On the Sensitivity of Satellite-Derived Cloud Properties To Sensor Resolution and Broken Clouds

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Abstract. The sensitivity of cloud properties derived from meteorological imagers to sensor resolution is investigated by a comparison of results obtained from 1x1km^2 versus down-sampled 3x3km^2 resolution MODIS reflectances. Focus is put on deviations caused by the plane-parallel albedo bias for completely overcast, single-phase pixels (67% of cloudy pixels), and by broken clouds (20% of cloudy pixels). For pixels corresponding to overcast water clouds, a low bias of -5.6% in cloud optical thickness and -3.8% in liqud water path is observed. A method to significantly reduce these biases is described, if information on unresolved variability in reflectance is available. For broken clouds, retrieval results are found to be rather unreliable. Again, a significant improvement in accuracy is achieved, if information on the sub-pixel cloud fraction is used in the retrieval.

Keywords: Satellite Imager, cloud property retrievals, sensor resolution, plane-parallel albedo bias.
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INTRODUCTION

Cloud properties retrieved from meteorological satellite imagers provide important reference data for the evaluation of clouds in climate and weather prediction models. Current operational retrievals assume the presence of a plane-parallel cloud covering individual satellite pixels. Thereby, variability at spatial scales smaller than the sensor resolution is neglected. Due to the high variability of clouds, and the non-linear relation of radiances and cloud properties, satellite-inferred cloud climatologies are known to be sensitive to the spatial resolution of the sensor [1]. To assess the significance of differences between satellite-inferred cloud climatologies obtained with different spatial resolution, a quantitative estimate of the sensitivity, or better yet a correction method, seems highly desirable. The aim of the present study is to quantify the resolution sensitivity for selected mechanisms using downsampled reflectances, and to investigate some promising approaches to correct for this sensitivity.

DATA AND METHODS

To quantify the effect of sensor resolution on satellite-retrieved cloud properties, 1x1 km^2 radiances from the MODIS spectral imager are used as baseline. These reflectances have also been downsampled into *super-pixels* of 3x3 km^2, which is the resolution of the SEVIRI imager flown on the current geostationary METEOSAT satellites. Both low- and high-resolution reflectances have been input into the Cloud Physical Properties (CPP) retrieval[2], which determines the cloud optical thickness (COT), effective radius (REFF) and water path (LWP) from the reflectance at 0.6 µm and 1.6 µm following the method of [3]. The retrieval is done for the *cloudy uncertain* and *cloudy certain* classes of the MOD35 product, and the thermodynamic phase is chosen based on the MOD06 *Cloud_Phase_Optical_Properties* classification. The 1x1 km^2 cloud products are also aggregated into 3x3km^2 super-pixels, which allows a direct comparison of the results obtained at low and high resolution. The CPP products have been verified to compare well with the operational MODIS products[4,5], so we expect that our results are not limited to the CPP algorithm. For this study, 3 months worth of MODIS scenes of the Netherlands from June until August 2006 are used. Results have been calculated for 3x3 (i.e. a total of 9) super-pixels extracted from each scene and centered on the geographic location 52.0N, 5.5E .

MECHANISMS FOR RESOLUTION SENSITIVITIES

TABLE 1. Frequency of occurrence of different classes of cloud coverage and cloud thermodynamic phase for a total of 1675 3x3km^2 super-pixels, based on the 1x1km^2 MODIS MOD35/MOD06 products.

Pixel Cloud Coverage	Frequency of occurrence [%]	Thermo-dynamic Phase	Frequency of occurrence [%]
Clear-sky	48.4		
Broken	10.7	Water	89.4
		Ice	2.2
		Mixed	8.3
Overcast	40.8	Water	62.3
		Ice	20.8
		Mixed	17.0

Several mechanisms contribute to the resolution sensitivity of satellite-derived cloud property datasets, and need to be considered[5]. For overcast pixels containing either ice or water clouds, the well-known plane-parallel albedo bias is the primary reason[1]. Its effects will be studied quantitatively in the next section. For broken clouds, satellite-observed reflectances contain clear-sky contributions, which affect the accuracy of cloud property retrievals, as is shown in a later section.

To identify the importance of the mechanisms, the occurrence frequencies of certain situations are listed in **Table 1** for the region and period investigated. Based on 1x1km^2 MODIS MOD06/MOD35 products, we have classified the super-pixels according to cloud coverage (clear-sky, broken, overcast) and thermodynamic phase (water, ice, mixed) into a total of 7 classes. About half the super-pixels contained clouds, while the rest corresponded to cloud-free cases. Of the cloudy pixels, 20% were only partly cloud-filled. The majority of cloudy pixels contained water clouds, with a 62 and 89 percent contribution for the overcast and broken pixels, respectively.

Two additional mechanisms not further discussed here still should be mentioned. As either water or ice cloud optical properties are used by the retrieval, mixed-phase clouds will cause inaccurate retrievals. The numbers given in **Table 1** suggest that this occurs in less than 10% of cloudy cases. Second, in the present investigation, a perfect classification of pixels has been assumed. In any real cloud retrieval scheme, the cloud detection and thermodynamic phase classification steps will introduce additional errors and resolution sensitivities, which are not accounted for in this study.

EFFECTS OF THE PLANE-PARALLEL ALBEDO BIAS

TABLE 2. Systematic (Bias) and random (SDev) deviations in satellite-retrieved cloud optical thickness (COT), effective radius (REFF), and liquid water path (LWP) resulting from a change of sensor resolution from 1x1km^2 to 3x3 km^2. Values have been obtained for a total of 426 super-pixels classified as single-phase, overcast water cloud based on the high-resolution images, and are given as absolute and relative values. The last two columns labeled **UR** refer to results for the *unscented retrieval* described in the next section.

Quantity	Mean	PPH Bias		PPH SDev		UR Bias		UR SDev	
COT	22.2	-1.2	-5.6%	4.5	20.3%	-0.5	-2.1%	1.7	7.7%
REFF[μm]	10.2	0.2	1.8%	0.8	7.4%	0.1	0.9%	0.4	4.3%
LWP [g/m^2]	155.1	-6.0	-3.8%	29.5	19.1%	-2.2	-1.4%	10.7	6.9%

The term plane-parallel albedo bias (PPH bias) refers to the fact that for a heterogeneous cloud, the use of an average COT will lead to an overestimate of top-of-atmosphere albedo, if it is calculated using the assumption of a plane-parallel-horizontally homogeneous cloud. By inversion of argument, lower resolution satellite images will cause an underestimate of COT, as the images contain less variability in reflectance. This error in COT will also propagate to estimates of REFF and LWP.

As outlined previously, retrieval results have been obtained using both high- and low-resolution reflectances as input. Summary statistics are given in **Table 2** for pixels classified as overcast water cloud. For COT, and LWP, significant low biases of -5.6 and -3.8 % are found, while the bias for REFF is minor with 0.2%. Random errors are much larger, with values from 7 to 20 %. The results for overcast ice cloud pixels are generally similar.

AN UNSCENTED CLOUD PROPERTY RETRIEVAL

The *unscented transform*[6] is a method to propagate the mean and covariance of a multi-dimensional random variable through a nonlinear transform. A minimal set of samples (4 for the 2D case), the *sigma points*, are determined having a prescribed mean and covariance. We propose to apply the *unscented transform* to the satellite retrieval of COT and REFF based on [3] to incorporate information on unresolved variability and to correct for the effects of the PPH bias. **Figure 1** visualizes this *unscented retrieval* of REFF and COT. An xy plot of reflectance at a non-absorbing (0.6 μm) and an absorbing wavelength (1.6 μm) is shown, with COT and REFF varied as free parameters. The reflectance mean and sub-pixel covariance is indicated by the blue ellipse, and 4 possible sigma points are marked. The retrieval is now done for the 4 sigma points instead of for the mean, and estimates of the mean and covariance matrix of COT and REFF are calculated from the 4 retrieval results using standard statistics.

COTs from 3x3km^2 reflectances obtained with the standard and the unscented retrieval are shown versus the 1x1km^2 resolution results in **Figure 1**. For the unscented retrieval, the covariance matrix is found from the 1x1km^2 resolution reflectances. The low bias of COT is reduced by a factor of 3-4, while the standard deviation is also reduced to about half its original size. **Table 2** also lists results for LWP and REFF, where similar decreases of errors are observed.

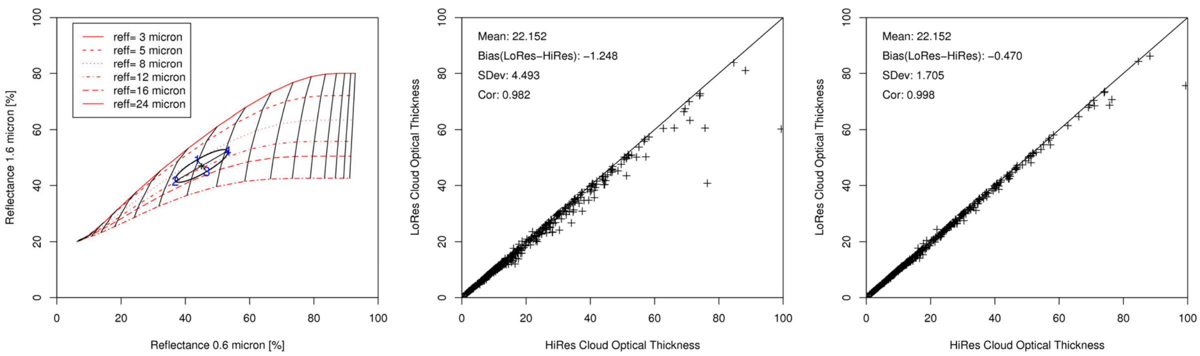

FIGURE 1. (left) Principle of the unscented retrieval. Instead of deriving cloud optical thickness and effective radius for the mean reflectance, they are calculated as average retrieval results for 4 sigma points. These sigma points are chosen to match the 1st and 2nd statistical moment of sub-pixel variability in reflectance. (center) Retrieved cloud optical thickness for low-resolution (3x3km^2) versus high-resolution(1x1km^2) MODIS reflectances using the pixel-mean value. (right) Retrieval results using the unscented retrieval described in the text versus the high-resolution results.

Overall, these results indicate that a significant reduction of random and systematic errors resulting from the PPH bias and differing sensor resolution is possible for overcast, single phase pixels, if information on the sub-pixel reflectance covariance matrix is used in the retrieval process through the unscented transform. Extensions of the unscented transform have been proposed, which might allow for further performance improvements[7]. However, the principle limitation precluding an operational implementation is the fact that the required information about sub-pixel variability is currently not available. It is also worth pointing out that the unscented retrieval is not restricted to the estimation of the effects of the PPH bias, but can also be used to provide error estimates.

BROKEN CLOUD EFFECTS

As noted previously, approximately 20% of all cloudy pixels at 3x3km^2 resolution contain broken clouds, based on the 1x1km^2 MOD35 cloud mask. For these pixels, there is a significant clear-sky contribution to the total satellite-observed reflectance, which will affect the quality of cloud retrievals [2].

Table 3 presents statistics comparing the low- and high-resolution results for broken water cloud pixels. The values for COT and LWP correspond to mean values for the entire super-pixel, while REFF has been calculated as mean of the cloudy part. [7] have proposed to separate the reflectance into cloudy and cloud-free contributions using an effective sub-pixel cloud fraction. To determine the accuracy of this approach, the reflectance originating from the cloudy part (again selected based on the MOD35 cloud mask) of the super-pixel have been obtained, and used as retrieval input. Overall, these results show that the quality of the retrieved cloud properties deteriorates strongly in the presence of broken clouds versus completely overcast situations. If a reliable estimate of sub-pixel cloud fraction, and the reflectance originating from the cloudy part of the pixel is available, these errors can be approximately cut in half.

TABLE 3. Systematic (Bias) and random (SDev) deviations in satellite-retrieved cloud optical thickness (COT), effective radius (REFF), and liquid water path (LWP) resulting from a change of sensor resolution from $1\text{x}1km^2$ to $3\text{x}3km^2$ for broken water clouds. Values have been obtained for a total of 161 3x3 super-pixels. The results labeled "**CF-Cor.**" use the MODIS cloud mask to obtain the reflectance originating from the cloudy part of the super-pixel.

Quantity	Mean	Bias		SDev		CF-Cor. Bias		CF-Cor. SDev	
COT	3.1	1.3	43.8%	1.8	58.5%	.-0.2	-6.8%	0.8	25.5%
REFF[µm]	9.5	0.3	2.6%	2.4	25.3%	0.2	1.7%	1.4	11.8%
LWP [g/m^2]	20.0	10.9	54.6%	13.4	66.9%	-0.8	-4.1%	5.5	27.7%

A further interesting feature is the positive bias of low- versus high-resolution COTs, which contradicts the expectations based on the PPH bias. The explanation can by found from the mean 0.6 µm reflectance originating from the clear-sky part of broken-cloud super-pixels, having a value of 19.0%, versus the mean of reflectances from entirely cloud-free pixels of 7.8%. The difference in numbers indicates that for broken-cloud situations, the supposedly clear-sky reflectance still contains significant cloud contamination, and our use of the MODIS cloud mask does not lead to a satisfactory separation of cloudy and cloud-free contribution.

CONCLUSIONS AND OUTLOOK

In this study, we have analyzed the resolution sensitivity of satellite-retrieved cloud properties introduced by unresolved broken clouds, and by the PPH bias in overcast situations. For this purpose, retrieval results using $3\text{x}3km^2$ resolution MODIS reflectances have been compared to those obtained at $1\text{x}1km^2$ resolution.

The PPH bias is found to cause a low bias (scatter) of 5.6% (20.3%) for COT and 3.8% (19.1%) for LWP for overcast water clouds. It is shown that information on unresolved variability can strongly reduce these deviations by using the unscented transform[6] in the retrieval. For pixels containing broken clouds, retrieval results become inaccurate. Here, an estimate of sub-pixel cloud fraction is shown to reduce the resulting errors by about a factor of 2.

To apply these suggested corrections in practice, reliable estimators of unresolved variability in reflectance and of sub-pixel cloud fraction are required, and will be the focus of our future research efforts. The high-resolution visible channel of the SEVIRI instrument can likely provide valuable information. In addition, spectral signatures, and the application of certain texture features[8] seem promising candidates. Unfortunately, the quality of an estimate of sub-pixel cloud-fraction will likely be dependent on the choice of cloud masking algorithm, and will be affected by cloud contamination of clear-sky pixels as found in the last section.

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