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Studies of Aerosols Advected to Coastal Areas with the Use of Remote Techniques

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Abstract

This paper presents the results of the studies of aerosol optical properties measured using lidars and sun photometers. We describe two case studies of the combined measurements made in two coastal zones in Crete in 2006 and in Rozewie on the Baltic Sea in 2009. The combination of lidar and sun photometer measurements provides comprehensive information on both the total aerosol optical thickness in the entire atmosphere as well as the vertical structure of aerosol optical properties. Combination of such information with air mass back-trajectories and data collected at stations located on the route of air masses provides complete picture of the aerosol variations in the study area both vertically and horizontally. We show that such combined studies are especially important in the coastal areas where depending on air mass advection directions and altitudes the influence of fine or coarse mode (in this case possibly sea-salt) particles on the vertical structure of aerosol optical properties is an important issue to consider.

Key words: AOT, remote sensing, air trajectory, AERONET, ACCENT.

1. INTRODUCTION

Aerosol properties in marine boundary layers over regional seas and coastal environments vary from those in open ocean regions. In coastal areas aerosols which are in the zone of direct interaction between the atmosphere and the ocean surface are characterized by fast temporal and spatial changes of aerosol concentrations (Smirnov *et al*. 2006, Gao *et al*. 2011). The spectrum of aerosol size distribution functions is complicated and strongly depends on weather conditions in the marine boundary layer, especially on wind speed, duration and direction as well as relative humidity. Additionally, it indirectly depends on the sources of aerosol generation and the air mass advection (Zhang *et al*. 1999, Vignati *et al*. 2001, Dubovik *et al*. 2002).

Coastal areas are also sources of marine aerosols, which can play an important role due to the fact that breaking waves occur in this area even at small wind speeds (Monahan and MacNiocall 1986, Resch *et al*. 1986, Blanchard and Syzdek 1988, Wu 1988, 1990, Zieliński and Piskozub 2005). Based on results of many research findings, models have appeared dealing with problems of dependence of marine aerosol generation, transport and deposition from the marine boundary layer on various physical parameters of the atmosphere (Fairall *et al*. 1983, Fitzgerald 1991, Gong *et al*. 1997). Especially well described is the dependence of concentration and size distribution of marine aerosols on wind speed over the ocean (Welton *et al*. 2002, Petelski and Piskozub 2006, Witek *et al*. 2007, Fantoni *et al*. 2010, Rajeev *et al*. 2010).

The appropriate correction of the atmospheric impact on the registered signal is an important problem in the remote sensing of the Earth's surface, and it is especially significant in coastal areas (Smirnov *et al*. 2002, Zieliński and Zieliński 2002). A thorough understanding and explanation of aerosol impact on light transmission in the atmosphere requires knowledge of aerosol optical properties (Markowicz *et al*. 2008). Optical properties of aerosol particles are important in calculations of the solar radiation that reaches the Earth's surface, and they force climatic changes in the areas where their concentrations are high, such as coastal regions (Badarinath *et al*. 2010, Giannakaki *et al*. 2010). In cases when aerosol concentrations in the atmosphere depend on advections of air masses from various regions, over land or sea, aerosol optical thickness becomes an important parameter (Smirnov *et al*. 2000). The knowledge of variations of this parameter facilitates the solution of problems with solar radiation transmission through the atmosphere as well as those concerned with climatology and remote sensing of the seas and oceans. The value of this parameter depends on aerosol concentration in the atmospheric column, particle size distribution function, aerosol optical properties and the source and history of air masses in the area of measurements.

This paper provides information on combined aerosol studies made with lidars and sun photometers in two different coastal areas, in Crete on the Mediterranean Sea and in Rozewie on the Baltic Sea coast. We concentrate on aerosol optical thickness measurements and its variations with aerosol advections into the study area.

2. CAMPAIGN OVERVIEW

The data presented in this paper were collected during two international campaigns, the Studies Of Aerosol Properties (SOAP) and the COastal Aerosol STudies (COAST). The ACCENT affiliated SOAP study took place

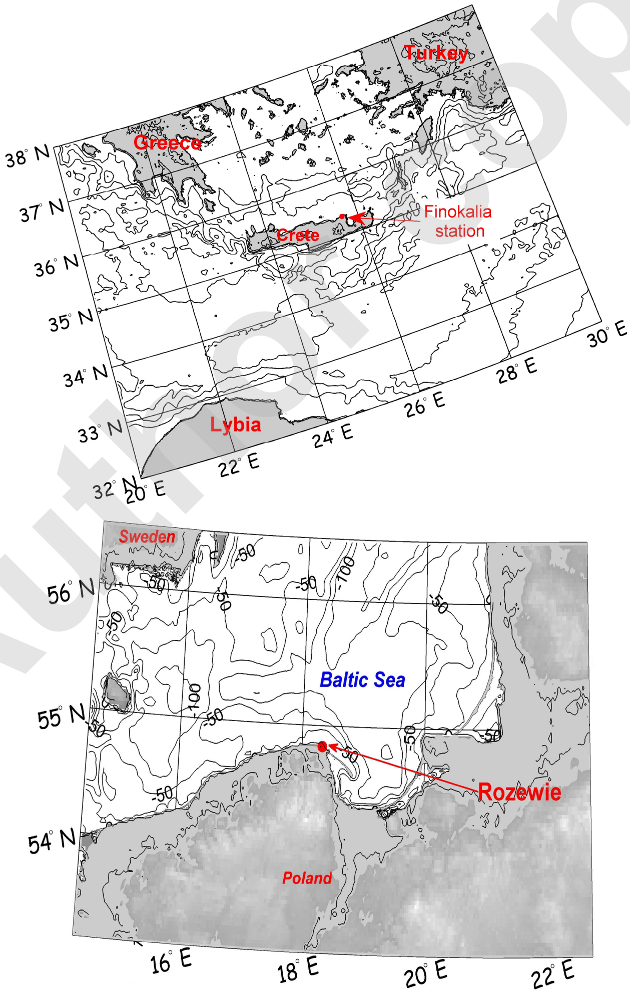

Fig. 1. Location of measurement stations in Crete (top) and Rozewie (bottom).

in Crete in July and August 2006. The measurement campaign started on 25 July using the lidar LB series provided by Raymetrics S.A. from Greece which was located at the Finokalia station (35°20′N, 25°40′E). The Raymetrics LB backscatter lidar system is an active laser remote sensing instrument that measures backscattering and with use of appropriate algorithms provides vertical profile of suspended aerosols. The lidar measurements were conducted until 5 August. The first Microtops sun photometer measurements were made on 28 July at Gouves (35°19′N, 25°17′E). There is a CIMEL CE-318 sun photometer operating at Gouves. The Microtops measurements at Gouves were continued until 2 August when the Microtops was placed at the Finokalia station. It was operated there until 7 August and then between 7 and 10 August in Gouves again.

The COAST 2009 experiment took place in Rozewie (54°49′N, 18°20′E) on the coast of the Baltic Sea. The ensemble of instruments included the LB series lidar and Microtops sun photometers among others. Additional sun photometer studies were made onboard r/v Oceania, which was anchored offshore from Rozewie. The location of the measurement stations is presented in Fig. 1.

3. INSTRUMENTATION

The LB series lidar is a backscatter lidar with one wavelength (532 nm) and one detection channel. The telescope diameter is 200 mm. This system can be used to determine vertical profile of aerosol optical parameters, the temporal evolution of aerosols, clear air layering in the troposphere, boundary layer mixing height, cloud base height, and cloud dynamic evolution. The vertical range of the system exceeds 12 km with a spatial resolution of 7.5 m with the useful part of the optical path, which starts at 200 m. The basic technical parameters are given in Table 1.

Measurements of Aerosol Optical Thickness (AOT) were performed with hand-held Microtops II sun photometers. These instruments facilitated investigations of AOT at different wavelengths and were used at all locations (Table 2).

Single measurement “shots” were acquired over about 1 min periods (in which measurements were made at all wavelengths, 10 s per channel: 340, 380, 440, 500, and 675 nm) every 20 min. Simultaneously the instruments measured total ozone column (at 305, 312, and 320 nm) and water vapor (at 940 and 1020 nm) in the entire atmosphere column. During the measurements the photographic documentation was made by using the wide-angle lens that was pointed on the solar target. The wide angle photos were used during further quality analyses (Ponczkowska *et al*. 2009).

Table 1

Basic technical parameters of the LB10 lidar system by Raymetrics S.A.

Pulsed laser source	ND: YAG, GRM, Q-switched, solid state laser
Emitted wavelength	532 nm
Pulse energy	70 mJ
Pulse duration	6-8 ns
Repetition rate	10-20 Hz
Angular beam divergence	<0.9 mrad
Spatial resolution	7.5 m
Optical emitter	
Beam expander	X3 with achromatic optical elements
Divergence	<0.3 mrad
Optical receiver	
Mirror diameter	200 mm, Cassegranian
Interference filter bandwidth	0.5 nm at 532 nm
Field of view	0.5-2 mrad

Table 2

Technical parameters of Microtops II sun photometers used during the studies

Optical channels	380 ± 0.4 nm, 4 nm FWHM 440 ± 1.5 nm, 10 nm FWHM 500 ± 1.5 nm, 10 nm FWHM 675 ± 1.5 nm, 10 nm FWHM 870 ± 1.5 nm, 10 nm FWHM
Resolution	0.01 W m^{-2}
Dynamic range	>300000
Viewing angle	2.5°
Precision	1-2%
Non linearity	max. 0.002%

Three hand-held spectral Microtops II sun photometers (http://www.solarlight.com/products/sunphoto.html, Morys *et al.* 2001) with visible wavelengths were used to retrieve aerosol optical thickness. The AOT was measured at 380, 440, 500, 675, and 870 nm. To minimize the potential sun pointing error, we performed 5 scans at each measurement session. Scans with the smallest standard deviation have been used in data processing. Cloud contamination was eliminated through visual inspection of sky conditions during measurements and the analysis of the images from the satellites.

The calibration factors were derived during different campaigns, such as the Maritime Aerosol, Clouds and Radiation Observation in Norway (MACRON) in 2007 (http://www.igf.fuw.edu.pl/meteo/stacja/macron.php) or POLAR-AOD (http://polaraod.isti.cnr.it:8080/Polar) intercomparison campaign in 2008 in Tenerife and factory constants stored in the instrument's internal memory. Two independent attempts during the MACRON experiment provided significantly lower values than the other data. These systematic differences may result from the weather conditions. During the MACRON campaign the AOT decreased rapidly before the sunset (Northern Norway) and/or some thin Cirrus clouds were reported close to sun disk over the study area. The results obtained one year later during the POLAR-AOD campaign on Tenerife differ very little from the factory constants. Since calibration factors obtained during the POLAR-AOD campaign differ very little from the factory values, providing long time stability of the instruments, we decided to use averages between the factory and POLAR-AOD values (Markowicz *et al.* 2011).

The CIMEL Electronique 318A sun photometer (www.cimel.fr) is a multi-channel, automatic sun-and-sky scanning radiometer that measures the direct solar irradiance and sky radiance at the Earth's surface. Measurements are taken at pre-determined discrete wavelengths in the visible and near-IR parts of the spectrum to determine atmospheric transmission and scattering properties. A sensor head fitted with 25 cm collimators is attached to a 40 cm robot base which systematically points the sensor head at the sun.

The CIMEL Electronique 318A in Crete is a part of the AERONET network (http://aeronet.gsfc.nasa.gov) and has been calibrated in accordance with the Project guidelines. In this work we present data from level 2.

4. RESULTS AND DISCUSSION

4.1 Experiment SOAP in Crete 2006

For analyses we selected 2 days of measurements during which we had cloud free conditions and the measurements lasted for 10 hours each time. The relative humidity patterns were the same on both days. To calculate the air mass back-trajectories we used the NOAA HYSPLIT model. On 29 July 2006 we had air masses reaching Crete from up north. At all altitudes the back-trajectories indicate the continental type of air (Fig. 2) modified over the Aegean Sea. This type of trajectories is typical for Crete in summer (Lelieveld *et al*. 2002).

The aerosol optical thickness measured with CIMEL and the Microtops II sun photometers at 5 wavelengths is presented in Fig. 3. The distance between both measurement stations was less than 500 m.

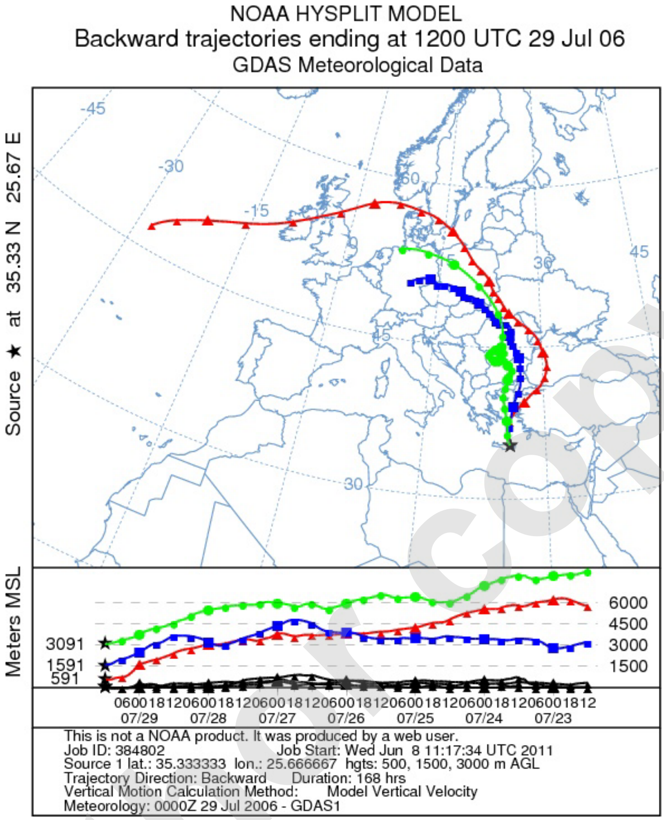

Fig. 2. Air mass back-trajectories obtained for the measurement area in Crete on 29 July 2006. Colour version of this figure is available in electronic edition only.

Both instruments were operated over the same period of time that day. Data presented in both graphs seem very consistent both in values and trends of changes during the day. In both cases it is visible that the AOT was higher until 06:00 UTC when it started decreasing until 10:00-11:00 UTC. Since then the values of the AOT kept increasing up to around 0.21 at 500 nm. The values obtained from CIMEL are slightly lower than those from the Microtops which may be related to different calibration constants used in both instruments. These values are typical for clean summer conditions in this area (Lelieveld *et al*. 2002).

The values of the Ångström exponent obtained for 29 July are significantly above 1 indicating the presence of smaller particles. This is supported by the aerosol fine, coarse mode and total AOT comparison (http://disc.sci.gsfc.nasa.gov/aerosols/services/mapss/mapssdoc.html#aeronet_sda). Fine mode particles are dominant in the air during this day (Fig. 4).

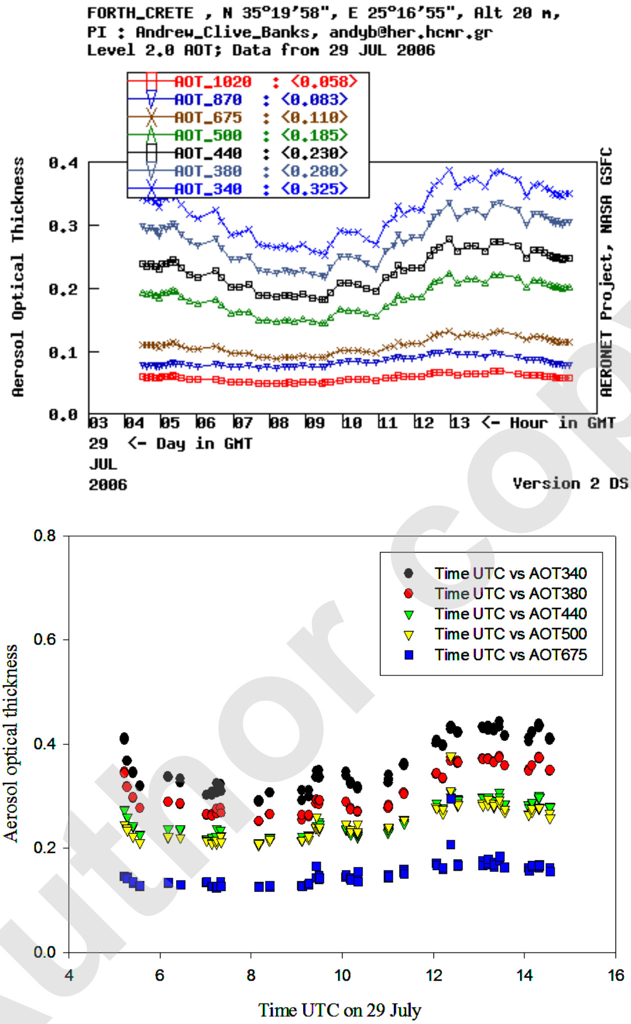

Fig. 3. Aerosol optical thickness measured with CIMEL (top) and Microtops II (bottom) sun photometers on 29 July 2006 in Crete. Colour version of this figure is available in electronic edition only.

In both figures it is evident that between 07:00 and 12:00 UTC there was a slight change in the type of aerosol particles present in the air over the measurement station. The Ångström exponent values dropped significantly and the coarse mode particles (potentially sea salt particles) were more present during this period of the day than earlier or later. The lidar measurements on 29 July show the advection of aerosol particles over the measurement region (Fig. 5). The back-trajectories show that 4 days before (25 July) the air

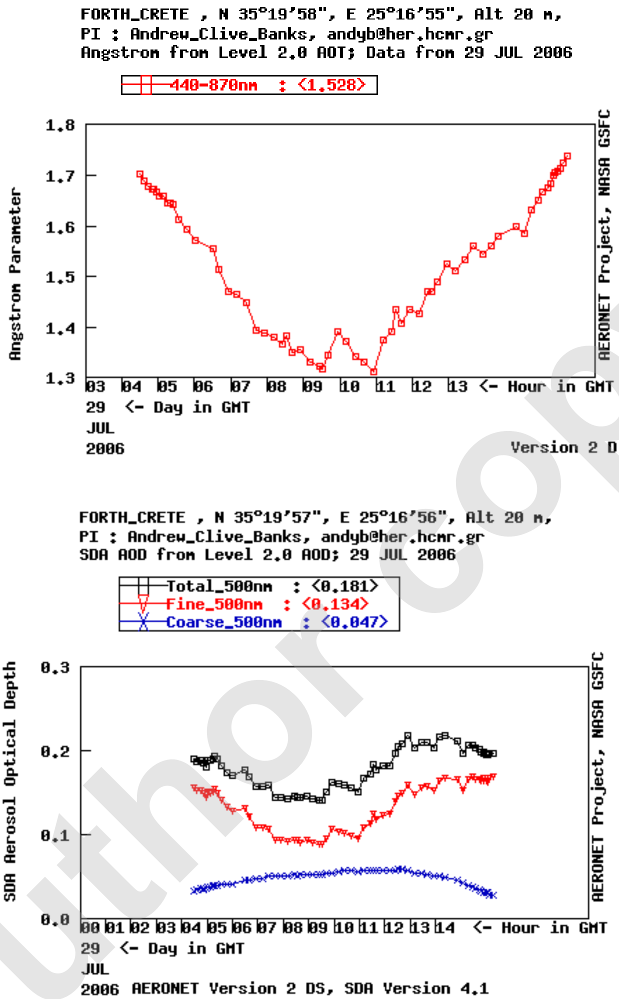

Fig. 4. Ångström exponent (top) and fine to coarse mode relation (bottom) on 29 July 2006 in Crete. Colour version of this figure is available in electronic edition only.

masses were over south-east part of Poland, over the collated SolarAOT station (49.86°N, 21.87°E, 443 m a.s.l.). The AOT measured there using the Microtops II was about 0.22 (at 500 nm) and the Ångström exponent was 1.5. These results, which are consistent with observations at the Finokalia station, show small aerosol emission or small air mass transformation between Central Europe and Crete.

In the first graph we can see enhanced backscatter which relates to an aerosol plume at around 2.0 km a.s.l. and above. The lidar signals are range

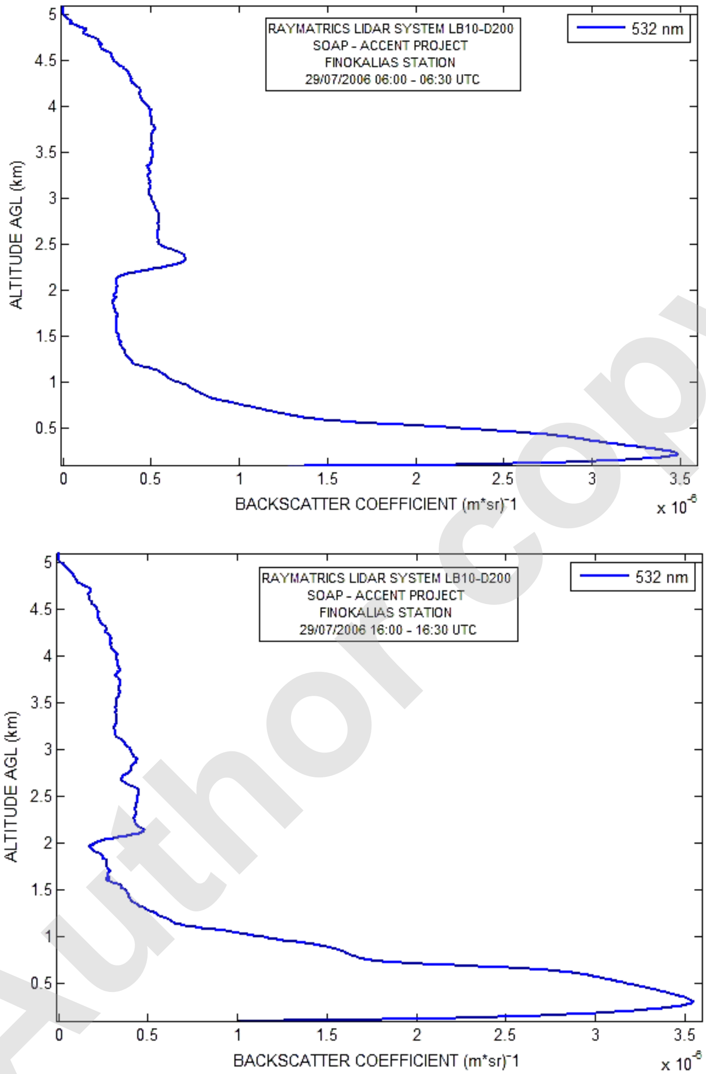

Fig. 5. Aerosol backscatter coefficient *versus* altitude measured with lidar on 29 July 2006 in Crete between 06:00 and 06:30 UTC (top) and 16:00-16:30 UTC (bottom).

corrected. This may be related to an increase of the coarse mode influence on the entire ensemble of aerosol particles in the area (Fig. 4). At around 16:00 UTC (Fig. 5 bottom) this layer is already developed and fine mode particles are dominating (Fig. 4). The averaged values of the AOT at 532 nm obtained from the lidar measurements were 0.207 between 11:00 and 11:30 UTC and 0.218 between 16:00 and 16:30 UTC, thus did not vary much.

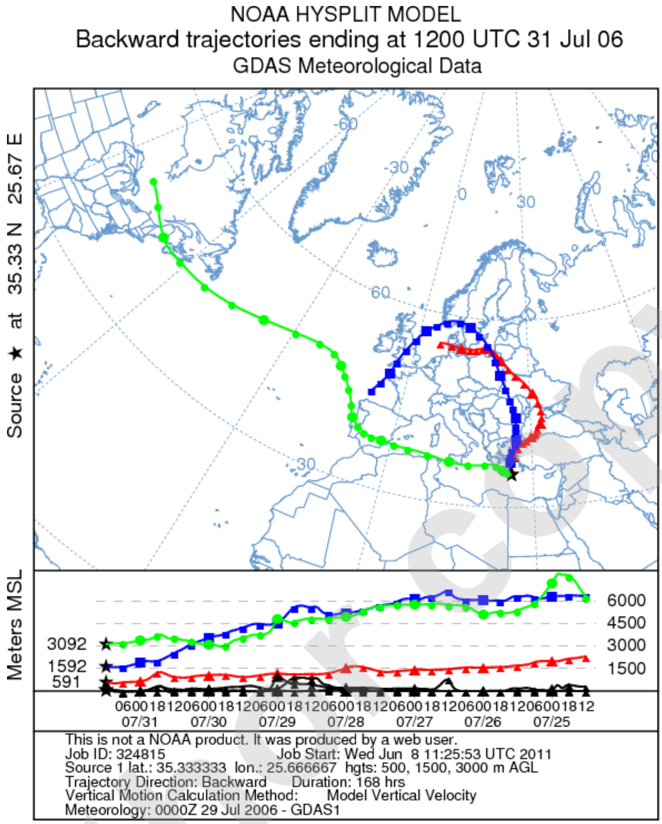

Fig. 6. Air mass back-trajectories obtained for the measurement area in Crete on 31 July 2006. Colour version of this figure is available in electronic edition only.

Much higher values of the AOT were measured on 31 July 2006 even though the air mass back-trajectories were the same with exception to that at a level of 500 hPa (Fig. 6).

The AOT values obtained for 31 July from the CIMEL and Microtops II measurements are presented in Fig. 7. Again the AOT values obtained from the Microtops II are consistently higher than the ones obtained from CIMEL. Nevertheless in both cases the values are exceptionally high during the entire day, exceeding 0.3 at 500 nm. The Ångström exponent values and the fine to coarse mode relation indicate the presence of small particles in the air during the day. The air mass trajectories and the AOT values suggest their nonnatural origin (Lelieveld *et al*. 2002). Only in earlier hours the Ångström exponent was slightly lower which might indicate the presence of larger particles, however the fine to coarse mode relation shows rather uniform conditions

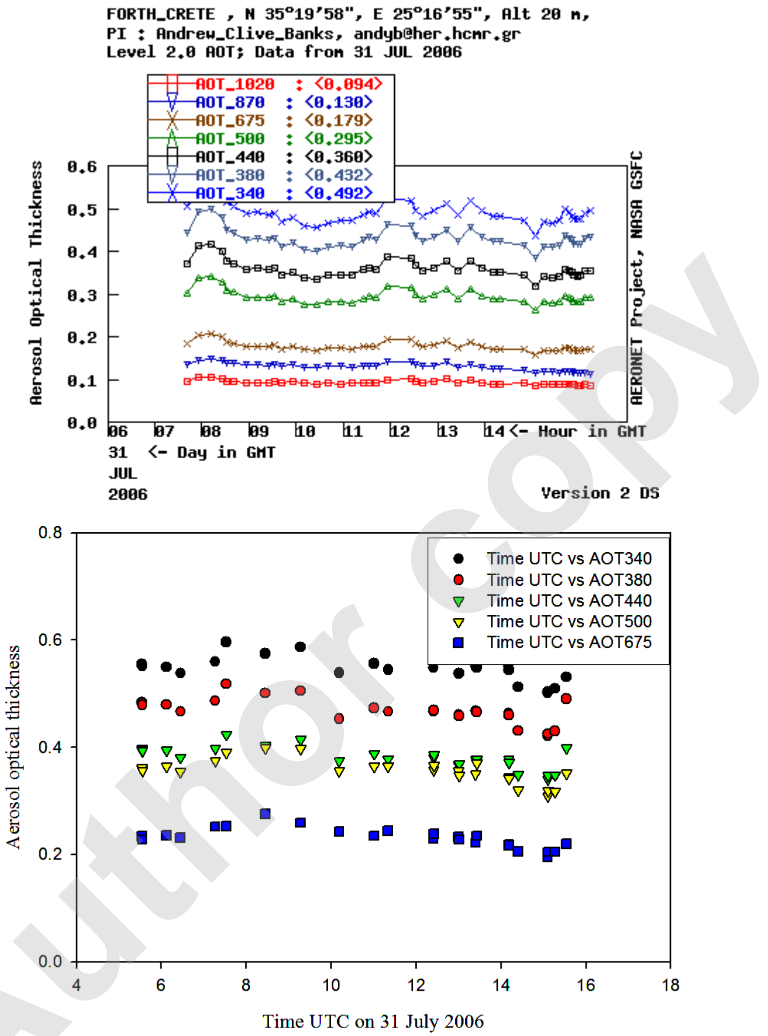

Fig. 7. Aerosol optical thickness measured with CIMEL (top) and Microtops II (bottom) sun photometers on 31 July 2006 in Crete. Colour version of this figure is available in electronic edition only.

during the day (Fig. 8). Similarly to 29 July, the back-trajectories 4 days before passed over the SolarAOT station. The AOT measured on 27 July was also larger (0.25-0.27 at 500 nm) in comparison to the previous case as well as the Ångström exponent which was about 1.6.

The lidar backscatter profiles show some aerosol structures between 1 up to 3 km a.s.l. (Fig. 9). The graphs show that the AOT values changed during

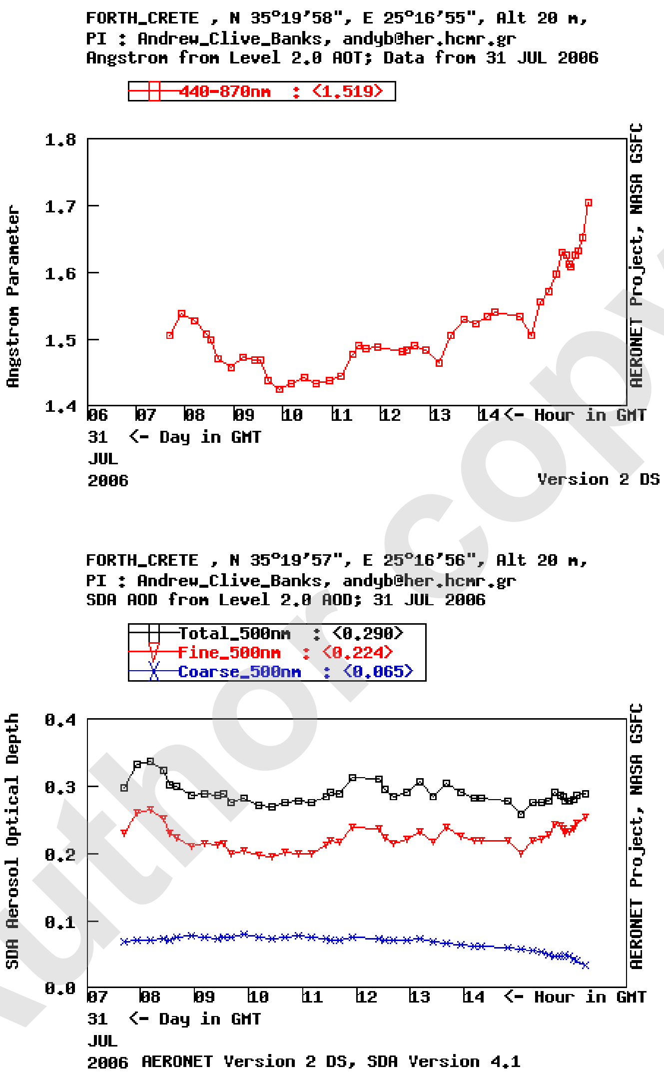

Fig. 8. Ångström exponent (top) and fine to coarse mode relation (bottom) on 31 July 2006 in Crete. Colour version of this figure is available in electronic edition only.

the day with the development of the aerosol layer between 1 and over 3 km a.s.l. The averaged AOT values obtained from the lidar at 532 nm were 0.320 between 06:00 and 06:30 UTC, 0.294 between 11:00 and 11:30 UTC, and with well pronounced aerosol layer they reached 0.460 between 16:00 and 16:30 UTC.

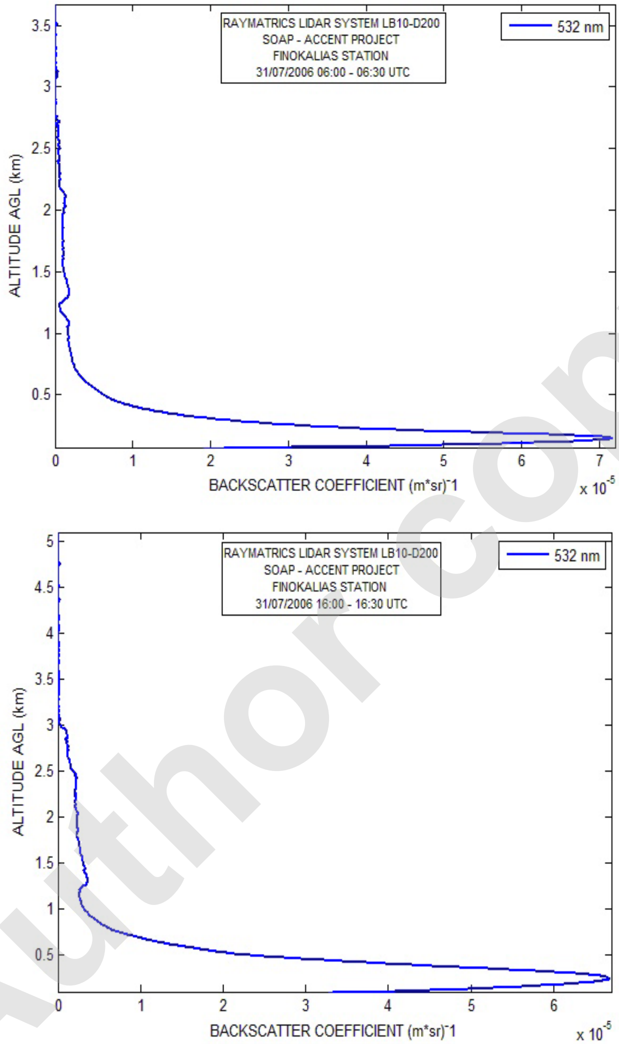

Fig. 9. Aerosol backscatter coefficient *versus* altitude measured with lidar on 31 July 2006 in Crete between 06:00 and 06:30 (top) and 16:00-16:30 UTC (bottom).

4.2 Experiment COAST 2009 in the Baltic Sea

We present the results from two days of measurements which were made on 27 and 29 September 2009. The studies were made in Rozewie, which is the farthest northerly Polish point. The station is located about 10 m a.s.l. and some 100 m from the beach. Therefore, with exception of southerly winds, it is a good point for marine aerosol measurements. During the entire campaign we had very strong winds (stormy conditions). For analyses we chose two cases, with westerly winds and northerly winds. Figure 10 presents the air mass back-trajectories on 27 September 2009 in Rozewie.

The air mass back-trajectories show the advection of air masses from over the North Sea region. Only the low trajectory (around 0.5-1 km a.s.l.) was going over the northern Germany. The aerosol optical thickness measured with the Microtops II sun photometer ranged from 0.25 to 0.35 at 500 nm during the entire day (Fig. 11).

The AOT values measured at the Hamburg station (Fig. 12) which is located on the route of air masses to Rozewie are also high, at an average level of 0.191 at 500 nm. The AOT values in Hamburg were lower than in Rozewie. This may have been the case due to the influence of coarse mode particles (marine aerosols) produced with high wind speed, which was recorded on that day near Rozewie.

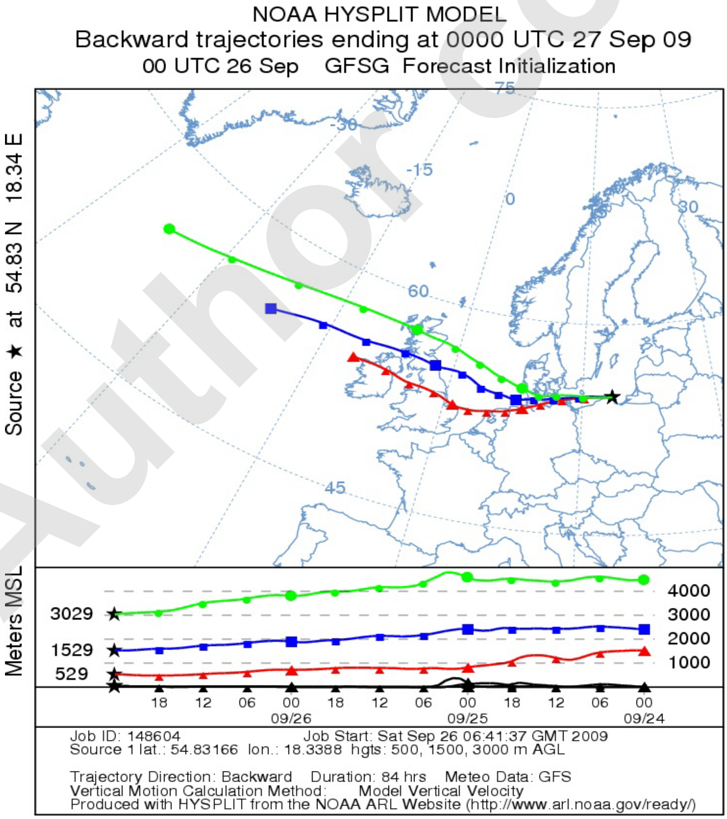

Fig. 10. Air mass back-trajectories obtained for the measurement area in Rozewie on 27 September 2009. Colour version of this figure is available in electronic edition only.

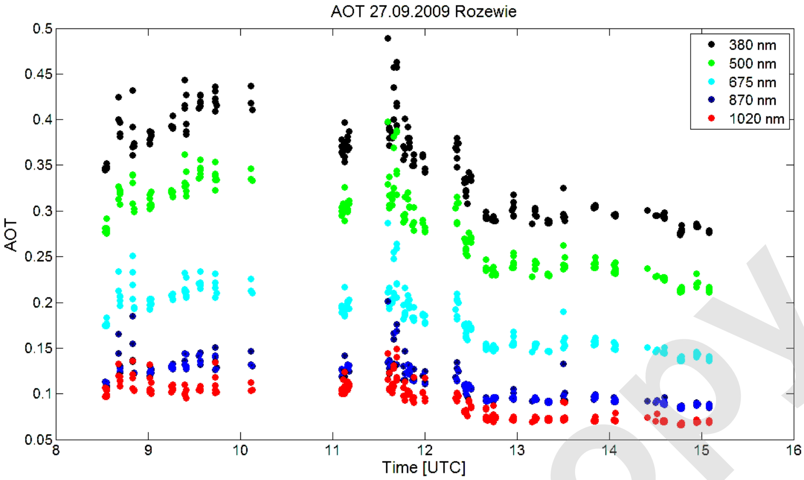

Fig. 11. Aerosol optical thickness measured with Microtops II sun photometers on 27 September 2009 in Rozewie. Colour version of this figure is available in electronic edition only.

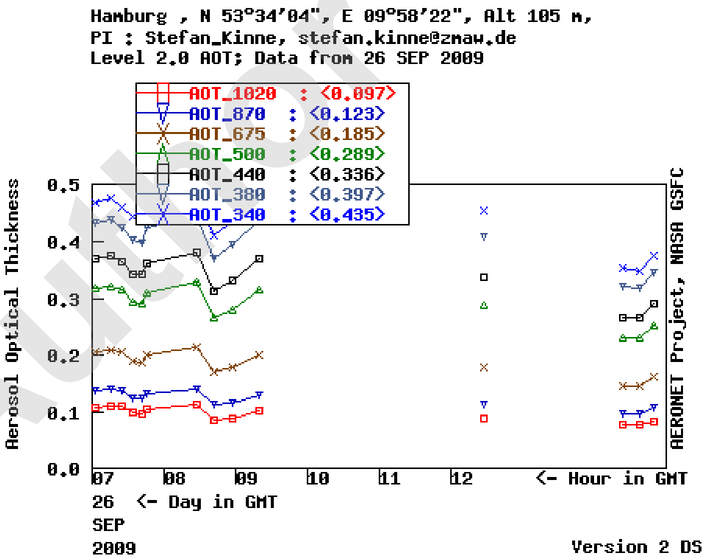

Fig. 12. Aerosol optical thickness measured with CIMEL on 26 September 2009 in Hamburg. Colour version of this figure is available in electronic edition only.

The Ångström exponent values varied in Hamburg significantly on 26 September. Also the fine to coarse mode relation shows that the fine mode particles were dominating in the entire ensemble of aerosols starting

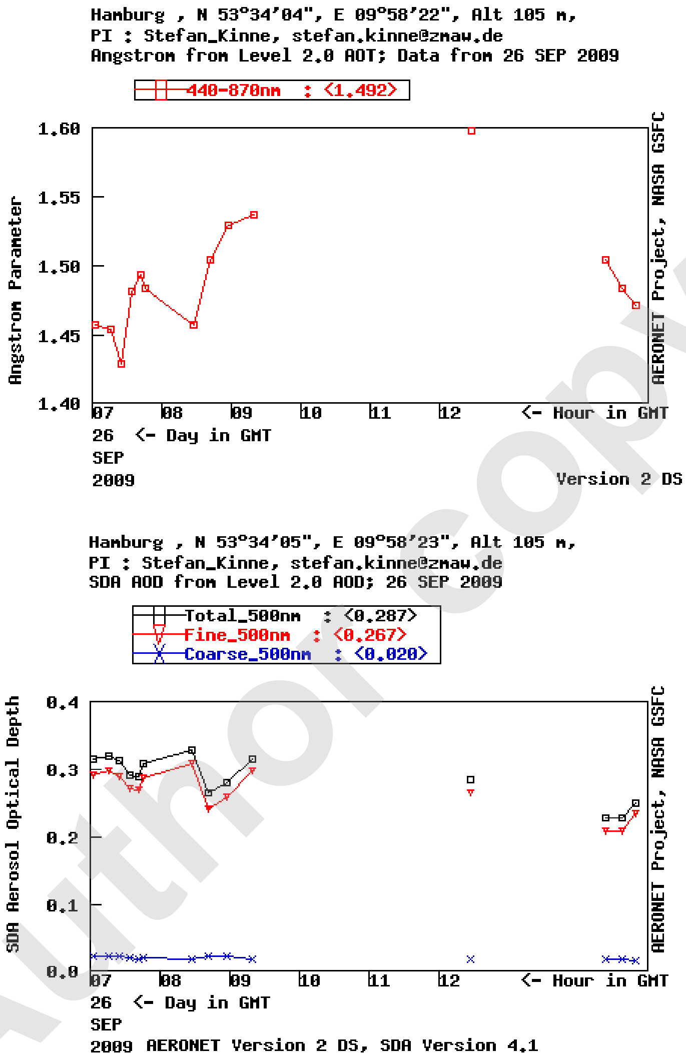

Fig. 13. Angstroem exponent (top) and fine to coarse mode relation (bottom) on 26 September 2009 in Hamburg. Colour version of this figure is available in electronic edition only.

around 07:00 UTC (Fig. 13). Again this may be reflected over 20 hours later in Rozewie (Fig. 14).

The lidar (range corrected) obtained vertical profiles of aerosol plumes show not much particles in the atmospheric column over Rozewie at 11:00 UTC, however at 15:00 UTC aerosol structures are visible at altitudes between 1 and 10 km a.s.l. (Figs. 14 and 15).

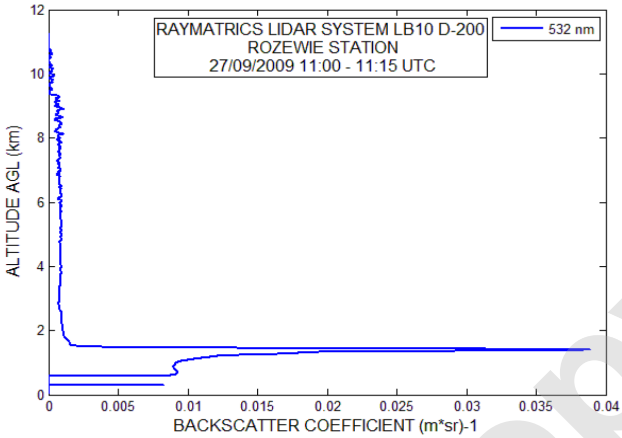

Fig. 14. Aerosol backscatter coefficient *versus* altitude measured in Rozewie on 27 September 2009 at 11:00 UTC.

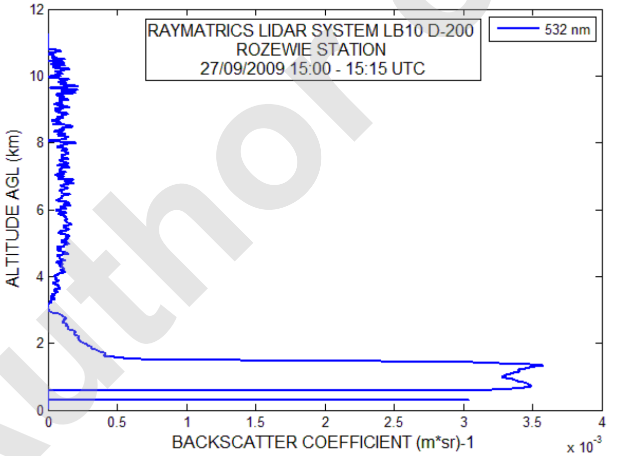

Fig. 15. Aerosol backscatter coefficient *versus* altitude measured in Rozewie on 27 September 2009 at 15:00 UTC.

The aerosol structures observed at 15:00 UTC in Rozewie must be related to the advection of air masses from over the western direction. The delay of some 20 hours in the detection of increased aerosol presence is realistic on that day since the wind speed reached very high levels and the straight line distance between Hamburg and Rozewie is around 450 km. On 26 and 27 September 2009 wind speed reached a level of an average of 8.3 m/s in the region. Therefore, the comparable levels of AOT in Hamburg and Rozewie make sense.

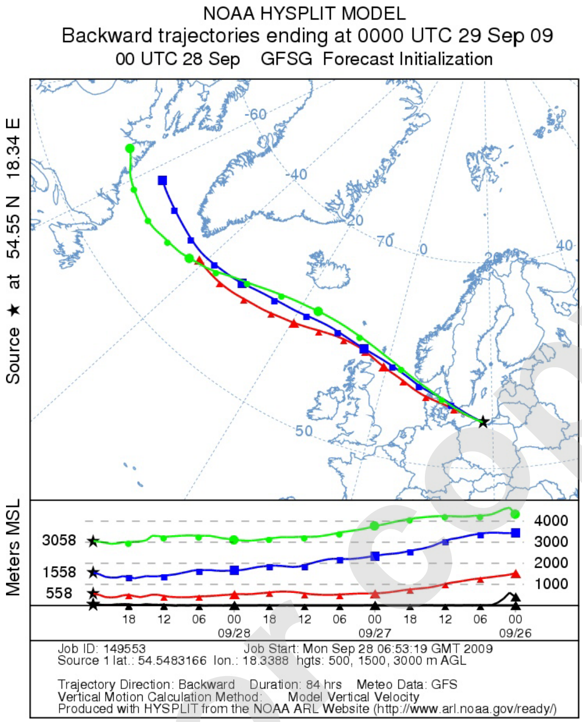

Fig. 16. Air mass back-trajectories obtained for the measurement area in Rozewie on 29 September 2009. Colour version of this figure is available in electronic edition only.

Different situation was observed on 29 September 2009. The air mass back-trajectories were reaching Rozewie passing almost entirely over the marine regions of the Danish Straits and the North Sea at all altitudes (Fig. 16).

The aerosol optical thickness measured using the Microtops II sun photometer in Rozewie was at a lower level (from 0.082 to 0.125 at 500 nm) than in the case of 27 September (Fig. 17). It is clear that the AOT values were decreasing during the day reaching their minimum values of 0.082 at 500 nm in late afternoon. There is also a small peak of higher AOT values at all wavelengths between 13:30 and 15:00. This may be connected with a plume of aerosols which was observed with a lidar (Fig. 21).

The AOT values measured at the Palgrunden station in Sweden (Fig. 18), located on the route of air masses to Rozewie are lower (daily average AOT of 0.067 at 490 nm) in comparison with those obtained in Rozewie. We can see that in both stations the values are low and the AOT values in Palgrunden

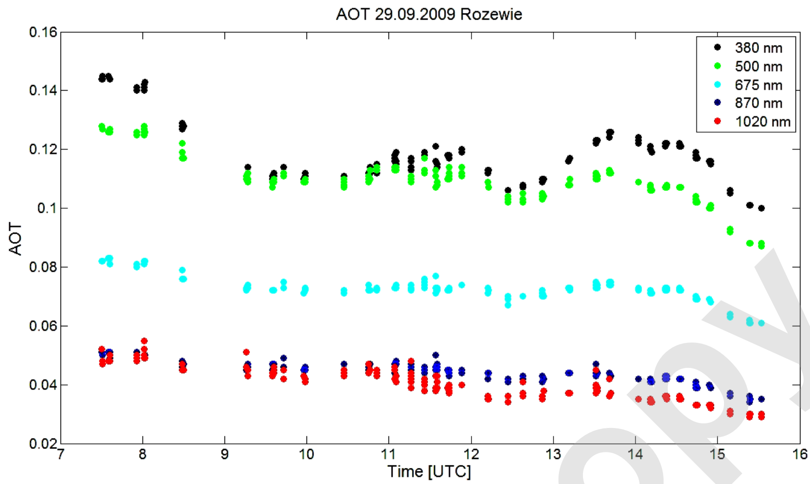

Fig. 17. Aerosol optical thickness measured with Microtops II sun photometers on 29 September 2009 in Rozewie. Colour version of this figure is available in electronic edition only.

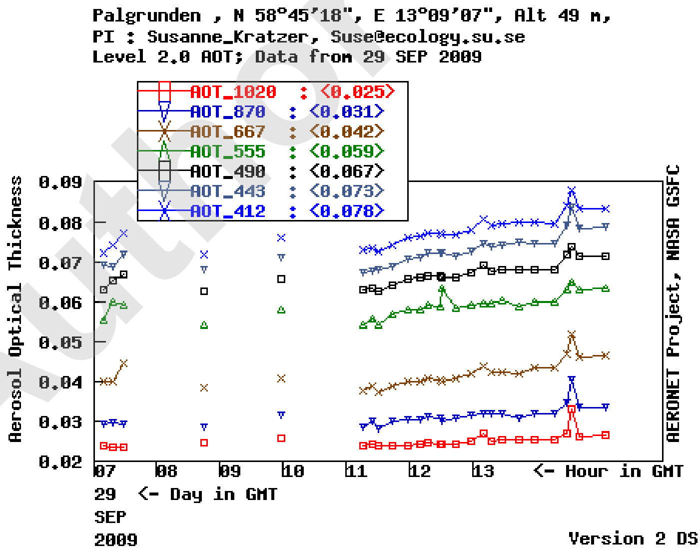

Fig. 18. Aerosol optical thickness measured with CIMEL on 29 September 2009 in Palgrunden. Colour version of this figure is available in electronic edition only.

show an increasing tendency during the measurement day. Similar to 27 September, the AOT values in Rozewie may be higher due to the influence of marine aerosols. During the entire measurement day the wind speed

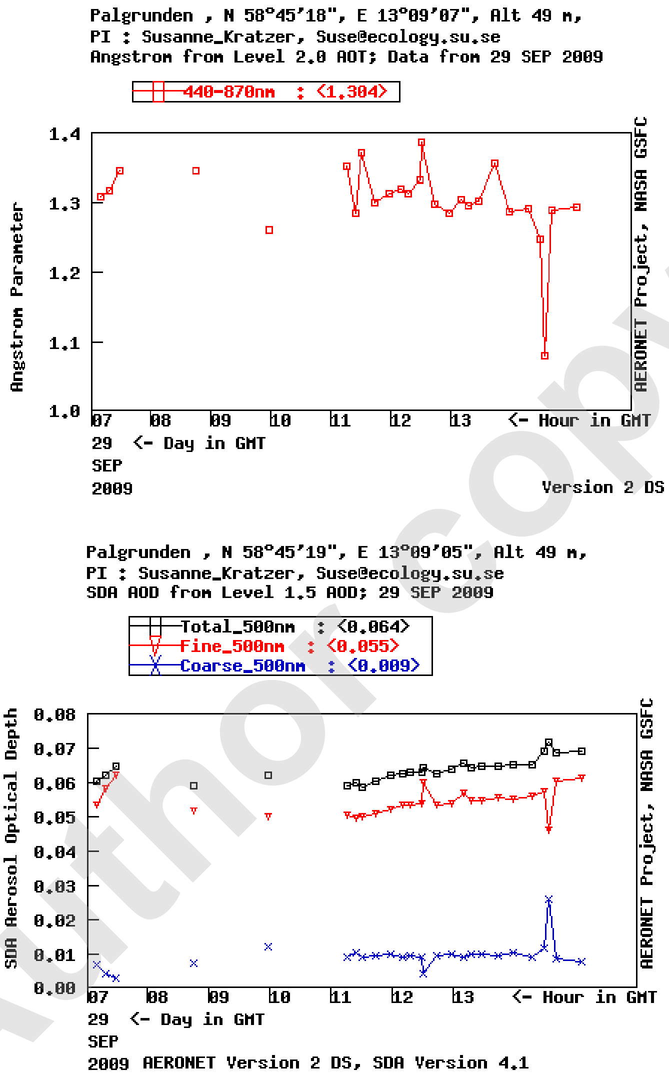

Fig. 19. Ångström exponent (top) and fine to coarse mode relation (bottom) on 29 September 2009 in Palgrunden. Colour version of this figure is available in electronic edition only.

was high and the wind direction from over the open sea could transport marine aerosols to the measurement station in Rozewie.

The Ångström exponent did not vary much during the day in Palgrunden station and the values of over 1.3 indicate the domination of fine mode particles. The fine and coarse mode relation for this day in Palgrunden is available for level 1.5 on the AERONET site. It is clear that the fine mode dominated during the entire day (Fig. 19).

The low AOT values measured at both stations are reflected with very low aerosol presence in Rozewie measured with lidar (Figs. 20 and 21).

At 11:00 UTC the aerosol presence in the atmospheric column over Rozewie was very small. Only between 5 and 7 km a.s.l. there is a very thin layer of aerosols present in the graph but the backscatter coefficient is at a level of less than 0.001 km^{-1} $srad^{-1}$. The AOT values are also the lowest

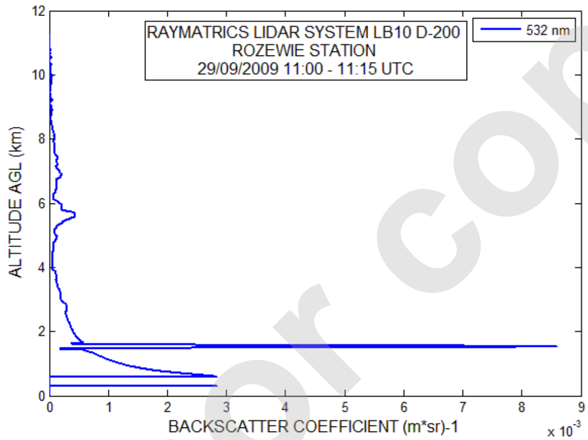

Fig. 20. Aerosol backscatter coefficient *versus* altitude measured in Rozewie on 29 September 2009 at 11:00 UTC.

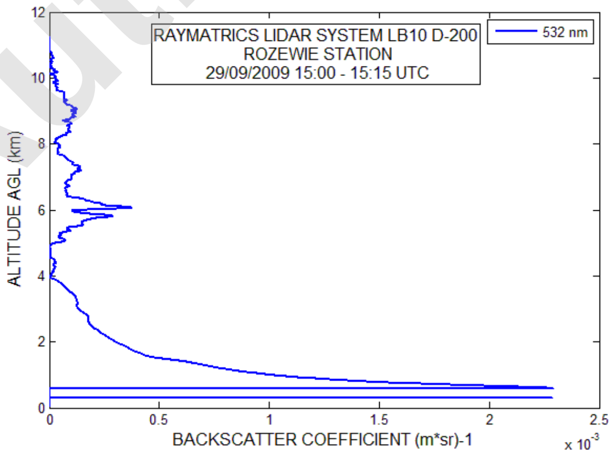

Fig. 21. Aerosol backscatter coefficient *versus* altitude measured in Rozewie on 29 September 2009 at 15:00 UTC.

around this time of the day. Later, at 15:00 UTC the backscatter coefficient increases and there is a detectable layer of aerosols between 3 and 9 km a.s.l.; however, the AOT values measured in Rozewie are at a similar level than at 11:00 UT, while in Palgrunden the AOT values increased during the day.

The daily average AOT values obtained in Rozewie on 27 September (0.25-0.35 at 500 nm) and on 29 September (0.082-0.125 at 500 nm) show two different cases. Table 3 gives AOT values obtained by different researches for the Baltic region. The values obtained on 27 September indicate the continental type of aerosols, while the values from 29 September show clean marine aerosols in the air. This situation resulted from the direction of air advection to the station.

Table 3

AOT levels at 550 nm obtained by various authors for the southern Baltic stations at 8 m/s and recalculated to RH = 80%

Author	Air mass type	AOT at 550 nm	Region
Weller and Leiterer (1988)	Continental Marine	0.62 0.18	Baltic Baltic
Wendisch and Von Hoyningen-Huene (1994)	Continental Marine	0.29 0.10	Baltic Baltic
Schifrin *et al*. (1980)	Marine/coastal	0.20	Baltic
Kuśmierczyk-Michulec *et al*. (2001)	Continental/mixed Marine	>0.26 0.26<	Baltic Baltic
Zielinski and Pflug (2007)	Continental Marine	0.21 0.09	South. Baltic coastal South. Baltic coastal

5. CONCLUSIONS

Joint measurements using lidars and sun photometers provide complete information on both the total aerosol optical thickness in the entire atmosphere as well as the vertical structure of aerosol optical properties. Applying only sun photometers to aerosol optical thickness studies does not provide information on the type of aerosols and their contribution to the AOT. The use of lidars provides information on the present plumes of aerosols, their altitude and limits, and thus on the impact of the boundary layer on the total AOT measured. The continuous use of lidars also provides information about the evolution of the aerosol plume with time and space. This method provides data quickly which can be further utilized in statistical studies of such optical parameters as extinction and the thickness of the atmosphere under various meteorological conditions.

We showed that in order to detect the dynamics of potential aerosol composition changes it is necessary to use data from different stations where measurements are made using the same techniques. The combination of such information with air mass back-trajectories and data collected at stations located on the route of air masses provides comprehensive picture of aerosol variations in the study area both vertically and horizontally.

Both the Baltic Sea and the Mediterranean Sea are difficult areas for aerosol measurements due to advections of continental air masses from many directions. The so-called “clean” aerosol conditions are sparse. With exception to 29 September 2009 in Rozewie, in both station cases we did not measure significant local contribution of aerosols (sea-salt particles). The potential contribution of sea salt particles on 29 September 2009 can be seen from the aerosol optical depth and Ångström coefficient values. They also fit to the pattern given by other researchers for the marine aerosol conditions measured in the Baltic area. The ensemble of aerosols was dominated by small particles advected to the study area from different parts of Europe.

Therefore, while analyzing aerosol data in such areas it is important to distinguish between the sources of aerosols. Three types of aerosols which depend on wind direction can be distinguished in coastal areas. These are continental, marine, and a mixture of marine and continental and each of them has different optical properties.

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