(A)ATSR Exploitation Plan Volume 6

Review of Remotely Sensed Aerosol and Cloud Products and their Applications

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1 INTRODUCTION

Aerosols are important in various scientific disciplines, such as radiative transfer, cloud formation, air quality, visibility, atmospheric stability, the hydrological cycle, human health and, in particular, climate change (discussed further in the following sections). Since the concept of aerosol-radiation-climate interactions was first proposed around 1970, substantial progress has been made in determining the mechanisms and magnitudes of these interactions, particularly in the last ten years. In recent years, the characterization of aerosols has been significantly improved through intensive field experiments, ground-based network measurements, and satellite remote sensing and its integration with model simulations.

Aerosols play important roles in the atmosphere, and can cause both positive and negative radiative forcing:

- They scatter and absorb sunlight, altering the amount of solar radiation reaching the Earth's surface (direct radiative forcing);
- They can lead to heating of the lower atmosphere if they contain light absorbers (semi-direct affect);
- They act as Cloud Condensation Nuclei (CCN) thus increasing cloud droplet concentration and therefore affect cloud albedo (indirect radiative forcing) and precipitation formation (a second indirect affect) (Andreae and Crutzen, 1997);
- They are involved in heterogeneous chemical reactions.

The global effect of aerosols is a reduction in the amount of radiation reaching the Earth's surface by -0.5 to -2.5 W m^{-2}, which is comparable in magnitude with the positive forcing of +2.0 to +2.5 W m^{-2}, caused by greenhouse gases (IPCC, 2001).

The Intergovernmental Panel on Climate Change (IPCC) recognises that the role of aerosols in climate is one of the largest uncertainties in our understanding of the present climate system and in our abilities to predict future climate change (Chylek and Henderson, 2003). The mechanism of aerosol direct effects is more difficult to establish due to spatial and temporal aerosol variability. Large uncertainties also exist in current estimates of aerosol forcing because of incomplete knowledge concerning the distribution and the physical and chemical properties of aerosols as well as aerosol-cloud interactions (Yu et al., 2006).

2 REMOTE SENSING OF AEROSOLS

2.1 Theoretical basis

Aerosols are formed either by the conversion of gases to particulate matter or by the disintegration of liquids or solids (Friedlander, 1977). They may also result from the re-suspension of material or the break-up of agglomerates. Dust, smoke, fume, haze, and mist are all terms in common use with somewhat different popular meanings. Thus dust usually refers to solid particles produced by disintegration processes, while smoke and fume particles are generally smaller and formed from the gas phase. Mists are composed of liquid droplets.

The particle sizes of interest in aerosol behaviour range from molecular clusters of 1 nm to fog droplets and dust particles as large as 100 μm (Friedlander, 1977). Particles with a radius less than 0.1 μm are often termed Aitken particles and particles are described as large when their radii exceed 1 μm (Dundas, 1997). For small particles, the diffusion effects are significant and particle coagulation is rapid. Large particles fall out of the atmosphere relatively quickly due to gravitation or are scavenged by cloud and precipitation.

Aerosol particles vary in composition, containing both inorganic and organic types. We can consider classes of particles as sulphates, nitrates, organic aerosol, black carbon, mineral aerosols (desert dust), sea salt and volcanic aerosols (see section 2.1.3).

2.1.1 Radiative properties

Atmospheric aerosols influence the radiative budget in three ways, first by backscattering incoming solar radiation, secondly by absorbing solar and thermal radiation, and thirdly by changing the albedo and lifetime of clouds. The interactions between aerosols and solar radiation are therefore determined by a combination of aerosol properties (loading, chemical composition, size distribution, shape), surface properties (e.g., spectral and angular variations of surface albedo), clouds (cloud fraction, optical thickness, and vertical distribution), and geographical parameters (latitude, season; Yu et al., 2006). The aerosol *direct effect* refers to the direct impact of aerosols on radiation, causing light to be reflected. A *semi-direct effect* is caused by absorbing aerosols which results in light being directly absorbed leading to heating (this is mainly caused by soot or aerosols containing other light-absorbing materials). The aerosol *indirect effect* results from aerosols acting as CCN; small, numerous cloud droplets are formed on small aerosols, whilst larger droplets form on large aerosols. Clouds with large droplets reflect sunlight less effectively compared to clouds with small droplets. Small droplet clouds therefore contribute to a cooling effect. The indirect effect is discussed in more detail in section 5 whilst the scattering, absorption and extinction mechanisms are introduced in the following subsections.

2.1.1.1 Scattering

Rayleigh scattering occurs when molecules within the atmosphere are smaller than the wavelength of visible light; light is then scattered by these molecules. Equal amounts of light are scattered both in forwards and backwards directions. Light at the shortest wavelengths is scattered preferentially, resulting in a blue hue to the sky. Rayleigh scattering is therefore also termed 'blue-sky' scattering. If Rayleigh scattering was the sole form of scattering within the atmosphere, i.e. in an unpolluted atmosphere, visibility would extend to about 250 km; the curvature of the earth would limit the visibility more than the scattering itself. However, the atmosphere is not unpolluted and particles and gases are present which are similar to or larger than the wavelength of light.

Mie scattering occurs within the atmosphere when particles are similar or slightly larger than the wavelength of the incident light. Mie scattering is not strongly wavelength dependent and produces the almost white glare around the sun when a lot of particulate material is present in the air. It also gives us the white light from mist and fog. Because of their diversity, aerosol particles have a wide range of sizes. However, the ones most important for optical scattering turn out to be comparable to the wavelength being scattered, for typical size distributions. Particles of this size scatter light more in the forwards direction. Geometric scattering occurs when particles are large compared with the wavelength of the light.

2.1.1.2 Absorption

Most of the aerosol particles are so weakly absorbing at visible and near infra-red wavelengths that their extinction is almost entirely due to scattering, rather than absorption. However, soot (black carbon) particles are quite strong absorbers, and the absorption increases at short wavelengths. While this decreases the radiation flux at the surface, it heats the atmosphere locally. The heating can in turn cause a third climate forcing effect, known as the semi-direct radiative effect, where the heating of the atmosphere can reduce the local relative humidity. This then reduces the chance of cloud formation, which would have otherwise caused surface cooling, so the net effect is to increase the amount of energy reaching the surface. Thus the semi-direct radiative effect is opposite to the direct and indirect effects. In the thermal infra-red, aerosols are more absorbing but clear effects are only noticeable for large particles such as desert dust and volcanic ash, or for large concentrations such as sulphate aerosol particles following large eruptions such as Mt. Pinatubo.

2.1.1.3 Extinction / attenuation

Extinction or attenuation is the sum of scattering and absorption, so it represents the total effect of radiation passing through the medium. Aerosol optical depth (AOD) is a quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere. It is a measure of the integrated columnar aerosol load and the single most important parameter for evaluating direct radiative forcing.

$$\tau(\lambda) = \int_0^\infty \beta_e(z,\lambda)\,dz$$

where τ = Aerosol optical depth
λ = wavelength
β_e = extinction coefficient
z = depth

AOD is not directly measurable, but rather must be retrieved from observations of atmospheric spectral transmission or computed from aerosol scattering models that include aerosol type, refractive index, and size distributions. The solar irradiance, I, at a given wavelength can be expressed as:

$$I = I_0\, exp(-m\delta)$$

where I_0 = extraterrestrial (top-of-the-atmosphere) irradiance of the sun
m = the air mass
δ = the total optical depth

The air mass equals 1 for a vertical path and is roughly proportional to 1/cos z where z is the zenith angle of the sun during the observation. The total optical depth δ at a given wavelength is composed of several components such as scattering by gas molecules, δ_R (Rayleigh scattering), extinction by aerosol particles, δ_A, absorption of trace gases, δ_G, like ozone, and possible cloud contamination. Thus, the AOD can be obtained from the total optical depth by subtracting modelled estimates of the other components:

$$\delta_A = \delta - \delta_R - \delta_G$$

Because AOD is essentially a difference between two larger numbers, it is very sensitive to small calibration errors and to a minor degree also to the methods chosen to model the other components. More sophisticated instruments like sky-scanning radiometers can be used to determine other very important optical parameters including single-scattering albedo, phase

function or complex index of refraction (WMO/GAW report No.153, 2003). In general, an optical depth of 0.1 indicates a relatively clear day with visibility more than 40 km but still containing a radiatively important aerosol effect; a global average optical depth is about 0.12 (Ramanathan et al, 2001). An optical depth of 0.5 is quite hazy, and visibility is only about 10 km. An optical depth of 1.0 and above would virtually obscure the sky from view.

The Ångström exponent is defined by the spectral dependence of the aerosol optical depth. It mainly depends on the aerosol size distribution; typical values range from 2.0 for fresh smoke particles, which are dominated by accumulation mode aerosols, to nearly zero for large dust particles (Dubovik et al., 2000).

The single scattering albedo (SSA) is an important optical characteristic of the absorption properties of aerosol particles, which defines the ratio between scattering and absorption in the total light extinction:

$$SSA = K_s / (K_a + K_s)$$

where K_a = absorption coefficient
K_s = scattering coefficient.

SSA depends on the scattering and absorption properties of atmospheric particles and represents an important parameter to evaluate the aerosol radiative impact.

The presence in the atmosphere of desert dust layers can lead to either a cooling or a warming effect, depending on properties such as SSA and the altitude of the layer (e.g. Sokolik and Toon, 1999; Tegen and Fung, 1995; Liao and Seinfeld, 1998). In particular, Hansen et al. (1997) showed that when cloud effects are included in the radiative forcing analysis, aerosol SSAs smaller than 0.91 lead to warming and higher values lead to a cooling of the climate system.

2.1.2 Chemical properties

Aerosols in continental atmospheres consist mainly of sulphate (SO_4^{2-}), nitrate (NO_3^-), sea-salt (NaCl), organic matter and elemental carbon. The traditional view that aerosols are dominated by sulphates (Pruppacher and Klett, 2000) has now been modified by recent observations, showing that a large proportion is composed of carbonaceous material (70-80% in terms of number, Van Dingenen et al., 2004) and, more specifically, organic compounds (up to 70% in terms of mass, Turpin et al., 2000), particularly in urban areas (Putaud et al., 2004). Recent work has highlighted the importance of atmospheric HUmic-LIke Substances (HULIS) (Kiss et al., 2003; Graber and Rudich, 2006; Muller et al., 2008), which are thought to represent

approximately 30% by mass of the water soluble organic fraction of tropospheric aerosol (Havers et al., 1998, McFiggans et al., 2005).

Chemical ageing, that is heterogeneous chemical reactions occurring on the surface of a particle, is an important atmospheric process. This process alters the chemical composition of particles, converting hydrophobic particles into more polar, hygroscopic particles. However, understanding such chemical processing is still in its early stages. For example, oxidation of dicarboxylic acids by OH-radicals has been suggested to yield isomers of oxodicarboxylic acids, which are more polar and hygroscopic (Römpp et al., 2005). Ozone reactions with organic particulate matter, such as soot, organic acid films or organic aerosols have also been found to alter the chemical properties of aerosol surfaces, increasing hydration of such particles, making them more hygroscopic (Chughtai et al., 1999). For example, ozonolysis of long chain unsaturated carboxylic (fatty) acids has been found to lead to the formation of smaller molecules of higher hygroscopicity, such as aldehydes and carboxylic acids (Eliason et al., 2003). Mechanisms which have been proposed to explain the acid-catalyst heterogeneous reactions of organic matter include hydration, hemiacetal and acetal formation, polymerisation and aldol condensation (Jang et al., 2003; Iinuma et al., 2004), whilst ozonolysis (without the presence of acid) of oleic and linoleic acid has also been shown to contribute to activation of particles to cloud droplets (Broekhuizen et al., 2005). Chemical ageing also occurs during cloud processes via aqueous phase reactions.

2.1.3 Sources

Aerosols can be classified as primary and secondary aerosols based on the source and chemical reactions. They can be directly emitted as particles (primary aerosols) into the atmosphere by volcanoes, through the effect of wind lifting dust particles in arid regions, from combustion during biomass burning, from sea spray, from vegetation etc, or can be derived from living organisms. They can also be the result of chemical reactions (gas-to-particle conversion) (secondary aerosols). Table 1-1 summarizes the main sources of aerosols.

Particles emitted by combustion sources (primary emissions) mainly start their atmospheric lifetimes in the sub-micron size range (although they do also span all size ranges), whilst condensation of organic compounds after the reaction of atmospheric oxidants and gases (secondary organic aerosol, SOA) affects mainly the ‘accumulation’ mode, 0.2 µm to 0.5 µm.

In the atmosphere, SOAs in the nucleation mode are usually produced by gas-to-particle conversion, whilst SOAs in the accumulation mode are usually produced by coagulation of small particles and heterogeneous condensation of gas vapour and semi-volatile compounds (which are generated by photooxidation of anthropogenic hydrocarbons and biogenic volatile organic compounds (VOCs) such as terpenes) onto aerosols.

Natural	Anthropogenic
Primary Mineral aerosol Sea salt Volcanic dust Organic aerosols	***Primary*** Industrial dust Soot Biomass burning
Secondary Organic aerosols from VOCs Nitrates from NO_x Sulphates from volcanic SO_2 Sulphates from biogenic gases	***Secondary*** Organic aerosols from VOCs Nitrates from NO_x Sulphates from SO_2

Table 1-1: Main sources of aerosols

Up to 90% of organic aerosol mass in urban areas can be attributed to SOA (Lim and Turpin, 2002), formed mainly from precursors such as benzene, toluene, xylenes and trimethylbenzenes (aromatic compounds) from fossil fuel emissions, although formation mechanisms are complex.

Terrestrial and anthropogenic sources contribute significantly to atmospheric aerosols, particularly water soluble aerosols, with human and industrial aerosols being highly abundant, especially in the nuclei mode size range. Human activities, such as burning fossil fuels, changing land-cover, industrial activities and transportation, all have large impacts on climate. Anthropogenic aerosols enhance scattering and absorption of solar radiation. They also produce brighter clouds that are less efficient at releasing precipitation. These in turn lead to large reductions in the amount of solar irradiance reaching Earth's surface, a corresponding increase in solar heating of the atmosphere, changes in the atmospheric temperature structure, suppression of rainfall, and less efficient removal of pollutants. These aerosol effects can lead to a weaker hydrological cycle, which connects directly to availability and quality of fresh water, a major environmental issue in the 21st century (Ramanathan, et al., 2001). Aerosol indirect effects on clouds remain an enormous challenge from both the observational and modelling perspectives. Only recently have studies focused on the estimation of the aerosol indirect radiative forcing, following the improvement of satellite and modelling techniques.

Primary biological aerosol particles (PBAP) are also ubiquitous components of atmospheric aerosols and cover a large range of particle sizes: from viruses (thousandths of a micrometer) to large pollen (~300 μm) (Fuzzi et al., 1997; Bauer et al., 2002). PBAPs describe airborne solids, dead or alive, derived from living organisms, including microorganisms and other parts of living things (Matthia-Maser and Jaenicke, 1995).

2.1.4 Sinks

The fate of aerosol suspended in the atmosphere is to be altered, removed or destroyed. The average aerosol lifetime is of the order of a few days to a week, which is dependent upon its size and location. Aerosols are transported through the atmosphere and are removed via dry or wet deposition that transports aerosol species to aquatic and terrestrial environments. Dry deposition directly transports particles to the earth's surface via gravitational or turbulent settling (larger aerosols settle out of the atmosphere very quickly under gravity, and some surfaces are more efficient at capturing aerosols than others), whilst wet deposition transports species via precipitation. Wet deposition has been estimated to remove 70-85% of the mass of tropospheric aerosols (Kanakidou et al., 2005). Consequently, aerosols are removed from the atmosphere by precipitation in two ways, within and below the cloud base:

i) nucleation scavenging ('rain out') whereby aerosols are incorporated as cloud condensation nuclei; and

ii) impaction scavenging in which aerosols are 'washed out' by cloud droplets and/or precipitation.

Wet scavenging is considered to be one of the largest sources of uncertainty in global models of the sulphur cycle, with its significance in organic carbon cycling also important (Roelofs, 2001). In addition, the inhalation of aerosols may be considered as a further sink.

2.2 Ground based aerosol measurements

AOD can be determined from the ground through measurements of the spectral transmission of solar radiation through the atmosphere using rather simple and relatively inexpensive instruments pointed directly at the sun called sun photometers or filter radiometers. The Ångström exponent, which gives an indication of the column integrated aerosol size distribution, can be derived from simultaneous AOD measurements at several wavelengths.

Several dedicated campaigns employing correlated ground, airborne, and space-based observations have been set up to reduce uncertainties in modelling and forecasting mineral aerosol effects on climate. The European Mediterranean Dust Experiment (MEDUSE, e.g. Soderman and Dulac, 1998; Hamonou et al., 1999), the second Aerosol Characterization Experiment (ACE 2, e.g. Raes et al., 2000), the Saharan Dust Experiment (SHADE, e.g. Tanre et al., 2003) are just a few examples.

2.2.1 AERONET

The AERONET (AErosol RObotic NETwork) programme is a federation of ground-based remote sensing aerosol networks (http://aeronet.gsfc.nasa.gov/). AERONET includes about 200 sites around the world (see Figure 2-1), covering all major tropospheric aerosol regimes (Holben et al., 1998). The programme provides a long-term, continuous and readily accessible public domain database of aerosol optical, mircrophysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases.

Routine ground based AOD observations are of utmost importance for the calibration and validation of AOD retrievals from satellites. In addition they are necessary to correct for aerosol effects in the retrieval of other satellite products.

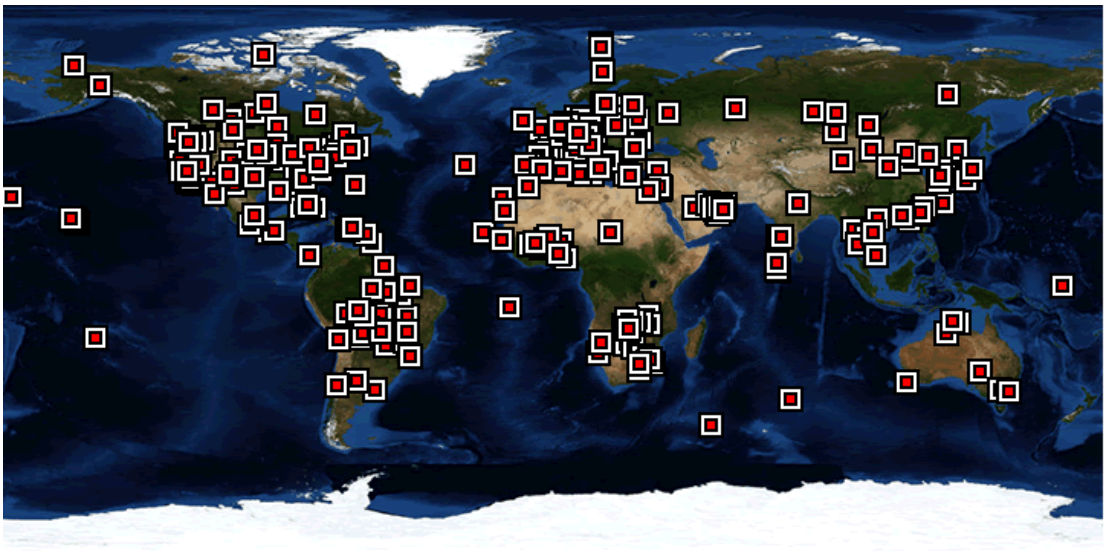

Figure 2-1: Image showing the location of AERONET sites (http://aeronet.gsfc.nasa.gov/cgi-bin/site_info)

2.3 Satellite Aerosol Products

It is generally accepted that our knowledge of cloud dynamic and radiative properties falls well short of that required by modern climate analyses and prediction schemes. Due to the many different aerosol sources and their short lifetimes, tropospheric aerosols are highly variable in both space and time. Satellite remote sensing is the only means capable of providing global observational aerosol data that are needed for assessing direct and indirect aerosol effects.

Satellite remote sensing of aerosol optical properties is best over surfaces with a low and preferably constant albedo. Most land surfaces have high surface reflectivities, which makes

satellite remote sensing extremely difficult. On the other hand, the albedo of the ocean is low and relatively well characterised. Therefore most studies have focused on oceanic regions. While the presence of dust can be readily detected in day-time imagery by the increase in clear-sky albedo over the ocean using visible channels (e.g., Tanré et al, 1997; Waquet et al., 2005), the detection of dust contamination in night-time imagery must rely on its impact on thermal wavelengths.

As already discussed, natural and anthropogenic aerosols have different proportions of fine and coarse aerosols. Urban/industrial pollution and smoke from vegetation burning (mostly anthropogenic) have mostly fine aerosol, while dust and marine aerosols (mostly natural) are dominated by coarse aerosol but with significant fine aerosol fraction (Tanré et al., 2001; Kaufman et al., 2001). Therefore, by determining aerosol particle size from space, scientists are able to classify aerosols as natural or anthropogenic, thereby determining the anthropogenic portion of the aerosol loading and subsequently determining aerosol forcing from the aerosol effect (Kaufman et al., 2005).

2.3.1 The (A)ATSR aerosol product

The (A)ATSR, on account of its unique dual angle viewing geometry, is especially sensitive to atmospheric aerosol and there is great potential for using (A)ATSR data, generally in combination with data from other sources, to examine and quantify the radiative properties of atmospheric aerosols. (A)ATSR instruments provide a long-term record of accurate estimates of aerosol properties at regional and global scales since the start of the ATSR-2 mission in 1995, when the visible channels were added to the infra-red channels established on ATSR-1. Aerosol retrievals are undertaken using a method of optimal estimation, which has been well validated. The aerosol algorithm uses four spectral bands (0.55, 0.66, 0.87, 1.6 μm) for retrievals of aerosol optical depth, effective radius and surface albedo. These data can be used to examine and quantify the radiative impacts of atmospheric aerosols, and the effects of regional and temporal variations in aerosol loading on climate. Mischenko (2007) highlighted that the excellent calibration of the (A)ATSR channels is one of the major sources of uncertainty in the AVHRR aerosol trends.

AATSR and ATSR-2 have seven spectral bands, four in the visible and near-infrared (effective wavelength 0.555, 0.659, 0.865 and 1.6μm), which are potentially useful for aerosol retrieval. The (A)ATSR dual-view provides first a forward view of a region (zenith angle approximately 55°) and about two minutes later a nadir view of the same region. Using a dual or a multiple-angle view of the same scene (at nearly the same time) should improve significantly the accuracy of the satellite AOD retrieval (Flowerdew and Haigh, 1996).

Aerosols influence both the visible and infra-red channels of the (A)ATSR instruments, with larger effects in the forward than in the nadir view. The challenges of aerosol retrieval are such that until recently global algorithms have tended to use nadir-only views of the visible channels. More restricted applications on regional scales have also shown the benefits of utilising the dual and forward views but considerable care is required over land. Nonetheless the latest products from the Grey et al algorithm and the GlobAEROSOL algorithm offer distinct improvements. Further possibilities to differentiate large particle sources, such as Saharan dust, using the infra-red channels increase the likely success of differentiating aerosol types with (A)ATSR data. Recent projects have demonstrated the utility of an ATSR Saharan dust index for detecting Saharan dust over the oceans.

The AOD retrieval from (A)ATSR is based on computing the top of atmosphere (TOA) reflectance, given expectations of the likely aerosol properties and the underlying surface reflectances. A detailed description of an aerosol retrieval algorithm applied to ATSR-2 data is given by Veefkind and de Leeuw (1998). The algorithm can also be applied to different sensors. Based on this algorithm, Veefkind et al. (1999) used the forward look of the ATSR-2 to demonstrate that the AOD in the mid-visible channel (0.555μm) over the ocean can be retrieved using the ATSR-2 with an accuracy of 0.03 and the retrieval is in ‘‘good agreement’’ with the ground truth sun-photometer measurements. Robles-Gonzalez et al. (2000) compared the ATSR-2 dual algorithm retrieval averaged on a 10 km by 10 km grid with ground based sun-photometer measurements and found an agreement within 0.05. North (2002) estimated the accuracy of the AOD deduced form the ATSR-2 dual angle imagery to be 0.02 or 20% of the AOD, whichever is larger.

More recently, Grey et al. (2006) showed the potential of a dual-angle retrieval method, by developing and testing an (A)ATSR algorithm for retrieving AOD and bidirectional reflectance over land. The algorithm is based on a physical model of light scattering (North el al. 1999) that requires no *a priori* knowledge of land cover. AOD measurements using this algorithm were compared with other satellite retrievals (MISR, MODIS and TOMS) and AERONET measurements. Good agreement (r^2 = 0.70) was found between (A)ATSR and sun-photometer measurements, and with MISR-derived AOD (r^2=0.84). However, correlations with MODIS- and TOMS-derived AOD were found to be lower.

Thomas et al. (2006) applied a single-view optimal estimation algorithm, developed under the Oxford RAL Aerosol and Cloud (ORAC) project, to AATSR and SEVIRI, and compared it with a dual-view AATSR retrieval with AERONET measurements, produced by the Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO). The results for TNO/AATSR and ORAC/SEVIRI indicate that there were no obvious land/sea delineations. The ORAC/AATSR was found to perform well over the oceans (within 0.1 AOD of AERONET) yet it showed elevated optical depths over some land areas. Whilst the single-view ORAC

algorithm performed slightly better over the sea (0.02 AOD of AERONET), this work demonstrates the potential of dual angle algorithms for retrieving AOD, especially over land areas since it is less sensitive to assumptions about surface reflectance.

The minimum acceptable accuracy of the TOA radiative flux of $\Delta F = 0.5$ W/m^2 leads to the required accuracy in satellite based AOD retrieval of about $\Delta\tau = 0.015$ over the land and $\Delta\tau = 0.010$ over the ocean. None of the current operational satellite-based instruments for AOD retrieval have been able to achieve this accuracy (Chylek and Henderson, 2003). Theoretical analysis suggests that the uncertainties in aerosol phase function (due to uncertainties in aerosol shape, size distribution and optical properties) are the major obstacles for accurate AOD retrieval. These uncertainties lead to a much larger error in AOD retrieval at large scattering angles (usually at close to nadir view) than at off-nadir views at medium scattering angles. Chylek and Henderson (2003) suggested that in order to achieve the required accuracy in AOD retrieval, future satellite instruments using a single or dual-view AOD retrieval algorithm should use off-nadir views at medium scattering angles (between 50° and 100°).

(A)ATSR radiances are currently being studied within the NERC funded the ADIENT (Appraising the Direct Impacts of Aerosol on Climate) programme. Projects are being undertaken in which radiance comparisons are being performed to test the consistency between the United Kingdom Chemistry Aerosol (UKCA) model and (A)ATSR measurements. Retrievals make assumptions about aerosol optical properties and the surface which are often inconsistent with model measurements of short-wave (SW) flux. Therefore, this should provide a stringent test of understanding the direct effect, aerosol distribution, aerosol and surface optical properties and the radiative transfer modelling. In addition, within ADIENT, comparisons of GlobAEROSOL output (discussed below) with model data are being made.

2.3.2 Aerosol products which use (A)ATSR data

2.3.2.1 GlobAEROSOL

GlobAerosol is an ESA Data User Element (DUE) project whose aim is to produce a global aerosol dataset from 1995 to 2007 by merging ATSR-2, AATSR, MERIS and SEVIRI satellite data. The products produced are AODs at 0.55 and 0.87μm, Ångström coefficient, and estimated speciation. The datasets support the information needs of users in climate and meteorological research, trans-boundary pollution and air quality agencies.

2.3.2.2 SYNAER

The SYNergetic Aerosol Retrieval (SYNAER) product is a method which combines simultaneous high spatial resolution AATSR and high spectral resolution SCIAMACHY measurements. The method exploits complementary information of a radiometer and a spectrometer on board one satellite platform to extract AOD and speciation (chosen from a representative set of pre-defined mixtures of water-soluble, soot, mineral dust, and sea salt components).

2.3.2 Other aerosol products

Previous studies have demonstrated that AOD can be retrieved from several visible and infrared sensors. In the future, it is likely that a way forward will be to utilise forms of synergistic retrievals with other aerosol instruments, and incorporating best knowledge of bidirectional reflectance distribution functions (BRDF). Good reviews of aerosol remote sensing have been provided by Kokhanovsky et al. (2007) and Martin (2008).

Table 2.1 summarises the aerosol products available from other sensors.

Sensor	Resolution	Advantages and Disadvantages
AVHRR	1km, Two satellites Twice per day	Most of the aerosol retrieval studies in the past have used data of the Advanced Very High Resolution Radiometer (AVHRR), which has two channels in the visible and near-infrared. Day-time overpasses occur during the period of maximum surface/air temperature (~13:00 to 14:00 local time) and night-time overpasses occur during the period of minimum surface/air temperature (~02:00 to 03:00 local time). It provides a unique source of information about aerosol properties due to the extensive length of their combined data record and the global coverage. However, the spectral information is limited because the AVHRR bands are broad and not well enough separated. Also, the near-infrared channel suffers from severe water vapour absorption. The AOD retrieval from AVHRR remains a relatively large error of 0.07 to 0.10 over the ocean (Coakley et al., 2002).
MERIS	0.3km	The Medium Resolution Imaging Spectrometer (MERIS) was launched in February 2002 on-board the Envisat spacecraft and is making global observations of TOA radiances. Aerosol optical properties are retrieved over land using Look-Up Table (LUT) based algorithms and surface reflectances in the blue and the red spectral regions. MERIS provides AOD and Ångström coefficients. However, it provides no information on speciation. Vidot et al. (2008) compared AOD retrieved by MERIS to AERONET AOD, finding that over land, MERIS aerosol optical thicknesses are well retrieved in the blue and poorly retrieved in the red, leading to an underestimation of the Ångström coefficient.

Sensor	Resolution	Advantages and Disadvantages
MISR	1km, Terra and Aqua Twice per day Terra: 10:30am/pm local time Aqua: 1:30am/pm local time	The Multiangle Imaging SpectroRadiometer (MISR), which is on-board the sun-synchronous polar orbiting satellite Terra, measures upwelling solar radiance in four spectral bands (centred at 446, 558, 672, and 866 nm) and at nine view angles spread out in the forward and aft directions along the flight path (at nadir, ±70.5, ±60.0, ±45.6, and ±26.1of nadir) (Diner et al., 2002). It acquires global coverage once per week. A wide range of along-track view angles makes it feasible to more accurately evaluate the surface contribution to the TOA radiances and hence retrieve aerosols over both ocean and land surfaces (including bright desert aerosol source regions and regions that would have been contaminated by sunlight for a mono-directional instrument). Evaluation studies show that overall, about two thirds of MISR AODs are within 20% or ±0.05 of coincident AERONET measurements (Yu et al. 2005). Over dark ocean, the MISR early post-launch AODs overall have a high bias of 0.038 (Kahn et al., 2005a; Abdou et al., 2005). The MISR multi-angle data also sample scattering angles ranging from about 60 to 160 in mid-latitudes, providing information about particle size and shape. These quantities are of interest for identifying aerosol airmass types.
MODIS	1km, Terra and Aqua Twice per day Terra: 10:30am/pm local time Aqua: 1:30am/pm local time	The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor has been observing and reporting on aerosol characteristics since the beginning of the Terra satellite mission in 2000. MODIS, with its 2330 km viewing swath width flying onboard Terra and Aqua, provides almost complete global coverage in one day. It acquires data in 36 high spectral resolution bands between 0.415 and 14.235 μm with spatial resolution of 250 m (2 bands), 500 m (5 bands), and 1000 m (29 bands). Seven of these channels between 0.47 and 2.13 μm are used to retrieve aerosol properties over cloud and surface-screened areas (identified by using other channels and examining spatial variability). Over vegetated land, MODIS retrieves aerosol optical depth at three visible channels with high accuracy, i.e., ±0.05±0.2 (Chu et al., 2002; Remer et al., 2005). Because of its wide spectral range over ocean and the greater simplicity of the ocean surface, MODIS has the unique capability of retrieving aerosol optical depth with great accuracy, i.e., ±0.03±0.05 (Remer et al., 2002, 2005), and quantitative aerosol size parameters (e.g., effective radius, fine-mode fraction of aerosol optical thickness). At low AOD the uncertainties associated with MODIS size parameters are greater (Remer et al., 2005; Kleidman et al., 2005). Recent comparisons show that MODIS ocean retrievals of fine-mode fraction are systematically higher than suborbital estimates of the submicrometre fraction by about 0.2 during the ACE Asia campaign (Anderson et al., 2005b).
POLDER	6 km	POLarization and Directionality of the Earth's Reflectances (POLDER) is an aerosol sensor that consists of a wide field-of-view imaging spectro-radiometer capable of measuring multi-spectral, multi-directional, and polarized radiances. The observed multi-angle polarized radiances can be exploited to better separate the atmospheric contribution from the surface contribution over both land and ocean. The POLDER onboard the Japanese Advanced Earth Observation Satellite (ADEOS-1 and -2) has collected aerosol data over both land and ocean. A similar POLDER instrument flies on the PARASOL satellite (Polarisation et Anisotropie des Reflectances au sommet de l'Atmosphère, couplées avec un Satellite d'Observation emportant un Lidar) launched in December 2004. A limitation of POLDER is its rather coarse spatial resolution of about 6 km, which affects the ability to account for scene heterogeneities. In addition, larger aerosol particles, such as desert dust, do not polarize sunlight and therefore cannot be retrieved quantitatively.
SEVIRI	3km (1 km high resolution visible channel), 15mins	The Spinning Enhanced Visible and Infra-Red Scanner (SEVIRI) is a new geostationary sensor in orbit 35,800 km above the equator. Despite a coarse spatial resolution, SEVIRI benefits from a high temporal resolution and 12 spectral channels (4 visible/NIR, 8 IR) - the Oxford-RAL Aerosol and Cloud retrieval scheme (ORAC) uses the visible channels at 0.64, 0.81, 1.6 μm to generate the aerosol products.

Sensor	Resolution	Advantages and Disadvantages
CALIPSO	vertical resolution: 30-60 m horizontal resolution: 333 m	The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite provides new insight into the role that clouds and atmospheric aerosols (airborne particles) play in regulating Earth's weather, climate, and air quality. CALIPSO combines an active Light Detection and Ranging (LIDAR) instrument with passive infrared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. CALIPSO was launched on April 28, 2006.

Table 2-1: Other satellite instruments providing remotely sensed aerosol products

3 THE APPLICATIONS OF AEROSOL PRODUCTS

Since the concept of aerosol-radiation-climate interactions was first proposed around 1970, substantial progress has been made in determining the mechanisms and magnitudes of these interactions, particular in the last ten years (Yu et al., 2006). In recent years, the characterization of aerosols has been significantly improved through intensive field experiments, ground-based network measurements, and satellite remote sensing and its integration with model simulations. This has led to the development of the applications discussed in the following subsections.

3.1 Radiative effects

Due to a high spatial and temporal variability of aerosol loading, and due to complicated and not fully understood link between aerosols and cloud properties, the total aerosol forcing of the climate system remains uncertain. In addition to global climate, aerosols affect the climate of specific regions and their water cycle. For example, South East Asia with its large ‘‘brown haze’’ is of special interest due to a possible impact on the Indian monsoon cycle (Ramanathan et al., 2001) as are East Asian and Saharan dust transports, and the outflow of biomass burning aerosols.

The interactions between aerosols and solar radiation are determined by a combination of aerosol properties (loading, chemical composition, size distribution, shape), surface properties (e.g., spectral and angular variations of surface albedo), clouds (cloud fraction, optical thickness, and vertical distribution), and geographical parameters (latitude, season; Yu et al., 2006). Assumptions associated with radiative transfer (RT) modelling also influence the assessment of the aerosol direct effect. These aerosol optical properties vary with the wavelength of radiation. The wavelength-dependence of AOD is usually represented by the Ångström exponent (Ångström, 1929, 1930), with high values of Ångström exponent indicative of small particles and low values indicative of large particles. At visible wavelengths, the SSA generally decreases with wavelength for non-dust aerosols and increases for dust aerosols (Dubovik et al., 2002). Aerosol optical properties also depend strongly on the size distribution. Therefore any factors affecting the size distribution will impact the optical properties.

Most of the aerosol particles are so weakly absorbing that their extinction is almost entirely due to scattering, rather than absorption. However, soot (carbon) particles are quite strong absorbers, and the absorption increases at short wavelengths. While this decreases the radiation flux at the surface, it heats the atmosphere locally. The heating can in turn cause a third climate forcing effect, known as the semi-direct radiative effect; the heating of the atmosphere can suppress the local relative humidity and thereby reduce cloud formation,

which would have otherwise caused surface cooling, so the net effect is to increase the amount of energy reaching the surface.

The addition of anthropogenic aerosols to the atmosphere may change the radiative fluxes at the TOA, at the surface, and within the atmospheric column. A positive radiative effect at the TOA indicates addition of energy to the earth-atmosphere system (i.e., a warming effect) whereas a negative effect indicates a net loss of energy (i.e., a cooling effect). Yu et al. (2006) designated a perturbation of net (downward minus upward) irradiance (summed over solar and thermal infrared spectrum) by anthropogenic aerosols (both directly and indirectly) as aerosol climate forcing (ACF) and they distinguish this from the aerosol radiative effect (ARE) of the total aerosol (natural plus anthropogenic). Due to a lack of data and computational resources, evidence of the aerosol effect on global radiation (warming or cooling) was uncertain.

(A)ATSR data can be used to quantify the aerosol forcing of specific events. For example, previous work has used (A)ATSR data to derive a global distribution of ship tracks and estimate their radiative forcing using backscattered radiation at the TOA. Ship tracks are produced by the emission of aerosols from ships into the clean marine boundary layer, which alters cloud reflectance.

3.2 Stratospheric aerosols

As discussed previously, identifying the presence of aerosols in order to accurately retrieve surface temperature is a practical priority. The eruption of Mount Pinutubo in 1991 first demonstrated the impact of stratospheric aerosols on sea surface temperature (SST) retrievals, and the potential for using (A)ATSR to examine aerosols. Stratospheric aerosols, such as those released during volcanic eruptions, provide a surface where the ozone destruction reactions take place very rapidly. It has also been observed that it takes much longer for aerosols to be removed from polar regions than from tropical regions. (A)ATSR retrievals of stratospheric aerosols (i.e. anomalies, atmospheric lifetime), especially over polar regions, could therefore provide useful information for studies of ozone depletion due to sulphate aerosols.

3.3 Aerosol transport

At a regional level, atmospheric aerosols are influenced by the synoptic situation. For example, the characteristics associated with heat wave development can strongly affect the regional atmospheric aerosol properties. Anticyclonic summer heat waves result in the accumulation of pollutants, increased forest fires, and induced high ozone and particulate

matter levels. This is due to high temperature and radiation, stagnation of air masses and weak dry deposition, which favour accumulations. Similarly, winter freezing episodes also result from anticyclonic circulations – this type of circulation is favourable to the long-range transport of aerosols (sinking air and gentle winds). Coefficients adopted for background tropospheric aerosols have been included in the 'atmospheres' used to develop the (A)ATSR retrievals. (A)ATSR can therefore provide information on background aerosols and variations in air quality during such events.

Saharan dust aerosol particles are relatively large (e.g. several μm) and are transported in the troposphere, typically at heights of 1.5–4.5 km. The transport of the dust can also be associated with unusually high atmospheric temperature and low relative humidity, which have been traced as far as the Caribbean. Previous work has shown that (A)ATSR can provide information regarding the transport of mineral dust – for example, aerosol plumes have been identified over the Sahel and Southern Sahara region by using the 0.55 μm band in the forward direction (the forward view is more sensitive to atmospheric scattering due to the longer path length).

(A)ATSR could be used, in conjunction with back-trajectory analysis, to investigate the source of long-range aerosol plumes. As discussed above, (A)ATSR can also be used to examine the transport of large aerosol plumes, such as those originating in the Sahel. Furthermore, (A)ATSR fire maps could be used to help document the spatial extent of rainforest fires and to identify the air masses containing the smoke aerosols.

3.4 Atmospheric stability

Absorbing aerosols, such as elemental carbon, which strongly absorbs visible light, or mineral dusts, which absorb long-wavelength infrared, can lead to heating of the lower atmosphere. This changes the differential heating of the atmosphere and therefore atmospheric stability that influences convective and turbulent motions and cloud development.

3.5 Air quality and visibility

The most obvious characteristic of air pollution is the loss of visibility. This is primarily due to suspended airborne particles, which scatter light efficiently, giving the atmosphere a 'hazy' appearance. In addition to visibility and climate implications, these particles have significant health impacts which have been increasingly recognized. Finally, particles may act as sinks of reactive species such as HO_2, particularly in remote regions, hence affecting the chemistry of the gas phase as well.

Visibility loss caused by aerosols is also an issue. This is primarily due to suspended airborne particles, which scatter light efficiently, giving the atmosphere a 'hazy' appearance. In addition to visibility and climate implications, these particles have significant health impacts which have been increasingly recognized.

3.6 Health

Aerosols have been linked to many health problems effecting allergy sufferers and those with respiratory conditions like asthma and emphysema. In light of many recent studies, there now exists overwhelming scientific evidence that inhaled aerosols increase the risk of respiratory and cardiopulmonary disease. While it is accepted that the concentration of aerosols is associated with the incidences of these conditions, the effect of specific aerosol properties such as type, size, and spatial and temporal distribution are not well known.

3.7 Improved satellite products for trace gases

Retrievals of trace gas concentrations from satellite measurements of radiance are expected to improve through the utilisation of good aerosol data. Benefits are particularly expected for retrievals of tropospheric trace gases from visible and shortwave infra-red reflectances for which (A)ATSR aerosol retrievals are particularly relevant. Some studies have already taken place with respect to nitrogen dioxide. Other candidate molecules include carbon dioxide and methane. Since aerosol effects can be large in polluted and dust-affected regions of the world, progress in accurate retrievals of tropospheric trace gases will require consideration of aerosol input data, such as that from (A)ATSR.

4 POSSIBLE EXPLOITATION OF (A)ATSR AEROSOL PRODUCTS

It is evident that there are numerous strategic scientific issues which need to be addressed regarding aerosols. The importance of aerosols in moderating or amplifying radiative forcing is generally accepted. For aerosol data, the following steps are recommended:

1. Careful regional validation/characterisation of the aerosol data should be performed, particularly over land, including aerosol properties such as type and radius.

2. The use of (A)ATSR aerosol data should be promoted to users, along with very good information on the quality of the data and training in its use.

3. The combination of (A)ATSR aerosol data with other appropriate datasets such as MODIS or MERIS aerosol should be investigated (as for GlobAerosol and SYNAER).

4. The development of operational (A)ATSR aerosol products should be supported and implemented.

5. The use of (A)ATSR aerosol data for climatological air quality studies should be investigated.

6. Support should be given to intercomparisons of aerosol data with regional and global aerosol models.

7. Investigations should be performed of the utility of (A)ATSR data for improvement in the retrievals of tropospheric trace gases from visible/shortwave infra-red measurements.

5 REMOTE SENSING OF CLOUDS

5.1 Theoretical basis

Aerosols act as cloud condensation nuclei; water vapour condenses onto aerosols to form cloud droplets, in a process known as heterogeneous nucleation. Aerosols therefore modify cloud droplet growth, which affects cloudiness and precipitation in both magnitude and location. This aerosol-cloud interaction can play a significant role in both the radiative balance of the atmosphere and in the hydrological cycle. The implications for both the understanding and prediction of future climate change are significant.

Activation of CCN is one of the most important processes in cloud and rain formation (Khain and Sednev, 1996). To form raindrops, cloud particles have to increase in mass more than a million times and these cloud particles are nucleated by aerosols with a radius as small as 0.01 μm (Wallace and Hobbs 1977). Clouds therefore play an important role in the processing of atmospheric aerosols, since they contribute to both the removal of aerosols and new aerosol formation (Xu et al., 1999). Frequently, when an air parcel ascends, resulting in expansion and adiabatic cooling, supersaturation occurs. The number of CCN increase with rising supersaturation since progressively smaller aerosols can be activated to form drops. Water vapour condenses onto some aerosols to form cloud droplets. This is known as heterogeneous nucleation (described by Köhler theory, outlined below), and is the process that forms droplets in natural clouds, requiring much lower supersaturation than homogeneous nucleation (condensation without the aid of an aerosol) (Aitken, 1881); early simulations indicated that a relative humidity of 800% would be needed before small droplets formed spontaneously (Wilson, 1800).

Different aerosols can have different impacts upon precipitation. Small aerosols (Aiken nuclei) which cause a narrowing of the size distribution of cloud droplets lead to reduced or suppressed precipitation, since a range of droplet sizes are required for warm rain to develop. In polluted clouds it is suggested that there are too many small droplets and not enough larger or ‘giant’ droplets. However, it has recently been suggested that due to reduced collection efficiency, such clouds may continue to ascend to altitudes where graupel and ice crystals form – these clouds are deeper and produce heavy rain, lightening and hail. Therefore, under certain conditions, a delay in the onset of warm rain due to aerosols can result in delayed downdraft formation, allowing for a more invigorated updraft which produces deeper and stronger convection. For example, this effect may be experienced ‘downwind’ of urbanised regions. In contrast, the presence of ‘giant’ nuclei can act to enhance precipitation. Giant aerosols produce large cloud droplets near the cloud base – the effects of such giant CCN are significant when the concentration of small, Aitken nuclei is high, as in urban clouds. Giant CCN act as a destabilising factor, by accelerating collisions and coalescence between the

water drops which causes early development of large drops in lower parts of the cloud. Furthermore, giant CCN accelerate precipitation formation through the ice phase, due to formation of ice by nucleation. Large droplets formed by the giant CCN produce graupel particles earlier – these have high coagulation efficiency with drops and therefore grow more rapidly as they are lifted in the updraft region, yet they remain close to the cloud base which can also promote ice multiplication processes in supercooled regions.

5.2 Satellite cloud products

Future and current climate simulations, using state-of-the-art models, are very sensitive to changes in the current cloud parameterisation schemes. Indeed, models can even introduce compensating errors that hide additional sensitivities to certain parameters. Accordingly, the scientific community has put an imperative on the validation of these cloud parameterisations by confronting the model simulations with observations. While high-resolution measurements obtained in experimental campaigns are necessary to develop the parameterisations, the evaluation of model cloudiness requires comparison with global climatological data. Such climatological comparisons can highlight specific areas of disagreement, but do not always explain the reasons why the observations and models disagree as other model problems can manifest in the simulated cloudiness. For comparison with climate models, observational studies that are restricted seasonally and/or spatially to identify specific synoptic regimes are becoming more important.

5.2.1 The (A)ATSR cloud product

Despite the apparent proliferation of cloud data, the information about cloud properties is often limited to frequency information and optical thickness along with environmental data (e.g. cloud top temperature and pressure). While there is relatively good agreement in some cases between sensors for gross measures of cloudiness (e.g. seasonal and zonal means) there is still considerable disagreement in detail. Long term global datasets of cloud optical and physical parameters are essential. The required long term cloud data can be obtained from the long term dataset of visible reflectances from 1995 until the present day, from ATSR-2 and AATSR. Several different algorithms have been developed over the years and one of these forms the basis of the GRAPE (Global Retrieval of ATSR Cloud Parameters and Evaluation) project that has performed an initial analysis of the ATSR-2 dataset with future data from the AATSR to be added at a later stage. The GRAPE project is producing a new cloud database which will include the following parameters, along with associated error measurements (enabling the use of this data in some form of data assimilation at a later date):

- Cloud Optical Depth
- Cloud Phase
- Cloud Particle Size
- Cloud Top Pressure
- Cloud Fraction
- Cloud Water Path

High-level cirrus clouds have a strong influence on Earth's radiation budget. The brightness temperature (BT) difference between 11 μm and 12 μm channels on (A)ATSR is large over thin cirrus due to differences in emissivity at these wavelengths and can therefore be used to provide information on cirrus. Contrails and resulting cirrus clouds also have significant climate impacts; contrail detection algorithms (CDA) have been successfully used with (A)ATSR data and clearly show the presence of ship tracks.

Cloud detection tests are implemented as part of the (A)ATSR processing. (A)ATSR's 1.6 micron channel, together with the 54 degree forward view, allows improved distinction between low level water clouds and high level ice clouds.

5.3 Application of cloud products

As mentioned previously, aerosol indirect effects on clouds remain an enormous challenge from both the observational and modelling perspectives. Only recently have studies been able to focus on the estimation of the aerosol indirect radiative forcing, as a result of the improvement of satellite and modelling techniques. For example, Anderson et al., (2003) suggested that the aerosol radiative forcing may be overestimated in current climate models by comparing forward and inverse model calculations. Quaas and Boucher (2005) evaluated and improved the representation of the aerosol indirect effect (AIE) in a general circulation model. They derived statistical relationships of cloud-top droplet radius and aerosol index (or AOD) from satellite retrievals using MODIS and POLDER data and fit an empirical parameterization in a general circulation model to match the relationships. Their results on the aerosol indirect radiative forcing effect are consistent with the inverse calculation in Anderson et al. (2003).

5.4 Possible exploitation of (A)ATSR cloud product

It is also generally accepted that our knowledge of cloud dynamic and radiative properties falls well short of that required by modern climate analyses and prediction schemes, due to a high spatial and temporal variability of aerosol loading, and due to a complicated link between aerosols and cloud properties. This means that the total aerosol forcing of the climate system remains uncertain. In addition to their effect on global climate, aerosols affect the climate of specific regions and their water cycle. Once the practical priority of identifying the presence of clouds in order to retrieve surface temperature has been satisfied there is clearly much scope for using AATSR's multi-angle multi-wavelength viewing geometry to characterise and investigate the properties of clouds. It is therefore recommended that the development of operational (A)ATSR cloud products should be supported and implemented. These products will need to be supported by good validation activities.

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APPENDIX A: LIST OF ACRONYMS

AATSR	Advanced Along-Track Scanning Radiometer
(A)ATSR	All three ATSR instruments
ACE	Aerosol Characterization Experiment
ACF	Aerosol Climate Forcing
ADEOS	Advanced Earth Observation Satellite
ADIENT	Appraising the Direct Impacts of Aerosol on Climate
AEB	(A)ATSR Exploitation Board
AEP	(A)ATSR Exploitation Plan
AERONET	AErosol RObotic NETwork
AIE	Aerosol Indirect Effect
AOD	Aerosol Optical Depth
ARE	Aerosol Radiative Effect
ATSR	Along-Track Scanning Radiometer
ATSR-1	The ATSR instrument on the ERS-1 satellite
ATSR-2	The ATSR instrument on the ERS-2 satellite
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Functions
BT	Brightness Temperature
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CCN	Cloud Condensation Nuclei
CDA	Contrail Detection Algorithm
DUE	Data User Element
Envisat	Environmental Satellite
EO	Earth Observation
GAW	Global Atmosphere Watch
GRAPE	Global Retrieval of ATSR Cloud Parameters and Evaluation
HULIS	HUmicLIke Substances
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
LUT	Look-Up Table

MEDUSE	MEditerranean DUSt Experiment
MERIS	MEdium Resolution Imaging Spectrometer
MISR	Multiangle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NERC	Natural Environment Research Council
ORAC	Oxford-RAL Aerosol and Cloud
PARASOL	Polarisation et Anisotropie des Reflectances au sommet de l'Atmosphère, couplées avec un Satellite d'Observation emportant un Lidar
PBAP	Primary Biological Aerosol Particle
PI	Principal Investigator
POLDER	POLarization and Directionality of the Earth's Reflectances
RAL	Rutherford Appleton Laboratory
RT	Radiative Transfer
SCHIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY
SEVIRI	Spinning Enhanced Visible and Infra-Red Scanner
SHADE	Saharan Dust Experiment
SOA	Secondary Organic Aerosol
SSA	Single Scattering Albedo
SST	Sea Surface Temperature
SW	Short-Wave
SYNAER	SYNergetic Aerosol Retrieval
TNO	Toegepast Natuurwetenschappelijk Onderzoek
TOA	Top Of Atmosphere
TOMS	Total Ozone Mapping Spectrometer
UKCA	United Kingdom Chemistry Aerosol (model)
VOC	Volatile Organic Compound
WMO	World Meteorological Organisation

APPENDIX B: AEROSOL PARAMETERS

Parameter	Symbol (unit)	Definition	References
Aerosol Optical Depth	τ	Defined as the integral over the vertical column of the aerosol light extinction coefficient.	
Extinction coefficient	σ_e^1 (km^{-1})	For radiation propagating through a medium, the fractional depletion of radiance per unit path length.	
Scattering coefficient	σ_s^1 (km^{-1})	A measure of the extinction due to scattering of monochromatic radiation as it traverses a medium containing scattering particles	
Absorption coefficient	σ_a^1 (km^{-1})	A measure of the extinction due to absorption of monochromatic radiation as it traverses a medium.	
Volume phase function	$p^1(\theta)$ (km^{-1}sr^{-1})	Phase function is defined as the energy scattered per unit solid angle in a given direction to the average energy in all directions.	
Single scattering albedo	ϖ_0	Defined as $\sigma_s^1 / (\sigma_a^1 + \sigma_s^1)$, describes the relative contributions of scattering and absorption to the total light extinction. Purely scattering aerosols (e.g. sulphuric acid) have values of 1, while very strong absorbers (e.g., black carbon) have values of around 0.3.	WMO/GAW No.153
Asymmetry parameter	g	It is measure of the preferred scattering direction (forward or backward) for the light encountering the aerosol particles. In radiative transfer studies, asymmetry factor 'g' is equal to the mean value of the cosine of the scattering angle, weighted by the angular scattering phase function $p^1(\theta)$, see above. The asymmetry factor approaches +1 for scattering strongly peaked in the forward direction and -1 for scattering strongly peaked in the backward direction; g=0 indicates scattering directions evenly distributed between forward and backward directions, i.e. isotropic scattering (e.g. scattering from small particles); g<0 scattering in the backward direction (i.e. scattering angle > 90 degree, often backscattering is referred to scattering at 180 degree; g>0 scattering in the forward direction (i.e. scattering angle a<90, often forward-scattering is referred to scattering at 0 deg. For larger size or Mie particles, g is close to +1.	NASA website