Impact of Breaking Waves on Sea Salt Production and Local Change of Aerosol Optical Properties

A. Strzalkowska, T. Zielinski, P. Makuch, P. Pakszys and T. Petelski

Abstract In this paper we discuss local impact of breaking waves on production of sea salt aerosols and hence on the change of aerosol size distribution and particle optical properties. Our studies were made between 17 and 27 July 2012 at the Coastal Research Station (CRS) in Lubiatowo on the Polish Baltic coast. During the studies aerosol optical depth was measured using Microtops II sun photometers and AERONET and MODIS data were used to support the further analyses. We show that with the local wave breaking phenomenon the aerosol optical depth may increase by a magnitude of even one order and that the ensemble of aerosol particles may shift from the dominating fine mode to coarse mode (sea salt). Such shift may have a strong local impact on the radiative forcing and hence on a local climate.

Keywords Aerosol · Baltic · Microtops · AERONET

1 Introduction

Atmospheric aerosols originate from a wide variety of sources in both marine and continental environments. Aerosol content varies significantly depending upon whether the air mass is natural or modified anthropogenically, marine or continental, rural or urban (Zielinski and Zielinski 2002).

Therefore, characterizing aerosols not only requires describing their spatial and temporal distributions but their multi-component composition, particle size distribution and physical properties as well. Aerosols formed over land by either primary or secondary formation processes are transported over the oceans and contribute substantially to the aerosol concentrations over the oceans (Kastendeuch and Najjar 2003; Smirnov et al. 2003; Glantz et al. 2006). Sea spray aerosol is directly produced at the sea surface through the interactions between wind and surface waves

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(Hobbs 2000). Sea salt aerosols are among most abundant components of atmospheric aerosols, and thus they exert strong influence on radiation, cloud formation, meteorology and chemistry of the marine atmosphere. An accurate understanding and description of these mechanisms is crucial to modeling climate and climate change (Smirnov et al. 2009, 2011). Secondary aerosol formation from gases released from the sea surface and even ship emissions contribute significantly to marine atmosphere aerosol loading.

It has been reported that the mass concentrations from sea spray aerosol and desert dust show the largest aerosol contributions on a global scale (Andreae and Rosenfeld 2008; Jickells et al. 2005; Lewis and Schwartz 2004; de Leeuw et al. 2011; Petelski et al. 2014). Aerosol particles are important both because they affect atmospheric processes and, in case of the world's oceans, after deposition to the sea surface, because they affect processes in sea water.

Aerosols have a strong impact on climate both due to scattering and absorption of incoming solar radiation (direct effect) and through their effects on cloud properties and associated cloud albedo (first indirect effect) and precipitation (second indirect effect). 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 areas, such as the Baltic Sea basin, which are very urbanized and industrialized. A thorough understanding and explanation of aerosol impact on light transmission in the atmosphere requires knowledge of aerosol optical properties, such as extinction, phase function and single scattering albedo, as well as microphysical aerosol properties, such as size distribution and light refractive index. This is especially relevant concerning knowledge of the real and imaginary parts of the light refractive index on aerosol particles including mineral dust additions (de Leeuw et al. 2011; Zielinski and Zielinski 2002). The optical properties of dust 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, e.g. Baltic Sea, a typical regional sea, surrounded by highly industrialized areas (Dzierzbicka-Głowacka et al. 2013).

The ground-based methods are, in principle, the easiest to use and the most accurate monitoring systems. Aerosol optical depth (AOD) is the single most comprehensive variable to remotely assess the aerosol burden in the atmosphere using ground-based instruments. Knowledge of the real 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. Therefore, the AOD is used in local studies on aerosols, their role in atmospheric pollution and to make atmospheric corrections to satellite remotely sensed data (Zielinski and Zielinski 2002).

Sea salt is the most characteristic type of marine aerosol, and it enters the atmosphere due to the strong influence of wind on the sea surface. As a result, wind waves are formed and the particles are precipitated from the wave crests. Emission of sea salt to the atmosphere strongly depends on the force, speed and direction of wind (Jacob et al. 1995). Marine aerosols also can be generated by rainfalls or acoustic waves (Blanchard and Woodcock 1957; Blanchard 1963; Fitzgerald 1991).

In this paper we discuss the results of the studies of aerosol optical properties under the conditions of breaking waves in the coastal area of the Polish coast on Baltic Sea. We show that the sea salt production in the coastal area significantly changes the optical properties of aerosols, hence influencing the radiative budget on a local scale.

2 Methodology

The studies took place at the Coastal Research Station (CRS) in Lubiatowo on the Polish Baltic coast (54°48′42.0″N, 017°50′25.6″E), which is located about 70 km northwest of Gdansk (Fig. 1) on a typical South Baltic sandy coast. The area is dominated by westerly and south-westerly winds, which are strongest in the autumn and winter. Water salinity amounts to 7.5 PSU during summer and 7.7 PSU in the winter (http://mlb.ibwpan.gda.pl/index.php/en/).

The shore in the vicinity of the CRS Lubiatowo is an open and natural beach, characterized by a gentle slope (about 1.5 %). Due to existence of the sand bars, waves approaching the shore from deep sea are subject to significant transformation in the surf zone and most of wave energy is dissipated due to multiple wave breaking (http://mlb.ibwpan.gda.pl/index.php/en/). Such conditions are very favorable for the production of sea salt particles.

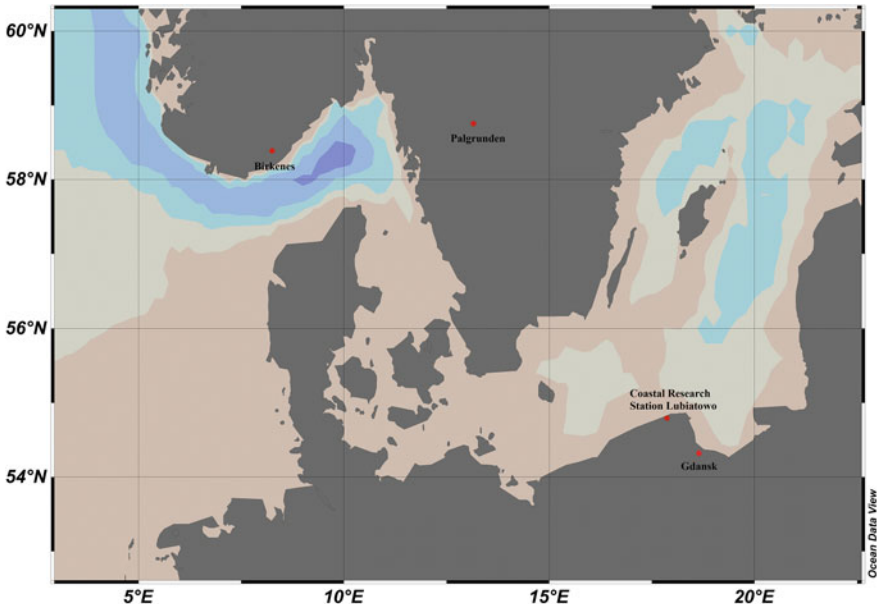


Fig. 1 Location of the coastal research station in Lubiatowo

The experiment lasted between 17 and 27 July 2012. The research team measured the aerosol optical depth (AOD) using a Microtops II sun photometer each measurement day started early in the morning and lasted till late afternoon weather permitted (no clouds or rain). Additionally, information on meteorological data (temperature, pressure, relative humidity) were collected from the appropriate weather services (e.g. www.rp5.kz) and the air mass back trajectories have been calculated using HYSPLIT (Draxler and Rolph 2014). Information on the AOD and types of aerosol particles were taken from the AERONET Birkenes station in southern Norway. Finally, the MODIS images were used to verify the AOD for the studied area.

The Microtops II sun photometer (produced by Solar Light Company USA) is a hand-held device capable of measuring aerosol optical depth of atmospheric aerosols, direct irradiance in each band and the water vapor column. The device is equipped with five channels and each of channels has different wavelength value (380, 440, 500, 675, 870 nm). The measurement procedure results in quick, lasting only 10 s, scanning of vertical column of atmosphere. Microtops II measurements were made in a series of five "shots". The scans are completed one after another and group into series for two minute time intervals. Only the lowest value is used since such value guarantees the least disturbed measurement of all 5. The full information on the Microtops II sun photometer and the Langley calibration technique used by the authors have been described in Morys et al. (2001), Zielinski et al. (2012), Strzalkowska et al. (2014).

The aerosol optical depth, a dimensionless, wavelength dependent parameter which refers to the weakening of direct sunlight passing through the atmosphere is a function of concentration of particles, their size distribution and chemical composition. The AOD value changes with the height above the sea level and similarly the Ängström parameter have been described in details before by e.g. Smirnov et al. (2009), Zielinski and Zielinski (2002), Zawadzka et al. (2014), Strzalkowska et al. (2014). The wavelength dependence of aerosol optical depth can be expressed using an empirical formula described by Ängström as follows (Weller and Leiterer 1988; Smirnov et al. 1994; Eck et al. 1999; Carlund et al. 2005):

$$\mathrm{AOD} = \beta \times \lambda^{-\alpha} \tag{1}$$

The β coefficient characterizes the degree of atmospheric turbidity due to aerosols and equals to the AOD for λ = 1 μm. The Ängström exponent (α) is calculated from a minimum of two wavelengths and is calculated from the following formula:

$$\alpha(\lambda_1, \lambda_2) = \frac{\ln\mathrm{AOD}(\lambda 1) - \ln\mathrm{AOD}(\lambda 2)}{\ln\lambda 1 - \ln\lambda 2} \tag{2}$$

3 Results and Discussion

The studies lasted between 17 and 27 July 2012. During this period good photometric conditions, i.e. with no or small number of scattered clouds were observed only on 17, 18, 20 and 21 July. Therefore, in the reminder of the paper only these days have been further analyzed. The wind and sea wave conditions at the study site on these days are presented in Table 1.

During these days the air masses arrived from the westerly sectors. The air mass back trajectories calculated using the NOAA HYSPLIT Model are presented in Fig. 2.

It is clear that during all days the air masses were advected over the CRS in Lubiatowo from the north-westerly directions at all three altitudes above the sea level (500, 1,500 and 3,000 m). Wind speeds were relatively high, especially the wind gusts were at the same level or even slightly increasing. These conditions lasted for 5 days resulting in waves of heights around 2 m or even higher, which were breaking in the area, creating a wide breaking zone (over 500 m wide). In such conditions sea salt production is enhanced and this could be seen with the AOD values.

3.1 17 July 2012

On 17 July 2012 a large storm cloud system developed over the northern Poland, which resulted in mild rains lasting until noon. Thus on that day the Microtops II measurements at the CRS station in Lubiatowo were made every 30 min after 14:15 UTC. The average daily AOD at 500 nm was up to 0.154 and Ängström exponent of about 0.8 (Fig. 3).

Analyses of the MODIS (The Moderate Resolution Imaging Spectroradiometer) (not shown) pictures from both the Terra and Aqua instruments reveal large cloud systems over and the AOD at 500 nm not exceeding 0.2.

Table 1 Wind and sea wave conditions at the station in Lubiatowo on 4 selected measurement days

Date	Wind speed [min–max] (m/s)	Wind gust [min–max] (m/s)	Significant wave height (m)	Maximum wave height (m)
17.07	1–7	2–16	1–1.5	1.5–2
18.07	1–6	2–16	1–1.8	1.5–3
20.07	2–8	4–18	1–2	1.5–3
21.07	2–6	4–14	1–1.5	1.5–2.2

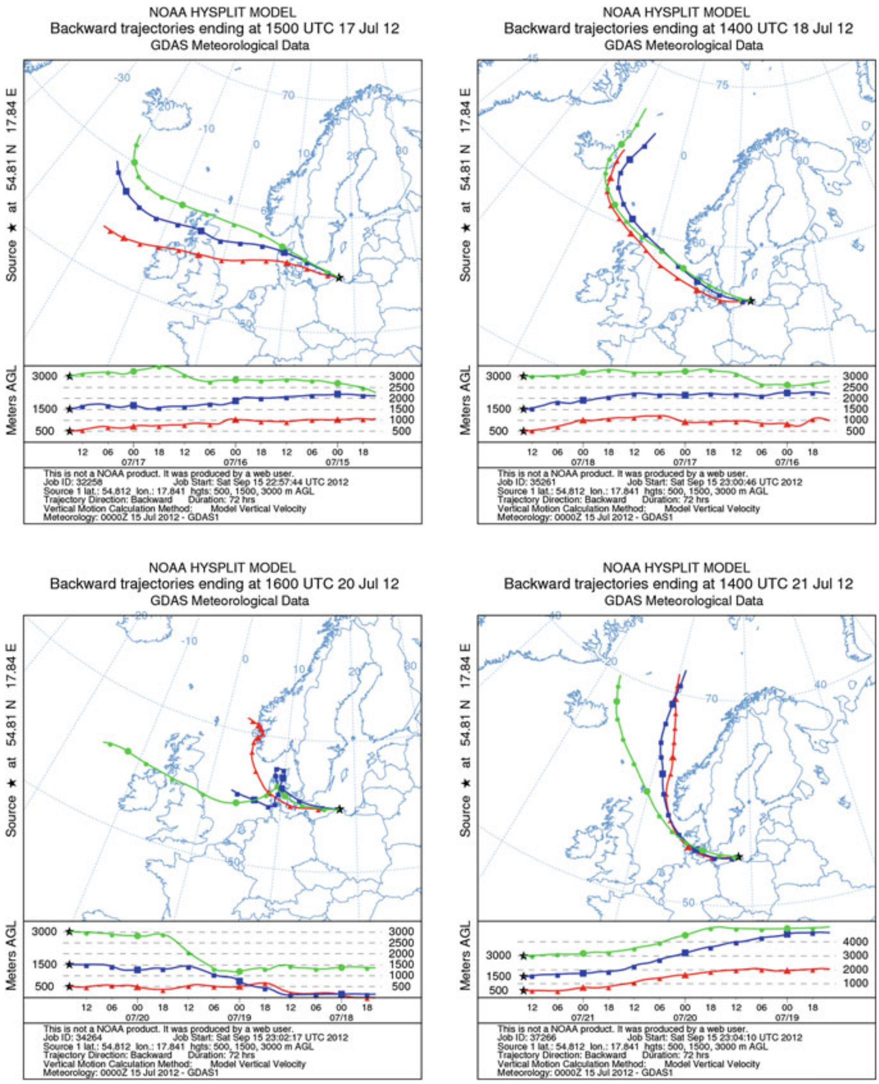


Fig. 2 Air mass back trajectories calculated for 17, 18, 20 and 21 July 2012 for Lubiatowo using the NOAA HYSPLIT model

The back trajectories obtained from the NOAA HYSPLIT Trajectory Model show the advection of air masses over the CRS station in Lubiatowo from north-west. Prior to the study area the air masses passed over the AERONET station in Birkenes (Norway). With an average daily wind speed of 20 km/h on 17 July and a distance of 700 km between the CRS station and the Birkenes station the same air

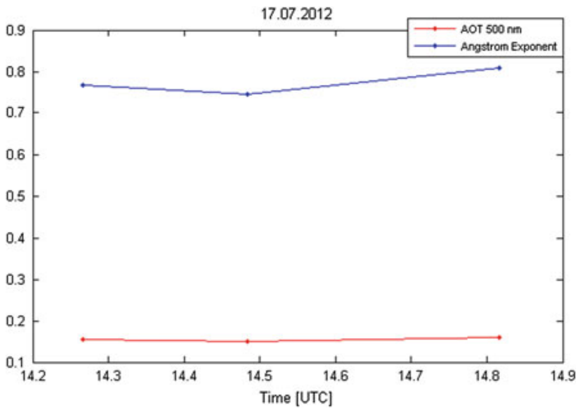


Fig. 3 The AOD (500 nm) and Ängström exponent (440–870 nm) on 17 July 2012 at the CRS station in Lubiatowo

masses passed the AERONET station some 35 h before the CRS station. The average daily AOD at 500 nm (Level 2) on 16 July in Birkenes was 0.053 and the Angstrom exponent (440–870 nm) equaled to 1.469, indicating presence of rather small particles in the air (Fig. 4a, b). This observation is also supported by a dominating role of fine mode over the coarse particles measured in Birkenes.

The comparison of the AERONET and the Lubiatowo data indicates the impact of breaking waves on aerosol production in Lubiatowo—AOD is an order of magnitude higher than in Birkenes and the Angstrom exponent indicates the presence of coarse mode particles, due to the breaking wave production of fresh particles, namely sea salt.

3.2 18 July 2012

On 18 July entire north Poland was under the influence of Atlantic air masses. A warm front from over Germany arrived over the study area. On that day Microtops II based measurements were made between 8:00 (UTC) until 13:15 (UTC). An average daily AOD value at 500 nm above the CRS station was 0.16 and the Ängström exponent was 0.65 (Fig. 5).

Again, during the entire day thick, scattered clouds were observed, which limited the number of sun photometric measurements. The cloud cover is evident from the very poor number of data presented with the MODIS (not shown in this article). The Aqua instrument registered only clouds, while the Terra instrument showed the AOD values not exceeding 0.2.

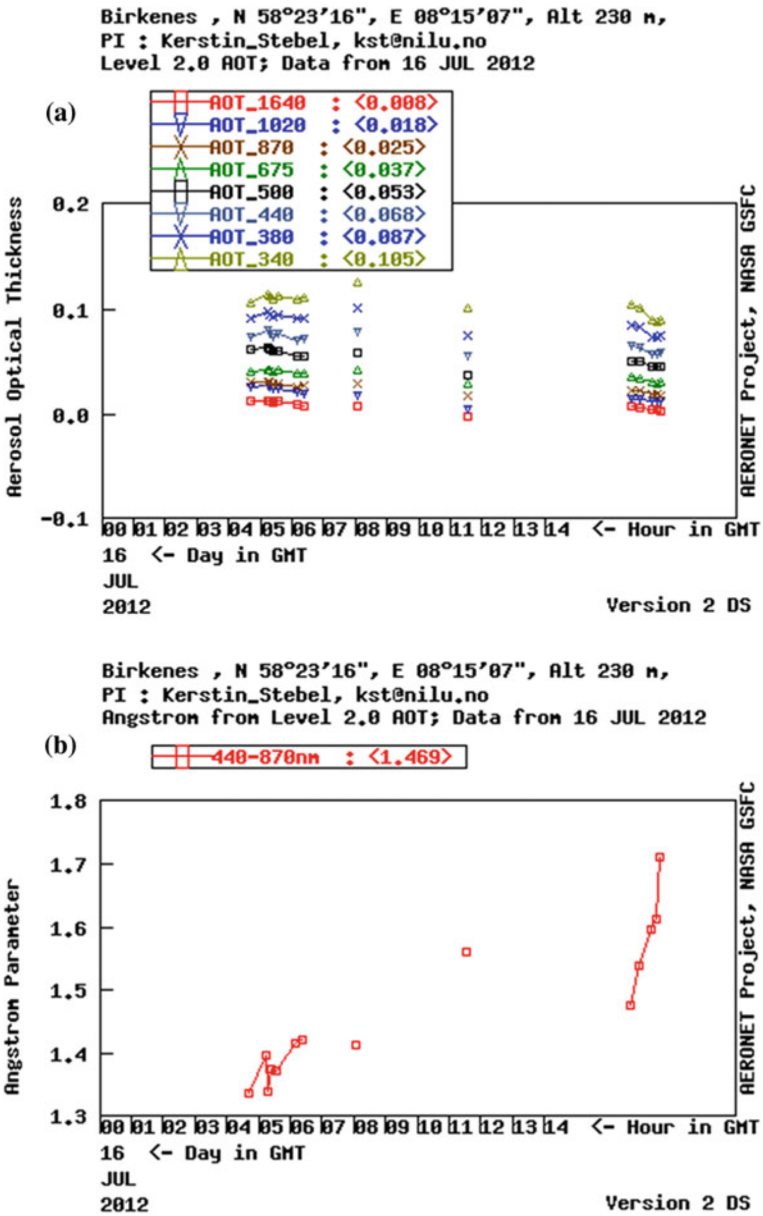


Fig. 4 The level 2.0 AOD (**a**) and the Ängström exponent (440–870 nm) (**b**) at the AERONET Birkenes station on 16 July 2012

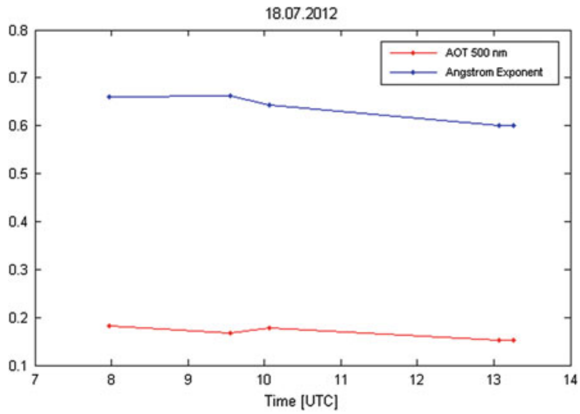


Fig. 5 The AOD (500 nm) and Ängström exponent (440–870 nm) on 18 July 2012 at the CRS station in Lubiatowo

NOAA HYSPLIT Trajectory Model shows that the air masses were advected to the CRS station from the west. The air masses passed two AERONET station on the way, the Birkenes station and the Palgrunden station (on 16 July the average AOD was 0.068 at 555 nm). Similar to 17 July 2012 the average daily wind speed of 20 km/h on 18 July the same air masses passed the AERONET station in Birkenes some 35 h before the CRS station. The AOD and Ängström exponent measured at the Birkenes station on 17 July are presented in Fig. 6a, b.

The average AOD at 500 nm at the Birkenes station was 0.050 and the Ängström exponent—1.803. These values indicate clear air and with presence of rather small particles. This situation is confirmed by the fine (0.045) to coarse ratio (0.006) for that day. Again these values are one order of magnitude lower than those obtained above the CRS station in Lubiatowo, 0.16 and 0.65, respectively. Due to wind speed and height of breaking waves these values indicate the presence of sea salt particles in the study area.

3.3 20 July 2012

On 20 July active atmospheric fronts caused storms and rains over the northern Poland. The Arctic air masses were blocked from being advected over the study area. Low pressure system caused strong winds. On 20 July the Microtops II measurements were made between 12:40 (UTC) and 15:05 (UTC). The daily average AOD at 500 nm was 0.179 and the Ängström exponent—0.74 (Fig. 7).

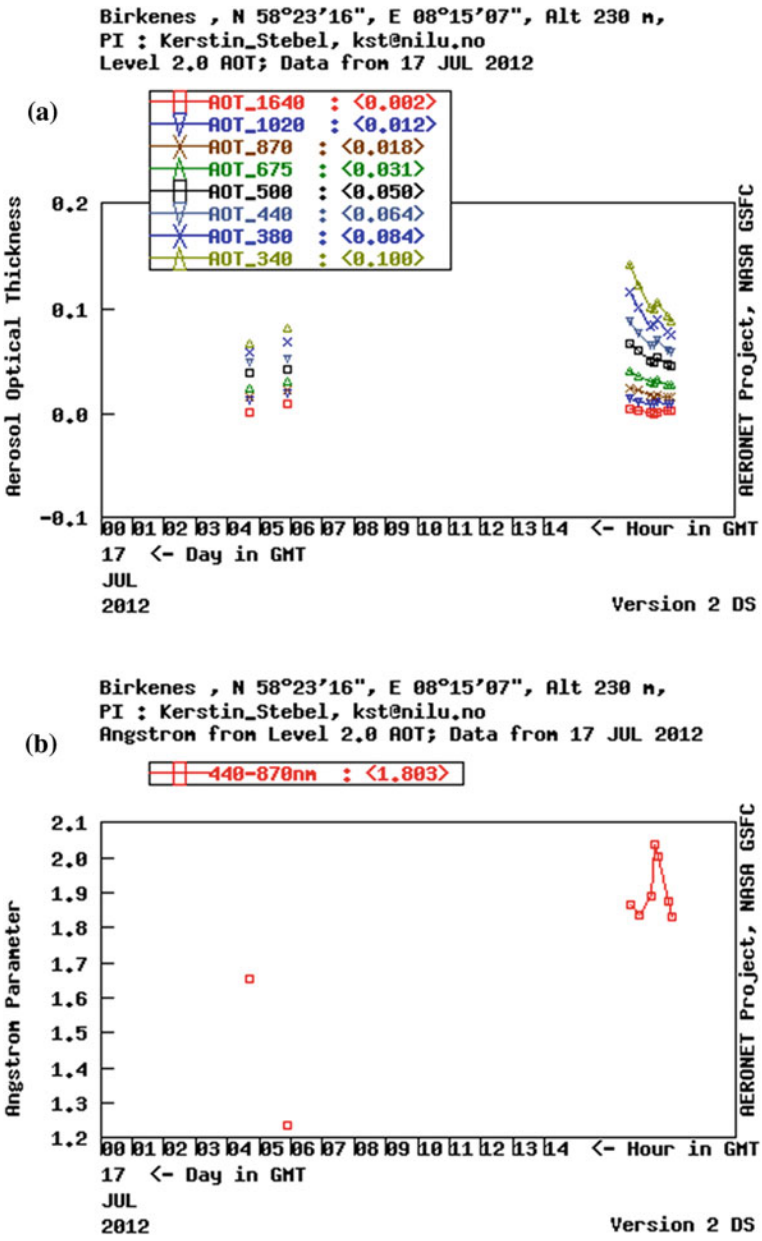


Fig. 6 The level 2.0 AOD (**a**) and the Ängström exponent (440–870 nm) (**b**) at the AERONET Birkenes station on 17 July 2012

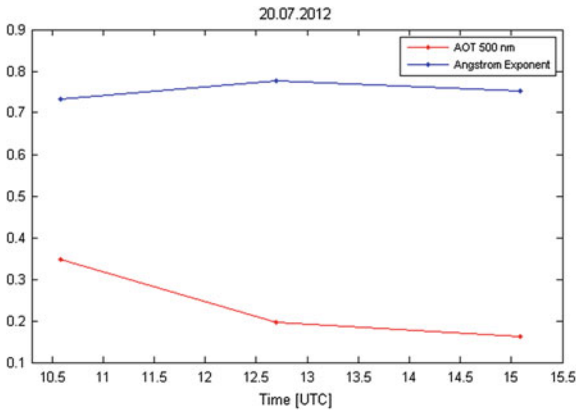


Fig. 7 The AOD (500 nm) and Angstrom exponent (440–870 nm) on 20 July 2012 at the CRS station in Lubiatowo

The analyses of the AOD from the MODIS were impossible due to the cloud coverage over the area.

Again the analyses of the back trajectories reveal that the air masses were advected to the study area from the west and they passed the Birkenes station. With the stable wind speed conditions the air masses passed the Birkenes station on 18/19 July (Fig. 8).

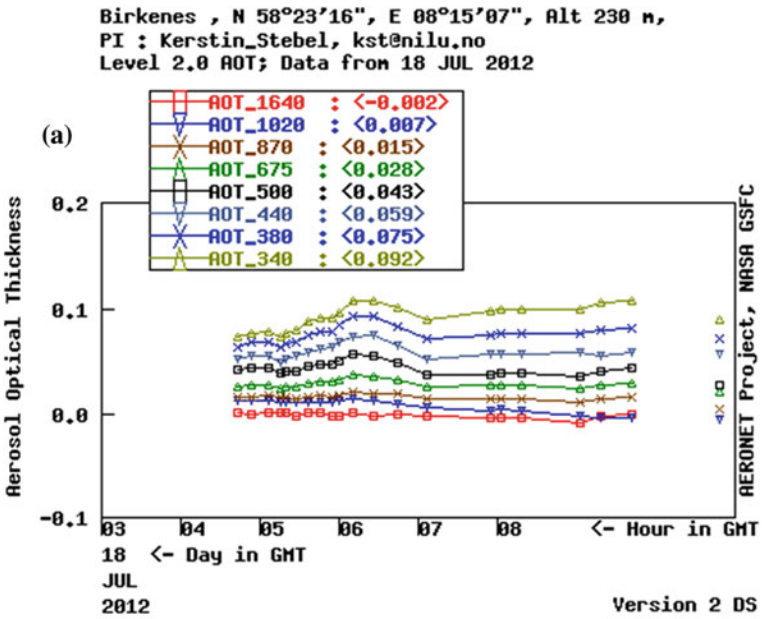
The average AOD at 500 nm at the Birkenes station was 0.043 and the Angstrom exponent—1.918, which indicate clear air and with presence of rather small particles. This situation is confirmed by the fine (0.042) to coarse mode ratio (0.005) for that day. These values are one order of magnitude lower than those obtained above the CRS station in Lubiatowo, 0.179 and 0.74, respectively, which indicate presence of sea salt particles due to high breaking waves

3.4 21 July 2012

On 21 July 2012 the low pressure system moved towards north (Scandinavia) and the northern Poland was under the cold front. On that day the Microtops II measurements were made between 12:03 (UTC) and 13:46 (UTC). The average AOD at 500 nm was 0.2 and the Ängström exponent—0.58 (Fig. 9).

The analyses of the MODIS pictures showed that the Terra instrument registered clouds and the Aqua instrument provided AOD at 500 nm at a level of 0.2 for the study area.

Just like on previous days the air masses were advected to the study area from the west and they passed the Birkenes station. With the stable wind speed conditions the air masses passed the Birkenes station on 19/20 July. The daily average AOD at 500 nm on 20 July was 0.038 and the Ängström exponent—1.814 (Fig. 10).



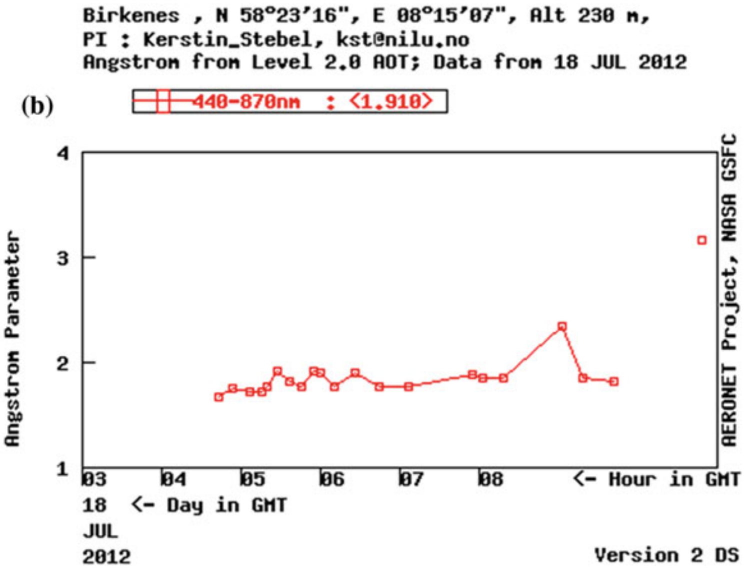


Fig. 8 The level 2.0 AOD (**a**) and the Angstrom exponent (440–870 nm) (**b**) at the AERONET Birkenes station on 18 July 2012

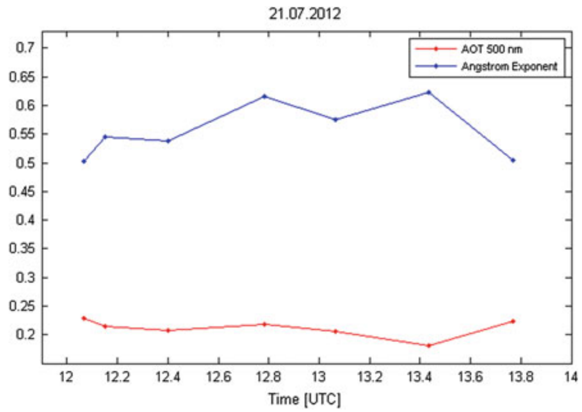


Fig. 9 The AOD (500 nm) and Ängström exponent (440–870 nm) on 21 July 2012 at the CRS station in Lubiatowo

Similar to the previous measurement days the values of the AOD and the Ängström exponent are an order of magnitude lower in Birkenes than in Lubiatowo. The fine (0.033) to coarse mode ratio (0.007) for that day shows the presence of small particles in the air, which is again in total opposition to the situation at the CRS study station.

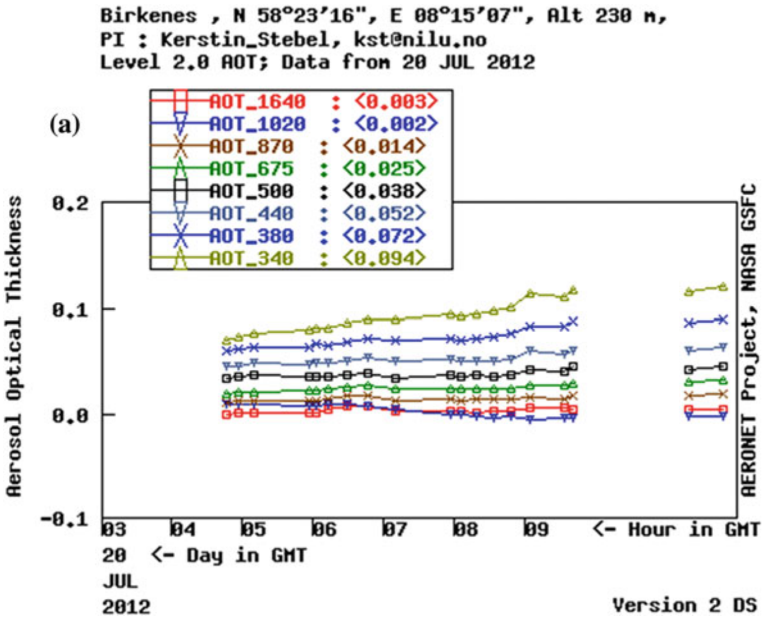


Fig. 10 The level 2.0 AOD (**a**) and the Ängström exponent (440–870 nm) (**b**) at the AERONET Birkenes station on 20 July 2012

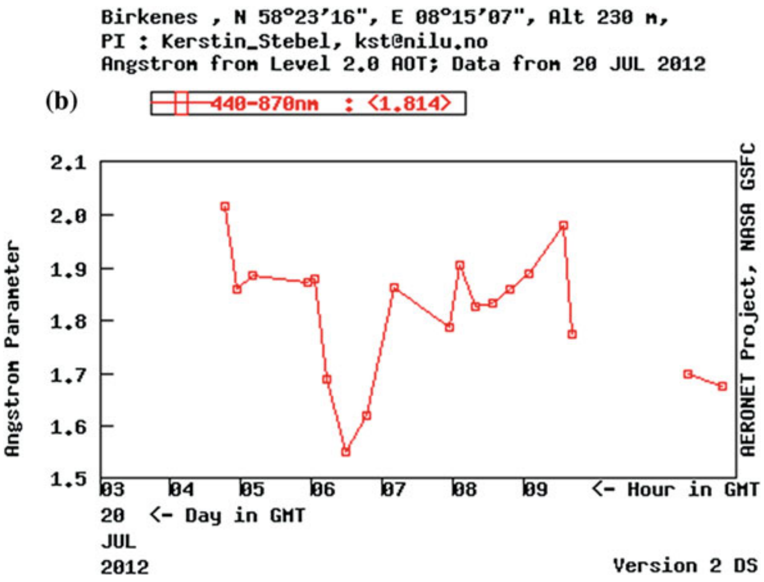


Fig. 10 (continued)

4 Conclusions

The results obtained from our studies indicate strong shift in aerosol size distribution due to the impact of the wave breaking. Despite small number of measurement points due to adverse weather conditions (cloudiness) with very advantageous wind directions and speeds during the five measurement days we were able to show a local change in the aerosol ensemble. During all studied days we registered AOD of an order of magnitude higher at the CRS station than at the AERONET station in Birkenes a day before (with wind speed and direction this should have been the same air mass). With high breaking waves and a large breaking zone (500 m) local production of sea salt must have been significantly increased. This is confirmed by a relatively low Ängström values around 0.6–0.7, versus around 1.7 in Birkenes. Such situation changes the local aerosol situation and thus their radiative properties which directly influence the radiative forcing. Even though we show a local phenomenon, it may have a more spatial impact and this needs further studies.

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