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Atmospheric Measurement Techniques Discussions

Interactive comment on "Reconstruction of 3-D cloud geometry using a scanning cloud radar" *by* F. Ewald et al.

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We thank referee #1 for his/her careful reading, comments and suggestions which we address in the following. The authors' answers are printed in italics:

> *Remark: The figure numbers in the referee comments are corresponding to the figures in the original manuscript. The figure numbers in the authors' answers are corresponding to figures at the end of this text.*

General comments

- It is too bad that the authors end this manuscript with two cloud images without any quantitative error measures between radiance estimated from the reconstructed cloud field and radiance observed from either camera or imager. For a scientific paper, the authors may wish to improve this bit a little more. I understand it may be difficult because it involves instrumental calibration and assumptions used in Monte Carlo simulations, etc. However, visualised similarity in photos cannot be directly translated into a success in cloud retrievals from shortwave radiance measurements.

  → *We understand your objection to the ending of this paper. However, the two cloud images at the end of this manuscript should merely give an outlook on future studies which will combine a microphysical retrieval with the appraoch described in this manuscript. With the study at the end of this manuscript we want to test and demonstrate the feasibility of our approach when confronted with real measurements.*

- As the authors point out, the smallest RMSE in 870-nm radiance doesn't necessarily correspond to the best performance in liquid water content field. Similarly, I am not sure that the smallest RMSE in radiance will correspond to the best performance in cloud retrievals. If the authors cannot address this issue in real observations, at least, this should be relatively straightforward using synthetic measurements.

  → *We think that this question should be answered in a subsequent study which is in preparation. It was our objective to keep this manuscript as compact as possible without touching a completely new topic concerning cloud retrieval sensitivity etc.*

- Following the comment above, it would make more sense if reconstruction performance is also evaluated, for example, at 1640 nm to see the impact of cloud droplet size, which is an important factor for scanning cloud radar. I understand that the authors are trying to keep the droplet size constant so the scan strategy and interpolation methods can be isolated and properly evaluated. But again, if the authors emphasises the primary impact of their work is on passive remote sensing including cloud side retrievals (by the way, the references Marshak et al. (2006) and Zinner et al. (2008) both focused on cloud droplet size retrievals!), I think addressing this issue would greatly enhance the value of the manuscript.

→ *In order to accommodate this remark we also did all calculations and comparisons at 2100 nm which is one of the wavelengths that Nakajima and King (1990) is based on. The differences between the different interpolation methods become a litte bit more pronounced for 2100 nm (see Fig. 5) since radiative smoothing is considerably less compared to 870 nm. In Fig. 6 at the end of this text we show the results for different scan resolutions at 2100 nm. Here, the overall picture compares to the results at 870 nm. If desired we could change all plots to 2100 nm in our manuscript.*

- It is a bit weird that the manuscript talks about Figure 1, then jumps to Figure 4, and then comes back to Figure 2, etc. Could the authors please sort out the order of the figures properly?

→ *We corrected this in the revised manuscript.*

Specific comments

- Page 11347, Line 19–21: I am a bit confused about this statement. The authors seem to suggest that knowing complex-shaped cloud side at spatial resolution for 100m or less is important, but the reconstructed cloud field shown in the

manuscript has a resolution at 100 m at best. Shouldn't this imply that even scanning cloud radar measurements wouldn't be good enough for cloud side retrievals? Could the authors please clarify?

→ *We agree with your point that current, scanning cloud radars can hardly reach the spatial resolution of imaging systems. Nevertheless in the last years several studies (Varnai and Marshak, 2002; Marshak et al., 2006; Fielding et al., 2013) emphasized the urgent need to get hold on information on cloud geometry. In one of our studies in preparation we are going to use the appraoch described in this paper to answer this questions for microphysical retrievals from cloud sides.*

We therefore added following lines in our revised manuscript to clarify this:

Page 11354, Line 20ff

> *For a cloud 5* km *away the anticipated horizontal resolution of the front-facing cloud side lies in between 100–200* m*. In view of these constraints the scan resolution of current cloud radars hardly reach the high spatial resolution of current passive imaging radiometer. Nevertheless this spatial resolution still gives additional information for clouds with a cloud base of 2–5* km*.*

- Page 11351, Figure 1 and Figure 3&4: Figure 1 shows column-integrated properties of clouds in a (x, y) coordinate, while Figure 3&4 represent quantities in a (Θ, Φ) coordinate. I found Figure 1 not very helpful because one needs to imagine how radar scans in order to match Figure 1 and Figure 3&4. The authors may wish to provide a 3D plot or some cross-section profiles to help readers understand the text. Additionally, perhaps I miss it, but I don't think it is clearly mentioned where the radar is located until Figure 8. I could guess it is in the bottom-left corner from the text, but this kind of information should be clearly put.

→ *In order to help the reader to keep track of the discussion we added a 3D plot showing the scan pattern and some cross-section profiles (see Fig. 2 at the end of this text). Several times throughout the text we now described the radar location which is indeed located in the bottom-left corner.*

Page 11348, Line 25 [added]

> *Througout this study the radar is positioned in the lower left corner of the model domain shown in Fig. 1.*

Page 11356, Line 10 [added]

> *As already mentioned the radar is positioned in the lower left corner of the model domain.*

Page 11357, Line 22

> *As before, the radar simulator was situated in the lower left corner (...)*

We also changed the original Fig. 1 (see Fig. 1 at the end of this text) for a better comparison with the revisited interpolation analysis (see Fig. 3 at the end of this text, for the complete revisited interpolation analysis compare answer to referee #1). The caption of Fig. 1 now reads:

> ***Figure 1.*** *This figure shows the .5 $\mathrm{km} \times 7.5\,\mathrm{km}$ sub-domain of a trade wind cumuli large eddy simulation (Seifert and Heus, 2013) that was used to test the radar reconstruction under controlled conditions. The radar simulator was positioned in the lower left corner. The main figure shows liquid water path (LWP) in gm^{-2} while the smaller figures on its bottom and to the right shows cross-sections of liquid water content (LWC) in gm^{-3} for $X = 3.75$ and $Y = 3.75$.*

- Page 11353, scan strategy: The authors directly point out that S-RHI is better (or favoured) than S-PPI, due to the consideration of cloud advection. Could

the authors please confirm whether thorough evaluation has been done to draw such a conclusion? Results may depend on wind speed and whether wind information is available, etc., so the authors may wish to consider providing conclusion/discussions from all aspects. Words like "never", "impossible" are strong words that should be avoided; we are all doing something that has been thought "never" in the past.

→ *We agree that this discussion in its current form is too short to justify our choice. However we think that many aspects of a thorough evaluation of scan modes was already done by Fielding et al. (2013). For this reason we refer to work done by them and rewrote several paragraphs as quoted below:*

Page 11353, Line 17-24

> *Scan pattern and scan resolution are among the first parameters to be chosen. In his study Fielding et al. (2013) conducted extensive research on the potential ability of different scan strategies to reconstruct 3D clouds. His work proved that an scan mode perpendicular to the wind direction at a fixed azimuth yields the best results for radiation closure studies with advection wind speed above 10 ms^{-1}. Moreover, he argues that sector-type scan modes are not the best choice for radiation closure. Since we search for additional information for radiance measurements from cloud sides sector-type scan modes are our tool of choice. These scan strategies allow simultaneous measurements of specific cloud sides with collocated solar radiance measurements. In addition, the higher spatial sampling density of facing cloud sides is another decisive argument for this kind of scan strategy.*
> *Two of these sector-type scan modes are the sector range-height-indicator (S-RHI) scan pattern which is a vertical elevation scan*

> *for stepwise changing azimuth angle and the sector plane-parallel-indicator (S-PPI) scan pattern which is a horizontal azimuth scan for stepwise changing elevation angle. In our study S-RHI is favoured over S-PPI, because it can be used to partially correct for the cloud motion component tangential to the radar position. A wind profile from a nearby radiosonde station can then be used to compensate for the horizontal drift of the cloud. Hereby the S-RHI produces consecutive vertical profiles which better fits to subsequent retrievals of vertical profiles of cloud microphysics. Moreover, the S-RHI scan reconstruction only gets compressed or strechted by deviations of the local cloud drift from the mean wind profile. The vertical structure of the S-PPI reconstruction would get teared apart by deviations from the mean wind profile. For this reasons the (S-RHI) scan pattern seems to be the better choice for the reconstruction of isolated cloud sides.*

(...)

Page 11354, Line 6 [new paragraph inserted]

> *Just as (Fielding et al., 2013) Taylor's frozen turbulence hypothesis was used in this study. Taylor's hypothesis makes the assumption that advection of a field of turbulence happens mainly due to the mean flow as long as its eddy velocity is small compared to the mean velocity. (Barker2004) tested his cloud optical depth retrieval for the frozen turbulence hypothesis and found that complex changes for radiances and irradiances can occur over a 10-min span. (kassianov2005) determined the decorrelation length of about 15 min for the sky cover over a ground-based instrument. Since (Fielding et al., 2013) found that surface irradiance RMSE during a 5 minute scan period can already be substantial we limited the time duration of scan patterns to 5 minutes to minimize the*

> *errors associated with the temporal evolution of the cloud that are caused by turbulence and convection during the acquisition.*

(...)

Page 11355, Line 1-4

The time period for a $azimuth range S-RHI scan with adequate resolution and scan speed is in the order of minutes. Dependin$ $D motion including turbulence is not achiveable with current cloud radar systems.$

- Page 11354, Line 9: small typo "then" should be "than".

  → *Although this sentence is no longer in the new revision of our manuscript we thank you for this correction!*

- Page 11355, Interpolation methods: Since the section of interpolation methods immediately follows "Remapping radar data to Cartesian space considering cloud motion", readers may wonder if the authors perform interpolation in reflectivity or liquid water content. I believe the answer should be liquid water content, but it would be better to describe this kind of important detail clearly.

  → *We agree with you that the interpolation should be done in liquid water content. However, in our application both approaches yield equivalent results. We reasoned this in an additional paragraph inserted after Sec. 3.2:*

  > *The subsequent interpolation was done one the full domain size of .5*$\times 7.5 \times 4\,\mathrm{km}$ *with a coarser grid spacing of* $\times 50 \times 25\,\mathrm{m}$ *for computational efficiency. Since we fixed the effective radius* r_{eff} *throughout the domain the conversion from radar reflectivity* z *to* LWC *(Eq. 6) produced equivalent results whether we applied it before or after the linear interpolation. When cloud effective radius is directly connected to LWC using e.g. a power law relationship*

like Fielding et al. (2013) the conversion with Eq. 6 should happen before the interpolation. This happens as the linear relationship between radar reflectivity z and LWC in Eq. 6 becomes non-linear when inserting Eq. 2 with an variable cloud effective radius.

- Figure 5: I cannot understand what has been shown because x- and y- label and values are all missing. Neither text nor figure caption mention where this cross-section has been chosen with respect to Figure 1, 3 and 4, and why. Additionally, how do those radar scans in Figure 5b correspond to text in 3.2 and 3.3? Are they the fields after remapping? If they are, shouldn't they be in irregular grids? Overall, the figure and descriptions need to be greatly improved.

  → *In the original Fig. 5 we tried to exemplary illustrate the different interpolation artifacts on a simpler, more abstract LWC field. Your comment rightfully pointed out that in doing so we lost our reader as we lost the reference to the actual LES used. For this reason we are now discussing the artifacts on the basis of the described UCLA LES. In Fig. 3 at the end of this text you will find the revised version of the original Fig .5. It is designed to be similar to Fig. 5 in Fielding et al. (2013) to better compare our study with theirs. As the plot has changed completly we also rewrote the paragraph on Page 11356, Line 10-20:*

  The interpolation artifacts can be seen more clearly in the liquid water path and the liquid water content. As already mentioned the radar is positioned in the lower left corner of the model domain. In Fig. 3 the LWP and two horizontal LWC cross-sections of the reconstructed cloud are shown for each interpolation method for a scan resolution of 2. The grid box structure (Fig. 3a) of the nearest-neighbour method becomes dominant in the LWP at the far end of the cloud. The discontinuous jumps in the liquid water content remain clearly visible throughout the cloud volume as well as in cloud

  parts facing the radar position. The tendency of the Inverse distance method (Fig. 3b) to form circular patterns around measurement points (bull's-eye effect) becomes evident at greater lateral distances of adjacent scans. Besides this artifact remains also visible in the LWC field throughout the cloud. With both methods the artifacts of the scan pattern remain imprinted in LWP fields as well as LWC fields. In contrast the barycentric (Fig. 3c) and natural neighbour interpolation (Fig. 3d) yield much smoother results. Also both methods produce very similar fields. The shape of the cloud boundaries appears smooth in the LWP as well as the LWC field. Both interpolations result in a slightly blurry reconstruction compared to the original cloud field, especially at cloud edges. Here the natural neighbor interpolation produces blurrier fields of LWC and LWP compared to the barycentric approach. A distinct difference exists for regions far away from the radar position. The LWP interpolated by the natural neighbor method gets too smooth compared to the original LWP field. This is due to decreasing measurement density as the radial distance increases. Opposite to this the structure of the barycentric interpolation LWP field gets unnaturally stretched in the lateral direction. This happens because the tetrahedrons of the Delaunay triangulation get stretched in the lateral direction at larger radial distance while the measurement density in the radial direction stays constant.

- Figure 6: Information on scan resolution should be included in caption.

  → *We now included the information on scan resolution in its caption:*
  ***Figure 6.** Comparison of Power Spectrum Density of the reconstructed liquid water content fields (compare Fig. 4) for different interpolation methods and* $scanresolution.(...)$

- Figure 7: Could the authors please indicate which line (or boundary) represents 1 resolution and which one represents 5 resolution? I know one can compare Figure 7 with Figure 6 to identify which one represents 1 resolution. The reason I ask is because these two lines seem to switch their order in the higher frequency regions for Barycentric method. Could the authors please confirm that? If indeed two lines switch the order, what does it mean physically and why?

  → *We agree that an indication for scan resolution was missing in this figure. In the revised version of the figure the different scan resolutions are marked with different linestyles (see Fig. 4 at the end of this text). The dashed (5 resolution) and solid (1 resolution) lines are now explained in the caption:*

  > ***Figure 7.*** *(...) The red shaded area encloses the PSDs of the natural neighbour interpolation. Thereby the dashed line represents the 5 scan resolution while the solid line represents the 1 scan resolution.*

  We revisited our PSD calculations and found out that we were also plotting scales that are smaller than the Nyquist-limit of 100 m *(with 50* m *spatial resolution of the cloud reconstructions). The PSD calculation for the new figure were only done down to 100* m*. But the switch happens already at larger scales at around 150* m*. As already described in the quote two answers above we think that this happends due to the artifact at greater radial distances:*

  > *(...) the barycentric interpolation LWP field gets unnaturally stretched in the lateral direction. This happens because the tetrahedrons of the Delaunay triangulation get stretched in the lateral direction at larger radial distance while the measurement density in the radial direction stays constant.*

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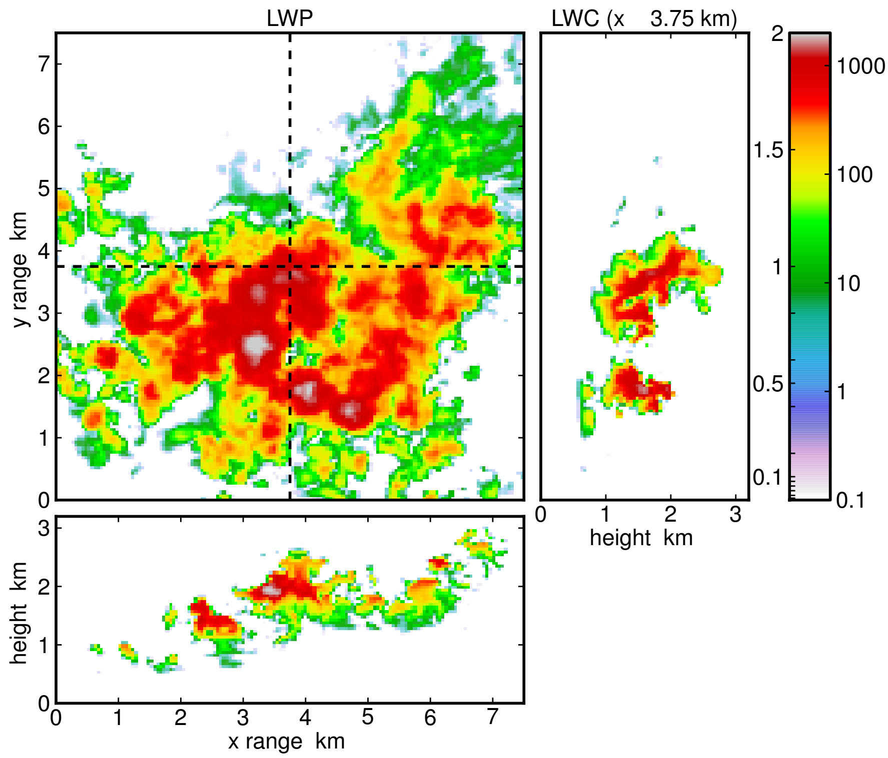

LWP
LWC (x 3.75 km)
y range km
x range km
height km
height km
1000
100
10
1
0.1

Fig. 1.

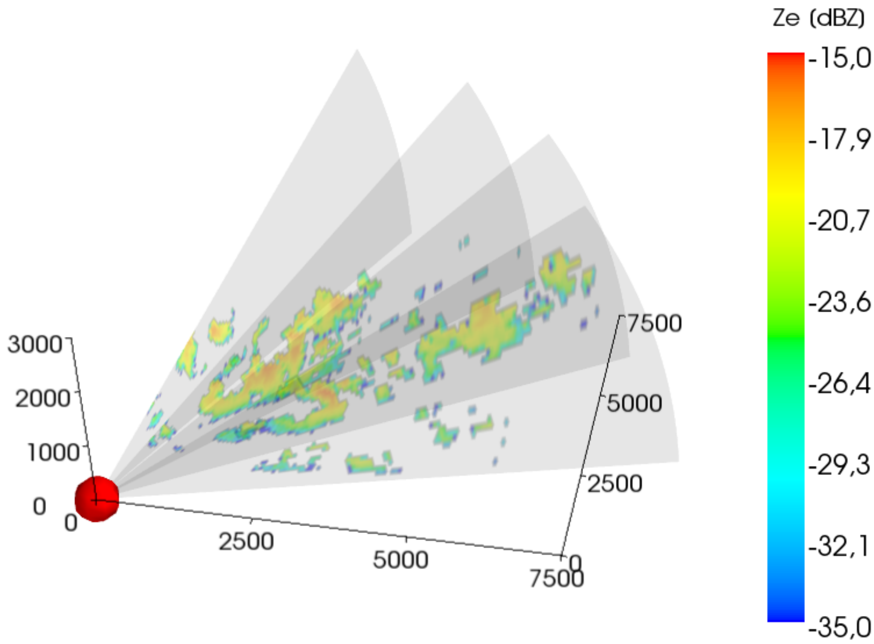
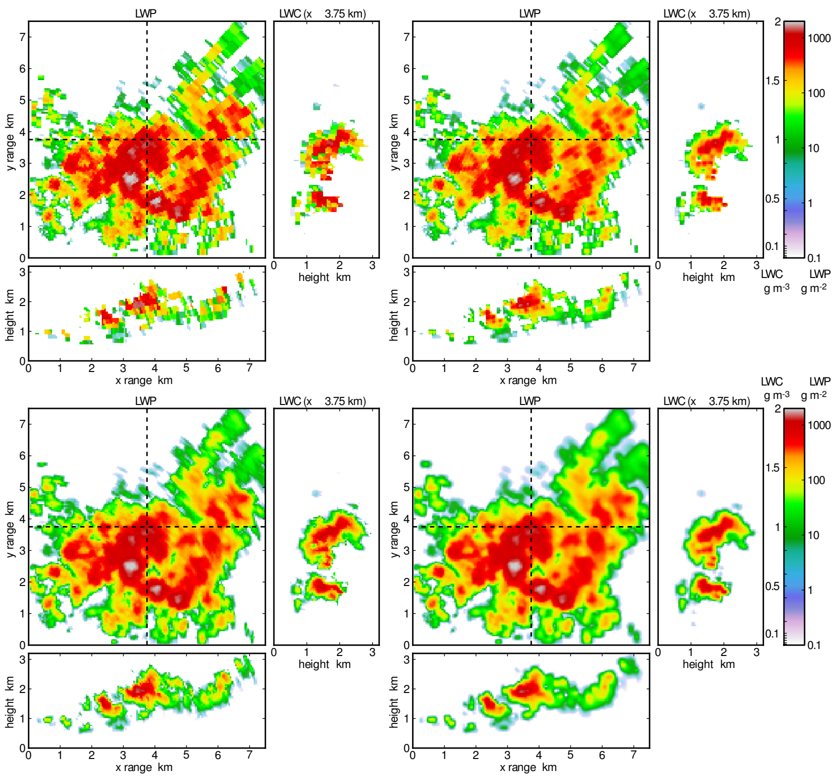
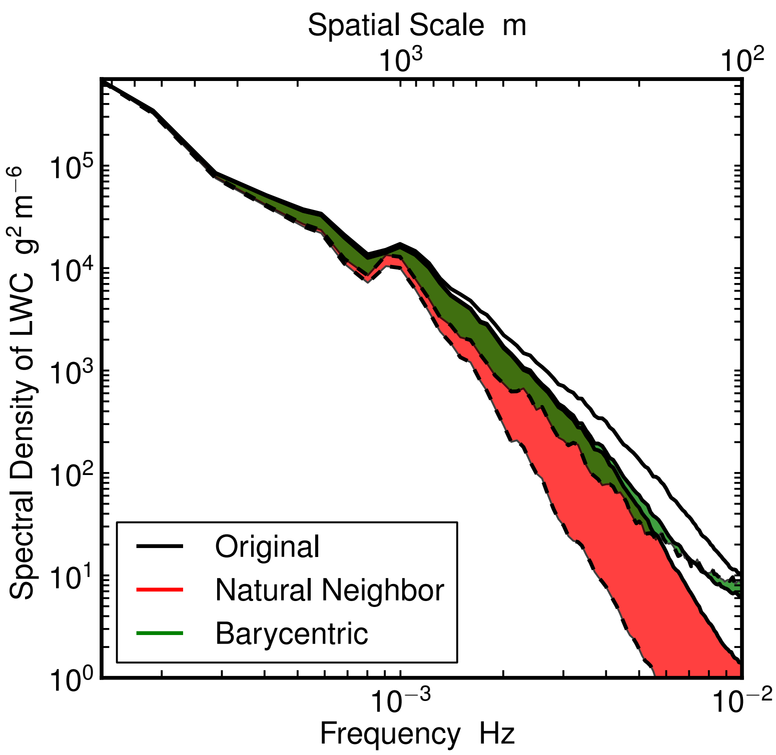

Ze (dBZ)
-15,0
-17,9
-20,7
-23,6
-26,4
-29,3
-32,1
-35,0

Fig. 2.



LWP
LWC (x 3.75 km)
y range km
height km
x range km
LWC g m-3
LWP g m-2

Fig. 3.



Spatial Scale m
Spectral Density of LWC g2 m−6
Frequency Hz
Original
Natural Neighbor
Barycentric

Fig. 4.

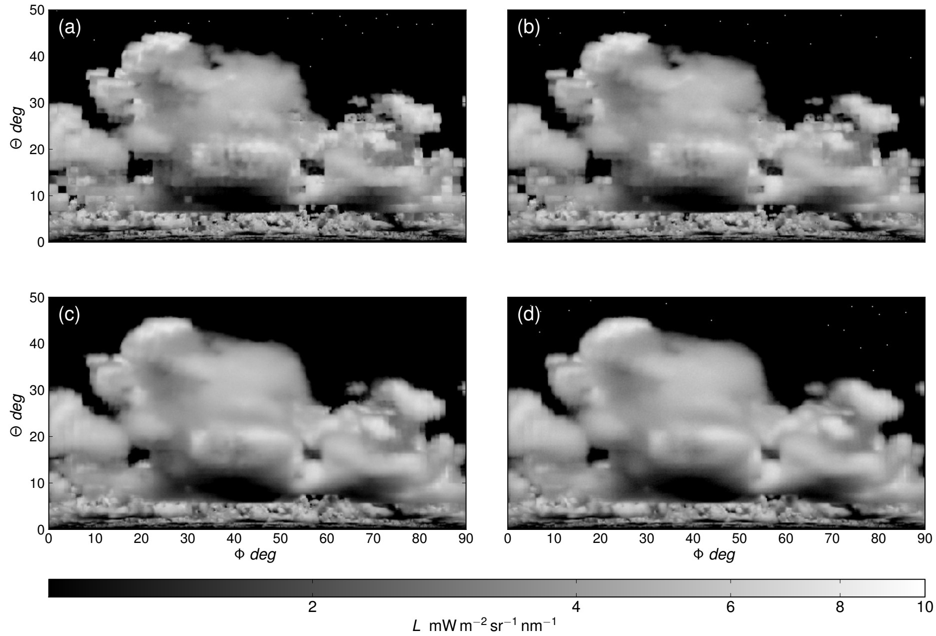


Fig. 5.

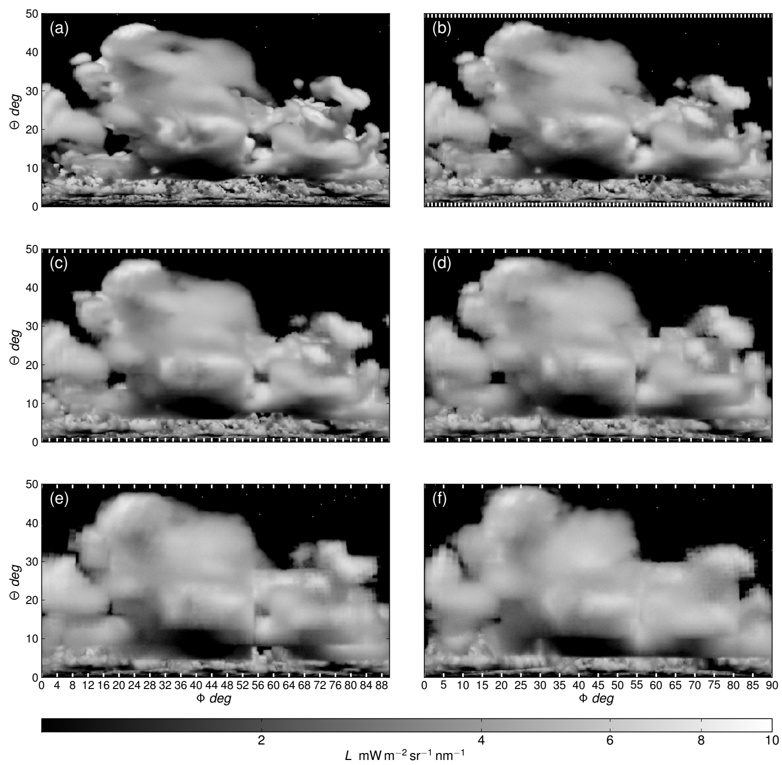


Fig. 6.