is degraded, the cloud and aerosol forcing errors are not trivially related.

6. Appendix B, paragraph above formula B6: rich->reach, bottom of same page, "form the 3D effect" -> "from the 3D effect"

Changed, thanks.

7. Size of clouds: how is the size of a cloud calculated exactly (when are two cloudy pixels connected: only if they are neighbors in horizontal/vertical direction, or also if neighbors along the diagonal directions? Are the results sensitive to this choice?)

Cloud pixels are considered connected when neighbors exist along the diagonal directions. We have tried both ways (with and without considering diagonal neighbors) and the basic results does not depend on the way by which the pixels are considered connected (it changed the numbers of the size distribution but not the shape). We chose to use this definition because it is more conservative with respect to the importance of the small clouds (the other method resulted in more smaller clouds, but not by a significant amount). We added to the text (section 2. Analysis): "Pixels are considered to belong to the same cloud when two adjacent pixels are connected in any of the 8

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possible directions."

Short comment by Jane Hurley 1) The point of an appendix is to be able to read a paper without having to read the appendix - not the other way around, as is the case here.

First, we would like to thank Dr. Hurley for taking the time to freely offer her comments in the discussion. We are delighted that she found the paper interesting enough to read the Appendix as well as the body of the paper. The paper contains a great many mathematical details that we felt unnecessary to understand the two main points of the paper: (1) small clouds are surprisingly important in number, total area and contribution to the total outgoing radiative flux in a cloud field and (2) lower resolution data inherently can not represent such cloud fields correctly (either in terms of aerosol properties or cloud properties). To describe these points in a fluent way and to discuss the possible consequences, we minimized the mathematical details in the body of the text. However, those details are included in the Appendix for interested readers, like Dr. Hurley, to examine in depth. We disagree with Dr. Hurley in that we feel that one does not have to read the Appendix to understand the paper, and that the body of the paper tells a coherent and complete story in its own right.

2) More explanation about moments - what are they - you haven't explained at any point.

We meant statistical moments (1=mean, 2=variance, 3=skewness). We have added a few words in the text to clarify this point.

3) Is it reasonable to assume that reflectance is independent of cloud area? Don't larger clouds have particles with different optical properties to smaller clouds? Also, more likely to be thicker?

The reflectance depends strongly on the cloud area. We write in the body of the paper (in the results part): " The reflectance distribution (eq. 4) is a product of two functions

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with opposing trends. The total area per cloud size is larger for the small clouds while the average reflectance is greater for larger (thicker) clouds. However, both the data and the analytical derivation (which can be found in Appendix B) show that for our measured slopes of the power-law distribution, the total-area-function decreases faster than the total-reflectance-function increases with cloud size" In Appendix B we give more mathematical information and link the cloud reflectance to the cloud area and in figure A2 we show it graphically.

4) It is unlikely that cloud area is a continuous variable. There must be some minimum cloud size below which clouds cannot form, ie. area is too small for sufficient vertical motion to cause cloud formation.

There may be a size too small even for a small cloud, but that size is definitely below the 30 m resolution of our data base, and on the other hand, there may not be a discernible lower size limit for a cloud. Some of us have spent hours watching small clouds form and dissipate. We can see wisps and filaments of cloud that appear to be only a few meters in length. We can imagine even smaller pockets of cloud that we are unable to see from the ground. Smaller clouds may require less vertical motion to form, and those updrafts could be turbulent in nature rather than organized cells. Smaller clouds may appear statistically while a larger cloud is forming or dissipating. We can't prove or disprove a lower size limit, but there is no indication in the data at 30 m that such a size limit exists. We write in the summary: "5) For any resolution significant cloudy parts will be missed. This is an outcome of the nature of the power-law distribution of cloud areas. Since there is no physical limit at the highest Landsat resolution of 30 m this distribution may well extrapolate toward finer resolutions, suggesting that small clouds of only a few meters may contribute significantly to the total cloud fraction and reflectance."

5) A map of LandSat locations used would be helpful.

This would unnecessarily increase the size of the paper. The exact coordinates are

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given in table 1.

6) Several plots are missing axis labels.

Thanks - we fixed it.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 6379, 2008.

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