VALIDATION OF DIFFERENT CLOUD PHASE RETRIEVAL METHODS FROM SEVIRI USING GROUND-BASED CLOUD RADAR AND LIDAR OBSERVATIONS

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ABSTRACT

Four satellite cloud phase determination methods from SEVIRI were evaluated by comparing one year of retrievals (May 2004-April 2005) with ground-based observed cloud phase from cloud radar and lidar at Cabauw, the Netherlands. The aim of this research was to assess which cloud phase determination method was suited best to derive cloud phase climatology. Differences between these methods were quantified by studying seasonally averaged liquid water phase ratio; the skill of the methods was assessed using weighted correlation coefficients between daily liquid water phase ratio from SEVIRI and ground-based observations.

For the temperature thresholding methods, using the commonly used threshold of 260 K, the difference in liquid water phase ratio is 30-35% during the summer and autumn months, decreasing to ~20% during the remainder of the period investigated.
Further, brightness temperature difference 10.8-12.0 μm ($BTD_{10.8-12.0}$) has a poor quality in deriving cloud phase climatology. Thirdly, the difference in seasonal liquid water phase ratio between CTT and $BT_{10.8}$ is only a few percent, which raises the suggestion that correction for cloud emissivity does not play a large role at the threshold of 260 K. Finally, 0.6 and 1.6 μm reflectance ratio shows an increasing difference in seasonal liquid water phase ratio with ground-based observations towards the winter season due to unfavorable viewing geometries.

1. INTRODUCTION

Clouds play a very important role in the climate system of the Earth. Thermodynamically, clouds act as sources and sinks of energy through condensation and evaporation of water. Clouds reflect and absorb solar radiation and emit and absorb terrestrial radiation. The interaction between clouds and radiation is of great importance to the surface energy balance. However, this interaction is of a complex nature and is dependent upon quantities such as cloud particle size, cloud temperature, cloud phase, water vapour and aerosol abundance, and surface reflectivity. Accurate measurements on these cloud properties are therefore of great importance to gain knowledge on this interaction. After cloud detection, determination of cloud phase can be regarded as the next step to retrieve cloud properties from satellite measurements.

During the past few decades several approaches to infer cloud phase from satellite imagery have been developed. Arking and Childs (1985) developed a microphysical index including information on cloud thermodynamic phase based primarily on information from the 3.7 μm channel of the Advanced Very High Resolution Radiometer (AVHRR) on-board the National Oceanographic and Atmospheric Administration (NOAA) satellite. Strabala *et al.* (1994) developed a tri-spectral method to determine cloud phase using radiances of the 8.5-, 11- and 12-μm bands of the Moderate-Resolution Imaging Spectroradiometer (MODIS), which was further improved by Baum *et al.* (2000) by adding 0.6-, 1.6-, and 1.9 μm channel reflectances. Rossow and Schiffer (1999) use a threshold of 260 K for the cloud top temperature derived from 10.8 μm brightness temperature to discriminate water from ice clouds in the International Satellite Cloud Climatology Project (ISCCP) algorithms. This threshold is to provide a good balance of errors.

Despite the progress made in retrieving cloud phase information from passive imagers, most validation efforts have been performed on a limited number of case studies. Little is known about the accuracy of the various cloud phase determination methods when applied to large data sets, which form the basis for long term climate monitoring applications, like for example ISCCP and the Satellite Application Facility on Climate Monitoring (CM-SAF) of the EUropean METeorological SATellite agency (EUMETSAT). In this paper we explore which method is most appropriate to derive cloud phase for climate monitoring purposes. In order to answer this question, the accuracy of four satellite cloud phase retrieval methods is assessed by comparing results to ground-based cloud phase observations of cloud radar and lidar at the CloudNET site of Cabauw, the Netherlands, using a method described in Illingworth *et al.* (2006).

2. METHODS

Satellite retrieval methods

Four cloud phase retrieval methods using SEVIRI data, one visible and near-infrared reflectance method and three thermal infrared temperatures methods were examined:

1. reflectance ratio 0.6/1.6 μm ($R_{0.6/1.6}$); measured 0.6 and 1.6 μm reflectance are compared to pre-calculated Lookup Table values from the Doubling Adding KNMI model, DAK, (Stammes, 2001) to distinguish water from ice clouds (Feijt et al, 2004).

2. Brightness temperature thresholding from the 10.8 μm channel ($BT_{10.8}$).

3. Cloud top temperature (CTT), which consists of the $BT_{10.8}$ which is corrected for the cloud emissivity,ε. The cloud emissivity is obtained from the cloud optical thickness at 0.6 μm, $\tau_{0.6,}$ as follows (Feijt, 2000):

$$\tau_{10.8} = \tau_{0.6} \frac{Q_{10.8}}{Q_{0.6}} \quad (1a)$$

$$\varepsilon = 1 - e^{-\tau_{10.8}/\mu} \quad (1b)$$

   with $Q_{0.6}$ and $Q_{10.8}$ being the extinction efficiencies at 0.6 and 10.8 μm, respectively, and μ being the cosine of the viewing zenith angle.

4. Brightness temperature differencing between 10.8 and 12.0 μm ($BTD_{10.8-12.0}$); it was suggested by Inoue (1985) that large positive $BTD_{10.8-12.0}$ values occurred for semi-transparent ice clouds. However, it was shown by Minnis *et al.* (1998) that large positive $BTD_{10.8-12.0}$ values are possible for both water and ice cloud particles. Our experimental set-up enables us to check their theoretical results.

All cloud phase determination methods were applied using SEVIRI data at pixel level. For the temperature thresholding methods, a value of 260 K, being similar to the value used within ISCCP (Rossow and Schiffer, 1999), was used. The ice phase was assigned to cloud flagged pixel brightness temperatures lower than the threshold value, whereas the water phase was assigned to temperatures higher than the threshold value. The threshold for the $BTD_{10.8-12.0}$ method was $\Delta T=1$ K. Measured values higher than the threshold were labelled as ice clouds, lower values as water clouds.

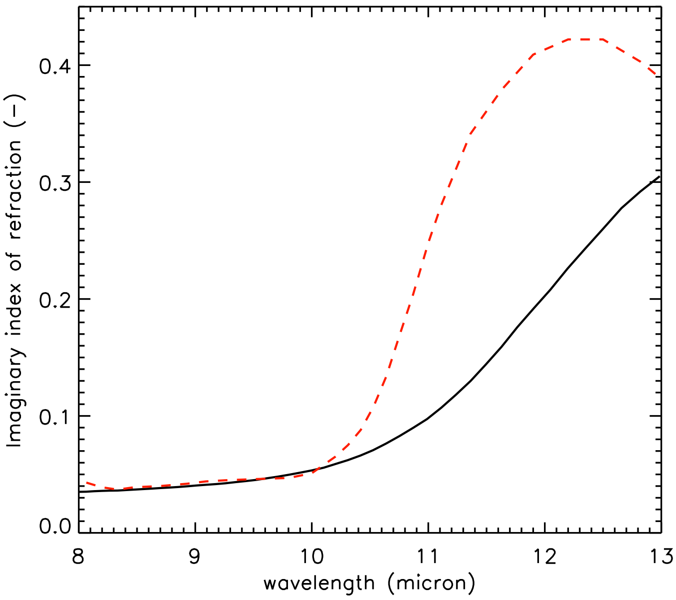

Figure 1: **Imaginary index of refraction for water (solid line) and ice (dashed line) particles between 8 and 13 μm. Water indices are from Downing and Williams (1975), ice indices are from Warren (1984).**

Ground-based cloud phase retrieval method

The retrievals from the four SEVIRI cloud phase methods were compared to cloud phase retrievals obtained from simultaneous lidar and cloud radar observations from the CloudNET site at Cabauw (www.cloud-net.org). The method works as follows: first, from NWP data the level where the wet bulb temperature, $T_{w,\ \mathrm{equals}}$ $0^{\circ\circ}$ C is assessed. Then, the cloud radar vertical Doppler velocity profile is used to refine the first estimate from the NWP data, since in general at the melting layer a large and sharp increase in falling velocity of the cloud particles can be seen. Finally, the lidar backscatter attenuation coefficient is used to detect layers of supercooled water clouds within ice layers. More information on this method is provided in Illingworth *et al.* (2006).

Comparison study

The skill of the four satellite cloud phase determination methods was assessed in three steps. Firstly, the frequency distribution of differences between daily SEVIRI and ground-based liquid water phase ratio (φ_{day}) was analyzed. Secondly, seasonally weighted averages of mean liquid water phase ratios were compared. Lastly, weighted correlation coefficients between SEVIRI and ground-based φ_{day} values were examined.

3. RESULTS

Figure 2 shows the frequency distribution of the differences between SEVIRI and ground-based derived daily liquid water phase ratio, which is defined as the number of retrieved water clouds to the total number of clouds in a day. All methods show a bias towards positive values, as is indicated by positive median differences. Further, it can be seen that for the temperature thresholding methods differences in φ_{day} are larger than 60% at about 25% of the days. The large positive differences might be connected to the assumption that clouds are composed of ice particles at temperatures lower than 260 K, whereas from literature it is known that cloud tops can consist of ice particles at temperatures lower than about 268 K (e.g. Pruppacher and Klett, 1997).

The BTD$_{10.8\text{-}12.0}$ method has a higher frequency of large negative differences compared to the other four methods. This means that clouds are labelled as ice too often in cases where water is detected from the surface. This can largely be explained by the fact that BTD$_{10.8\text{-}12.0}$ is positive for both water and ice particles. In addition, $BTD_{10.8-12.0}$ approaches zero for water and ice clouds having $\tau < 2$ and $\tau > \sim 8$.

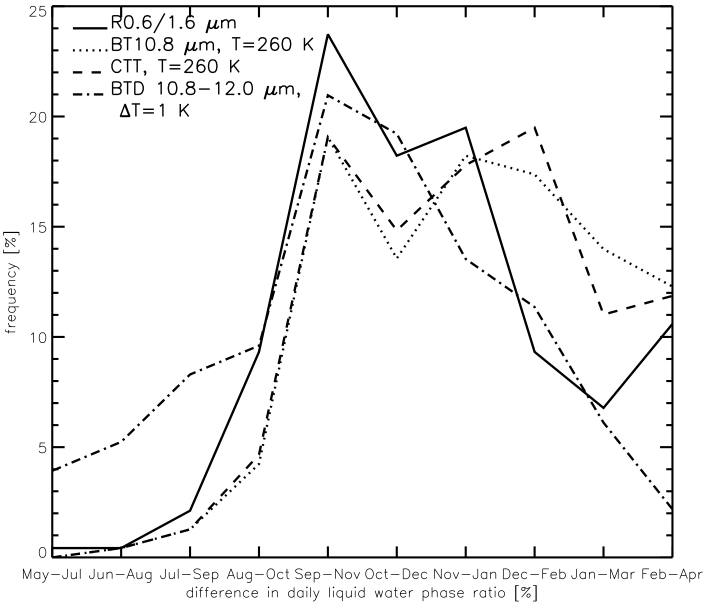

Figure 2: **Frequency distribution of differences in daily liquid water phase ratio, φ_{day}, between SEVIRI and ground-based observations for all methods. $BT_{10.8}$ and CTT are performed at threshold value 260 K, $BTD_{10.8-12.0}$ at $\Delta T=1$ K. Values on the x-axis represent the center value of the bin.**

Seasonally weighted averages of liquid water phase ratios, φ_{seas}, are presented in Figure 3. φ_{seas} was calculated from φ_{day} values, weighted by the ratio of the daily available collocated to total time slots. In order to obtain sufficient statistics for each point in the graph, the three-month periods comprised the two latter months of the previous period. That is, the first three-month period consists of the months of May, June, and July 2004, whereas the second three-month period consists of June, July, and August 2004. Ground-based observed φ_{seas} shows a downward trend from 40% in the period May-July 2004 to 24% in the period February-April 2005.

From the Figure it follows that from May-July until September-November 2004 a large difference in φ_{seas} of 30-35% between the temperature thresholding methods and surface observations exists. This difference decreases after the period mentioned, but remains 20% at least.
The large difference might be connected to the applied assumption that a transition between water and ice particles exists at a certain threshold value. This limits the thresholding technique, since in nature, (super-cooled) liquid water and ice crystals coexist at temperatures between 233 K and 268 K (Pruppacher and Klett, 1997). Using ground-based lidar measurements at Chilbolton, United Kingdom, Hogan *et al.* (2003) found that the frequency of occurrence of super-cooled water particles in stratiform clouds decreases from 27% at 268 K to about 0% below 238 K.

Further, part of the large difference between SEVIRI and surface observations is caused by differences in spatial and temporal sampling of clouds; liquid water phase ratio from ground-based measurements is determined from a transect through an advected cloud system, in contrast to liquid water phase ratio from SEVIRI, which is determined from an area averaged reflectance or radiance. Roebeling *et al.* (2006) showed that for cloud liquid water path retrievals of stratocumulus clouds, about 50% of the difference between instantaneous satellite and ground-based values was related to factors such as collocation, parallax, the position of the ground-based station and the sampling of different cloud portions. With respect to the ground-based reference data set used, cloud radar detects very thin cirrus clouds, whereas these clouds can hardly be detected by the SEVIRI instrument. As a result, the liquid water phase ratio from ground-based measurements is underestimated.

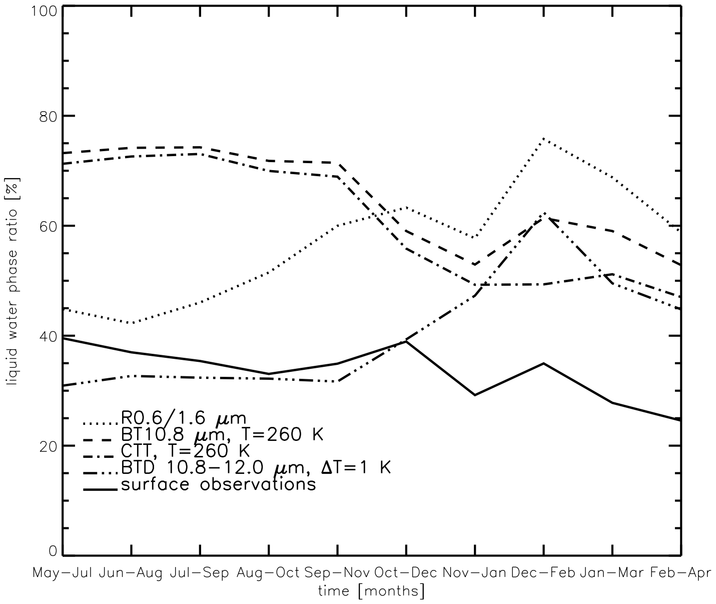

Figure 3: **Liquid water phase ratio (in %) for the $BT_{10.8}$ at 260 K (fine dash), CTT at 260 K (dashed-dotted), $BTD_{10.8\text{-}12.0}$ at 1.0 K (dashed triple dotted), KNMI reflectance 0.6/1.6 μm (dotted) and ground-based observations (solid). Running averages are used with a shift of one month.**

Another striking feature shown in Figure 3 is that for $R_{0.6/1.6}$ the difference between SEVIRI and ground-based derived φ_{seas} increases towards the winter season. This increase might be explained by unfavorable viewing geometries (high solar zenith angles), at which the DAK Lookup Tables approach their limits and the pre-calculated reflectance values are less robust. In addition, in case of ice an ice cloud overlying a water cloud, the ice cloud needs to be of a certain optical thickness before the $R_{0.6/1.6}$ method labels the cloud as ice.

It can be seen from Figure 3 that the difference in seasonal mean liquid water phase ratio derived from $BT_{10.8}$ and CTT is within a few percent for the largest part of the period investigated, which suggests that applying the emissivity correction to $BT_{10.8}$ does not play a large role.

Figure 4 depicts the weighted correlation coefficients between φ_{day} from the SEVIRI methods and ground-based observations. The correlation coefficient was used to indicate the skill of each method. It is obvious that for the temperature threshold methods and $R_{0.6/1.6}$ the skill decreases towards the winter season with correlations going from ~0.60 down to 0.30-0.35, increasing again at the end of the year investigated. Further, it is indicated that $R_{0.6/1.6}$ has a lower correlation than the temperature threshold methods from June-August until October-December 2004.
For $BTD_{10.8\text{-}12.0}$, correlation is poor for the largest part of the year, having values lower than 0.2 for about 50% of the time.

4. DISCUSSION AND OUTLOOK

In this paper the skill of four cloud phase determination methods from SEVIRI data was examined for cloud phase climatology purposes. From May 2004 until April 2005, daily and seasonal mean liquid water phase ratios from the various methods were compared to the same quantity derived from ground-based observations from lidar and cloud radar. Further, weighted correlation coefficients between satellite and ground-based derived liquid water phase ratios were analyzed.

All SEVIRI methods show an overestimation in the amount of water clouds. For the temperature thresholding methods, the difference in liquid water phase ratio is 30-35% during the summer and autumn months, decreasing to ~20% during the remainder of the period investigated.
This large positive difference is most probably related to the applied assumption that clouds consist of ice particles at temperature lower than 260 K, whereas in nature clouds can consist of ice at

temperatures lower than about 268 K. Consequently, the threshold value of 260 K seems to be too high.

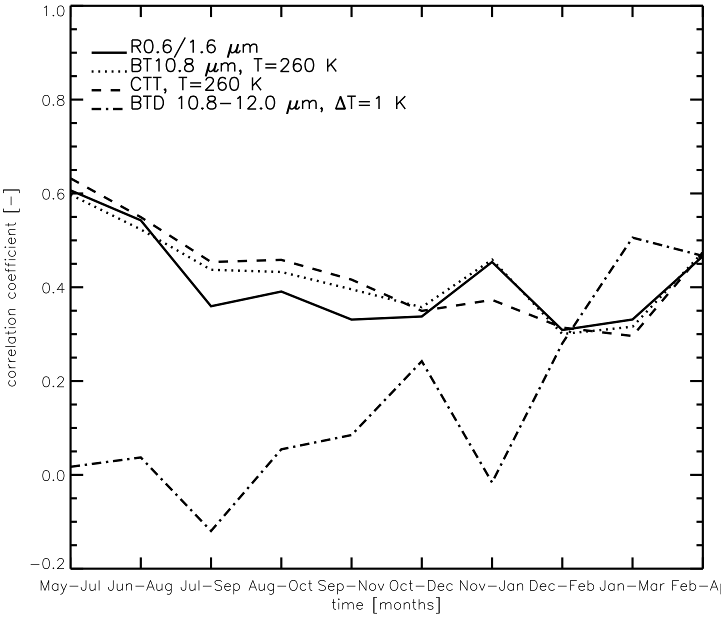

***Figure 4:* Weighted correlation coefficients based on daily liquid water phase ratio for $BT_{10.8}$ (dotted), CTT (coarse dash), $BTD_{10.8\text{-}12.0}$ (dashed-dotted), and KNMI reflectance 0.6/1.6 μm (solid) methods. Running averages are used analogously to Figure 3.**

Further, the difference in retrieved liquid water phase ratio between CTT and $BT_{10.8}$ is only a few percent throughout the majority of the year, which suggests that correcting brightness temperature at 10.8 μm for cloud emissivity has only a minor effect on the statistics of cloud phase determination when applying the temperature threshold of 260 K.

Brightness temperature differencing ($BTD_{10.8\text{-}12.0}$) has a poor skill compared to the other four methods, which most probably is related to the fact that the difference in brightness temperature between 10.8 and 12.0 μm is positive for both water and ice clouds (see e.g. Figure 14c and 14d of Minnis *et al.*, 1998), which makes it difficult to choose a proper threshold value. Moreover, since $BTD_{10.8\text{-}12.0}$ values decline towards zero for clouds with $\tau < 2$ and $\tau > \sim 8$, the applicability of this method is actually restricted to semi-transparent clouds.

Cloud phase determination using 0.6 and 1.6 μm reflectance ($R_{0.6/1.6}$) shows an increasing difference in seasonal liquid water phase ratio towards the winter season. This increase is related to effects resulting from low sun elevations towards winter time, at which the DAK Lookup Tables have less robust reflectance values. Furthermore, when ice clouds have water clouds below them, the ice cloud needs to be of a certain optical thickness to be detected by the $R_{0.6/1.6}$ method.

Future plans include a more detailed research on the possibilities to determine cloud phase from thermal infrared channel radiances only. Especially methods including the combination of 8.7-, 10.8-, and 12.0-μm brightness temperatures will be evaluated and optimized using our data set of one year MSG and collocated ground-based observations.

5. ACKNOWLEGDEMENTS

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