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Discriminating raining from non-raining clouds at mid-latitudes using multispectral satellite data

T. Nauss[1] and A. A. Kokhanovsky[2]

[1]Laboratory of Climatology and Remote Sensing, University of Marburg, Germany
[2]Institute of Remote Sensing, University of Bremen, Germany

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Correspondence to: T. Nauss (nauss@lcrs.de)

Abstract

We propose a new method for the delineation of precipitation using cloud properties derived from optical satellite data. This approach is not only sufficient for the detection of mainly convective driven precipitation by means of the commonly used connection between infrared cloud-top temperature and rainfall probability but enables the detection of stratiform precipitation (e.g., in connection with mid-latitude frontal systems). The scheme presented is based on the concept model, that precipitating clouds must have both a large enough vertical extent and large enough droplets. Therefore, we have analyzed Terra-MODIS scenes during the severe European summer floods in 2002 and retrieved functions for the computation of an auto-adaptive threshold value of the effective cloud droplet radius with respect to the corresponding optical thickness which links these cloud properties with rainfall areas on a pixel basis.

1. Introduction

Water affects all aspects of human life and rainfall is a key parameter in the hydrological cycle. Detailed knowledge about the spatio-temporal distribution of rainfall is therefore crucial for state of the art hydrological models. Moreover, this information can further improve the reliability of short-term for- and nowcasting applications (e.g. in the context of flood prediction and monitoring). Therefore, many rainfall retrievals based on optical and/or microwave satellite sensors have been developed over the past decades (e.g. Adler and Negri, 1988; Kummerow et al., 2001; Joyce et al., 2004). While optical retrievals mainly focus on the tropics where precipitation is generally linked with deep convective clouds that can be easily identified in the infrared and/or water vapor channels (Levizzani et al., 2001; Levizzani, 2003), microwave sensors aboard of polar orbiting satellites (low earth orbit, LEO) can principally be used to delineate stratiform raining cloud regions with homogenous cloud-top temperature spatial distributions. On the other hand, these retrievals bear problems concerning the medium temporal resolution of the LEO systems and the high but in general unknown emissivity of land surfaces (Ferraro et al., 1994) that in some extent restricts the application of passive microwave techniques to ocean surfaces. Therefore, optical sensors at a geostationary orbit play still a very important role for the quasi-continuous monitoring of precipitation processes.

In order to improve the quality of optical rainfall retrievals, some authors have suggested to use the effective cloud droplet radius a_{ef} that is defined as the ratio of the third to the second moment of the cloud droplet spectrum (Hansen and Travis, 1974) and can be retrieved from multi-spectral satellite data. They propose to use values of a_{ef} of around 14 μm as a fixed threshold value (THV) for precipitating clouds (e.g. Rosenfeld and Gutman, 1994; Lensky and Rosenfeld, 1997; Ba, 2000) but these studies have been focused on convective systems and a fixed THV seems to be not applicable for a reliable delineation between raining and non-raining stratiform clouds that are typical for wide warm or cold frontal bands of mid-latitude frontal systems (Houze, 1993, further referred as advective/stratiform precipitation). With this in mind, the authors propose a new technique for the identification of precipitating clouds using optical imagery based on an auto-adaptive THV for a_{ef} with respect to the corresponding cloud optical thickness τ.

2. A new concept model for the identification of precipitating clouds at mid-latitudes

Due to the very homogenous spatial distribution of cloud-top temperature T for (warm) clouds with values of T differing not significantly between raining and non-raining regions, advective/stratiform precipitation is generally underestimated or even not detected by some of the advanced infrared temperature threshold techniques like the Convective-Stratiform-Technique CST (Adler and Negri, 1988) or the Enhanced Convective-Stratiform-Technique ECST (Reudenbach, 2003). Therefore, we propose the consideration of the effective cloud droplet radius a_{ef} and the cloud optical thickness τ instead of the brightness temperature for the detection of precipitation. In contrast to the previous studies that focus on convective clouds and mentioned above, no absolute THV of a_{ef} is used. Instead, our technique is based on an auto-adaptive THV of a_{ef} with respect to the corresponding value of τ. This idea is based on the concept, that rainfall is favored by both large enough droplets that can fall easily against updraft wind fields and a large enough vertical cloud extent that allows droplets to grow and prevents them from evaporation below the cloud bottom (which in turn has an influence on the required droplet size; see also Lensky and Rosenfeld, 2003).

In order to proof our concept, satellite derived cloud properties have been compared to ground based radar data to derive a function for the auto-adaptive THV of a_{ef} with respect to the corresponding τ on a pixel basis. The cloud properties have been retrieved by the fast computing but still very accurate Semi-Analyitcal CloUd Retrieval Algorithm SACURA (Kokhanovsky et al., 2003; Nauss et al., 2005; Kokhanovsky and Nauss, 2005) using data from the Moderate Resolution Imaging Spectroradiometer (MODIS, http://modis.gsfc.nasa.gov/) aboard NASA's Terra and Aqua satellites with a spatial resolution of 1 km^2. SACURA is based on asymptotic solutions and exponential approximations (EA) of the radiative transfer theory valid for weakly absorbing media (Kokhanovsky and Rozanov, 2003, 2004), which are applicable for cloud retrievals up to a wavelength of around 2.2 μm. For a single scattering albedo $\omega_0=1$, the equations coincide with more general asymptotic formulae valid for all values of ω_0 (Germogenova, 1963; van de Hulst, 1982; King, 1987) and differ only insignificantly from general equations as $\omega_0 \rightarrow 1$. However, the EA provides much simpler final expressions, which can be used as a basis for a high-speed cloud retrieval algorithm (Kokhanovsky et al., 2003). SACURA has been validated over sea and land surfaces against the commonly used but computer-time expensive look-up table approaches of the Japanese Space Agency JAXA (Nakajima and Nakajima, 1995; Kawamoto et al., 2001) and the NASA MODIS cloud property product MOD06 (Platnick et al., 2003) showing good agreement for optically thick (e.g., raining) cloud systems (Nauss et al., 2005; Kokhanovsky et al., 2005). The technique used for the computation of auxiliary ground albedo data and the processing of the received MODIS files are described by Nauss and Bendix (2005). Since the final rainfall retrieval should be applicable to geostationary sensors, data from the 0.66 μm and 1.6 μm MODIS channels similar to those available on Meteosat-8 SEVIRI are used by SACURA.

In order to derive a rainfall delineation function, the spatial distribution of the SACURA-derived a_{ef} and τ values has been compared to corresponding (+/−7 min time difference) ground based radar data from the German weather service (DWD, 2005) for 15 MODIS scenes over Central Europe taken during the extreme summer floodings in August 2002. This time frame has been chosen because it includes not only mainly convective systems but all precipitation processes typical for mid-latitude cyclones. Therefore, one can assume that a function for an auto-adaptive THV of a_{ef} derived using this dataset is suitable for the description of the precipitation processes at least over Central Europe. Figure 1 shows the resulting rainfall probability for the respective combinations of τ and a_{ef}. The exponential shaped pattern of the probability distribution clearly corroborates our initial hypothesis, that rainfall is connected to large enough combinations of the two cloud parameters.

In order to find a discrimination function for raining and non-raining cloud areas that performs best for a large variety of scenes, we iteratively retrieved pairs of the two cloud parameters for each of the 15 MODIS scenes mentioned above that encircle the rainfall area defined by the radar data with a bias better than +/−5%. Fitting these value combinations results in the following formula for the THV of the effective radius which is close to the 45% precipitation probability (see Fig. 1):

$$a^*_{ef}(\tau) = \frac{A}{\tau} \qquad (1)$$

where A=920 μm. The standard error of this approximation is equal to 0.83. It follows that an assumed fixed $a^*_{ef}(\tau)$ of 14 μm corresponds to clouds with $\tau \approx 66$. For smaller τ, the THV for the effective radius is considerably larger. Please note that Eq. (1) is equivalent to a static THV of the liquid water path of about 0.6 kg/m^2.

3. Exemplary application of the discrimination function to MODIS data from 30 August 2004

In order to get a first impression of the performance of the new Rain Area Delineation Scheme (RADS), we applied Eq. (1), which is based on the MODIS scenes from August 2002, to a Terra-MODIS scene from 30 August 2004, 10:38 UTC (Fig. 2). Clouds in the eastern part of the scene shown in Fig. 2a belong to a partly occluded cyclone centered over the North Sea and in the north-western part, convective clouds form due to post-frontal instability. For a better interpretation we computed the rainfall area twice: firstly using the new RADS and secondly using routines from the ECST (Reudenbach, 2003) which is similar to the well known CST (Adler and Negri, 1988) but additionally includes the water vapour channel temperature for a more reliable deep convective/cirrus clouds discrimination (Tjemkes et al., 1997, see also). The ECST routines have been used for the identification of convective rain areas since these regions approximately represent the performance of many present optical rainfall retrievals.

The different rainfall regions identified by the infrared convection scheme (CS, see above) and by RADS are shown in Fig. 2b. Both methods identify the convective cloud regions forming due to potential instability in the north-eastern part of the scene but the comma shaped trails in the southern part are identified only by RADS. The same applies for most of the post frontal clouds, where only the convective cores are additionally identified by the infrared scheme. Note that every pixel which was identified by the CS was also identified by RADS.

Figure 2c shows an overlay of the rainfall area identified by RADS and by the radar network of the German weather service. The black areas in the most north-western and north-eastern parts indicate the boundaries of the area covered by the radar stations. For the southern border, the northern slope of the Alps has been chosen in order to minimize ground clutter effects in the radar dataset. It can be clearly seen, that the radar based precipitation area is almost entirely identified by the RADS module. Some non-systematic over-/underestimations can be found merely at the edges of the comma shaped clouds in the southern part. Regarding the precipitating clouds in the post-frontal zone, mainly the cloud cores are identified by the satellite retrieval. This is partly caused by enhanced 3-D radiation effects at the cloud borders that are not accounted by the cloud property retrieval which assumes a plane-parallel, homogenous cloud layer. Moreover, the different perspectives between the satellite technique that identifies the cloud-top area responsible for precipitation formation and the radar product that detects the rainfall distribution near ground level could further increase the deviations between the two datasets.

Analogous to the visual impression, standard verification scores for dichotomous datasets are in a very good range (see Table 1). For the calculation of the verification scores see Stanski et al. (1989) or the web site of the WWRP (2005). The bias between the precipitating pixels identified by the radar and RADS is 0.85 which is an increase by more than factor 3 compared to the bias when only the CS would be used. The 1 km^2 pixel based probability of detection (POD) is 68%, the probability of false detection (POFD) equals 13%, and the false alarm ratio (FAR) is 21%. The critical success index (CSI) is 0.57 which is about factor 2.7 better then for the CS. Note, that this verification was based on a pixel basis of a single scene and no spatio-temporal aggregation (commonly 0.25 to 1° and 24 h) was performed. If we allow a spatial tolerance of 20 km, all scores differ from their optimum value by not more then +/−0.02 (see Table 1).

4. Conclusions

A new technique for the identification of precipitating clouds has been presented that delineates raining from non-raining cloud regions by means of the cloud effective droplet radius and the corresponding cloud optical thickness. The retrievals are performed using satellite measurements of the top-of-atmosphere reflectance at wavelengths 0.66 and 1.6 μm. The delineation rely on the the principle, that precipitating clouds must have large enough droplets and a large enough vertical extent to enable sufficient droplet growth and prevent rain droplets from evaporation beneath the cloud base, which in turn has an influence on the required droplet size again. The function for the computation of an auto-adaptive threshold value of the effective radius with respect to the optical thickness is based on a comparison between the rainfall area detected by ground based radar and corresponding cloud property distributions that have been retrieved using the fast computing SACURA technique. The present article shows only first but promising results of the new algorithm and the consideration of the two mentioned cloud properties seems to be important in the context of optical rainfall retrievals not only for the mid-latitudes but also on a global scale. The retrieval will be further evaluated and applied to Meteosat-8 SEVIRI data in an upcoming study.

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Table 1. Results of the standard verification scores applied to the rain-area as identified by RADS and CS on a pixel basis and by RADS but this time allowing a spatial tolerance of 20 km.

	RADS	CS	RADS (20 km)
Bias	0.85	0.25	1.00
POD	0.68	0.22	0.99
POFD	0.13	0.03	0.01
FAR	0.21	0.14	0.01
CSI	0.57	0.21	0.98
Cloud area	0.92	0.92	0.92

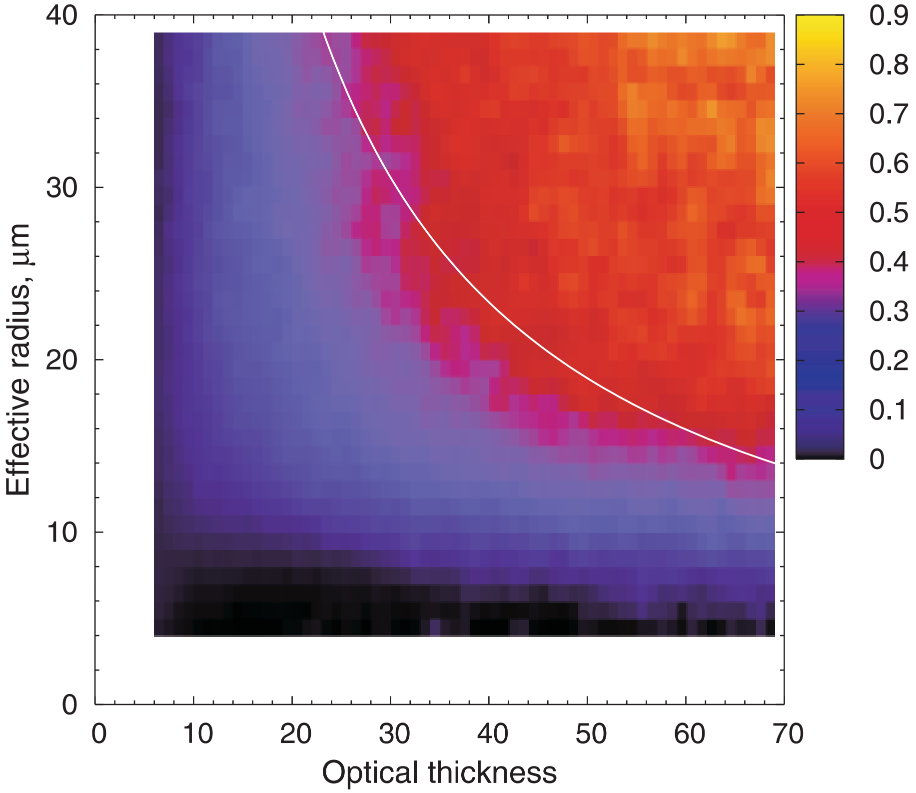

Fig. 1. Rainfall probability of respective combinations between cloud optical thickness and effective droplet radius derived from the comparison of 15 Terra-MODIS scenes between 1 and 15 August 2002 with radar network data from the German weather service over central Europe. The white line shows the delineation function given by Eq. (1).

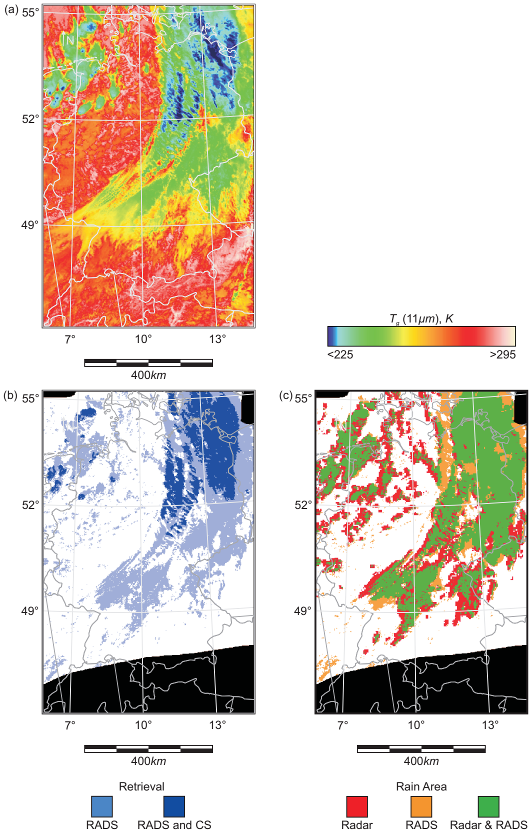

Fig. 2. Comparison between satellite and radar based rainfall areas for the Terra-MODIS scene from 30 August 2004, 10:38 UTC. Panel **(a)** shows the 11 μm brightness temperature, **(b)** the satellite derived rainfall area identified by the CS and RADS, **(c)** an overlay of precipitating cloud areas identified by RADS and ground-based radar data.