Papers

Influence of aerosol vertical profile variability on retrievals of aerosol optical thickness from NOAA AVHRR measurements in the Baltic region*

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Anna Rozwadowska

Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland;

e-mail: ania@iopan.gda.pl

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Abstract

The expected influence of variability in atmospheric aerosol profiles on retrievals of aerosol optical thickness (AOT) from NOAA AVHRR measurements is analysed. In particular, the bias in the AOT retrieval due to the assumption of a climatological aerosol profile in the retrieval algorithm is studied. The bias is defined as the difference between AOT retrieved with an algorithm using a climatological aerosol profile, and the actual AOT employed in the calculations of radiances at the top of the atmosphere (TOA). The TOA radiances are simulated by means of the MODTRAN code for different aerosol profiles. Atmospheric conditions and solar and satellite angles used in the bias simulations are typical of the Baltic region. In the simulations, the maximum absolute value of the bias amounts to nearly 40% in channel 2 and 14% in channel 1 of AVHRR.

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1. Introduction

Upward radiances at the top of the atmosphere (TOA) are an important source of information on the atmosphere and the Earth's surface. Therefore the precise modelling of the atmospheric component of these radiances is an important problem in remote sensing algorithms. Atmospheric aerosols control the variability of TOA radiances over a clear sky for a given position of the sun and a satellite. The vertical distribution of the type and concentration of aerosol particles varies in time and space, and depends mainly on aerosol sources, the synoptic situation and atmospheric stability. In general, in the case of a stratified scattering and absorbing atmosphere, the relative position of predominantly scattering and absorbing layers influences upward radiances at the top of the atmosphere. Satellite algorithms for aerosol optical thickness (AOT) are usually based on model relations between TOA radiances and AOT. Showing that variability in aerosol profiles only negligibly affects the TOA radiances and thus the retrieved aerosol optical thickness would reduce the number of variables in the algorithms, thereby simplifying them. The aim of the present study was to analyse the possible influence of variability in atmospheric aerosol profiles on angular distributions of the TOA upward radiances, and to assess the biases in AOT introduced by remote sensing algorithms that neglect this variability.

Typically, the variability of aerosol profiles is not included in remote sensing algorithms for either AOT or aerosol-type characterisation. Neither is it taken into account in the sensitivity analysis of the algorithms (e.g. Costa et al. 2004). However, some authors have indicated that in certain cases this parameter may be significant. Meloni et al. (2005) studied the influence of a vertical profile of Saharan dust on the calculation of the direct radiative forcing at the surface and at the top of the atmosphere. The vertical profile of Saharan dust in the atmosphere is generally characterised by a large aerosol concentration in the mid-troposphere; this is quite unlike the climatological distribution of other types of particles, which show a peak at the surface and a rapid decrease with height. At the TOA visible radiative forcing is weakly dependent on the vertical profile (up to 10% variation in the daily average forcing) for weakly absorbing particles and strongly dependent (the daily radiative forcing may vary up to 100%) for strongly absorbing particles. For values of the single scattering albedo of around 0.67, the sign of the forcing depends on the vertical profile. Mitchell et al. (2006) demonstrated the considerable effect of aerosol layer depth on the heating rate profile for an aerosol generated by a firestorm.

In the present study we analysed the possible influence of the variability of atmospheric aerosol profiles on angular distributions of TOA upward

radiances, focusing on its possible impact on AOT retrievals. We did not intend to analyse any particular case, rather to estimate the maximum uncertainty to be expected, and to specify the conditions under which a maximum uncertainty could be expected.

The analysis was based on simulations using the MODTRAN code (Berk et al. 1999a). The following tropospheric aerosol models were used in the study: urban/industrial, polluted maritime and clean maritime (d'Almeida et al. 1991). Radiances at the top of the atmosphere were modelled for three kinds of vertical profiles of aerosol attenuation coefficient for $\lambda = 550$ nm. Profiles similar to those included in MODTRAN were used as standard or climatological profiles and were employed in the retrieval algorithm. 'Real' TOA radiances were calculated for the extreme cases when the entire aerosol was concentrated near the surface (0–1 km layer), or in the layer 5–7 km above the surface. Aerosol optical thickness retrieved from TOA radiances by means of the algorithm were compared to the actual AOT values employed in the simulation of TOA radiances. The differences (biases) were calculated for various values of AOT, water vapour content (WV), solar zenith angle (SZA), satellite zenith angle, and relative azimuth between the satellite and the sun. The atmospheric conditions and solar and satellite angles used in the bias simulation are similar to those in the Baltic region.

2. Methods

Radiative transfer was simulated by the MODTRAN4 (v. 1) code (Berk et al. 1999a). MODTRAN has already been successfully used in remote sensing, e.g. in the analysis of data from AVIRIS (Green et al. 1998, Adler-Golden et al. 1999) and for atmospheric correction (Berk et al. 1999b). In the present work a modified version of MODTRAN was employed, containing a bidirectional reflectance function for a rough sea surface in the form given by Woźniak (1996).

In the simulations vertical profiles and contents of atmospheric gases from the MODTRAN Sub-Arctic Summer Atmosphere (60°N) were used. Water vapour and ozone were the exceptions. In these cases the MODTRAN profiles were scaled so that the total ozone and water vapour content in the atmosphere would be comparable to the values found over the Baltic Sea. The ozone content was constant in the simulations and set to 0.35 ATM-cm. For comparison, the mean ozone content at Belsk (Poland) varies from 0.296 ATM-cm in November to 0.405 ATM-cm in April (Dziewulska-Łosiowa 1991). The water vapour content (precipitable water) in the atmospheric column WV was a variable in the modelling. WV equal to 0.5 and 3.0 g cm^{-2} were used. These values of WV were estimated from air temperature and

air humidity measurements for the warm half of the year (from May to September, 1961 to 1990) at the Gotska Sandon station (Miętus 1998). According to a relation by Reitan (1960) and psychrometric tables (Kostyrko et al. 1986), $WV = 0.5$ g cm^{-2} corresponds to an air temperature of 0°C and a relative humidity of 40% and is practically the lowest magnitude of WV expected at Gotska Sandon from May to September. $WV = 3.0$ g cm^{-2} corresponds to an air humidity of 90% and an air temperature of 18°C and is the highest water content accepted by the MODTRAN Sub-Arctic Summer Atmosphere.

Three tropospheric aerosol models were employed in this simulation (d'Almeida et al. 1991):

- urban/industrial – contains mainly water-soluble components, soot and a dust-like component; characterised by a relatively steep spectrum of the absorption coefficient, relatively high absorption and low values of the asymmetry parameter (mean cosine of the scattering function) (Fig. 1); it is typical of highly polluted continental regions;
- polluted maritime – contains mainly water-soluble substances, soot and sea salt; its optical properties lie between those of the urban and the clean maritime aerosols (Fig. 1); it is typical of inland and coastal seas, like the North Sea, the Mediterranean Sea and the Baltic;
- clean maritime – contains sea salt and non-sea-salt sulphates; it has a flat spectrum of the attenuation coefficient, negligible absorption, and high values of the asymmetry parameter (Fig. 1); it is typical of remote oceans, like the south-east Pacific, the south Atlantic and the Indian Oceans.

The optical properties of the model aerosols listed above for a relative air humidity of 90% were employed in the simulation. 90% is the modal value of the probability distribution of air humidity for the period from May to September at Gotska Sandon (Miętus 1998). It is highly probable that the optical properties of real Baltic aerosols lie in the range of the optical properties of these three model aerosols.

Simulations were performed for three types of vertical profiles of the aerosol extinction coefficient at $\lambda = 550$ nm. The standard or 'climatological' profile (profile 2) in the simulations was based on MODTRAN aerosol profiles. The exact shape of the profile depended on the aerosol optical thickness. It is shown in Fig. 2 for AOT equal to 0.1, 0.2, 0.5 and 1.0. For comparison, MODTRAN profiles for horizontal visibility ranges of 20 km, 10 km, 4 km and 2 km are given. The climatological profile was employed in our satellite algorithm for AOT retrievals from AVHRR channels 1 and 2. The 'real' radiances at the TOA were simulated for two extreme cases:

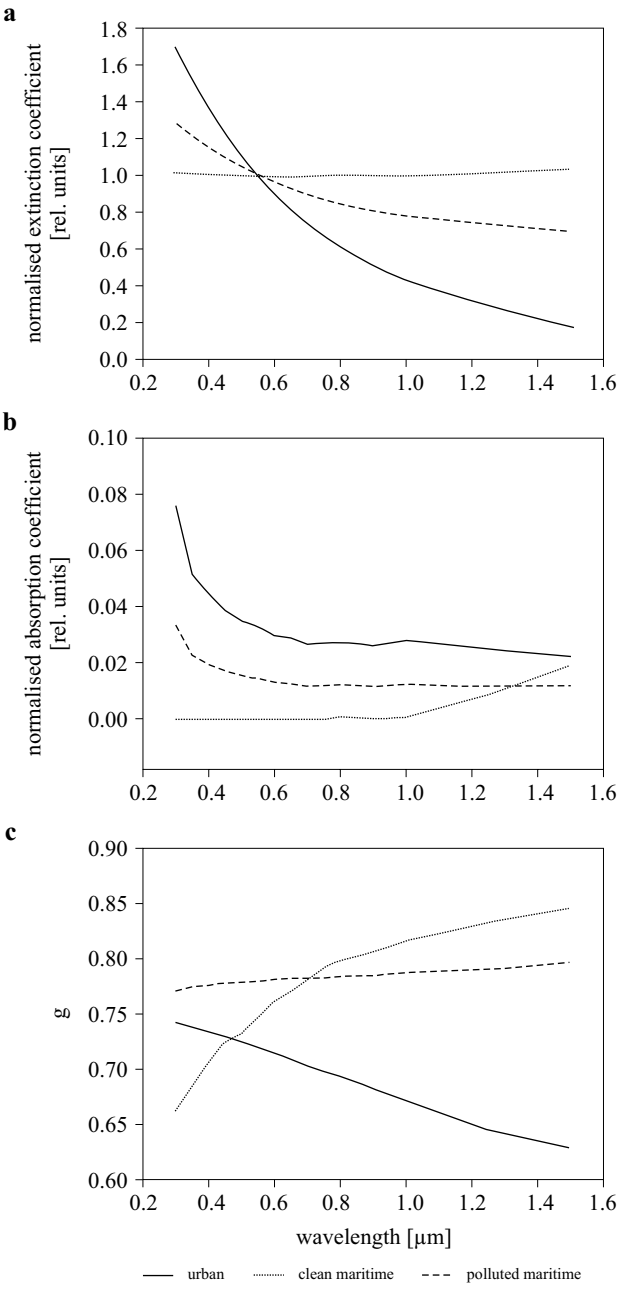

Fig. 1. Optical properties of model aerosols used in the simulations of aerosol profile bias in aerosol optical thickness (AOT) retrievals: normalised extinction coefficient (a), normalised absorption coefficient (b), parameter g – mean cosine of scattering function (c). Extinction and absorption coefficients are divided by the extinction coefficient for λ = 550 nm

- the aerosol is concentrated in the 1-km-thick near-surface layer (profile 0);
- the aerosol is concentrated in the 2-km-thick layer with its base at 5 km above the sea level (profile 1).

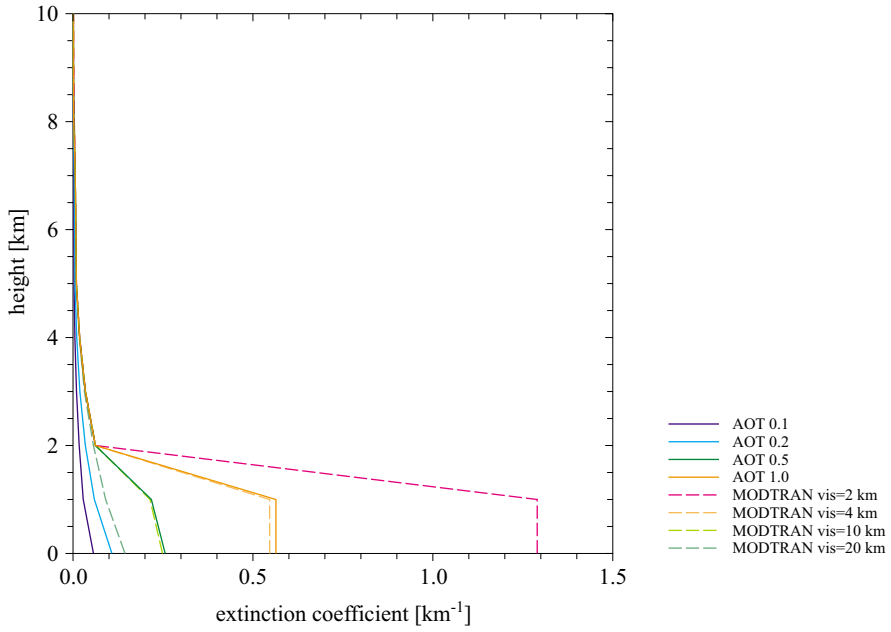

Fig. 2. 'Climatological' vertical profiles of the aerosol extinction coefficient for $\lambda = 550$ nm (solid lines), used in the aerosol optical thickness (AOT) retrieval algorithm, for AOT equal to 0.1, 0.2, 0.5 and 1.0. For comparison, MODTRAN profiles (dashed lines) are given for horizontal visibility ranges of 20 km, 10 km, 4 km and 2 km

The aerosol layers in profiles 0 and 1 are uniform with respect to aerosol concentration and optical properties. In the case of profile 2, the aerosol type does not change with altitude. Profile 0 represents the situation when the atmosphere is stable and a local aerosol source positioned at the surface is dominant. A profile similar to profile 1 may occur in the case of the advection of air with an aerosol concentration higher than in the surface layer. The advected aerosol is unrelated to the underlying surface and may reside at a certain height. The advection of polluted air from lower latitudes over the Arctic Ocean is an example of this. A similar situation may occur in the case of, say, fires (e.g. Meloni et al. 2004) and advection from highly polluted industrial areas or from deserts (e.g. Formenti et al. 2002). The cases mentioned above are extreme; the real aerosol profiles usually fall somewhere between them.

The simulations were performed for aerosol optical thicknesses AOT (550 nm) equal to 0.1, 0.2, 0.5 and 1.0, and for the spectral ranges of channels 1 and 2 of NOAA AVHRR (see Fig. 3). Whereas gas absorption is relatively weak in channel 1, absorption by water vapour becomes significant in channel 2. Table 1 gives the full list of input parameters for the simulations.

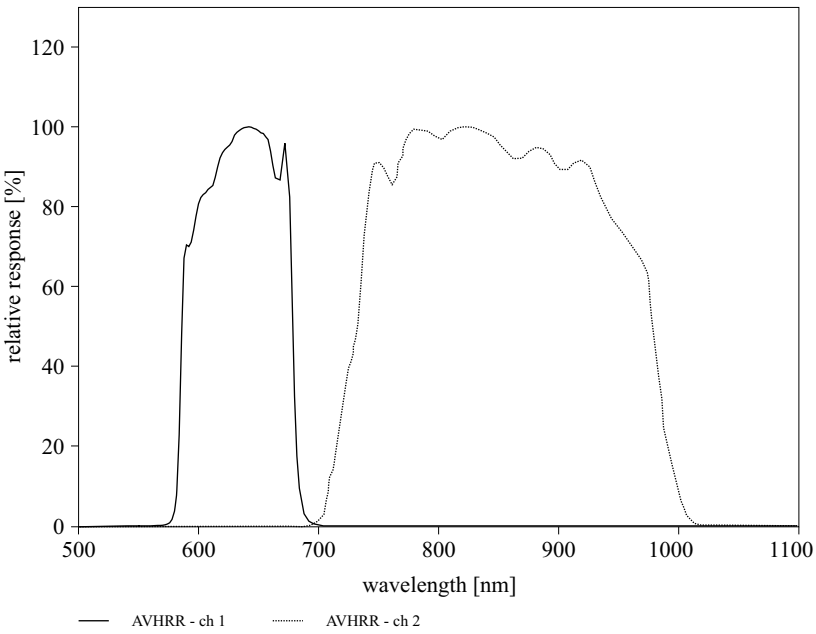

Fig. 3. Spectral characteristics of AVHRR channels 1 and 2 (NOAA 15)

Table 1. Model input parameters

Atmospheric model	Sub-Arctic Summer, 60°N
Atmospheric pressure	1010 hPa
Ozone	0.35 ATM-cm
Water vapour, WV	0.5, 3.0 g cm^{-2}
Solar zenith angle, SZA, ϑ_s	35°, 65°
Satellite zenith angle, ϑ_{sat}	1°, 8°, 16°, 23°, 31°, 38°, 44°, 52°
Relative azimuth between sun and satellite $azym_{sat-sol} = (azym_s + 180^\circ - azym_{sat})$	0–180°, every 10°
Aerosol models, AM	1 – urban 2 – clean maritime 3 – polluted maritime
Aerosol profiles, $prof$	0 – uniform layer 0–1 km 1 – uniform layer 5–7 km 2 – 'climatological'
Aerosol optical thickness, AOT (550 nm)	0.1, 0.2, 0.5, 1.0
Spectral channels, ch	1 – AVHRR channel 1 2 – AVHRR channel 2
Sea surface	reflective, rough, wind speed 7 m s^{-1} no water–leaving radiance

The retrieval algorithm was based on MODTRAN computations on the assumption that the aerosol profile is equivalent to the climatological profile (profile 2). The modelled relations between the AOT and the TOA radiance were approximated by a second-order polynomial for each case of SZA, the satellite angle, AOT, water vapour content and AVHRR channel. The error of these approximations is negligible, except for satellite angles near the solar glint, but such cases were rejected and therefore omitted from the analysis (see Fig. 4). Glint radiances are rarely used in satellite algorithms because the relations between the TOA radiances and AOT have two solutions in this angular region. Moreover, the contribution of sea surface reflection to the TOA radiance is then high, which introduces an additional error to the AOT algorithms.

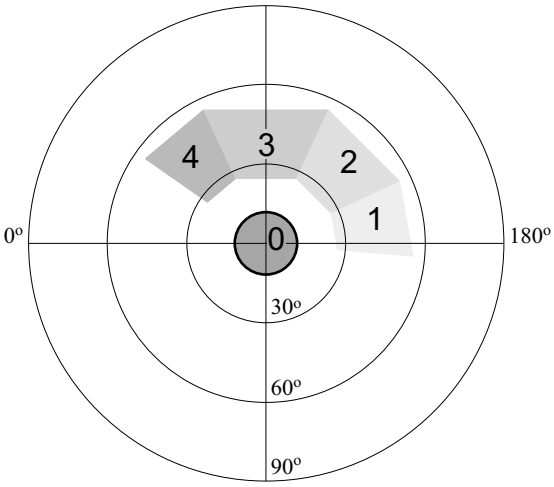

Fig. 4. Angular 'sectors' for which aerosol profile biases in aerosol optical thickness (AOT) retrievals were averaged. The averaged biases are shown in Figs. 6 and 7. Note that 0° is the azimuth of the forward scattering direction, 180° the azimuth of the backward scattering direction. Circles 30°, 60° and 90° represent satellite zenith angles

The bias (uncertainty) in AOT retrieval due to the assumption of a climatological aerosol profile in the retrieval algorithm is defined as the difference between the AOT retrieved from the TOA radiance by means of an algorithm employing a climatological aerosol profile ($prof = 2$) and the actual AOT used in the TOA radiance simulations for a given sun-pixel-satellite geometry (ϑ_s, ϑ_{sat}, $azym_{sat-sol}$) and water vapour content WV:

$$\varepsilon(\vartheta_s,\, \vartheta_{sat},\, azym_{sat-sol},\, prof = i,\, WV) = \tag{1}$$

$$= AOT_{retrieved}\big(L_{\mathrm{TOA}}\big(\vartheta_s,\, \vartheta_{sat},\, azym_{sat-sol},\, prof = i, WV,\, AOT\big),\, prof = 2\big) - AOT,$$

where L_{TOA} is the simulated radiance at the top of the atmosphere, calculated for the 'real' aerosol profile ($i = 0,\ 1$) and given AOT, ϑ_s and ϑ_{sat} are the zenith angles of the sun and the satellite, respectively, and $azym_{sat-sol}$ is the relative azimuth between the sun and the satellite defined as follows:

$$azym_{sat-sol} = (azym_s + 180^\circ - azym_{sat}). \tag{2}$$

The bias is positive when the AOT retrieved on the assumption of a climatological aerosol profile is higher than the actual AOT.

3. Results

This section presents the estimated bias in AOT retrievals resulting from the assumption of a climatological aerosol profile in the retrieval algorithm, and the dependence of the bias on the AVHRR channel, aerosol optical thickness, water vapour content in the atmosphere, solar zenith angle and satellite angles. The bias is assumed negligible when its absolute value is < 0.01. For comparison, 0.01–0.02 is an uncertainty in the AOT retrieval from surface radiometric measurements by the spherical AERONET algorithm (Dubovik & King 2000, Dubovik et al. 2000).

Because the bias depends on the satellite position with respect to the sun, it was analysed for five groups of satellite azimuth and zenith angles separately. These groups, further called sectors, are shown in Fig. 4. As mentioned before, the angular regions near the solar glint were omitted from the analysis.

For channel 1 the bias is quite variable, depending on the satellite angles. For aerosol profile 1, with the total aerosol located in the mid-troposphere, the bias is typically negative in sectors 1 (satellite azimuth and zenith angles close to the backward scattering directions) and 2. Its value increases towards the glint region to become positive in sectors 3 and 4. The modelling results indicate that in the case of strong aerosol advection in the mid-troposphere, in the backscattering region, we may expect AOT to be underestimated by our satellite algorithm with a climatological profile, while in the near-glint region AOT will be overestimated. For profile 0, with the total aerosol concentrated near the sea surface, the angular variability of the bias is usually the opposite. The bias is positive in sector 1 and negative in sector 4. However, its value rarely exceeds the range $-0.01 - +0.01$. For satellite angles around the zenith, the sign of the bias varies, being positive for profile 1 and a high water vapour content in the atmosphere ($WV = 3.0$ g cm^{-2}), and negative for all aerosol models in the cases of profile 0 and a high water vapour content ($WV = 3.0$ g cm^{-2}). For AVHRR channel 2 the absolute value of the bias is highest in sector 4, i.e. near the solar glint. The sign of the bias depends only on the profile, being

positive for profile 1 and negative for profile 0 for all the angular sectors and aerosol models considered in the present work. Some examples of the angular distribution of the bias for both channels 1 and 2 are presented in Fig. 5. Notice that the colour scale is different for each diagram.

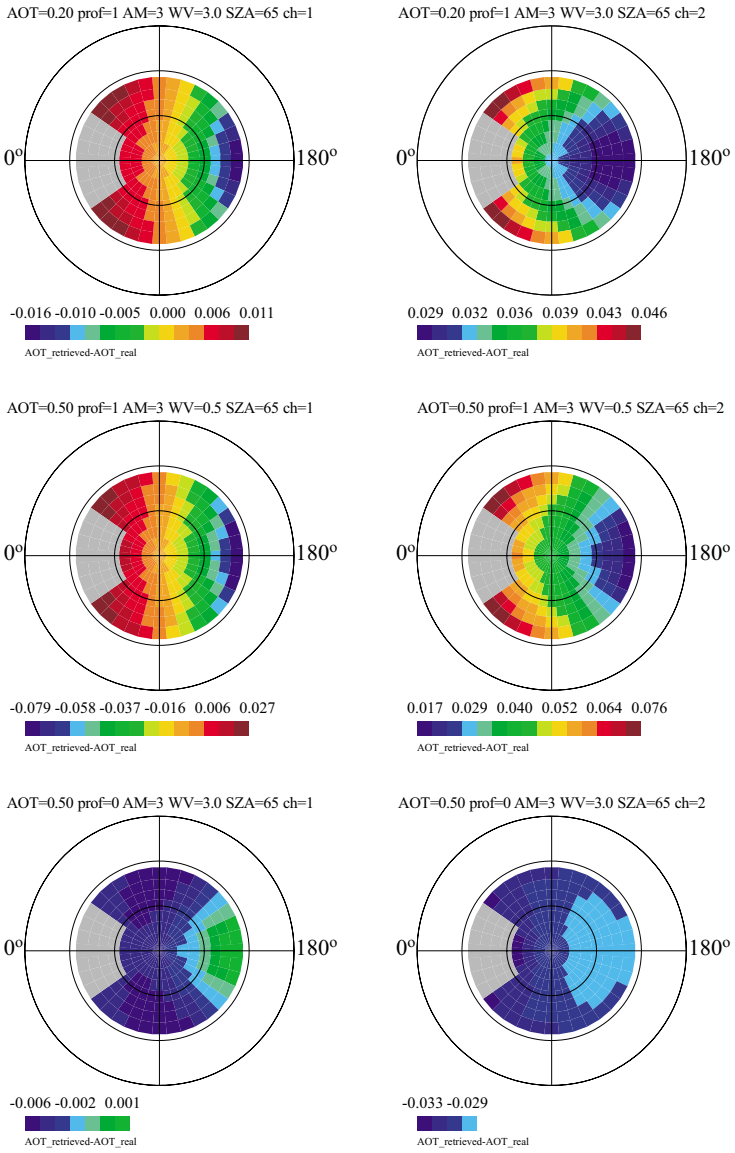

Fig. 5. Examples of the angular distribution of bias in aerosol optical thickness (AOT) retrievals for AVHRR channels 1 (left column) and 2 (right column) for selected AOT, profiles ($prof$), aerosol models (AM), water vapour contents (WV) and $SZA = 65°$. Axes as in Fig. 4

Figs. 6 and 7 show the bias dependence on aerosol optical thickness, water vapour content in the atmosphere and solar zenith angle

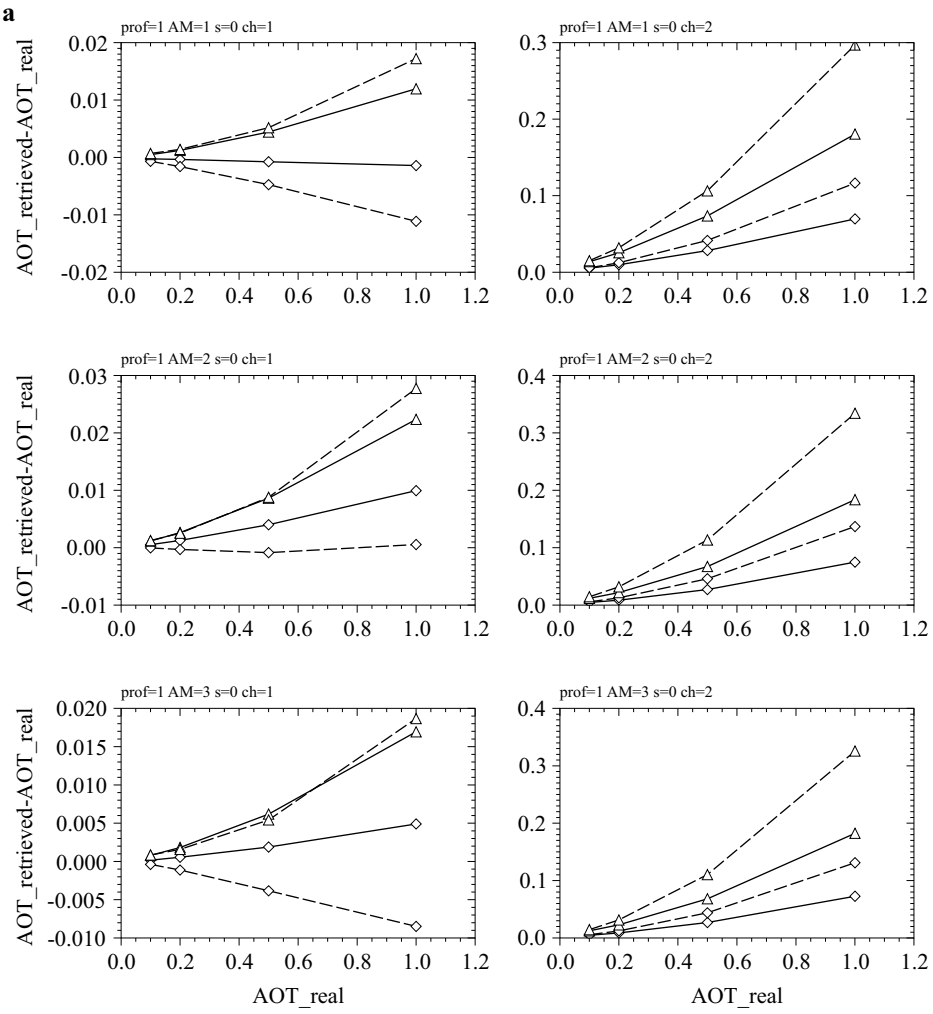

Fig. 6. Dependence of bias in aerosol optical thickness (AOT) retrievals on aerosol model (AM), solar zenith angle (SZA) and water vapour content in the atmosphere (WV) for aerosol profile $prof = 1$, AVHRR channels 1 (left column) and 2 (right) and angular sectors 0 (a) and 1 (b). Solid lines denote $SZA = 35°$, dashed lines $SZA = 65°$, diamonds $WV = 0.5$ g cm^{-2}, triangles $WV = 3.0$ g cm^{-2}. AOT_retrieved is the aerosol optical thickness retrieved from the radiance at the top of the atmosphere (TOA) by means of an algorithm employing a climatological aerosol profile ($prof = 2$); AOT_real is the actual aerosol optical thickness used in the TOA radiance simulations. $AM = 1$ is for an urban, 2 for a polluted maritime, and 3 for a clean maritime aerosol

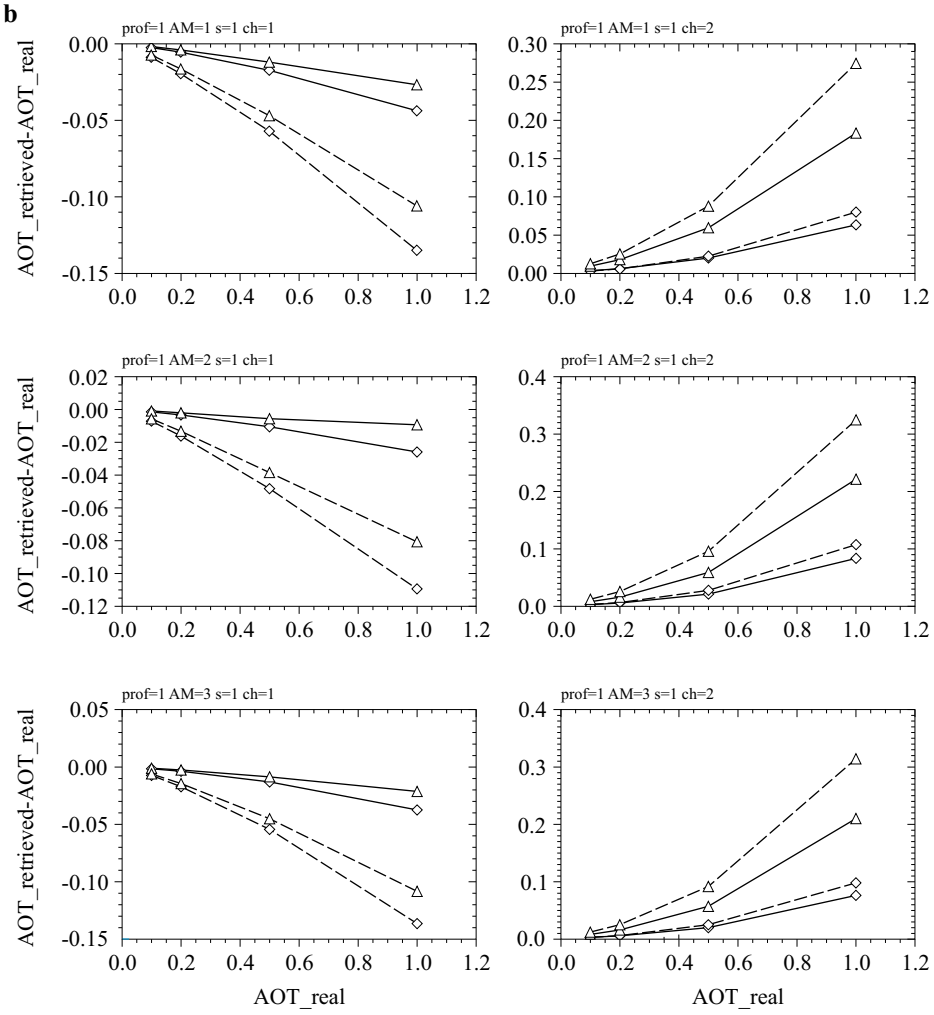

Fig. 6. (*continued*)

for sectors 0 and 1. Fig. 6 presents the biases for a selected profile (profile 1) and various aerosol models; Fig. 7 shows the biases for a polluted maritime aerosol ($AM = 3$) and both aerosol profiles considered in this paper. A similar dependence for the other sectors will also be discussed, but for the sake of brevity they are not shown in the figures.

In the case of channel 1, the concentration of the aerosol load in the near-surface layer practically does not influence AOT retrievals on the assumption of a climatological aerosol profile. For profile 0 errors are negligible regardless of AOT, solar zenith angle, water vapour content and aerosol model and sector. In the simulation the error exceeded ± 0.01 only

for $AOT = 1$ and $SZA = 65°$. The negligible bias may be explained by the fact that both profiles 0 and 2 are characterised by the bulk aerosol content in the lowest 1-km-thick layer. However, the appearance of a significant (dominant) aerosol layer at an altitude of several kilometres (profile 1) may result in a considerable bias in AOT retrievals from AVHRR channel 1 radiances.

For satellite angles close to the zenith (sector 0) and aerosol profile 1, the absolute value of the bias increases with an increase in AOT. It can be negative or positive, depending on the aerosol model, solar zenith angle and water vapour content. It is positive for larger amounts of water vapour ($WV = 3.0$ g cm^{-2}), regardless of SZA and the aerosol model, increasing with AOT and SZA. It reaches its highest absolute value ($|\varepsilon| = 0.03$) for $AOT = 1.0$, $SZA = 65°$, $WV = 3.0$ g cm^{-2} and a clean maritime aerosol.

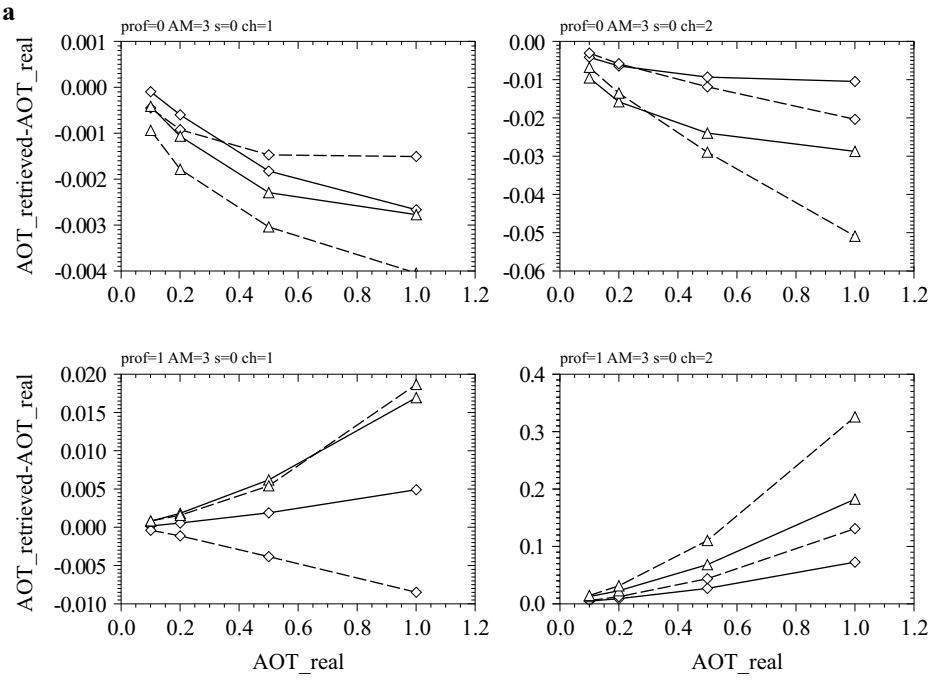

Fig. 7. Dependence of bias in aerosol optical thickness (AOT) retrievals on the aerosol profile ($prof$), solar zenith angle (SZA) and water vapour content in the atmosphere (WV) for aerosol model $AM = 3$, AVHRR channels 1 (left column) and 2 (right) and angular sectors 0 (a) and 1 (b). Solid lines denote $SZA = 35°$, dashed lines $SZA = 65°$, diamonds $WV = 0.5$ g cm^{-2}, triangles $WV = 3.0$ g cm^{-2}. $AOT_$retrieved is the aerosol optical thickness retrieved from the radiance at the top of the atmosphere (TOA) by means of an algorithm employing a climatological aerosol profile ($prof = 2$); $AOT_$real is the actual aerosol optical thickness used in the TOA radiance simulations

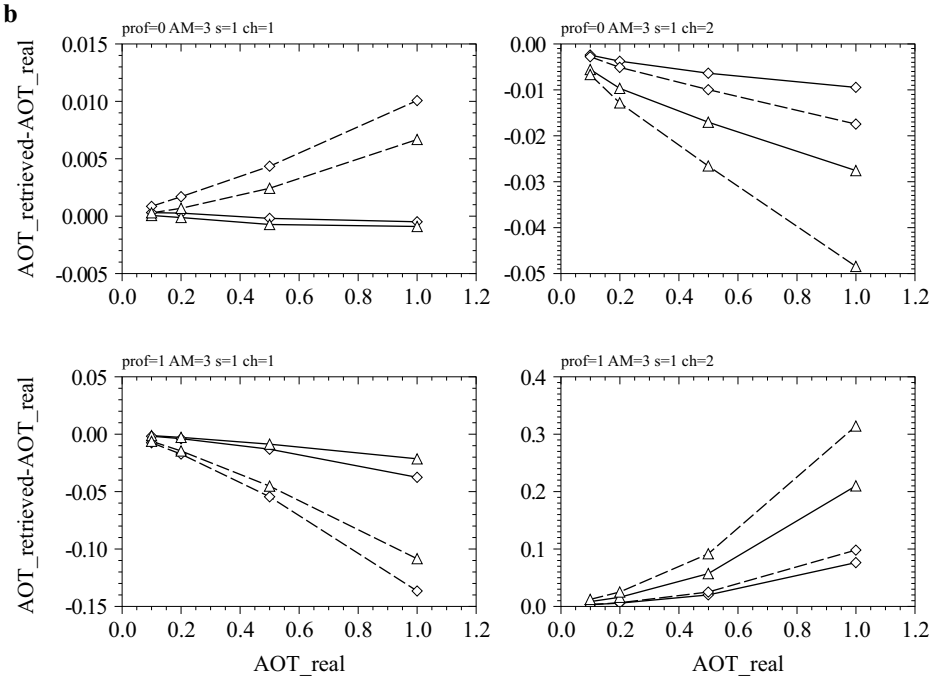

Fig. 7. (*continued*)

For absorbing aerosols (urban and polluted maritime models) and a low water content in the atmosphere ($WV = 0.5$ g cm^{-2}), the bias can be negative, especially for high SZA, but then its absolute value does not exceed the AOT measurement uncertainty. For $AOT = 0.2$, the value typical of the Baltic region, biases in sector 0 are always negligible.

For sectors 1 (near backscattering) and 2 and profile 1 the bias is negative. Its absolute value increases with an increase in AOT and SZA and decreases slightly with an increase in water vapour content in the atmosphere. For profile 1 the maximum absolute value of the bias is found for $AOT = 1$, $SZA = 65°$, $WV = 0.5$ g cm^{-2} and absorbing aerosols, that is, for the urban and polluted maritime models ($AM = 1$ and 3). The bias takes values of -0.09 and -0.14 for sectors 2 and 1, respectively. For $SZA = 35°$ the respective biases do not exceed -0.03 and -0.05. In the case of $AOT = 0.2$ the maximum absolute value of the bias is about 0.01 and 0.02 in the respective sectors 2 and 1.

For profile 1 the bias near the solar glint (sector 4) is positive. An increase in AOT, SZA and water vapour content results in an increase in the bias magnitude. It takes its highest value of 0.08 for $AOT = 1$, $SZA = 65°$ and $WV = 0.5$ g cm^{-2}. In sector 3 the bias behaves in a similar way, except

for the low water vapour content ($WV = 0.5$ g cm^{-2}), when an increase in the solar zenith angle reduces the magnitude of the bias to negative values in the case of $SZA = 65^\circ$ and absorptive aerosol models ($AM = 1, 3$). In these cases the absolute value of the bias increases with AOT. In these simulations the absolute value of the bias for angular sector 3 does not exceed 0.04. For AOT typical of the Baltic area ($AOT = 0.2$), the biases in both sectors are negligible, < 0.01.

The bias in channel 2 is considerably higher than in channel 1. Generally, the bias is negative for profile 0 and positive for profile 1, regardless of the aerosol model, aerosol optical thickness, solar zenith angle or water vapour content. Its absolute value increases with an increase in AOT, SZA and water vapour content, reaching its maximum value at $AOT = 1$, $SZA = 65^\circ$ and $WV = 3.0$ g cm^{-2} in these simulations. The influence of the aerosol model on the bias is relatively weak. The absolute value of the bias for a practically non-absorbing pure maritime aerosol is typically slightly higher than the biases for the absorbing models, i.e. urban and polluted maritime.

As in other sectors, near the zenith (sector 0) the bias is negative for profile 0 when the aerosol is concentrated closer to the sea surface than in the case of the climatological profile. It is positive when the aerosol load is shifted to the mid-troposphere (profile 1). The highest absolute values of the bias vary from 0.05 for profile 0 to 0.3 – 0.4 for profile 1. It can exceed 0.01 (up to 0.03) even when $AOT = 0.2$.

For sectors 1 (near backscattering) and 2 the maximum absolute value of the bias for retrievals from AVHRR channel 2 data is about 0.35 for profile 1 (positive bias) and 0.05 for profile 0 (negative bias). For $AOT = 0.2$ the respective maximum absolute values of the bias are 0.03 and 0.01.

For sectors 3 and 4 (satellite angles near the glint) and profile 1 the maximum values of the bias amount to 0.4 for $AOT = 1.0$ and c. 0.04 for $AOT = 0.2$. For profile 0 the absolute value of the bias does not exceed 0.02 for $AOT = 0.2$ and 0.06 for $AOT = 1.0$.

In channel 2, where atmospheric absorption is significant, the bias is mainly the result of a scattering aerosol layer being shifted upwards or downwards with respect to the main absorption layer of the atmosphere. In this spectral region the main absorber – water vapour – is concentrated near the surface. Shifting a scattering layer upwards increases the TOA radiances and thus generates the positive bias, while shifting it downwards increases the impact of absorption on the TOA radiances, diminishes the radiances, and the bias becomes negative. Aerosol absorption weakens the impact of the position of the aerosol layer – a scatterer – with respect to the main absorptive layer in the atmosphere. However, the aerosol models used in the simulation are characterised by relatively weak absorption. Within

the AVHRR channels the single scattering albedo varies from 1.0 for the pure maritime model to 0.97–0.93 for the urban model. The influence of the aerosol model on the bias is additionally modified by the differences in the spectral characteristics of the attenuation coefficients or the aerosol optical thickness. For the absorbing models, especially the urban one, the drop in AOT with λ is much steeper than it is for the pure maritime aerosol, which results in lower AOT in AVHRR channels, mainly channel 2, and in a decrease in the absolute value of the bias.

In channel 1 absorption, due to O_2, O_3 and water vapour, is much weaker than it is in AVHRR channel 2, whereas scattering, especially Rayleigh scattering, is considerably higher. Both Rayleigh scattering and gas absorption (except for O_3) are strongest near the surface. The bias now behaves differently. It changes sign depending on satellite angles. It is influenced chiefly by differences in scattering properties between a pure atmosphere (Rayleigh scattering) and aerosols. The aerosol scattering function is asymmetric (asymmetry parameter $g = 0.7$–0.8), whereas a pure atmosphere scatters forwards and backwards to an equal extent ($g = 1.0$). The bias can be explained by the change in position of the asymmetrically scattering aerosol layer with respect to the Rayleigh scattering near-surface layer of the pure atmosphere, in the presence of gas and aerosol ($AM = 1, 3$) absorption. Aerosol absorption and differences in spectral characteristics of AOT also modify the TOA radiances and the bias.

The highest absolute values of the bias were found for $AOT = 1.0$. However, in the southern and western Baltic Sea, the aerosol optical thickness for $\lambda = 550$ nm typically takes values below 0.5. The modal values of seasonal AOT distributions do not exceed 0.2 (Kuśmierczyk-Michulec & Rozwadowska 1999, Carlund et al. 2005). For $AOT = 0.2$ the absolute value of the bias found for channel 1 does not exceed 0.02, while for channel 2 it is < 0.04.

In the present bias estimation simplified cases were considered. Model aerosols with constant properties were used and aerosol profiles were 'exaggerated'. However, the aim of this study was to determine the expected range of the bias and the dependence of the bias on the relevant parameters, and to indicate conditions when the bias may become significant. Even though the observed bias may diverge from the values presented above, they should fall within the range of magnitude determined in this paper.

4. Summary and conclusions

In the present study we analysed the possible influence of variability of atmospheric aerosol profiles on angular distributions of the TOA upward radiances, focusing on its possible impact on AOT retrievals. Our intention

was to estimate the maximum uncertainty and to specify the conditions for which a maximum uncertainty may be expected.

The analysis was based on simulations by means of the MODTRAN code (Berk et al. 1999a). Urban/industrial, polluted maritime and clean maritime aerosol models were used in the study (d'Almeida et al. 1991). TOA radiances were modelled for three vertical profiles of the aerosol attenuation coefficient for $\lambda = 550$ nm: an aerosol concentrated near the surface (0–1 km; profile 0), an aerosol concentrated in a 5–7-km-thick layer above the surface (profile 1), and a MODTRAN-like 'climatological' profile (profile 2). The 'climatological' profile was used in our satellite retrieval algorithm. Aerosol optical thicknesses retrieved from the modelled TOA radiances by means of the algorithm were compared to real AOT employed in TOA radiance modelling.

The bias (uncertainty) in AOT retrieval due to the assumption of a climatological aerosol profile in the retrieval algorithm is defined as the difference between AOT retrieved from the TOA radiance (calculated for the 'real' aerosol profile ($i = 0$, 1) and a given AOT) by means of an algorithm using the climatological aerosol profile ($prof = 2$), and the actual AOT used in TOA radiance computation for a given sun-pixel-satellite geometry and water vapour content.

The bias was calculated for AOT ranging from 0.1 do 1.0, water vapour contents (WV) of 0.5 and 3.0 g cm^{-2}, solar zenith angles (SZA) of 35° and 65°, satellite zenith angles ranging from 1° to 57°, and the relative azimuth between the satellite and the sun changing from 0° to 180°. The atmospheric conditions and solar and satellite angles used in the bias simulation were typical of the Baltic region.

The findings are summarised as follows:

- In the case of channel 1, the aerosol concentration in the near-surface 1-km-thick layer (profile 0) practically does not influence AOT retrievals on the assumption of a climatological aerosol profile (profile 2). The bias is negligible regardless of AOT, solar zenith angle, water vapour content and aerosol model and sector. This may be explained by the fact that both profiles 0 and 2 are characterised by a bulk aerosol content in the lowest 1-km-thick layer. However, the appearance of a dominating aerosol layer at an altitude of several kilometres may result in a considerable bias in AOT retrievals from AVHRR channel 1 radiances. In this case, the bias is due to a shift in the absorbing ($AM = 1$ and 3) and asymmetrically scattering aerosol layer (asymmetry parameter g = 0.7–0.8) above the main part of the Rayleigh scattering (g = 1.0) and weakly absorbing near-surface layer of the pure atmosphere. The magnitude of the bias varies

depending on the satellite angles. For the total aerosol placed in the mid-troposphere (profile 1), the bias is typically negative in sector 1 (satellite azimuth and zenith angles close to the backward scattering directions) and its value increases towards the glint region to become positive in sector 4. The maximum absolute value of the bias (bias $\varepsilon = -0.14$) is found for sector 1, $AOT = 1$, $SZA = 65°$, $WV = 0.5$ g cm^{-2}, and absorbing aerosols, that is for the urban and polluted maritime models ($AM = 1$ and 3). In the case of $AOT = 0.2$ the maximum absolute value of the bias is c. 0.02. $|\varepsilon|$ increases as AOT increases. The influence on the bias of the other factors considered here varies depending on the sector.

- In channel 2, the bias is considerably greater than in channel 1. Generally, the bias is negative for profile 0 and positive for profile 1, regardless of the aerosol model, aerosol optical thickness, water vapour content and sun-pixel-satellite geometry. In the case of channel 2 the bias is governed by the position of the scattering aerosol layer with respect to the main absorbing gas layer in the atmosphere, which in the case of the channel 2 spectral range is the near-surface layer with water vapour as the main absorber. An upward shift in the scattering layer increases the TOA radiances and thus generates a positive bias, while a downward shift increases the impact of absorption on TOA radiances, diminishes the radiances, and the bias becomes negative. Its absolute value increases with an increase in AOT, SZA and water vapour content, reaching its maximum value at $AOT = 1$, $SZA = 65°$ and $WV = 3.0$ g cm^{-2} in these simulations. The maximum absolute value of the bias occurs in sectors 3 and 4 (satellite angles near the glint). For profile 1 this is 0.4 for $AOT = 1$ and c. 0.04 for $AOT = 0.2$, while for profile 0 it does not exceed 0.02 for $AOT = 0.2$ and 0.06 for $AOT = 1.0$ in our simulations.
- In channel 2 the influence of the aerosol model on the bias is relatively weak. The absolute value of the bias for a practically non-absorbing pure maritime aerosol is typically slightly higher than the biases for the absorbing models, i.e. urban and polluted maritime. Aerosol absorption weakens the impact of the position of the aerosol layer – a scatterer – with respect to the main absorptive layer in the atmosphere. The bias is additionally modified by differences in the spectral characteristics of AOT between the aerosol models.

Even though the observed bias may differ from the values presented above, they should fall within the range of magnitude determined in this paper. Given that in the present bias estimation, simplified 'exaggerated' cases were considered and that AOT over the Baltic Sea is typically < 0.2

and only very rarely exceeds 0.5, the expected aerosol profile bias is negligible for channel 1 of NOAA AVHRR, whereas for channel 2 it may be significant.

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