COMPARISON OF METEOSAT-8 and NOAA-17 BASED CLOUD MICROPHYSICAL PROPERTIES

R.A. Roebeling and A.J. Feijt

Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201, 3730 AE De Bilt, The Netherlands

ABSTRACT

Clouds and cloud-radiation interactions contribute most to uncertainty in climate predictions in climate model runs. To improve the understanding of cloud processes and the representations in models the IPCC calls for more measurements on cloud properties.

Within the SAF on Climate Monitoring (CM-SAF) KNMI developed the algorithms to retrieve cloud microphysical products from Meteosat Second Generation and NOAA-AVHRR satellites. The anticipated cloud products are cloud thermodynamic phase (CPH), cloud optical thickness (COT) and cloud liquid water path (CLWP). The algorithm to retrieve cloud physical parameters utilizes the reflection of clouds at a non-absorbing channel in the visible wavelength region to retrieve cloud optical thickness and the reflection at a water or ice absorbing channel in the near infrared to retrieve cloud particle size. By combining both types of information the cloud liquid water path can be calculated. The cloud reflectances are simulated with the Doubling Adding KNMI (DAK) radiative transfer model.

The Baltex Bridge Cloud campaign – 2 (BBC2) (http://www.knmi.nl/samenw/bbc2/) is an intensive cloud measurement campaign that was held in Cabauw, The Netherlands in April and May 2003. The ground based set-up includes among others ground based lidars, radars, microwave radiometers. Furthermore aircraft flights were made to measure cloud microphysical properties. About 100 researchers of 27 institutes from 7 countries were involved. BBC2 is the first measurement campaign for which both NOAA-17 and Meteosat-8 data are available. Within the CM-SAF BBC-2 data will be employed to validate Meteosat-8 and NOAA-17 retrieved cloud physical products, using pyranometer, lidar, radar and microwave radiometer measurements.

The differences between Meteosat-8 and NOAA-17 cloud physical products retrievals are analysed in three steps. Firstly, calibration results are presented of Meteosat-8 and NOAA-17 reflectances. Secondly, the interrelation of Meteosat-8 and NOAA-17 retrievals is assessed through an inter-comparison study. Finally, the potential of Meteosat-8 to derive daily cloud physical products is demonstrated.

1. INTRODUCTION

Accurate information on cloud properties and their spatial and temporal variation is crucial for climate studies. Clouds strongly modulate the energy balance of the Earth and its atmosphere through their interaction with solar and thermal radiation (King and Tsay, 1997). Despite their importance, clouds are represented in a rudimentary way in climate and weather forecast models. Cess et al. (1989) showed that clouds are the major source of uncertainty in model responses to climate forcing. The radiative behaviour of clouds depends predominantly on cloud properties such as thermodynamic phase, optical thickness and droplet effective radius. Satellites provide useful information on global cloud statistics and radiation budget (Feijt et al., 2003). With the launch of Meteosat Second Generation (Meteosat-8) and later METOP, better methods can be developed to improve the retrieval of cloud physical parameters.

Several researchers have developed methods to retrieve cloud optical thickness and cloud particle size from cloud radiances at a non-absorbing visible and a moderately absorbing solar infrared wavelength (Han et al. 1994, Nakajima and Nakajima 1995, Watts et al. 1998 and Jolivet et al. 2000). The principle of these methods is that the reflection of clouds at the non-absorbing wavelength is primarily a function of the cloud optical thickness, while the reflection at the absorbing wavelength is primarily a function of cloud particle size (Nakajima and King 1990). For the non-absorbing wavelength all methods use the 0.6 micron channel. For the absorbing wavelength some methods use the 3.7 micron channel (Han et al. 1994 and Nakajima and Nakajima 1995), while others use the 1.6 micron channel (Watts et al. 1998, Jolivet et al. 2000, Roebeling et al. 2001). Radiative Transfer Model (RTM) simulations of cloud reflections, at given viewing geometries and for predefined physical properties, are used to relate observed radiances to cloud physical properties.

Little research has been done on the application of the 1.6-micron channel for the retrieval of cloud properties. No research has been done so far on the application of these methods on Meteosat-8 data. The purpose of this study was to assess the accuracy of Meteosat-8 retrieved cloud physical properties from 0.6 and 1.6-micron narrow band radiances, by comparing them to validated NOAA-17 retrieved cloud physical properties. This study was identified important for the SAF on Climate Monitoring (CM-SAF) of EUMETSAT, where NOAA-AVHRR and Meteosat-8 products are complementary. The CM-SAF will generate and archive high quality data sets on climate relevant products from Meteosat Second Generation and NOAA-AVHRR and METOP satellites for a region covering Europe and Africa (Science plan, 2000).

The outline of this paper is as follows. Section 2 describes the method to retrieve cloud optical thickness (COT) and cloud liquid water path (CLWP) for semitransparent and opaque clouds. The procedure followed in conducting this study is described in Section 3. The results are presented in Section 4. The paper concludes with remarks on the accuracy of daily mean values of cloud optical thickness and cloud liquid water path retrievals from narrow band radiances of meteorological satellites.

2. METHODS

Radiative transfer calculations

The Doubling Adding KNMI (DAK) radiative transfer model is used to simulate cloud reflectivities for clouds with given optical thickness and particle size at the selected wavelengths. DAK is based on the doubling-adding method (Van der Hulst, 1980, Stammes, 1994) and solves the radiative transfer problem for solar radiation in the Earth's atmosphere monochromatically. DAK takes multiple scattering and polarisation into account, but thermal emission is not considered. The atmosphere is assumed to be plane-parallel and clouds are assumed homogeneous and plane parallel. DAK does not take 3D cloud effects, multilayer cloud effects and the presence of aerosols into account.

Retrieval of cloud physical properties

In the CM-SAF the cloud optical thickness (τ) and the droplet effective radius (r_e) are retrieved by combining reflected radiances at 0.6 and 1.6 micron, using the method of Watts et al. 1998 and Jolivet et al. 2000. The optical thickness is retrieved from the reflection of clouds at a non-absorbing wavelength in the visible region (0.6 micron), which is strongly related to optical thickness and has very little dependence on the effective radius. For high optical thicknesses ($\tau_{vis} > 10$) the reflectance at an absorbing wavelength (1.6 micron) is mainly a function of particle size, whereas for thin clouds ($\tau_{vis} <10$) it is mainly a function optical thickness. The cloud liquid water path (CLWP) is calculated form the cloud optical thickness and the droplet effective radius (Stephens, 1978):

$$CLWP = \frac{2}{3}.\tau_{vis}.r_e.\rho_l \tag{1}$$

Where ρ_l is the density of liquid water. r_e is the droplet effective radius of water particles, which is an adequate parameter to represent the size distribution of water particles and their radiative properties (Hansen and Hovenier, 1974). The effective radius retrieved from satellite data is based on reflectivity of the cloud top, hereinafter denoted as $r_{e(1.6\ \mu m)}$. There is a correlation between $r_{e(1.6\ \mu m)}$ and r_e , but it needs further study to define the relationship and variance between r_e and the retrieved $r_{e(1.6\ \mu m)}$.

Cloud measurement campaigns
CLIWANET was an EU funded project that focused on ground observations of cloud physical parameters i.e.: cloud droplet profiles of water clouds, cloud particle profiles, particle velocity for ice clouds measured with lidar and radar (Donovan, 2000), the cloud liquid water path and water vapour content (microwave radiometer), the sky or cloud base temperature (infrared radiometer) and vertical profiles of air temperature and pressure (radiosonde data) (Crewell et al., 2003). The CLIWANET ground-based stations were equipped with a microwave radiometer, a ceilometer, and an infrared radiometer. For the CLIWANET Network Campaigns in August-September 2000 (CNN1) and in April-May 2001 (CNN2), the stations were distributed over 11 sites in the Baltex modelling area. During the Baltex Bridge Intensive Experimental Campaign in August-September 2001 (BBC) a large number of instruments were shipped to the meteorological tower at Cabauw, the Netherlands (51.9N, 4.9E). The total measurement set-up included: several radar, lidar and microwave radiometer systems, an extended set of radiation instruments, three aircrafts and two tethered balloons.

In May 2003 the KNMI and the University of Bonn organised, as a follow up of CLIWANET, the second intensive (cloud) measurement campaign "BBC2" that was held at Cabauw, the Netherlands. Beside these two organizing research groups, more than 100 scientists from 20 institutes participated. Most of the objectives and many of the participants are the same as those of the first BBC campaign. Focus of BBC2 was on clouds and radiation, but other subjects of research were also included, such as turbulence in the atmospheric boundary layer and small-scale structures of rainfall. BBC2 provided the first set of ground measurements that can be applied for validation of Meteosat-8 retrieved cloud physical products.

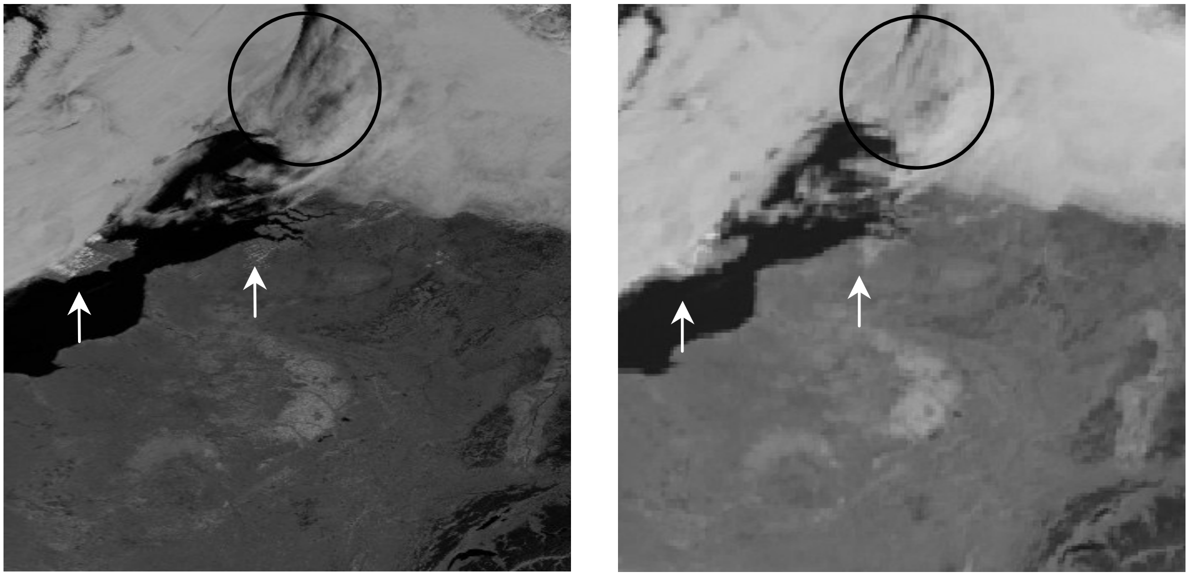
3. STUDY PROCEDURE

NOAA-17 and Meteosat-8 reflectances at 0.6 and 1.6 micron were compared to calibrate the Meteosat-8 reflectances. For both satellites we used the pre-launch calibration coefficients. The reflectances were normalised for the solar zenith angle, but not corrected for bi-directional reflectance effects. For 28 March 2004, 10:00 UTC a scene over Northern Europe covering the Netherlands, Germany and France, was selected for the calibration study. The NOAA-17 and Meteosat-8 images were re-projected to a stereographic projection and re-sampled to a similar spatial resolution.

In the CM-SAF cloud optical thickness and cloud liquid water path retrievals of NOAA-16 and NOAA-17 have been validated with ground-based measurements of the CLIWANET and BBC2 campaigns. For 19 April 2004, 10:00 UTC NOAA-17 and Meteosat-8 retrievals were compared. Both retrievals were done with the cloud physical product algorithm of the CM-SAF, using DAK look up tables. The COT and CLWP images were re-projected to a Mercator projection with a similar spatial resolution. Scatter plots of NOAA-17 and Meteosat-8 retrievals of COT and CLWP were analysed to assess the accuracy of Meteosat-8 retrievals. To demonstrate the potential of Meteosat-8 to generate daily cloud physical products a time series of CLWP and COT was analysed for Cabauw, The Netherlands during 19 April 2004, using all observations between 8 and 16 UTC.

4. RESULTS

Comparison of 0.6 and 1.6 micron normalized reflectances
Figure 1 shows NOAA-17 and Meteosat-8 1.6 micron images of the area that was used for the calibration study. The selected area comprises the typical scene types that can be observed over Europe, i.e. land, mountains and sea surfaces and both water and ice clouds. The difference in spatial resolution between NOAA-17 (1x1 km at nadir) and Meteosat-8 (3x3 km at nadir) can be seen clearly from the images. Typical features, such as the lake of Geneva, can be recognised on both images. On the other hand the broken clouds fields on the NOAA-17 image over Southeast UK and Northwest Belgium (see arrows) appear on the Meteosat-8 image as homogeneous cloud fields. Further, the contrast between semitransparent and opaque clouds is higher for NOAA-17 than for Meteosat-8. This can be observed for the semitransparent cloud field over the North Sea, which is indicated by the circles. Meteosat-8 has a low spatial resolution (3x6km) and a large viewing zenith angle of 60 degrees over Northern Europe, which explains the difference with NOAA-17 image. Finally, the higher brightness of Meteosat-8 indicates higher Meteosat-8 radiances than NOAA-17 radiances at 1.6 micron.



(A) (B)

Fig. 1. NOAA (A) and Meteosat-8 (B) 1.6 micron normalized reflectivities over Northern Europe for 28 March 2004 at 10.00 UTC.

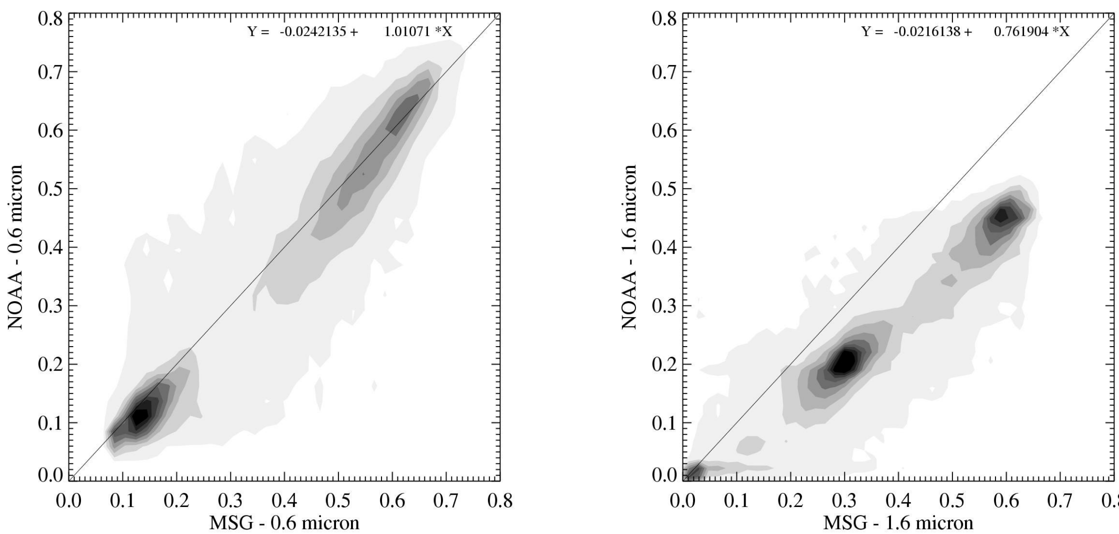
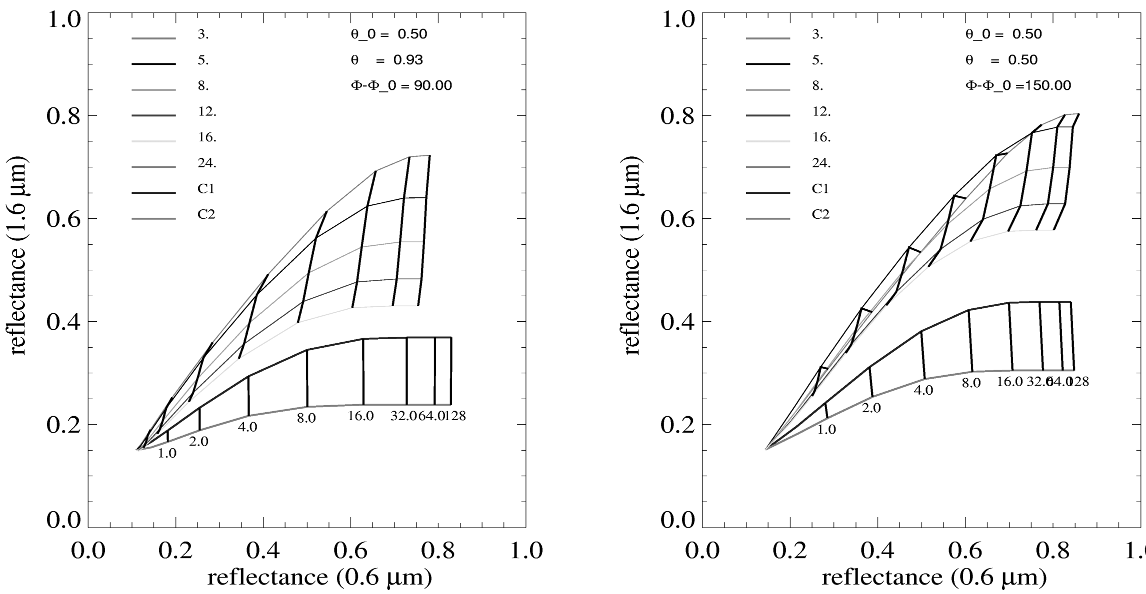


Fig. 2. Scatter plots of Meteosat-8 and NOAA-17 normalized reflectivities for 0.6 micron (A) and 1.6 micron (B). In the upper left corner the linear regression equations are given.

Figure 2 presents scatter plots of NOAA-17 and Meteosat-8 reflectivities for the 0.6 micron channel (A) and the 1.6 micron channel (B). For both channels the correlation between NOAA-17 and Meteosat-8 normalised radiances is high, with correlation coefficients of 0.95 and 0.96 respectively and offsets of the regression equations close to zero. The gain of the regression equation for the 0.6 micron channel is close to 1. Considering differences in spatial resolution, viewing conditions and time of overpass the NOAA-17 and Meteosat-8 the differences at 0.6 micron are within the uncertainty boundaries. However, for the 1.6 micron channel the gain is 0.76, which indicates that Meteosat-8 reflectances are approximately 30% higher than NOAA-17 relflectances. The observed differences may be explained by the Meteosat–8 calibration of the 1.6 micron channel. However, the report of Govaerts and Clerici, 2004 demonstrates that the vicarious calibration of the Meteosat-8 channels is stable and shows minor drift. The difference may also result from errors in the receiving or post-processing system. Further it should be realized that reflectances are not corrected for bi-directional effects. For the viewing geometries of NOAA-17 and Meteosat-8 bi-directional effects play a significant role. Figure 3 presents, for the viewing conditions of 28 March 2004 at 10.00 UTC, diagrams of simulated NOAA-17 and Meteosat-8 reflectances for water and ice clouds with various optical thicknesses and effective radii. These diagrams demonstrate clearly that for cloudy scenes Meteosat-8 reflectivities can be 40% higher than NOAA-17 reflectivities at 1.6 micron. However, for clear scenes (tau=0) the difference is almost zero. Moreover, the reflectances at 0.6 micron should be higher for Meteosat-8 as well, which is not reflected in Figure 2(A). Since there is no consolidate explanation for the observed differences yet, it was decided to use the pre-launch calibration coefficients provided by EUMETSAT.



(A) (B)

Fig. 3. DAK simulated reflectances at 0.6 and 1.6 micron for water and ice cloud with a different optical thickness and effective radius. The viewing geometries correspond with Northern Europe for 28 March 2004 at 10.00 UTC for NOAA-17 (A) and Meteosat-8 (B).

Comparison of cloud physical product retrievals

Figure 4 shows for The Netherlands and Germany NOAA-17 and Meteosat-8 cloud liquid water path retrievals for 19 April at 10:00 UTC. Visual inspection reveals a high similarity between NOAA-17 and Meteosat-8 retrievals. The structures of the cloud free areas, depicted as pixels with an optical depth equal to zero, are similar. The extended fields of thin clouds over The Netherlands and Germany have CLWP values below 200 $g.m^{-2}$ and are similar in terms of structures and magnitude of CLWP. For thick clouds the CLWP retrievals of Meteosat-8 tend to be higher than for NOAA-17. This is most evident for the thick clouds over Denmark, where NOAA-17 CLWP values vary between 300 and 700 $g.m^{-2}$ and Meteosat-8 CLWP values vary between 400 and 1000 $g.m^{-2}$.

Figure 5 presents scatter plots of NOAA-17 and Meteosat-8 cloud optical thickness (left) and cloud liquid water path (right) for 19 April 2004 at 10.00 UTC. This figure confirms that NOAA-17 and Meteosat-8 cloud products are correlated reasonably, with correlation coefficients of about 0.73. The gain of the regression equations is about 0.5, which indicates that Meteosat-8 retrieved cloud properties are larger than NOAA-17 retrieved cloud properties. This phenomenon occurs in particular for higher values of COT and CLWP. At higher latitudes (Northern Europe) the viewing conditions of Meteosat-8 are not favourable for the retrieval of cloud properties. Around noon the retrievals are very sensitive to errors because the sun and the satellite are in the same plane, with an azimuth difference angle of about 180 degrees. This is can be observed from Figure 3, which shows that for thick clouds (tau>16) the simulated reflectivities for Meteosat-8 vary less with optical depth and effective radius than for NOAA-17. Meteosat-8 viewing conditions are worse in winter because both the satellite and sun viewing angles are low. Considering collocation errors, differences in spatial resolution and viewing conditions the relationship between NOAA-17 and Meteosat-8 can be regarded satisfactory.

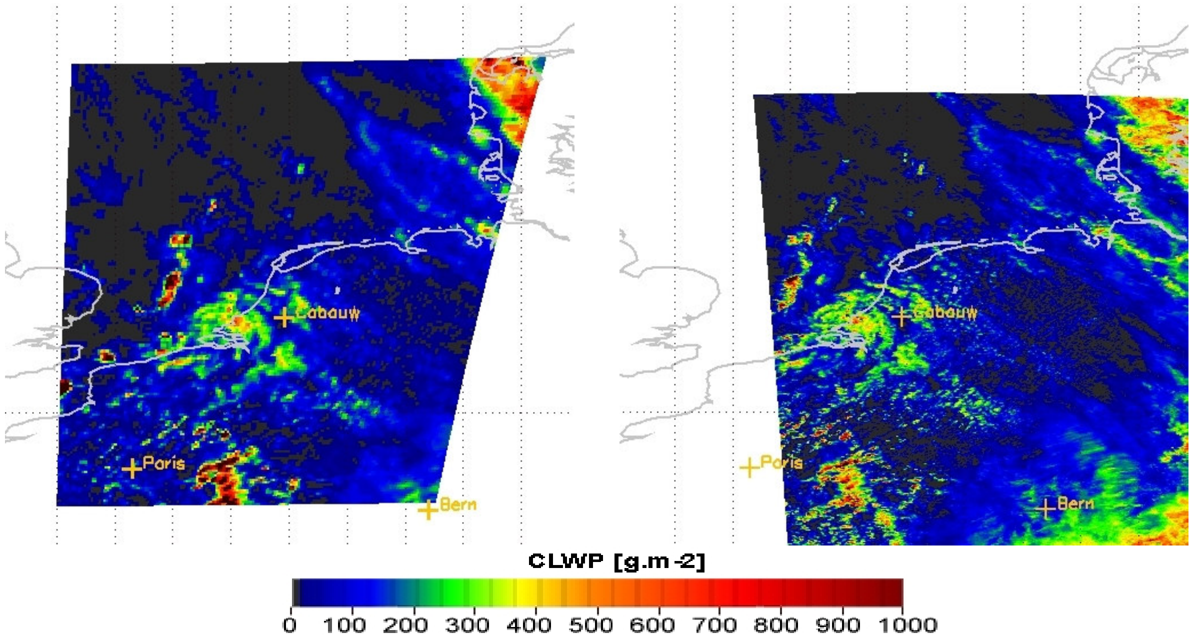


Fig. 4. Meteosat-8 (left) and NOAA-17 (right) retrieved cloud liquid water path for 19 April 2004 at 10.00 UTC.

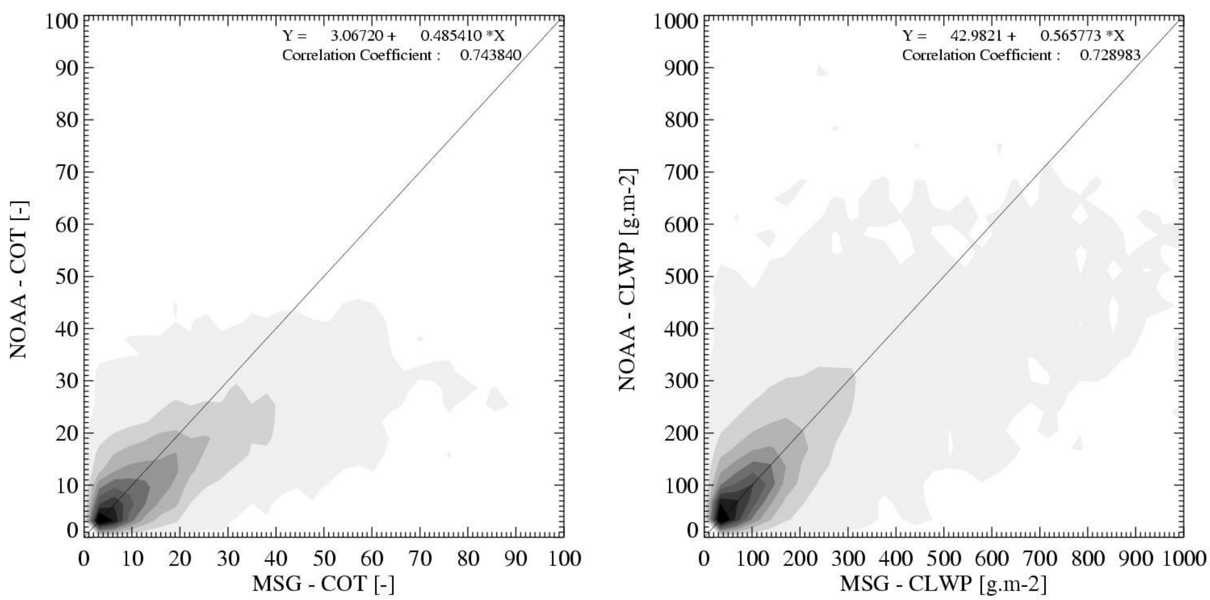


Fig. 5. Scatter plots of Meteosat-8 and NOAA-17 Cloud Optical Thickness (left) and Cloud Liquid Water Path (right) for 19 April 2004 at 10.00 UTC.

Time series of COT and CLWP retrievals for Cabauw

Since May 2003 NOAA operates its 1.6 micron channel only onboard NOAA-17, which has about 2 overpasses over Northern Europe daily. To calculate daily means of cloud properties two NOAA-17 overpasses is few compared to 48 Meteosat-8 observations. Figure 6 illustrates for Cabauw, The Netherlands the dynamics in Meteosat-8 derived COT and CLWP during 19 April 2004. The NOAA-17 overpass at 10:00 UTC is marked with an arrow. The time series show realistic variations in cloud properties during the day. This was confirmed by visual inspection of Meteosat-8 COT retrievals and radar observations in Cabauw, which corresponded well. At 10:00 UTC a field of thin water clouds covered Cabauw. The mean liquid water paths of the NOAA-17 and Meteosat-8 retrievals were 22 $g.m^{-2}$ and 15 $g.m^{-2}$, respectively. For Meteosat-8 the mean daily value was 73 $g.m^{-2}$. The Meteosat-8 standard deviation of 78 $g.m^{-2}$ demonstrates that the liquid water path varied strongly during 19 April 2004, and the instantaneous value may not be representative. Further research on the accuracy of cloud physical products over the day is needed to conclude if the observed variations are realistic.

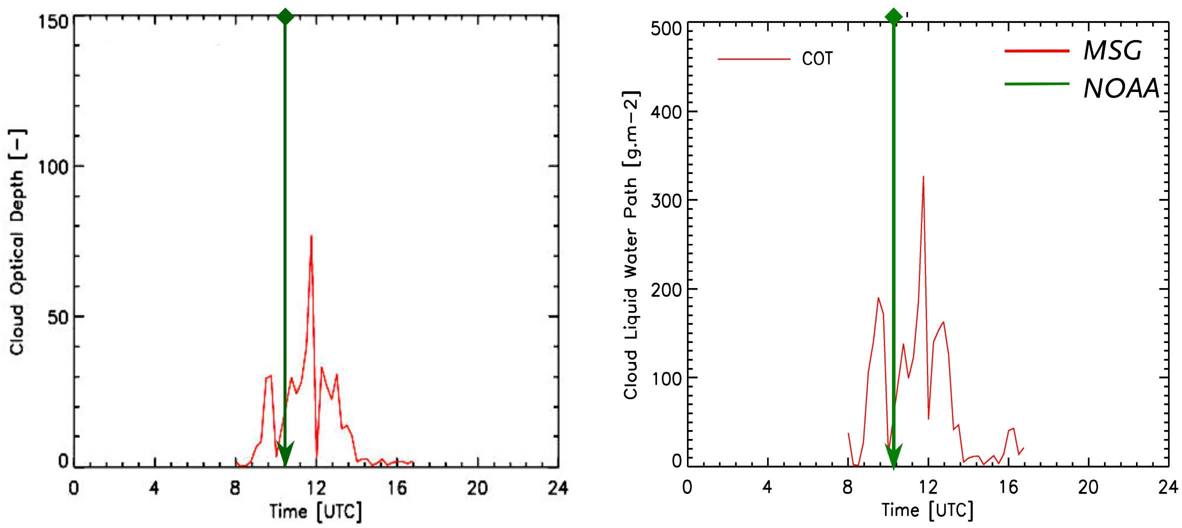


Fig. 6. Time series of Meteosat-8 cloud optical depth and cloud liquid water path for 19 April 2004. The arrow indicates the overpass time of NOAA-17 (10:06 UTC).

5. DISCUSSION AND CONCLUSIONS

Calibration of Meteosat-8 reflectances showed for the 0.6 channel high correlations with NOAA-17 reflectances. For the 1.6 micron channel there is a gain of 30% on the Meteosat-8 reflectances. Bi-directional effects may explain part of these differences. However, the differences are much smaller at 0.6 micron. Therefore it is not likely that bi-directional effects explain the differences entirely. Further investigations are needed to pin down the major cause of these differences.

From the cloud physical product comparison study emerged that Meteosat-8 retrievals are sensitive to specific viewing geometries for Europe. Firstly, Meteosat-8 observes with a high satellite zenith angle. Secondly, for a substantial number of observations and locations the satellite and the sun have identical azimuth angles. For this unique condition a high peak in the backscatter direction dominates the observed reflectivity of water clouds. Despite the geometry disadvantages the strength of Meteosat-8 is its high sampling frequency. Time series analysis demonstrated that sufficient observations are needed to derive daily statistics on cloud physical properties, a requirement that can only be met by geo-stationary satellites and not by polar orbiters.

6. ACKNOWLEDGEMENT

This work was part of the EUMETSAT funded Climate Monitoring Satellite Application Facility (CM-SAF) project.

7. REFERENCES

Cess, R.D., G. L. Potter, J. P. Blanchet, G. J. Boer, A. D. Del Genio, M. Deque, V. Dymnikov, V. Galin, W. L. Gates, S. J. Ghan, J. T. Kiehl, A. A. Lacis, H. Le Treut, Z. X. Li, Z. Liang, B. J. Mc Aveney, V. P. Meleshko and J. F. B. Mitchell, 1990: Interpretation of climate feedback processes in 19 atmospheric general circulation models. J. Geophysic. Res., 95, 16601-16615.

Crewell, S. et al., 2004, The BALTEX BRIDGE Campaign (BBC) - An integrated approach for a better understanding of clouds, Bull. Am. Meteo. Soc. (accepted).

Crewell, S., C. Simmer, A. Feijt and E. van Meijgaard, 2003, CLIWA-NET the BALTEX BRIDGE Cloud Liquid Water Network, BALTEX Secretariat Publications #26, Geesthacht

Feijt, A.J., D. Jolivet, R. Koelemeijer, R. Dlhopolsky and H. Deneke, 2003, Recent improvements to LWP retrievals from AVHRR, Atmos. Res. (accepted)

Govaerts Y. and Clerici M., 2004, MSG-1/SEVERI Solar Channels Calibration Commisioning Activity Report, EUM/MSG/TEN/04/0024

Han Q, Rossow W.B., Lasis A.A., “Near-Global Survey of Effective Droplet Radii in Liquid Water Clouds Using ISCCP Data,” J. of Clim. 7, 465-497 (1994).

Hansen, J. E. and J. W. Hovenier, 1974: Interpretation of the polarization of Venus. J. Atmos. Sci., 31, 1137-1160.

Hulst, H.C., 1980, "Multiple light scattering", Vols. 1 and 2, Acad. Press, New York,
Jolivet D., Feijt A., Watts P., 2000: Requirements for synergetic use of the ERM imager, ESA Contract RFQ/3-9439/98/NL/GD.

King D., and Tsay S.-C., 1997, “Cloud retrieval algorithms for MODIS: Optical thickness, effective radius, and thermodynamic phase,”

Knap, W.H., Hess, M., Stammes, P., Koelemeijer, R.B.A., and Watts, P.D., 1999: Cirrus optical thickness and crystal size retrieval from ATSR-2 data using phase functions of imperfect hexagonal ice crystals, J. Geophys. Res., 104, 31,721-31,730.

Nakajima T., King M.D., 1990: Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part 1: Theory, J. of Atmosph. Sciences. 47, 1878-1893.

Nakajima T. Y. and Nakajima T., 1995: Determination of Cloud Microphysical Properties from NOAA NOAA-17 Measurements for FIRE and ASTEX regions., J. of Atmosph. Sciences, 52, 4043 -4059.

Roebeling R.A., D. Jolivet, A. Feijt, 2001, Cloud optical thickness and cloud liquid water path retieval from multi-spectral noaa-NOAA-17 data, Proc. The 2001 EUMETSAT Meteorological Satellite Data User's Conference, Antalya, Turkey, 2001, 629-637.

Science plan, 2000, SAF/CM/DWD/SCI3.0

Stammes, P., 1994: Errors in UV reflectivity and albedo calculations due to neglecting polarization, SPIE 2311, 227-235.

Stephens G. L., G. W. Paltridge and C. M. R. Platt, 1978: Radiation profiles in extended water clouds. III. Observations. J. Atmos. Sci, 35, 2133-2141.

Watts P.D., 1996, Estimation of cloud droplet size, cloud optical depth and phase from ATSR. IRS'96 Current problems in atmospheric radiation. Deepak. 578-582.

Watts P.D., Mutlow C.T., Baran A.J., and Zavody A.M., 1998, “Study on Cloud Properties derived from Meteosat Second Generation Observations,” Final Report, EUMETSAT ITT no. 97/181.