ABSTRACT

Geostationary sensors bear the potential to derive and analyze daily and seasonal trends of aerosol optical depth (AOD) from spatially homogeneous data. However, to date most AOD retrieval algorithms from geostationary sensors are limited to sea surfaces. In this study, a multi-temporal technique to retrieve AOD over land from the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) on-board the geostationary Meteosat-8 satellite is presented. The proposed method takes advantage of SEVIRI's high temporal resolution of 15 minutes and improved spatial and spectral resolution in comparison to its predecessors Meteosat-1 to 7.

The crucial issue is the decomposition of the measured signal into its surface and atmospheric contributing parts. Assumed that surface characteristics remain constant during a certain time period, changes in observed reflectance can be assigned to varying atmospheric constituents and varying sun zenith and azimuth angles. Surface reflectance is estimated by the determination of the lowest reflectance within the observed time period for each satellite observation time of the day. Since clouds seriously affect the retrieval of AOD, clouds and cloud shadows are masked out and the data set is corrected for atmospheric gases prior to the AOD retrieval. Finally, AOD is calculated by means of the radiative transfer code SMAC.

The study area covers Switzerland and its neighboring areas (45.0N-48.5N, 5.0E-12.0E). SEVIRI data for the entire month of August, 2004, acquired daily between 6:12 and 17:12 UTC are used in order to test the method. In comparison to sun-photometer measurements from the Aerosol Robotic Network (AERONET), first results show promising AOD values.

1 INTRODUCTION

Aerosols influence the Earth's radiation budget significantly by reflecting, scattering, and absorbing electromagnetic radiation in the atmosphere and by modifying cloud properties due to their role as cloud condensation nuclei [1],[2]. The quantification of the aerosol effect on the climate system is a challenging and complex task in today's atmosphere and climate related science as aerosols highly vary in their chemical and physical characteristics as well as in their geographical and temporal atmospheric distribution. Further, information on aerosol loading also is of interest for the atmospheric correction of remote sensing data.

During the last decades, remote sensing has become a valuable complement to ground based measurements of aerosol parameters. Its capability of spatial homogeneous aerosol mapping advances the possibilities to locate aerosol sources and track their atmospheric dissemination by providing information in regions insufficiently covered by ground instrumentation. Current earth observing sensors provide operational aerosol maps over ocean and land (e.g. [3]) but most polar orbiting systems are limited to maximum cover a region once a day. Up-to-date geostationary instruments like the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) on-board Meteosat-8 offer considerable prospects to enhance the frequency of aerosol mapping due to their high temporal resolution.

Compared to water bodies, the remote sensing of aerosols over land is complicated by the higher variability and spatial heterogeneity of surface reflectance. For the inversion of aerosol optical depth (AOD), the precise approximation of surface reflectance is essential. SEVIRI's high temporal resolution moreover allows to account for the dependence of top of atmosphere reflectance (TOA) on the surface bidirectional reflectance (BRF).

The objective of this study is to demonstrate the capability of SEVIRI for sensing atmospheric aerosol properties. A single-channel, multi-temporal approach therefore is presented. Surface reflectance is estimated from the data itself and surface reflectance dependency on the sun-sensor geometry is considered. In contrary to multi-temporal approaches on data obtained from polar orbiting satellites the problem of finding an adequate length of a suitable time period is further
reduced as SEVIRI provides imagery on a frequency of 15 minutes. Thus, the probability of finding cloud-, cloud shadow-, and aerosol free observations in a rather short period increases significantly. Finally, this approach does not depend on the occurrence of specific surface types in the area of interest.

2 DATA BASIS

2.1 SEVIRI

SEVIRI measures reflected and emitted radiance in 11 spectral channels located between 0.6 µm and 14 µm and in a broadband high-resolution visible (HRV) channel. The solar channels suitable for the determination of atmospheric aerosol parameters are centered at 0.6 µm (0.56-0.71), 0.8 µm (0.74-0.88), and 1.6 µm (1.50-1.78), respectively and have a nominal spatial resolution of 3 kilometers at sub-satellite point as well as a temporal sampling rate of 15 minutes. SEVIRI represents a significant technical advancement to Meteosat-1 to 7 (3 spectral channels, 5 km spatial resolution at nadir, 30 minutes repetition rate). Further, operational since January 2004, the Meteosat Second Generation (MSG) program ensures the continuity of the European geostationary meteorological satellite service until around 2018 [4].

Level1.5 geo-located and calibrated top of atmosphere reflectance (TOA) data from Meteosat-8's SEVIRI sensor acquired daily between 6:12 and 17:12 UTC for the month of August, 2004 is utilized to test the proposed method. A summer month is chosen for a first implementation since the atmospheric aerosol concentration is expected to be higher, daytime is longer, and the probability of cloud and snow contamination of the data set smaller then for the other seasons. The study area is limited to Switzerland and neighboring regions (45.0N-48.5N, 5.0E-12.0E).

2.2 AERONET

The Aerosol Robotic Network (AERONET) is a global aerosol monitoring network of ground based sun photometer measurements. Cloud screened and quality-assured level 2.0 data is used to validate retrieved AODs. The accuracy of level 2.0 data is expected to be around 0.02 [5]. Level 2.0 AODs are interpolated to the reference wavelength at 0.55 µm [6]. Two AERONET stations are situated within the study area, Ispra (45.8N, 8.6E) in northern Italy and Laegeren (47.5N, 8.4E) near Zurich, Switzerland. Both are located in a rural environment and at an altitude of 235 and 735 m.a.s.l., respectively.

2.3 Meteorological Auxiliary Data

Meteorological auxiliary data from the Swiss Federal Office of Meteorology and Climatology's Alpine Model (aLMo) and from the National Center for Environmental Prediction (NCEP) are used to obtain additional information about the state of the atmosphere during image acquisition. Total column ozone data on a 1x1 degree grid (NCEP) as well as vertically integrated water vapor and sea level pressure with a horizontal grid size of 7 kilometers (aLMo) are available for each day at 12:00 UTC.

3 AOD RETRIEVAL METHOD

The sensible step to determine aerosol information from remotely sensed data is the decomposition of TOA reflectance into its surface and atmospheric scattering parts. Many natural surfaces show small reflectance values (e.g. water, vegetation) in the visible wavelength range. Hence, the aerosol backscattering leads to a brightening of measured TOA reflectance over such surfaces. Taking advantage of this fact, comparing TOA reflectance of a time series and assuming that there is at least one observation under 'aerosol-free' condition which serves as the surface reflectance estimate, enables the inversion of aerosol information. It is emphasized that an underestimation of the surface reflectance will lead to higher AOD values and vice versa. The length of the period is determined by obtaining sufficient cloud- and aerosol-free observations in a time range where no or minimum variations of surface reflectance is expected to appear.

The presented approach is based on the analysis of multi-temporal 0.6 µm channel SEVIRI images similar to a method applied on Geostationary Observational Environmental Satellite (GOES) data [7]. Primarily, the data set is prepared by correcting TOA reflectance for gaseous absorption, Rayleigh scattering, and a background aerosol extinction (assumed AOD of 0.05) as well as by removing cloud and cloud shadow contaminated pixels after [8] and [9], respectively. A continental aerosol is the model of choice based on the geographical study area [10]. The assumption of a standard atmospheric model is avoided by using meteorological data and the 6S [11] based Simplified Method for Atmospheric Correction (SMAC) [12] radiative transfer code is used herein for all radiative transfer calculations. Subsequently, a background composite consisting of the darkest pixels at individual locations for each daily observation time is created. As the data set already is fully atmospherically corrected for a background aerosol amount, the background composite represents estimated surface reflectance as a function of solar geometry at observation time. Sun angle dependent
Fig. 1. SEVIRI 0.66 µm channel raw and averaged estimated surface reflectance for the pixels located at the AERONET sites of Laegeren (left) and Ispra (right) as a function of daytime. Also shown is the top of atmosphere reflectance for August 1, 2004. Surface reflectance as well as the TOA reflectance graph for August 1 are plotted in Fig. 1 for the pixels located at the AERONET sites. A boxcar average with a width of 5 is applied on the background curve to compensate for minor inaccuracies (undetected cloud shadows, over- or under-correction). The trend of the background curve reproduces sub-pixel illumination dependent reflection characteristics as well as increasing intra-pixel cloud shadowing with higher sun zenith angles, which e.g. decreases surface reflectance during morning and evening hours. Finally, AOD at 0.55 µm is computed for every cloud- and cloud shadow free pixel of the August 2004 test data set, using meteorological data and SMAC.

4 RESULTS

The analysis and validation of SEVIRI retrieved AODs is based on comparisons to AERONET, considering exclusively measurements from either source within a maximum time delay of +/- 15 minutes. Fig. 2a shows the daily aerosol trend at Laegeren and Ispra for August 1, 2004. The curves at Ispra correspond almost congruently during the entire day whereas those at Laegeren diverge apparently in the afternoon around 15:00 UTC. An underestimation of surface reflectance cannot explain this deviation itself as the guessed surface reflectance curve is expectable smooth (Fig. 1) and would consequently lead to a general, not short-term AOD offset. In contrast, sub-pixel clouds or not detected thin clouds are temporary phenomena which inherently alter retrieved AODs.

The scatter plots displayed in Fig. 2b include the total of obtained values in August, 2004. Generally, an offset different to zero indicates an over- or underestimation of the surface reflectance and a gain different to one points to errors associated with the selection of the aerosol model. Thus, the offset of 0.05 for Ispra indicates a more precise estimate of the surface reflectance at Ispra than at Laegeren, but surface reflectance at either stations are slightly underestimated. A coefficient of determination of 0.39 for Laegeren and 0.79 for Ispra is achieved in this comparison with standard deviations of 0.08 for both stations. The slope of the regression line points to reasonable assumptions about the aerosol model used in this study, especially for the Ispra situation. The difference of correlation arises to a big part from the higher occurrence of clouds at Laegeren and for this reason higher probability of cloud misclassification during the test period, but might be also explained by the better fit of the aerosol model at Ispra. Note, that 265 values (19% of the total of 1395 observations) at Laegeren and 448 (32%) at Ispra are derived.

Fig. 2c shows the monthly trend of daily mean AODs for corresponding values. The daily average presupposes a minimum of three collective values per day. Again, close coincidence between the two graphs is achieved but SEVIRI daily mean AODs are throughout higher than the AERONET measurements, underlining the above mentioned generally underestimated surface reflectance. Although high differences of up to 0.25 (Ispra, August 25) occur sporadically, correlation is high at both stations. A coefficient of determination of 0.89 results for the Ispra site, 0.75 for the Laegeren site with standard deviations of 0.06 for both cases. Finally, an aerosol map for the month of August, 2004 is created by averaging the daily mean AODs of all pixels without any spatial interpolation. Fig. 3 illustrates the potential for using SEVIRI data for aerosol climatology. Similar products are operationally generated by e.g. the Moderate Resolution Imaging Spectroradiometer (MODIS)[3]. Altitude dependency of atmospheric aerosol concentrations can clearly be
Fig.2.a): Daily trend of derived and AERONET measured AODs at Laegern (left) and Ispra for August 1, 2004. b): Scatter plot of the total of retrieved AODs intersecting with AERONET measurements within a time delay of +/- 15 minutes. c): Monthly trend of daily averaged AODs from SEVIRI and AERONET.
Fig. 3. AOD map over Switzerland for August, 2004. The shown values represent averaged daily mean AODs. No valid values could have been retrieved for the black colored areas.

observed over the Alps, Vosges mountains, and southern Germany's Black Forest. Retrieved AODs do not seem to mirror larger water bodies like Lake Geneva, Lake Maggiore or Lake Constance, an indication of the independence of this method on surface types. Also, overall higher aerosol concentration can be observed over northern Italy representing the occurrence of higher concentration of industry and traffic. On the other hand, some larger gaps are present in high alpine regions. The main reason can be assigned to annual snow fields and glaciers. These surfaces are not only too bright to detect an aerosol signal but also tend to be misclassified in cloud masking algorithms. Since cloud shadow masking significantly relies on precise cloud masks, regions surrounding brighter high alpine snow- and glacier pixels are constantly and wrongly eliminated from the aerosol processing.

5 DISCUSSION AND CONCLUSION

A method for the retrieval of AOD from Meteosat-8's SEVIRI sensor has been presented, applied on a test data set, and validated with AERONET measurements as ground truth. It has been shown that SEVIRI's 0.6 µm channel is sensible to an aerosol signal and its variability. SEVIRI inversed AODs correlate with AERONET measurements on three different levels. The variability of daily AODs from SEVIRI show analog forms to the AERONET trends. Exceptions can be assigned to undetected clouds or sub-pixel clouds. Scatter plots including the entire data set of August, 2004 further suggested the ability of this method to retrieve AODs from SEVIRI data. Correlation increases if daily mean values of intersecting SEVIRI and AERONET are compared (Laegeren: 0.39 to 0.75, Ispra 0.79 to 0.89). Finally, the averaged aerosol map reflected reasonable geographical AOD distribution over Switzerland and neighboring areas showing no apparent connection of AODs to surface types.

The analysis indicates that SEVIRI derived AODs inaccuracies arise from different causes. A major source is the short-term occurrence of sub-pixel clouds, especially during convective weather situations or at the edge of clouds. This problem accentuates due to the low spatial resolution of SEVIRI. The quality of cloud masking also is essential due to its influence on the cloud shadow mask quality. It further eventually excludes valid pixels from the background composite creation step, although the general underestimation of surface reflectance rather supports the first thought. The differences of the coefficients of determination between the Laegeren and the Ispra results can to a major part be assigned to improper cloud masking and the assumption of the aerosol model which seemed to fit better to the Ispra case. Inaccuracies in estimated surface reflectance is also introduced by the calibration uncertainty of approximately 5% for the 0.6 µm channel [4] but [13] pointed out that this effect is reduced if extracting surface reflectance from the data itself. Further sources of errors incorporate the assumption of stable surface characteristics, the assumed background aerosol amount, the assumed aerosol model, inaccurate or missing meteorological data (water vapor and ozone absorption), radiative transfer calculations, topographic shadows, or the sensor-AERONET-sun geometry.

Altogether, the potential of SEVIRI for the remote sensing of atmospheric aerosols has been shown. The importance of
precise cloud, cloud shadow, and sub-pixel cloud masking has been outlined. Further advancements in cloud masking may lead to an improvement of the described method especially in rugged terrain. Future work will also have to include an expansion of the study region, incorporation of additional AERONET stations and seasons, as well as extended quantification of the single error sources.

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