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Climatology of aerosol optical properties in Northern Norway and Svalbard

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Abstract. We present comparisons between estimates of the aerosol optical thickness and the Ångström exponent in Northern Norway and Svalbard based on data from AERONET stations at Andenes (69 °N, 16 °E, 379 m altitude) and Hornsund (77 °N, 15°E, 10 m altitude) for the period 2008–2010. The three-year annual mean values for the aerosol optical thickness at 500 nm $\tau(500)$ at Andenes and Hornsund were 0.11 and 0.10, respectively. At Hornsund, there was less variation of the monthly mean value of $\tau(500)$ than at Andenes. The annual mean values of the Ångström exponent α at Andenes and Hornsund were 1.18 and 1.37, respectively. At Andenes and Hornsund α was found to be larger than 1.0 in 68% and 93% of the observations, respectively, indicating that fine-mode particles were dominating at both sites. Both sites had a similar seasonal variation of the aerosol size distribution although one site is in an Arctic area while the other site is in a sub-arctic area.

1 Introduction

Atmospheric aerosols are suspensions in air of solid or liquid particles, which are often observed as dust, smoke, and haze. Earth's climate forcing is affected by the "direct" and "indirect" effects of aerosols. The direct effect is caused by large aerosols particles, which can absorb radiation and scatter it back to space. The absorption associated with the direct effect tends to heat the planet, whereas the indirect effect tends to cool it (McCormick and Ludwig, 1967; Charlson and Pilat, 1969). Through the indirect effect, small aerosol particles can modify the microphysical and radiative properties of clouds. The ambient concentration of cloud condensation nuclei (CCN) and ice nuclei may increase with the aerosol particle concentration. For a fixed cloud liquid content, an increase in the CCN causes more and smaller cloud droplets, which make a cloud more reflective and longer lasting (Twomey, 1974; IPCC, 2007).

Aerosols can be due to both natural and anthropogenic (human) processes. Examples of natural aerosols are dust, sea salt, and sulfuric acid particles. The latter are occasionally injected into the stratosphere and may persist for years, whereas the other types of aerosols are mainly present for a few weeks in the lower troposphere. Anthropogenic aerosols originate from urban and industrial emissions, agricultural burning, domestic fires, deforestation, and farming practices.

Understanding optical properties of aerosols is important in investigations of climate change, since aerosols have a major impact on the radiative energy balance (Charlson et al., 1992). Knowledge of the aerosol forcing has improved during the last decades. However, lack of knowledge of the physical and chemical properties of aerosols and their spatial and temporal distribution, implies that a substantial reduction in the uncertainty of aerosol forcing estimates is still needed (Hsu et al., 2000; IPCC, 2007).

The aerosol optical thickness (AOT) of the atmosphere, which is one of the main characteristics of atmospheric aerosols, is obtained through optical measurements. Other aerosol properties, such as the Ångström exponent (α), the aerosol size distribution, and the aerosol single-scattering albedo, are required for evaluating the impact of aerosols in the climate system (Hsu et al., 2000) .

Studies based on field campaigns have provided detailed characterizations of regional, chemical, microphysical, and radiative properties of aerosols, along with relevant characterizations of surface and atmospheric conditions. But field campaigns are restricted by relatively short durations and limited spatial coverage. Surface networks, such as the Aerosol Robotic Network (AERONET), provide a needed long-term coverage, while measurements by satellite instruments provide extensive spatial coverage (Holben et al., 2001).

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Several studies have reported on the aerosol climatology in the Arctic, but aerosol observations in arctic regions are still scarce (Herber et al., 2002; Stohl, 2006; Law and Stohl, 2007; Tomasi et al., 2007; Rozwadowska and Sobolewski, 2010). The climate of sub-arctic areas have also aroused scientists' attention, and a number of aerosol observations have been made. The first observations of the aerosol optical properties in a European sub-arctic area were made at the ALOMAR station (Andøya island, Andenes, Norway) during summer campaigns in 2002 and 2003 (Toledano et al., 2006). These observations showed that the AOT and α values were not in the range typical for maritime aerosols. In 2006, long-term observations were made at the same place. Rodríguez et al. (2012a) reported results from long-term measurements in the period from 2002 to 2010, which included results from summer campaigns in the period from 2002 to 2005. They found the mean AOT to have a very low value of 0.10 ± 0.05, but found α values in the range 1.2 ± 0.4, indicating that either small continental aerosols ($\alpha = 1.6$) or large maritime aerosols ($\alpha = 0.8$) were dominating (Hess et al., 1998; Holben et al., 2001; Toledano et al., 2009).

An overview of the aerosol climatology at several sub-arctic stations in spring and summer 2007 was given by Rodríguez et al. (2012b). The AOT at three different stations (Andenes in Norway, Abisko in Sweden, and Sodankylä in Finland) was found to have a similar mean value of about 0.07 in spring-summer 2007. Higher α values were found at Sodankylä, indicating that the atmosphere at this site was dominated by a continental type of small aerosols, while Andenes and Abisko were influenced by both large maritime aerosols and small continental aerosols. The variation in the climate between arctic and sub-arctic areas is also an important issue that has been investigated using aerosol information from twenty sites in Scandinavia and Svalbard (Toledano et al., 2012). A seasonal variation of the AOT occurs in the Arctic, where a reduction of the AOT during summer has been observed because of the presence of arctic haze in spring (Stohl, 2006; Quinn et al., 2007). This phenomenon has not been observed in sub-arctic areas.

In this study, the mean AOT for the period 2008–2010 was found to have a low value of about 0.10 at both Andenes and Hornsund, consistent with the results found in the studies mentioned above. However, a seasonal variation was observed in 2010 at the sub-arctic site of Andenes, where the monthly mean AOT in summer was found to decrease to 0.03, and where the influence of large maritime aerosols that year was found to be less than in 2008 and 2009.

2 Methodology

2.1 Sites

In this paper, we study long-term measurements of aerosols above AERONET stations at Andenes (69 °N, 16 °E, 379 m altitude) and Hornsund (77 °N, 15 °E, 10 m altitude), located as shown in the map in Figure 1. The observation period at these two sites used in this paper is from 2008 to 2010, since there are no quality assured (Level 2.0) data available before May 2008 at Andenes. Both sites are above the Arctic circle. Andenes is located on the west coast of Northern Norway. The atmosphere at Andenes is influenced by Norwegian coastal water, which is a mixture of freshwater from Norwegian fjords and warm water from the Norwegian Atlantic Current (NAC). This mixture of coastal water represents a low-salinity current that flows westwards in the Skagerrak and northwards along with the Atlantic flow along the Norwegian coast. NAC is a warm brackish part of the Atlantic flow, which enters the North Sea north of Shetland, and the return current along the Norwegian coast flows northward in the Norwegian Sea towards Svalbard (Albretsen, 2011). Hornsund is located at the West Spitsbergen island in the Spitsbergen archipelago (Svalbard). The warm West Spitsbergen Current (WSC), which is the northernmost extension of the NAC, passes by the east coast of the island and keeps the water from freezing (Haugan, 1999). There is also a freshwater current coming from the Hornsund fjord, the large southernmost fjord on Svalbard.

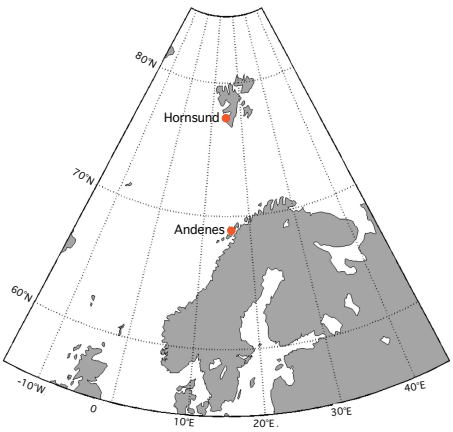

Fig. 1. Location of the two sites, Andenes and Hornsund.

2.2 Instrument and Data

More than 760 stations worldwide are connected through the public website of AERONET (http://aeronet.gsfc.nasa.gov).

The AERONET program operates a ground-based network of well-calibrated sun/sky radiometers. All spectral measurements of sun and sky radiances are calibrated and screened to be cloud-free (Smirnov et al., 2000). The accuracy of the AOT (τ) at mid-visible wavelengths is 0.01 to 0.02 (Eck et al., 1999). Three levels of data were provided by AERONET: Level 1.0 (raw data), Level 1.5 (cloud-screened data) (Smirnov et al., 2000), and Level 2.0 (quality-assured data). The details regarding quality assurance is available on the AERONET website.

The AERONET measurements are carried out by solar-powered CIMEL sun photometers, each being composed of an optical head, an electronic control box, and an automated robot system. Two collimators, one for direct sun radiance measurements and the other for sky radiance measurements, are installed in the optical head with a set of spectral filters in the range 440–1,020 nm. The real time operation of the data acquisition and motion steering is controlled by two microprocessors that are built into the electronic control box. First, the sun photometer's collimator for direct radiance measurements is pointed towards the sun with an accuracy of approximately 1°, and then a 4-quadrant detector is employed for accurate sun tracking. A sequence of measurements of both the direct sun radiance and the sky radiance can be performed automatically 6 times every clear day. The measurements will be canceled if the "wetness sensor" of the CIMEL is exposed to precipitation. The measured data from the memory of the CIMEL can be transferred to a PC or via the Data Collection System (DCS) of AERONET to one of three geostationary satellites: GOES, METEOSAT, and GMS, and then retransmitted to the ground receiving station (Holben et al., 1998).

Through the use of an inversion algorithm (Dubovik and King, 2000; Dubovik et al., 2006) based on spectral deconvolution (O'Neill et al., 2001a, 2003) and a bimodal representation of the aerosol size distribution, AERONET provides a set of columnar retrieval parameters that comprise the size distribution, the refractive index, and the single-scattering albedo of aerosols from direct sun and sky radiance measurements.

In this paper, we analyze quality assured Level 2.0 data from two AERONET sites at Andenes (69 °N, 16 °E, 379 m altitude) and Hornsund (77 °N, 15 °E, 10 m altitude).

3 Analysis

3.1 Variation of aerosol optical thickness (AOT)

3.1.1 Daily and monthly AOT

Figure 2 shows daily averages of $\tau(500)$, the AOT at 500 nm, at Andenes and Hornsund. Less data were found at Hornsund, since most of the observations there were done during spring and summer due to the cold weather in the winter and "polar night" from early December until mid-January. Also, since Andenes has lower latitude than Hornsund, more clear days for measurements can be found at Andenes than at Hornsund (Rodríguez et al., 2012a).

The three-year annual mean values (standard deviations) for $\tau(500)$ at Andenes and Hornsund were 0.11 (0.05) and 0.10 (0.05), respectively. For the three-year observation period, the daily average values of $\tau(500)$ were found to range from 0.02 to 0.37 at Andenes, and from 0.03 to 0.48 and Hornsund, when including the singular large value of 0.48, which occurred on Julian day 119 in 2008. When excluding this singular large value, $\tau(500)$ at Hornsund was found to range from 0.03 to 0.23. At both sites, 24% of the values of $\tau(500)$ were found to be below 0.07, indicating that a very clean atmosphere prevailed during spring and summer. Thus, there was a larger spread of the $\tau(500)$ values at Andenes than at Hornsund (disregarding the previously mentioned singular large value at Hornsund), and Andenes had a slightly higher annual mean value of $\tau(500)$ than Hornsund.

By computing the deviation of each monthly average value for $\tau(500)$ from the corresponding three-year monthly mean value, one obtains the monthly variability over the three-year period of the total aerosol content in atmosphere, which is shown in Figure 3. The base lines in the top and bottom panels of Figure 3 represent the three-year average of $\tau(500)$ at Andenes and Hornsund, respectively. At Andenes, $\tau(500)$ had a different behaviour in 2010 than in 2008 and 2009. In 2008 and 2009, the monthly mean values of $\tau(500)$ were higher than the three-year average. In contrast, the monthly mean values of $\tau(500)$ in 2010 were much lower than both the three-year average and the monthly mean values of $\tau(500)$ in 2008 and 2009. The typical decrease of τ to low values in summer that occurs in arctic areas (Stohl, 2006; Quinn et al., 2007) was observed at Andenes in 2010. Thus, the monthly mean value decreased to 0.03 in September 2010, and, as indicated above, each monthly mean value in 2010 was lower than the corresponding three-year monthly mean value.

As mentioned above, at Hornsund (bottom panel of Figure 3), the variation of the monthly mean value of $\tau(500)$ was less than at Andenes (top panel of Figure 3). However, many of the daily averages of $\tau(500)$ at Hornsund in summer of 2008 were lower than 0.05, indicating that the atmosphere above this station then contained less aerosols than at other periods.

3.2 Particles size

3.2.1 Daily Ångström exponent

The Ångström exponent α is the first spectral derivative of τ, and contains information of aerosol particle size (O'Neill et al., 2001a,b, 2003). Figure 4 shows daily averages of α at Andenes and Hornsund. The three-year annual mean values (standard deviations) of α for Andenes and Hornsund were 1.18 (0.31) and 1.37 (0.23), respectively. During the three-

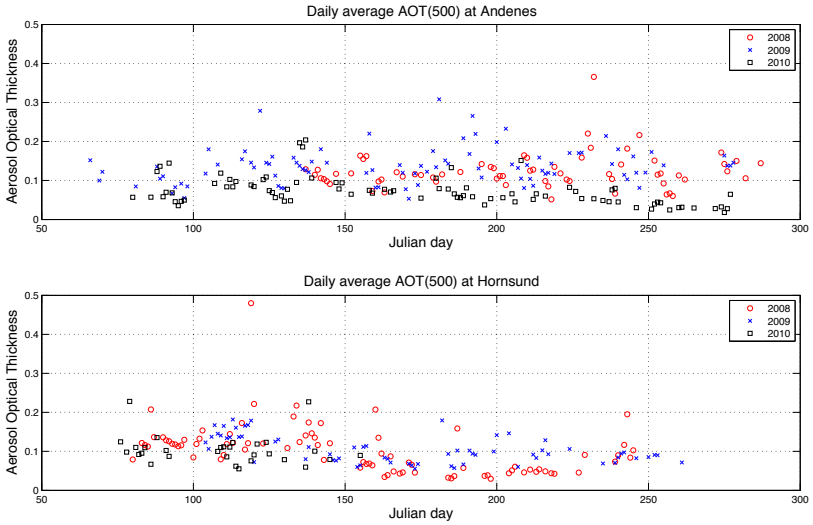

Fig. 2. Daily average values of $\tau(500)$ in the period from 2008 to 2010 at Andenes and Hornsund.

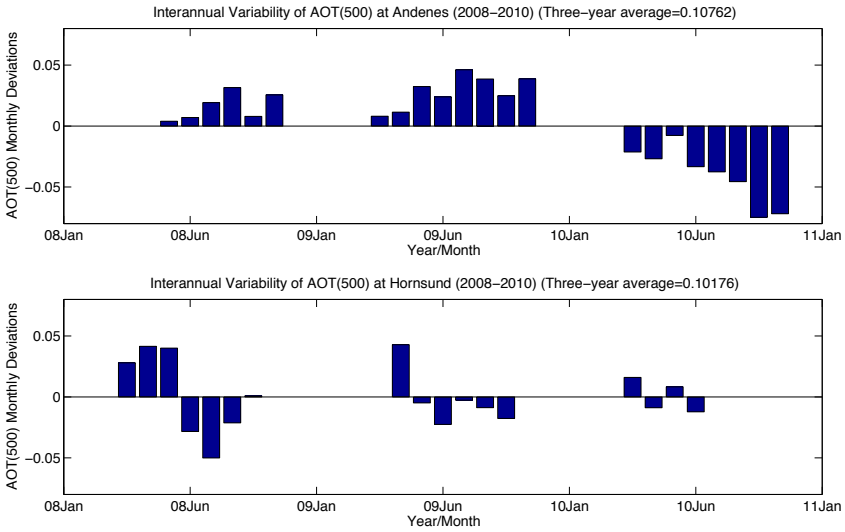

Fig. 3. Interannual variability of the aerosol optical thickness at Andenes and Hornsund.

year observation period, the daily average of α ranged from 0.40 to 1.82 at Andenes and from 0.58 to 1.86 at Hornsund. The α values, which were computed from observations at wavelengths in the range 440–870 nm, provide information about the aerosol size distribution. Values of α larger than 1.0 indicate that fine-mode particles dominate, while coarse-

mode particles dominate when α is smaller than 1.0 (Hess et al., 1998; Smirnov et al., 2002).

The distribution of the daily average values of α was more scattered at Andenes than at Horsund. The daily averages of α at Hornsund in summer of 2008 were generally higher than 1.4. At Andenes, 32% of the daily average values of α were lower than 1.0, while the corresponding percentage at Hornsund was only 7, indicating that more maritime aerosols were present at Andenes. But at Andenes in 2010, 91% of the daily average values of α were higher than 1.0, and 93% of the daily average values of $\tau(500)$ were smaller than 0.16, indicating a clear influence of fine-mode continental aerosol particles (according to the classification described in Rodríguez et al. (2012a)). On Julian day 119 in 2008 at Hornsund, a high daily average value of $\tau(500)$ of 0.48 was observed along with a high daily average of α of 1.74, indicating a high concentration of fine-mode particles, which might be due to the influence of smoke or some other kind of anthropogenic pollution. At Andenes, the highest daily average value of $\tau(500)$ of 0.37 along with a daily average value of α of 0.90 was observed on Julian day 232 in 2008, indicating that the atmosphere contained both coarse-mode and fine-mode particles, which might be due to a mixture of maritime and smoke/pollution aerosol particles.

3.2.2 Fine and coarse mode of aerosol optical thickness

The aerosol particle size distribution (PSD) was assumed to be bimodal, and accordingly the total AOT (τ) had contributions from both particle modes, i.e. $\tau = \tau_f + \tau_c$, where τ_f and τ_c are the contributions to τ due to fine-mode particles and coarse-mode particles, respectively. The radiation in the ultraviolet to near-infrared spectral range is largely influenced by fine-mode particles in the submicron size range and coarse-mode particles in the supermicron size range. The fine-mode and coarse-mode components of τ can be extracted from the spectral information content of the total AOT (τ) without intermediate computations of PSD. The algorithm used in AERONET is a "spectral deconvolution algorithm (SDA) (O'Neill et al., 2001a, 2003)". SDA uses the first and second spectral derivatives of τ (α and α') to separate the contributions to τ from the two modes. These two components of τ are defined optically, not by a microphysical cutoff of the associated PSD at some specific size, making the separation more reliable (O'Neill et al., 2001b).

At Andenes and Hornsund the daily average values of α were found to be larger than 1.0 in 68% and 93% of the observations, respectively, indicating that fine-mode particles had the greatest influence, see Figure 5. Most α values were found to be in the range from 1.3 to 1.7 (77%). Figure 5 also indicates there were more very small fine-mode particles at Hornsund than at Andenes. There were less sea salt particles at Hornsund than at Andenes because the warm brackish current from the Atlantic flow turns less salty when it meets the ice-dominated East Greenland Current (EGC), which carries cold, fresh water and sea ice in the Fram Strait (Saloranta and Haugan, 2001).

Figure 6 shows the fine-mode and coarse-mode contributions to τ at the two sites. The dominating fine mode of particles at each of the two sites can be observed from the similarity of the curve showing the total AOT (τ) and the fine-mode AOT (τ_f). Figure 7 shows the percentage monthly contribution to the total AOT from fine-mode particles. The remaining percentage represents the monthly contribution to the total AOT from coarse-mode particles.

At Andenes the contribution to the total AOT from fine-mode particles in different months ranged from 62% to 79% (see left panel of Figure 7). The lowest contribution of 62% occurred in April. The right panel of Figure 7 shows that the contribution to the total AOT at Hornsund from fine-mode particles in different months ranged from 67% to 85%. The lowest contribution occurred in May, while the highest occurred in September. At both sites the atmosphere was significantly dominated by fine-mode aerosol particles throughout the year.

The seasonal aerosol size distribution is shown in Figure 8. Unfortunately, the data at Hornsund were insufficient for representing the spring season (right panel of Figure 8). At Andenes, the aerosol size distribution during spring (MAM represents March, April, and May) in 2009 and 2010 had peak values of approximately 0.2 μm (fine-mode) and 1 μm (coarse-mode). However, the behavior in summer (JJA represents June, July, and August) in 2008 was similar to that in spring in 2009 and 2010.

During summer in 2008 and 2009, Andenes had a peak value for the fine mode of the aerosol size distribution at about 0.2 μm, and peak values for the coarse mode at about 1.5 μm in 2008 and 4 μm in 2009. At Hornsund, the peak values in summer in 2008 and 2009 were similar to those in Andenes (0.15 and 2 μm).

4 Conclusions

We have analyzed data recored by CIMEL sun/sky photometers at the AERONET sites at Andenes (69 °N, 16 °E, 379 m altitude) and Hornsund (77 °N, 15 °E, 10 m altitude) in the period from 2008 to 2010.

For the three-year observation period, the daily averages of $\tau(500)$ were found to range from 0.02 to 0.37 at Andenes, and from 0.03 to 0.23 and Hornsund (when disregarding a singular large value of 0.48). The three-year annual mean values for $\tau(500)$ at Andenes and Hornsund were 0.11 and 0.10, respectively. The standard deviation of $\tau(500)$ was 0.05 at both sites. At Andenes, the monthly mean value decreased to 0.03 in September 2010, and each monthly mean value in 2010 was lower than the corresponding three-year monthly mean value. The variation of the monthly mean value of $\tau(500)$ was less at Hornsund than at Andenes. A seasonal variation of $\tau(500)$ was observed in 2010 in the sub-

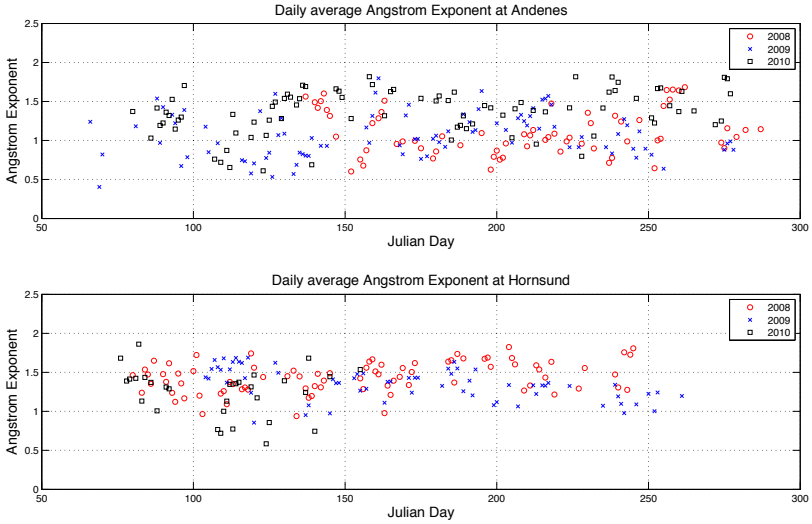

Fig. 4. Daily average values of the Ångström exponent α in the period from 2008 to 2010 at Andenes and Hornsund.

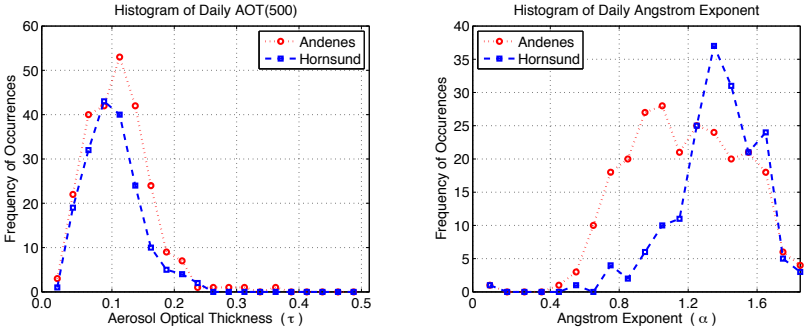

Fig. 5. Frequency distribution of the daily average of τ and α at Andenes and Hornsund.

arctic area at Andenes, where the influence of large maritime aerosols that year was found to be less than in 2008 and 2009.

The three-year annual mean values (standard deviations) of α of Andenes and Hornsund were 1.18 (0.31) and 1.37 (0.23). Thus, the standard deviation of α at Andenes (0.31) was higher than at Hornsund (0.23). At Andenes and Hornsund daily average values of α larger than 1.0 were found in 68% and 93% of the observations, respectively, indicating that fine-mode particles dominated at both sites. In summer of 2008 and 2009, Andenes and Hornsund had similar peak values of the aerosol size distribution (0.15 μm (fine-mode) and 2 μm (coarse-mode)).

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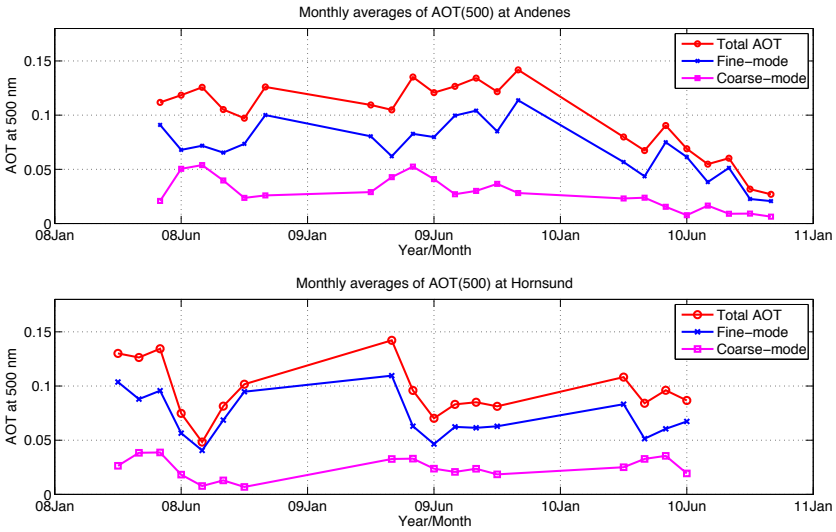

Fig. 6. Fine-mode and coarse-mode components of $\tau(500)$ at Andenes and Hornsund.

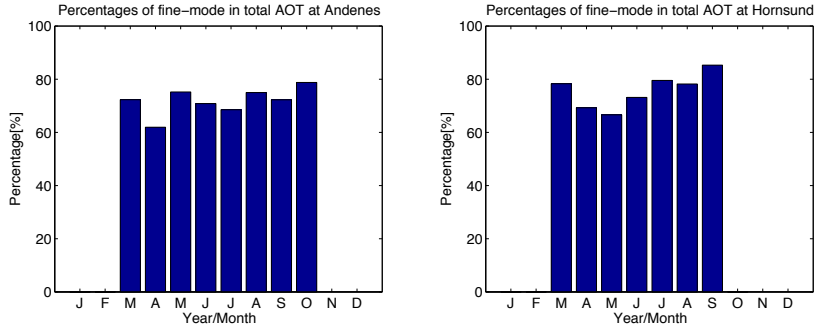

Fig. 7. Contribution of fine-mode particles for different months at Andenes and Hornsund.

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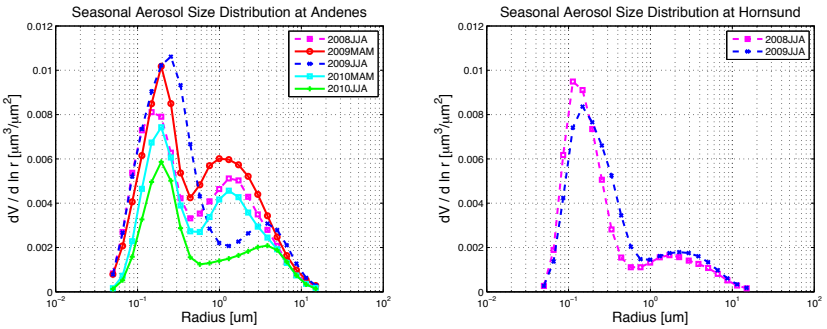

Fig. 8. Seasonal size distributions of aerosols for the period 2008-2010 at Andenes and Hornsund.

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