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Intercomparison of satellite dust retrieval products over the west African Sahara during the Fennec campaign in June 2011

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ABSTRACT

Four aerosol optical depth retrieval algorithms over the Sahara Desert during June 2011 from the IASI, MISR, MODIS, and SEVIRI satellite instruments are compared against each other in order to understand the strengths and weaknesses of each retrieval approach. Particular attention is paid to the effects of meteorological conditions, land surface properties, and the magnitude of the dust loading. The period of study corresponds to the time of the first Fennec intensive measurement campaign, which provides new ground-based and aircraft measurements of the dust characteristics and loading. Validation using ground-based AERONET sunphotometer data indicates that of the satellite products, the SEVIRI retrieval is most able to retrieve dust during optically thick dust events, whereas IASI and MODIS perform better at low dust loadings. This may significantly affect observations of dust emission and the mean dust climatology. MISR and MODIS are least sensitive to variations in meteorological conditions, while SEVIRI tends to overestimate the aerosol optical depth (AOD) under moist conditions (with a bias against AERONET of 0.31), especially at low dust loadings where the AOD < 1. Further comparisons are made with airborne LIDAR measurements taken during the Fennec campaign, which provide further evidence for the inferences made from the AERONET comparisons. The effect of surface properties on the retrievals is also investigated. Over elevated surfaces IASI retrieves AODs which are most consistent with AERONET observations, while the AODs retrieved by MODIS tend to be biased low. In contrast, over the least emissive surfaces IASI significantly underestimates the AOD (with a bias of −0.41), while MISR and SEVIRI show closest agreement.

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1. Introduction

The Sahara is the largest source of mineral dust aerosols in the world (e.g. Washington et al., 2003), and the atmosphere above it has some of the highest dust loadings. Large Saharan dust storms have been observed to increase the reflected shortwave radiation by as much as 100 W m^{-2} and to simultaneously significantly decrease the outgoing longwave radiation (Slingo et al., 2006). Dust may also have effects on ocean biogeochemistry through the transport of iron (e.g. Mahowald et al., 2005) and can affect fertility in the Amazon (Koren et al., 2006). Moreover, dust also interacts with the cloudy atmosphere and can change the

occurrence and microphysical properties of clouds (e.g. Mahowald & Kiehl, 2003; Lee & Penner, 2010). Dust loading over the Sahara peaks during the summer months when the Sahara has one of the deepest boundary layers on the planet (Cuesta et al., 2009).

Recent measurement campaigns have sought to deepen our understanding of climate and of dust activity in and near the Sahara. Such campaigns have included the African Monsoon Multidisciplinary Analyses (AMMA) project in 2006 (Redelsperger et al., 2006), which sought chiefly to understand the west African monsoon; Dust Outflow and Deposition (DODO) in 2006 (McConnell et al., 2008), which sought to quantify dust deposition into the ocean; the Saharan Mineral Dust Experiment (SAMUM) in 2006 and 2008 (Ansmann et al., 2011; Heintzenberg, 2009), which sought to measure dust composition and optical properties; Geostationary Earth Radiation Budget experiment Intercomparison of Longwave and Shortwave radiation (GERBILS) in June 2007 (Haywood et al., 2011), which sought to understand dust properties and the atmospheric radiation balance over the western Sahara; and most recently Fennec in June 2011 and June 2012 (Washington et al., 2012), which aims to understand the climate system

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of the western Sahara in summer. The Fennec approach has used ground (Marshall et al., in press; Todd et al., in press), aircraft (McQuaid et al., 2013; Ryder et al., 2013), and satellite (Banks & Brindley, 2013) observations, alongside numerical modelling.

The high dust loading in the turbulent Saharan summer atmosphere clearly has implications for the local climate. However, it is only relatively recently that multiple satellite retrieval algorithms have been developed which are able to quantify dust loadings over this region. Satellite observations are powerful tools which can also be used to study the distribution and intensity of dust sources (e.g. Schepanski et al., 2007; Ginoux et al., 2012). Depending on the methodology used, satellite retrievals will be variously sensitive to the amount of dust, meteorological conditions, and surface properties (e.g. Shi et al., 2011). Previous studies have sought to quantify the differences between the satellite retrievals over the Sahara, e.g. during a large regional dust storm in March 2006 (Carboni et al., 2012), and during GERBILS in June 2007 (Christopher et al., 2011). These studies briefly investigated the links between the retrievals and surface albedo, but it would be useful to set the dust retrieval algorithms within a wider context, by also considering atmospheric conditions and the surface emissivity, which the infrared retrievals may be more sensitive to. In addition, the information from the AERONET sites and aircraft flights established and undertaken under the auspices of the Fennec project provide valuable extra data to test the quality of the various retrievals from Saharan locations that were not sampled in previous studies. Indeed, the positioning of the Bordj Badji Mokhtar AERONET site is particularly well suited for quantifying aerosol loading associated with large dust events during boreal summer (Marshall et al., in press).

In this paper we present an analysis of co-located satellite aerosol retrieval products over the western half of the Sahara during the Fennec campaign in June 2011. We seek to quantify and understand the differences in the four specific retrievals from the IASI, MISR, MODIS, and SEVIRI satellite instruments with respect to dust loading, meteorological conditions, and surface properties, before evaluating the retrievals using data provided by AERONET (Holben et al., 1998) and aircraft observations made during the Fennec campaign.

2. Satellite, ground, and aircraft instrumentation

2.1. Satellite instruments and their retrieval products

The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) is located onboard the Meteosat Second Generation (MSG) series of satellites (Schmetz et al., 2002), which are in geostationary orbit above 0°N, 0°E, providing excellent coverage over Africa: these observations from SEVIRI have the advantage of a 15 minute temporal resolution, compared with the one or two observations over a given area per day provided by satellites in low Earth orbit. The nadir spatial sampling rate is 3 km (increasing to ~4.5 km at higher SEVIRI viewing zenith angles within the west African field of interest), with measurements made at 11 visible and IR wavelengths: of particular value are the 10.8 and 13.4 μm channels which can be used to infer dust aerosol optical depth (AOD) over land (Banks & Brindley, 2013; Brindley & Russell, 2009), using a method specifically designed for arid and semi-arid regions. The first step in the retrieval process is to flag pixels as dusty and/or cloudy (Derrien & Le Gléau, 2005; Ipe et al., 2004; MétéoFrance, 2012). In order for an AOD to be inferred for a given pixel, we require either that cloud is not flagged, or that dust is flagged. A 'pristine sky' value of the brightness temperature at 10.8 μm (T_{B108dfe}) is calculated for each timeslot in a 28-day rolling window period, accounting for variations in total column water vapour and skin temperature from European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim reanalyses. The deviation of the instantaneous T_{B108} value from the pristine sky value, due to dust, is given by:

$$\Delta T_{\text{B108}} = T_{\text{B108dfe}} - T_{\text{B108}} \quad (1)$$

An analogous calculation is made for ΔT_{B134} , which can be used to convert to dust AOD at 550 nm from a simulated relationship between $\Delta T_{\text{B108}}/\Delta T_{\text{B134}}$ and AOD (Brindley & Russell, 2009). The 13.4 μm channel is used to mitigate the effect of variations in dust height on the brightness temperature difference. The transfer coefficients for this relationship have been derived from radiative transfer simulations using the dust model described by Brindley & Russell (2009). While the algorithm attempts to account for the impact of variations in total column water vapour and surface temperature in order to isolate the dust only IR signal (Brindley, 2007), subsequent studies have suggested that at low dust loadings the retrieved dust optical depths may retain a sensitivity to, in particular, water vapour amount (Banks & Brindley, 2013). Over a three-year period, the correlation between the SEVIRI retrieval and individual AERONET sites ranges from 0.52 to 0.73. The RMS differences range from 0.19 to 0.46 and the biases range from -0.12 to 0.14.

Another widely used and useful qualitative tool which can be derived from SEVIRI is the 'desert dust' RGB imagery (Lensky & Rosenfeld, 2008), which employs brightness temperature differences in the 8.7, 10.8, and 12.0 μm channels to discriminate the presence of dust in the atmosphere. Dust appears pink in this analysis, although in moist atmospheres the dust signal can be masked (Brindley et al., 2012).

The Infrared Atmospheric Sounding Interferometer (IASI) instrument is carried by the METOP series of satellites. The dust retrieval method used here for IASI (Kluser et al., 2012, 2011) is based on singular vector decomposition of binned IASI spectra between 830 and 1250 cm^{-1} (8–12 μm). The rationale behind the approach is to avoid radiative transfer forward simulations of IASI spectra over deserts as surface emissivity is highly variable and unknown (e.g. DeSouza-Machado et al., 2010). Moreover the retrieval is designed to minimise the necessary a priori information such as atmospheric state (temperature and humidity profiles). Mineral dust composed of silicate minerals can be detected in the thermal infrared (Ackerman, 1997) due to Si–O resonance absorption bands (Hudson et al., 2008a,b). Maximum value filtered brightness temperature spectra (in 42 bins) are converted to 'equivalent optical depth' spectra (Kluser et al., 2011):

$$L_{\text{obs}}(\nu) = \exp(-\tau_{\text{eqv}}/\cos\theta) B_{\nu}(T_{\text{base}}) \quad (2)$$

where $L_{\text{obs}}(\nu)$ is the radiance at wavenumber ν observed from space, θ is the viewing zenith angle and $B_{\nu}(T_{\text{base}})$ is the spectral Planck-function evaluated for the baseline temperature defined as the maximum brightness temperature observed. The broad ozone absorption band around 1040 cm^{-1} is not used for dust retrieval. Singular vector decomposition has been performed for IASI spectra of equivalent optical depth covering North Africa, the Mediterranean and Arabia for a period of seven days. The singular vectors for the retrieval method, determined from this seven day period, are then used for dust retrieval for all 30 days in June 2011. The leading two singular vectors have been found to represent broad gas absorption and surface emissivity features, consequently dust optical depth is retrieved from the linear combination of higher order singular vectors. Extinction spectra of six mineral components of dust are projected onto the observed IASI spectra providing optical depth and weight for each component. Consequently, in contrast to most other dust retrieval methods, the singular-vector based approach is also able to account for variable mineralogy. In another iteration of the retrieval the thermal emission of the dust (Ackerman, 1997) is accounted for. After the IR optical depth (at 10 μm) of the dust has been determined the AOD is transferred to visible wavelengths (500 nm) by particle-size dependent transfer coefficients (Dufresne et al., 2002). Mathematical details of the method are presented by Kluser et al. (2011) and Kluser et al. (2012). The transfer coefficients are based on particle size, which is retrieved with great uncertainty, they are moreover the same for all mineralogical components (Kluser et al., 2012). The dust extinction models used in the current version neglect scattering by dust particles, which is only valid for small particles in the Rayleigh limit (e.g. Hudson et al.,

2008a,b). Surface temperature is underestimated at high thermal IR AOD, hence AOD would itself be underestimated. No hematite is contained in the dust models applied, which strongly absorbs solar radiation and is the main source of single-scattering-albedo reduction at solar wavelengths. Statistically, the correlation with AERONET is 0.76, the RMS difference is 0.17, the bias is 0.003, and the intrinsic retrieval uncertainty is about 20–30% (retrieved pixel-wise).

The Multi-angle Imaging SpectroRadiometer (MISR) was launched aboard the NASA Terra satellite into a sun-synchronous polar orbit in December 1999, and the data record currently extends over nearly 13 years. The instrument consists of nine cameras with view angles at the Earth's surface of $\pm 70.5^\circ$, $\pm 60.0^\circ$, $\pm 45.6^\circ$, $\pm 26.1^\circ$, and 0° (nadir), operating in four spectral bands centred at 446 nm (blue), 557 nm (green), 672 nm (red), and 866 nm (near infrared). The map-projected spatial resolution is 275 m at nadir and in the red band of all nine cameras. In the global observing mode, the remaining channels are spatially averaged and map-projected to 1.1 km resolution. The common swath width is ~400 km and global coverage is obtained every nine days at the equator and more frequently at higher latitudes (Diner et al., 2002).

The MISR standard aerosol retrieval algorithm reports AOD and aerosol type at $17.6 \text{ km} \times 17.6 \text{ km}$ spatial resolution by analysing 1.1 km-resolution MISR top-of-atmosphere (TOA) radiances from 16×16 pixel regions (Kahn et al., 2009b). Coupled surface-atmosphere retrievals are performed using all four spectral bands over most land surface types, including bright desert surfaces (Martonchik et al., 2009). The retrieval algorithm used to generate Version 22 of the MISR Standard Aerosol Product used in this study utilises a lookup table containing 74 aerosol mixtures consisting of eight component particle types (Kahn et al., 2010). Two of these components are a medium mode, non-spherical dust optical analogue developed from aggregated angular shapes and a coarse mode dust analogue composed of ellipsoids (Kalashnikova et al., 2005). The MISR aerosol retrieval over land employs two different algorithms sequentially. The first algorithm applies the assumption that surface angular shapes are spectrally similar, as described by (Diner et al., 2005). Different aerosol models and AODs are tested, and those that fail this test are excluded from further consideration. The second algorithm performs an empirical orthogonal function (EOF) analysis of the angular shape of the TOA equivalent reflectances within the retrieval region after the atmospheric path radiance has been removed by subtracting the TOA measurements within a reference pixel. Aerosol properties are assumed to be the same for all pixels in the region. The AOD and aerosol model are determined by finding the combination of path radiance and linear sum of low-order EOFs that best fit the observations (Martonchik et al., 2009).

The performance of the operational MISR aerosol retrieval over bright desert sources and its sensitivity to near surface aerosols and surface properties have been validated and used in a number of studies (Christopher et al., 2008, 2009; Frank et al., 2007; Kahn et al., 2009a; Martonchik et al., 2004). A global comparison of coincident MISR and AERONET sunphotometer data showed that overall, about 70% to 75% of MISR AOD retrievals fall within the larger of 0.05 or $0.20 \times \text{AOD}$, and about 50% to 55% are within the larger of 0.03 or $0.10 \times \text{AOD}$, except for sites where dust or mixed dust and smoke are commonly found (Kahn et al., 2005, 2009b, 2010).

The MODerate resolution Imaging Spectroradiometer (MODIS) is located aboard the NASA Terra and Aqua satellites. Each of the MODIS instruments provides global aerosol information once a day at the spatial resolution of $10 \text{ km} \times 10 \text{ km}$ at nadir. MODIS Deep Blue (Hsu et al., 2004, 2006) aerosol products use the blue wavelengths of the visible spectrum (412 and 470 nm referenced against 650 nm) to minimise the high surface signal in the visible wavelengths over bright surfaces such as the desert. Used here are the recently updated 'Collection 6' Deep Blue aerosol retrievals (the previous widely available product was 'Collection 5.1') from Aqua measurements: the similar method has been used for retrievals from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite instrument, as described by Sayer et al.

(2012). As compared to MODIS Collection 5.1, there are many improvements made in the Collection 6 Deep Blue algorithm. The most significant changes over desert regions include (1) the use of a newly developed Normalized Difference Vegetation Index (NDVI) dependent MODIS surface reflectance database to replace the previous static surface look-up tables; (2) a better dust aerosol model selection scheme using visible and thermal infrared bands simultaneously; (3) quality flag selection procedures; and (4) improved cloud flagging, decreasing the number of false detections. The resulting changes in monthly mean MODIS Aqua AODs for June 2011 from Collection 5.1 to Collection 6 are mapped in Fig. 1, indicating that Collection 6 retrieves more dust loading over the central Sahara, in contrast to Collection 5.1, which retrieves most dust on the desert margins, especially in the Sahel. These enhanced AOD values seen over the central Sahara are most likely due to the improvements in the dust model selection scheme made in the Collection 6 algorithm as mentioned above, which result in significant changes in retrieved AOD over regions where more absorbing dust aerosols prevail. The Deep Blue retrievals should be insensitive to both moisture and temperature, since the algorithm does not use channels with water vapour absorption. Similarly the retrieval should be insensitive to surface temperature, since only solar bands are used. The major assumptions in the Deep Blue algorithm are related to surface reflectance, aerosol microphysical properties, and aerosol height. The estimated uncertainty on an individual retrieval is $0.05 + 20\%$ in Collection 5.

Note that throughout this paper the names of the satellite instruments are used to denote AOD results from the specific dust retrieval algorithms introduced above. Other aerosol retrieval products exist for most of these instruments, for example the 'DarkTarget' MODIS algorithm (Levy et al., 2007) which is unable to retrieve aerosol over bright desert surfaces and so is not used here.

2.2. Ground-based and aircraft data

Ground and in-situ data are invaluable for understanding and validating satellite product data. From the ground, the Aerosol Robotic Network (AERONET) of sun-photometers provides multi-year time-series of AOD measurements from numerous sites (Holben et al., 1998). The nine AERONET sites in west Africa with co-located satellite product data in June 2011 are mapped in Fig. 2, with further details provided in Table 1. Two of these, Bordj Badji Mokhtar (BBM) and Zouerat (Marshall et al., in press; Todd et al., in press), were established within the framework of the Fennec project, with the goal of contributing to a new data set of atmospheric observations from the central Sahara (Washington et al., 2012). There are three levels of AERONET data for data quality purposes (Smirnov et al., 2000): Level 1 data, the 'raw' AOD measurements; Level 1.5, which are 'cloud-screened'; and Level 2, which are individually inspected and have the final calibration applied. The difference between Level 1 and Level 1.5 can be used as a crude measure for determining the influence of cloud on the observations (e.g. Brindley & Russell, 2009). Following the procedure outlined by Banks & Brindley (2013), AERONET data is regarded as representative for grid cells within a 25 km radius of the AERONET site, and observations are regarded as dusty where the Ångström coefficient $\alpha \leq 0.6$ and the AOD $\tau_{1020 \text{ nm}} \geq 0.2$ (Dubovik et al., 2002), where α is computed between 440 and 870 nm. Uncertainties in the AERONET measurements are of the order 0.01 to 0.02 (Holben et al., 1998).

During the Fennec campaign in June 2011, ground data were supplemented by aircraft data from flights across Mauritania and northern Mali (McQuaid et al., 2013), using the Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE) Falcon 20 aircraft. The Falcon 20 was equipped with the backscatter LIDAR Leandre New Generation (LNG, deVilliers et al., 2010) allowing the measurement of atmospheric reflectivity at three wavelengths (355, 532, and 1064 nm) to analyse the structure and radiative

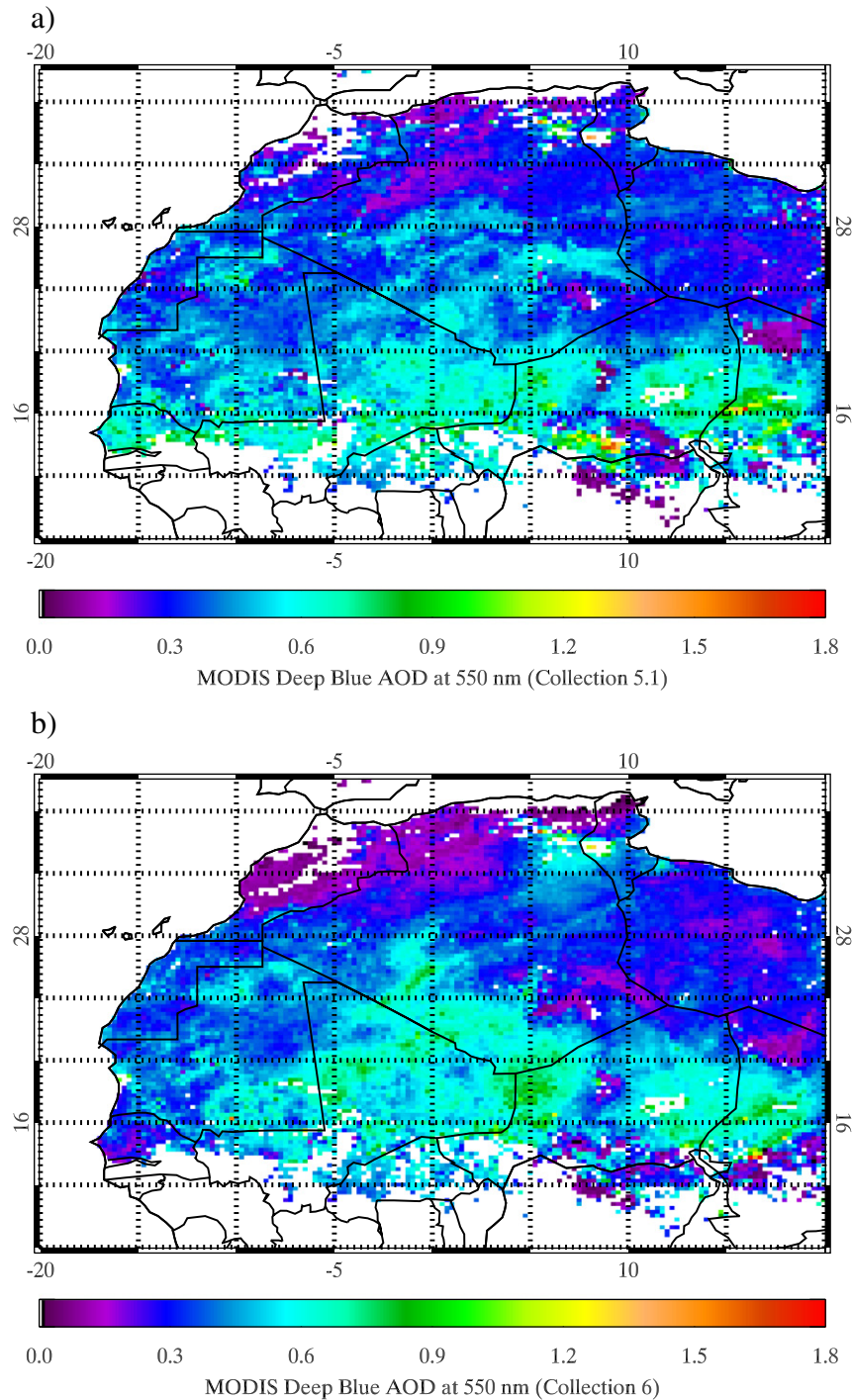


Fig. 1. Monthly mean MODIS Deep Blue retrieved AODs: (a) Collection 5.1, (b) Collection 6. One outlier in MODIS Collection 6 at 13.75°N, 16.75°E has a value of 2.07.

characteristics of desert dust plumes. The Falcon 20 was also equipped with a Vaisala AVAPS dropsonde launching device, radiometers (broad-band up- and down-looking Kipp and Zonen pyranometers and pyrgeometers), the CLIMAT radiometer (Legrand et al., 2000) as well as in situ PTU and wind sensors. The profiles of atmospheric extinction coefficient at 532 nm are retrieved using a standard LIDAR inversion technique (Cuesta et al., 2008; Fernald et al., 1972). The profiles of molecular extinction coefficient used in the inversion procedure are obtained from molecular density profiles computed using temperature and pressure data from dropsondes released during the flight (Bodhaine et al., 1999). The aerosol backscatter-to-extinction ratio used for the inversion is considered to be constant with altitude, set at

0.021 sr^{-1} . This value is intermediate between the value derived at 532 nm from space-borne, airborne, and ground-based LIDAR systems over northern Africa (i.e. 0.018 sr^{-1} , see Heintzenberg, 2009; Schuster et al., 2012) and those derived over Sahelian Africa (i.e. 0.024 sr^{-1} , see Omar et al., 2009; Schuster et al., 2012). Given the uncertainty on the backscatter-to-extinction ratio ($\pm 0.001 \text{ sr}^{-1}$), the uncertainty on the LIDAR-derived AODs is estimated to be of the order of 15%. For inversion, a backscatter ratio (the total backscatter coefficient divided by the molecular backscatter coefficient) of 1 is considered at 9.5 km above ground level (agl), i.e. above dust observed during the period of interest. In Section 4.2 we will show and discuss particulate extinction coefficient profiles (PEC) and AOD obtained from the PEC profiles

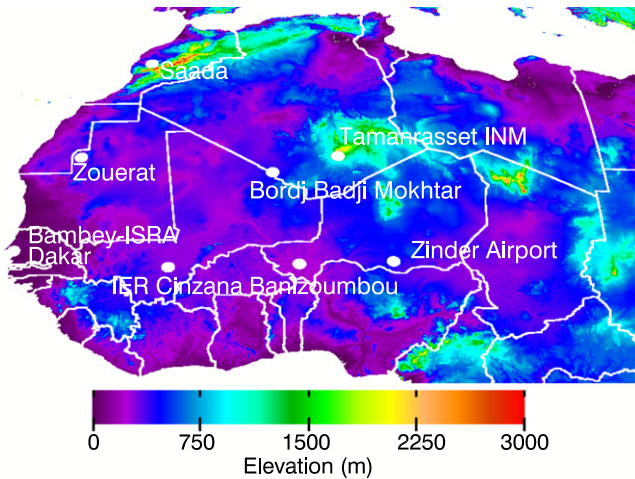


Fig. 2. Map of the nine AERONET sites with co-located data in June 2011, overlaid on the surface elevation (as developed by the Eumetsat Satellite Application Facility for Nowcasting (MétéoFrance, 2012)).

integrated between 0 and 9.5 km agl. Finally, the evolution of the integrated water vapour content in the lower atmosphere along the Falcon 20 flight track was derived from dropsonde-derived water vapour mixing ratio profiles integrated between 0 and 10 km agl.

3. Satellite product intercomparisons during June 2011

In order to compare the various satellite products, we have established a common grid onto which the satellite data are binned, at a latitude/longitude resolution of 0.25° . This resolution has been chosen so as to be coarser than the coarsest set of satellite data: in this case this is the MISR aerosol product, which has a resolution of 17.6 km (Kahn et al., 2010). Uncertainties are calculated by combining the pixel uncertainties that fall within each grid cell. The region chosen is the western half of the Sahara, $8\text{--}38^\circ\text{N}$, $20^\circ\text{W}\text{--}20^\circ\text{E}$, a domain which covers all desert areas which may contribute substantially to the dust aerosol loading over west Africa. The local equator crossing times for the satellites are ~ 0930 UTC for METOP (IASI), 1030 UTC for Terra (MISR) and 1330 UTC for Aqua (MODIS), although AERONET observations suggest that the general diurnal variability of dust loading is quite small (Smirnov et al., 2002). Where all satellite products are included in the comparisons we choose MISR as our temporal reference point. For each day for a given grid cell observed by MISR, we retain the corresponding observation from SEVIRI which is closest in time (within ± 15 min). If an IASI or a MODIS observation was made over the grid cell within five hours of the MISR observation, this is retained. Finally we impose the condition that all four satellite products must have made a valid AOD retrieval from these observations for the grid cell values to be included in the final intercomparison. Between the four satellite products, during

June 2011 there are 11,516 co-located retrievals over 6716 grid cells. Because MISR has a very narrow swath this does place a relatively stringent limit on the number of intercomparison points available. Hence, to allow a greater range of conditions to be sampled and a greater number of AERONET/aircraft coincidences to be included, we relax these criteria for specific cases and retain SEVIRI, IASI, and MODIS co-locations only. In these cases IASI becomes the reference satellite track. For all products, the gridded uncertainties are derived from the standard deviation of the mean of the AOD retrievals within the grid cell.

For comparison with AERONET, all valid AERONET observations within three hours of the IASI overpass are included and averaged to find the co-located AERONET values. MODIS and SEVIRI also validated against the AERONET data taken from the IASI timeslot (± 3 h). The uncertainties on the averaged observations are derived from the standard deviation of the mean of the AERONET measurements within this time period. Also mapped onto the intercomparison grid are co-located values of total column water vapour and skin temperature from ECMWF ERA-Interim re-analyses, re-gridded in time and space to the intercomparison grid. Emissivity at $8.7 \mu\text{m}$ (ϵ) as derived from MODIS data (Seemann et al., 2008) are also mapped alongside their co-located values, as are albedo values at 600 nm as derived from SEVIRI (Derrien & Le Gléau, 2005).

3.1. Intercomparisons across the west African Sahara

The distribution of mean co-located AODs for June 2011 for the four satellite products are mapped in Fig. 3. The four retrievals broadly agree on the dominance of the dust signal over eastern Mali and the central Sahara in general, although there are variations in the emphasis that they place on the strength of various dust events. For example, SEVIRI and MODIS, and to a lesser extent MISR, agree on the significance of a dust event in northern Algeria on the 1st June (which is the dominant contributor to the monthly mean in this area), a plume which does not appear as strongly in the IASI retrievals. It is clear that SEVIRI tends to report noticeably higher AODs than reported by the other retrievals, especially over a large area of the central Sahara: the values reported by the other retrievals are comparatively small, especially by IASI, as indicated by Table 2. High AODs appear to be an accurate representation of the dust loading in this area of the central Sahara, subject to the most frequent occurrence of haboob dust outbreaks (Marshall et al., 2008).

Due to the requirement for co-located data, there are many gaps in the spatial comparison. In some cases this is due to fewer occurrences of co-location, but more often the grid cells are excluded due to the prevalence of cloud, especially over the Sahel and sub-Saharan Africa, or due to other data quality issues. In the case of SEVIRI, observations are always available across the domain, but AOD retrievals may not be made due to the presence of cloud. Of the 53,918 points where and when all instruments made co-located observations, 39.6% of IASI points had valid AOD retrievals, as had 67.1% of MISR points, 52.8% of MODIS points, and 80.2% of SEVIRI points. Table 3 compares the product/product agreement on the presence of the valid retrievals, showing the highest agreement between SEVIRI and MISR. MODIS shows slightly less agreement with these two retrievals, although the bulk of the disagreement between these three products comes from unsuccessful MODIS retrievals. IASI has the lowest ratio of retrievals to observations, and so its agreement with the other products is markedly lower. IASI's low sensitivity to small amounts of airborne dust is due to the SVD technique and its application of dust spectra in the Rayleigh limit, which restricts the correct identification of the scattering signal of the dust. Moreover the dust vector in the IASI retrieval may not cover all components abundant in Saharan dust and may be insensitive to particle size and humidity effects (Kluser et al., 2011).

Turning to the successful retrievals only and looking at the mean value of all the co-located measurements, we find that, as suggested by Fig. 3, SEVIRI tends to retrieve the highest AODs compared to the

Table 1

Locations of the relevant AERONET sites (latitudes in $^\circ\text{N}$, longitudes in $^\circ\text{E}$, and altitudes in m), surface emissivities (at $8.7 \mu\text{m}$) and albedos, and averaged total column water vapour (TCWV, in mm) and skin temperature (T_{skin} , in K) during June 2011.

Site, country	Lat.	Lon.	Alt.	ϵ	Alb.	TCWV	T_{skin}
Bambey-ISRA, Senegal	14.71	−16.48	30	0.91	0.25	45	311
Banizoumbou, Niger	13.54	2.67	250	0.85	0.29	44	310
BBM, Algeria	21.33	0.95	400	0.76	0.39	21	315
Dakar, Senegal	14.39	−16.96	0	0.93	0.21	39	308
IER Cinzana, Mali	13.28	−5.93	285	0.90	0.22	45	309
Saada, Morocco	31.63	−8.16	420	0.91	0.22	18	307
Tamanrasset INM, Algeria	22.79	5.53	1377	0.92	0.28	13	311
Zinder Airport, Niger	13.78	8.90	456	0.83	0.34	37	309
Zouerat, Mauritania	22.75	−12.48	343	0.77	0.33	16	315

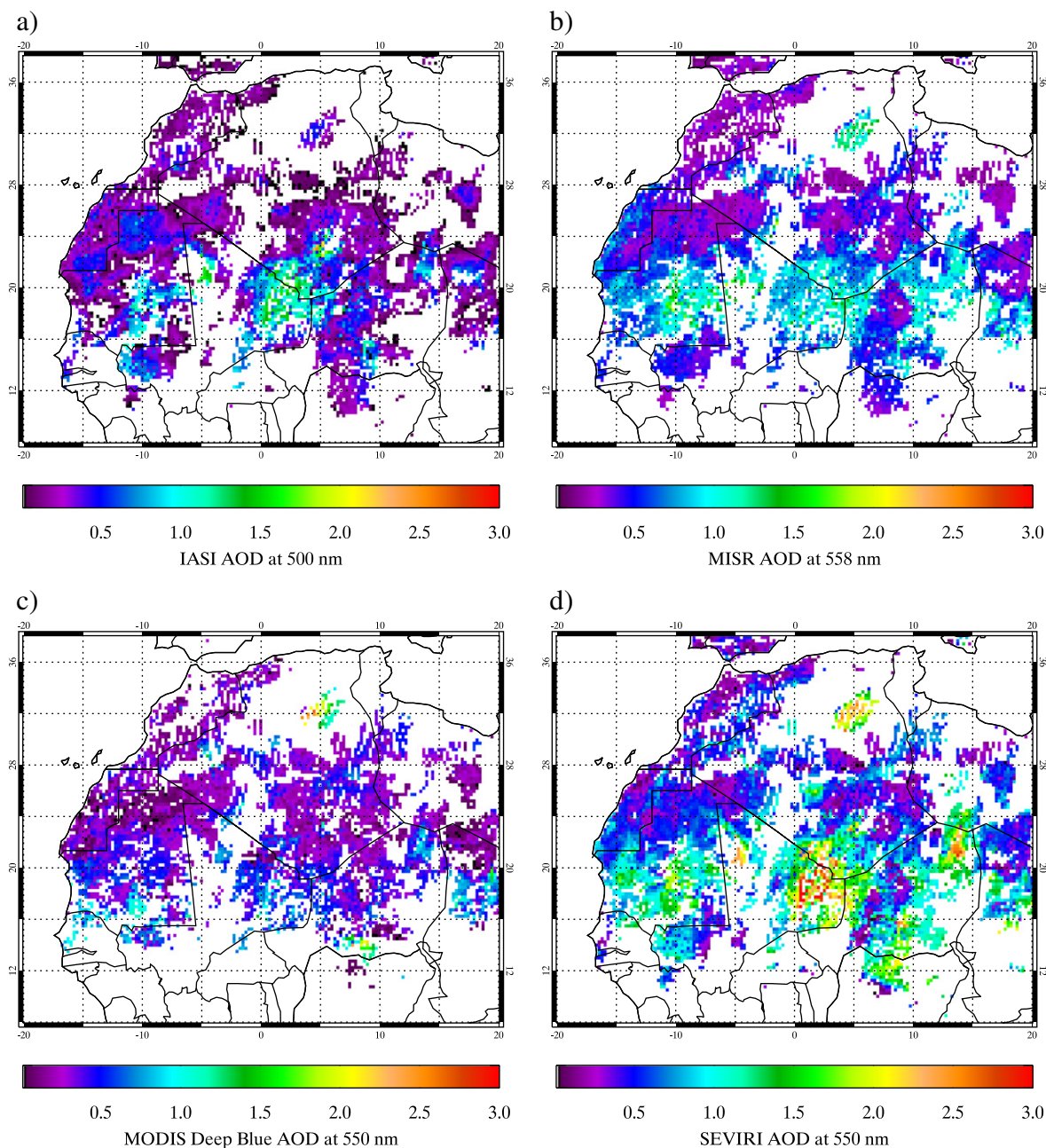


Fig. 3. Map of the June 2011 mean co-located satellite retrieved AODs: (a) IASI; (b) MISR; (c) MODIS; (d) SEVIRI. Regions in white did not have co-located data between all four satellite retrievals during the month. Co-located data are from points where all four products had a successful retrieval. Note that there are no more than 6 points in any grid cell. Eight grid cells in eastern Mali have SEVIRI AODs > 3, up to 3.40.

other products ($\overline{\text{AOD}} = 0.71$), followed by MISR (0.50) and MODIS (0.46), while IASI tends to retrieve the lowest AODs (0.30). Density plots of retrieval vs. retrieval AODs are shown in Fig. 4. Subdividing

Table 2

Overall mean co-located satellite retrieved AODs and their standard deviations. Included are subdivided means by various regimes of column moisture and skin temperature. The boundary between column moisture regimes is 20 mm, and between skin temperature regimes the boundary is 315 K.

Instrument	Mean	σ	Cool/dry	Warm/dry	Cool/moist	Warm/moist
IASI	0.30	0.33	0.19	0.31	0.28	0.41
MISR	0.50	0.31	0.28	0.45	0.55	0.73
MODIS	0.46	0.30	0.32	0.45	0.48	0.60
SEVIRI	0.71	0.53	0.44	0.60	0.86	0.95

by meteorological conditions (Table 2), the differing sensitivity of the various products to column moisture and to skin temperature becomes more readily apparent. The threshold values have been chosen so as to be similar to the median values for column moisture and skin temperature. The chosen column moisture threshold is 20 mm as used by Brindley et al. (2012), slightly above the median value of 18 mm. For comparisons with MISR the median skin temperature of the co-located data is 317 K, while for comparisons with AERONET it is 312 K, so the skin temperature threshold is set at 315 K (42 °C). Using this simple subdivision, all products show a tendency to retrieve higher AODs in warmer and moister conditions. From these data it would appear that SEVIRI and MISR are particularly sensitive to variations in column moisture, approximately doubling their AOD values between the dry and moist regimes in 'cool' conditions. In contrast, IASI shows a larger response to increases in skin temperature.

Table 3

Table of the percentages (out of all points where all four satellite instruments had co-located observations) of points where the two named satellite products agreed that the retrieval was either valid or invalid (due to, for example, cloud presence), or where the two satellite products disagreed on the validity of the retrieval.

	Agree	Disagree
SEVIRI/IASI	51.7	48.3
SEVIRI/MISR	83.5	16.5
SEVIRI/MODIS	69.4	30.6
IASI/MISR	54.3	45.7
IASI/MODIS	57.1	42.9
MISR/MODIS	72.3	27.7

MODIS appears to show a similar response to both factors. However, this kind of analysis does not take into account the potential for linkages between the meteorological conditions and dust activity. Warmer conditions are associated with the central desert where the dust sources are located, and where dust activity is at its strongest, which tends to have a higher skin temperature than the Sahel and the Mediterranean coast at this time of year. A complicating factor

is that heavy dust loading may in fact cool the lower atmosphere and the surface of a hot desert. For example, [Slingo et al. \(2006\)](#) report a surface cooling of $\sim 13^\circ\text{C}$ during a heavy dust event over Niger in March 2006. The relationship between column moisture and dust loading is also non-linear, since while high column moisture is associated with vegetated areas and heavy rainfall suppresses dust activation and transport, convective systems such as haboobs ([Marshall et al., 2011](#)), which bring moist 'cold-pool' outflows, are responsible for substantial dust uplift over west Africa and some of the thickest dust events. For example, LIDAR and radiosonde data from BBM show a clear association between moisture and dust at this location, and the highest AODs in haboobs ([Marshall et al., in press](#)). Furthermore, dust mobilisation by haboobs may be observable by satellite products only once the dust has travelled out from beneath the associated clouds.

This raises the question as to what extent the apparent relationships seen between meteorological conditions and AOD are a function of the sensitivity of the retrievals to these conditions? Or, more explicitly, to what extent is the dust activity itself related to these conditions? To address this question we recast the density plots of retrieval vs. retrieval AOD shown in [Fig. 4](#) as a function of column moisture ([Fig. 5](#)), to which the majority of retrievals appear most

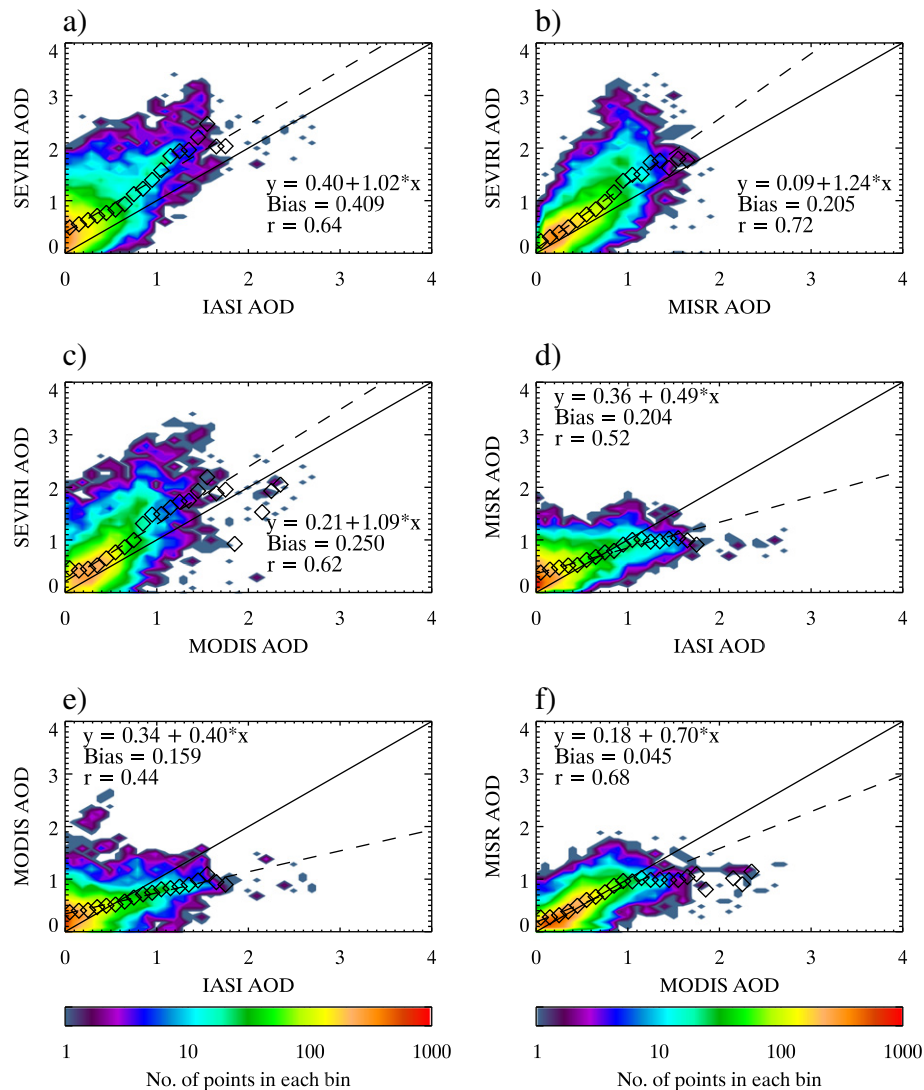


Fig. 4. Density plots of satellite product vs. satellite product AODs. (a) IASI/SEVIRI, (b) MISR/SEVIRI, (c) MODIS/SEVIRI, (d) IASI/MISR, (e) IASI/MODIS, (f) MODIS/MISR. The dashed lines indicate the lines of best fit for all points, while the diamonds represent the mean y-axis satellite AOD in each 0.1 x-axis AOD bin (for which there are ≥ 5 points). There are 11,451 points in each panel. The biases are $y-x$.

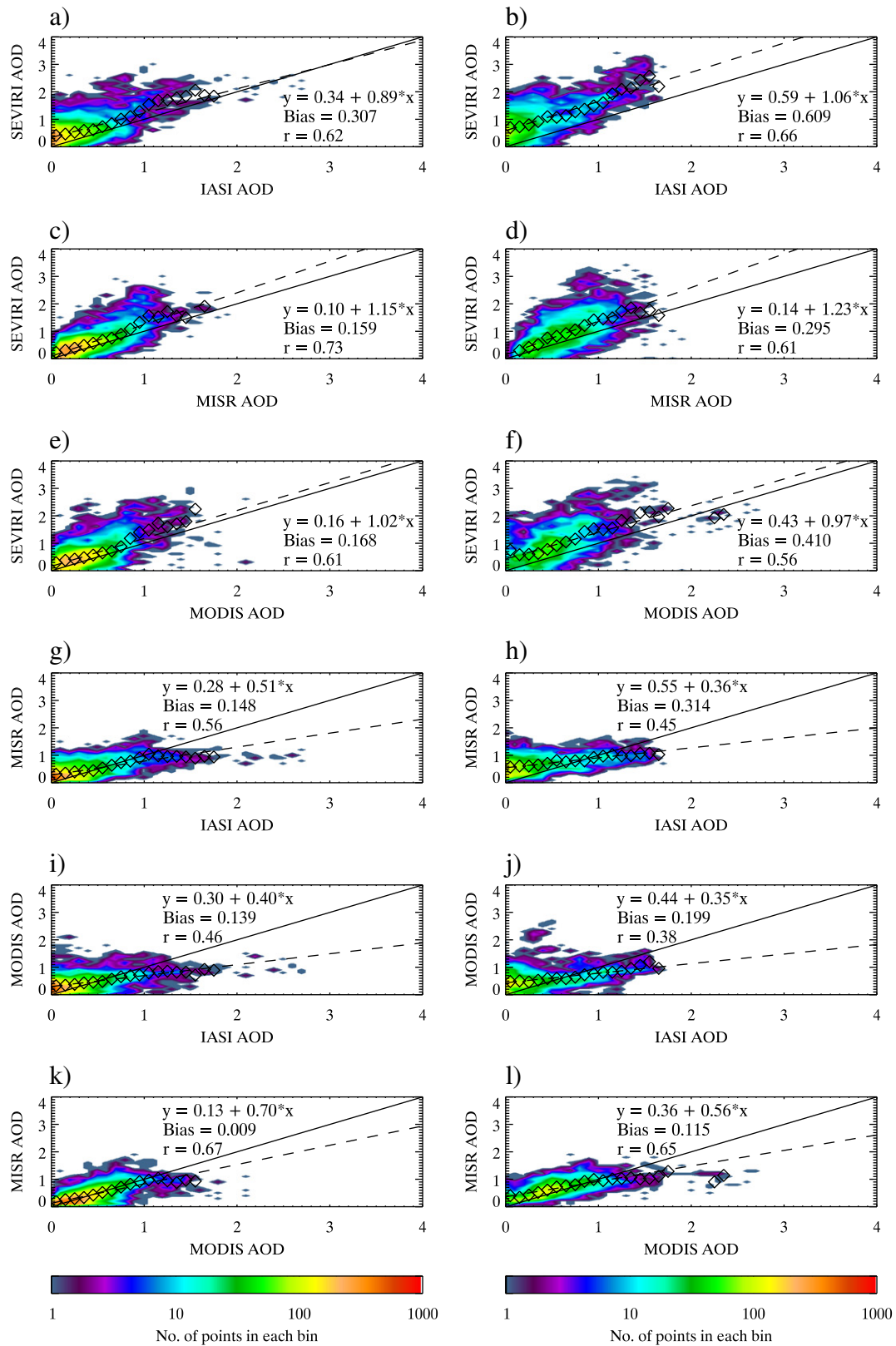


Fig. 5. Density plots of satellite product vs. satellite product AODs. (a) IASI/SEVIRI, (c) MISR/SEVIRI, (e) MODIS/SEVIRI, (g) IASI/MISR, (i) IASI/MODIS, (k) MODIS/MISR: 'dry' conditions. (b), (d), (f), (h), (j), (l): as for left-hand panels, but for 'moist' conditions. The boundary between moisture regimes is at 20 mm. The dashed lines indicate the lines of best fit for all points, while the diamonds represent the mean y-axis satellite AOD in each 0.1 x-axis AOD bin (for which there are ≥ 5 points). There are 7580 points in the left panels, 3871 points in the right panels. The biases are y-x.

sensitive overall. These indicate that the product biases between each other do vary according to the moisture regime in which the retrievals are made. SEVIRI's bias against all the other products

increases when moving from dry to moist conditions by a factor of ~ 2 . All products are biased high against IASI, especially in the moist regime, while MISR and MODIS show the smallest overall bias relative

to each other. Given the extent to which SEVIRI's bias against the other products increases with moisture, it is SEVIRI's retrieval that appears most likely affected by water vapour, beyond any association of the moisture content with the conditions which give rise to high dust loading. Briefly considering AERONET comparisons, the values of the mean AOD from the SEVIRI retrieval over all nine AERONET sites increases from 0.67 in dry conditions to 1.16 in moist conditions. By contrast, the mean AOD from AERONET increases from 0.70 to 0.84, indicating that SEVIRI is more sensitive to moisture than AERONET. Theoretically, given the direct sensitivity of the 10.8 μm channel used in the SEVIRI retrieval to column moisture this is perhaps not surprising, especially if variations in the atmospheric conditions are not adequately captured in the ERA-Interim analyses used in the retrieval process to account for this variability. Although we do not expect the visible channels used by the MISR and MODIS algorithms to be sensitive to the water vapour content, water vapour can have additional effects, such as causing aerosol swelling, that would indirectly affect the retrievals (e.g. Sullivan et al., 2009). In a similar manner, water vapour may indicate the presence of a different air mass with different aerosol content (e.g. Kahn et al., 2007).

Surface properties may also have a significant effect on the retrievals. Fig. 6 analyses the relationship between surface infrared emissivity, surface visible albedo, column moisture and retrieved AODs. Note that in general albedo is strongly anti-correlated with emissivity. Given the wavelength regimes that the different retrievals use we expect the MISR and MODIS results to be more susceptible to variations in surface albedo, while the SEVIRI and IASI retrievals might be expected to show sensitivity to surface emissivity. As noted earlier, except in a few specific locations, SEVIRI is biased high against the other products, and IASI is biased low. In the dry regime the pattern of AODs as a function of surface properties is consistent between all four satellite products, with the highest mean AODs to be found at high albedo and low emissivity, a combination which is most associated with sand seas, where the satellite products retrieve moderately high AODs (as in Fig. 3). In the moist regime there appear to be two contrasting patterns of AOD, one for the infrared IASI and SEVIRI retrievals, which we might expect to be most sensitive to moisture, and one for the MISR and MODIS retrievals made using the visible channels. The monthly mean IASI and SEVIRI retrievals tend to show stronger signals in the moist regime further up and left to the middle of the plots to lower albedo and higher emissivity, which is where eastern Mali, northern Niger and northern Algeria happen to lie on the albedo/emissivity grid. Meanwhile the retrievals from MISR and MODIS give peaks in AOD values towards high albedo and low emissivity, as in the dry regime, although there is a more homogeneous spread of AOD across the albedo/emissivity grid.

There are exceptions to this general pattern. Identifying specific geographical areas, in the moist regime at a relatively high albedo of 0.39 and a high emissivity of 0.91 is a bin where MISR and MODIS retrieve higher AODs than SEVIRI and IASI, corresponding to six grid cells in two regions: the dominant signal of high positive MISR and MODIS bias is at $\sim 17.5^\circ\text{E}$, $\sim 17^\circ\text{N}$, corresponding to an area of the Bodélé Depression in Chad (see Fig. 7). In this area the SEVIRI dust flagging may be filtered due to the high local emissivity (Ashpole & Washington, 2012; Banks & Brindley, 2013), which may be an overly stringent requirement in one of the world's biggest dust sources (Koren et al., 2006; Washington & Todd, 2005).

IASI has a positive bias against MISR and especially MODIS over specific mountainous regions such as the Hoggar mountains in southern Algeria and the Aïr mountains in Niger. These areas of high elevation have low skin temperature and column moisture, low albedo, and high emissivity with respect to the surrounding desert lowlands, and are found at an emissivity of ~ 0.91 and an albedo of ~ 0.2 predominantly in the dry regime. They are also areas identified by Shi et al. (2011) as having markedly lower MODIS Deep Blue Collection 5.1 AOD values compared to MISR. Low bias at high elevation has also

been observed for Deep Blue retrievals from the SeaWiFS instrument (Sayer et al., 2012). The shallowness of the atmosphere may have varying effects on the retrievals. For IASI this reduces the absorption in the infrared due to water vapour and hence may increase the signal seen by the satellite retrieval and mean that the retrievals are higher in these regions than elsewhere. Moreover the high emissivity of the volcanic rock in the Hoggar where the AERONET site of Tamanrasset is based may also affect the IASI retrieval. Meanwhile for MODIS the reduced atmospheric column reduces the path length through which the blue channels of the visible spectrum may be scattered, and so the surface may appear brighter: this may reduce the contrast between the lofted dust and the surface on which the Deep Blue algorithm depends.

The frequency distributions of the retrieved AODs over the whole domain are plotted in Fig. 8(a). Overall, IASI is most weighted towards the lowest AODs, with a peak in distribution at 0–0.1, while the peaks for MISR (0.2–0.3), MODIS (0.3–0.4) and SEVIRI (0.4–0.5) are all shifted to higher values. SEVIRI has the longest and widest tail in its distribution while MISR has the smallest maximum values. A substantial component to SEVIRI's wide tail is revealed in Fig. 8(b), which covers the region ($17\text{--}22^\circ\text{N}$, $0\text{--}5^\circ\text{E}$). Here, the dust loading is dominated by activity around the Malian/Algerian/Nigerien border (Fig. 3), an area which includes the BBM AERONET site. The frequency distribution of level 1.5 observations from this site seems to corroborate the occurrence of high dust loadings seen in this area by SEVIRI. A large fraction of the very high AODs retrieved by SEVIRI are solely from this region (Fig. 8(c)) although it is clear that the tendency for SEVIRI to show higher AODs compared to the other three satellite products is perpetuated across the domain. Further analysis of the observations and retrievals at a number of AERONET sites, including BBM, is presented in the following sections.

3.2. Intercomparisons over AERONET sites

To evaluate the accuracy of the satellite retrievals, we use AERONET data to provide 'ground-truth' of the aerosol loading. Scatterplots of AERONET/satellite retrieved AODs are presented in Fig. 9 for coincident IASI, MODIS, and SEVIRI data. MISR is not included in this analysis due to the scarcity of MISR overpasses of AERONET sites through the month. Since co-located Level 2 AERONET data are not available for a number of sites, Level 1.5 data are used. MODIS and SEVIRI AOD retrievals are provided at 550 nm, while IASI AOD retrievals are provided at 500 nm. AERONET measurements are not made at 550 nm, but we can use the AERONET AOD measurements at 675 nm and the Ångström coefficient (α , measured between 440 and 870 nm) to derive the AERONET AOD at 550 nm (Eck et al., 1999), using the relationship:

$$\tau_{550} = \tau_{675}(675/550)^\alpha \quad (3)$$

In terms of bias, the SEVIRI product shows the best overall agreement with AERONET, with a positive bias of 0.11. In contrast IASI and MODIS show negative biases of -0.21 and -0.32 respectively. The correlation coefficients are 0.78 for IASI and for MODIS, and 0.74 for SEVIRI. It is at the highest dust loadings that the biggest discrepancies are observed, where IASI and MODIS have substantially lower values than are observed by AERONET. Note that at high AOD the visible reflectance becomes less sensitive to changes in AOD, so for MISR and MODIS which retrieve dust using the visible channels there may be less AOD response to further increases in dust loading. There may also be a greater uncertainty at high dust loadings due to a greater sensitivity to other assumptions made in the retrievals such as those made for the aerosol properties, and similarly the uncertainty in the AERONET AOD also tends to be greater at high dust loading. By comparison SEVIRI is better able to retrieve such high values, although the retrieved AODs are still slightly lower than those observed

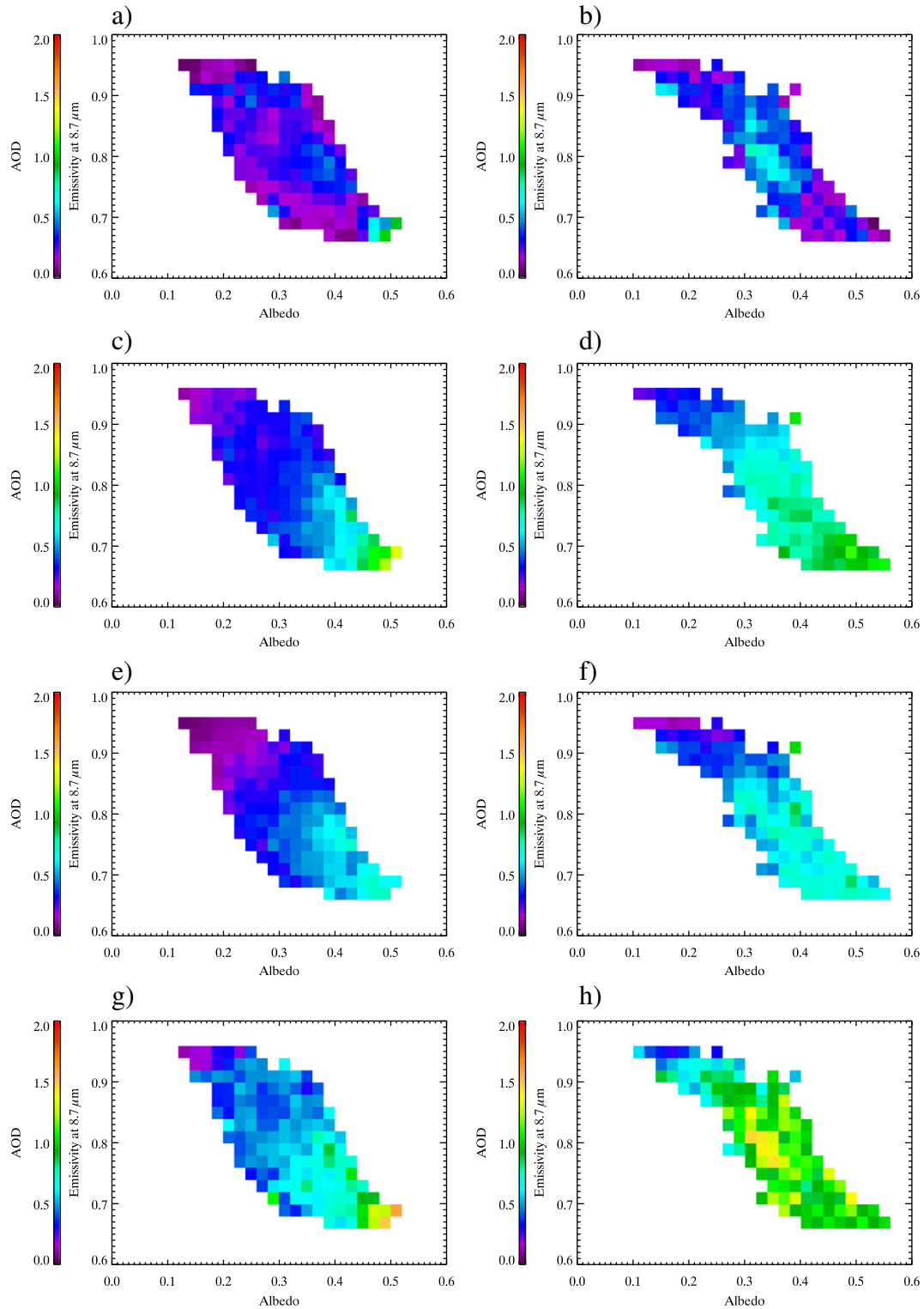


Fig. 6. Satellite retrieved mean AODs binned by albedo and emissivity at $8.7 \mu\text{m}$, in the dry regime for left-hand panels, in the moist regime for right-hand panels. The albedo and emissivity bin widths are 0.02. (a,b): IASI; (c,d): MISR; (e,f) MODIS; (g,h) SEVIRI.

by AERONET. So for example, on 21st June at BBM, when AERONET observed an AOD of 3.08, IASI retrieved 1.57, MODIS retrieved 1.22 (0.62 in the Collection 5.1 retrievals, indicative of the improvement in the retrieval of heavy dust in Collection 6), and SEVIRI retrieved 2.22. Hence we see that at high AODs SEVIRI shows best agreement with AERONET. Where the AERONET AOD is in excess of 1, the retrieval RMS differences (biases) are: SEVIRI: 0.48 (-0.06); IASI:

0.68 (-0.51); MODIS: 0.89 (-0.76). At lower AODs IASI shows improved agreement with AERONET (bias = -0.15). SEVIRI has a tendency to over-estimate the AODs, with a positive bias against AERONET of 0.15, while MODIS under-estimates compared to the AERONET observations with a bias of -0.24 .

The MODIS product shows little difference in its biases and RMS differences between the two regimes of column moisture, while IASI

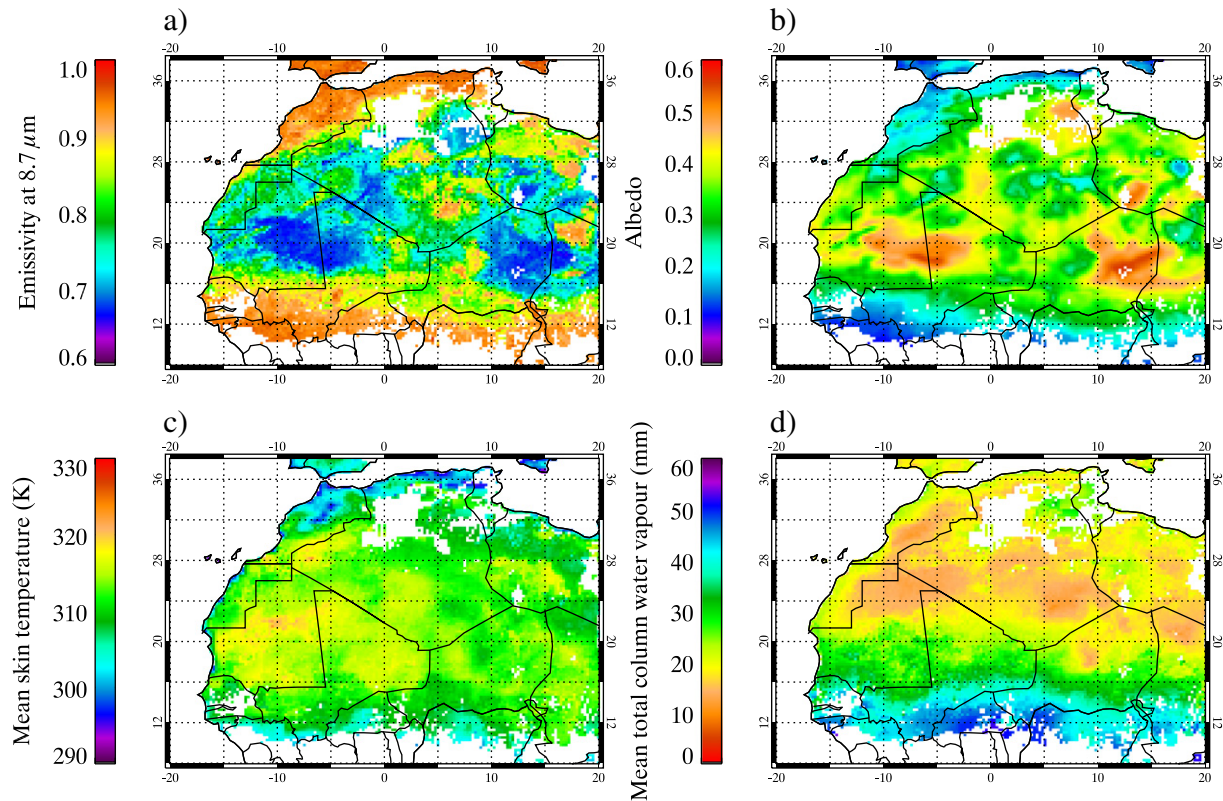


Fig. 7. Maps of surface properties and average meteorological conditions, for co-located IASI, MODIS, and SEVIRI points. (a) Emissivity at 8.7 μm , (b) albedo, (c) skin temperature, (d) total column water vapour.

does have a slightly more negative bias in moist compared to dry conditions. The sensitivity of the SEVIRI retrieval to column moisture is however quite pronounced: the bias jumps positively from dry to moist, from -0.03 to 0.31 , as does the RMS which jumps from 0.29 to 0.51 . That SEVIRI shows this positive bias even relative to AERONET again suggests that it is the retrieval itself which is being affected by the column moisture, beyond the possible relationship between moisture and dust activity. Moreover, we see that the divergence of the AODs between SEVIRI and AERONET is greatest at lower AERONET AODs and high moisture values, in particular at the Sahel sites (Banizoumbou, IER Cinzana, and Zinder Airport), under these conditions we suggest that the SEVIRI retrieval is less reliable.

Turning to surface properties, different patterns are clear among the three retrievals. Overall the SEVIRI product shows no significant difference in the quality of its retrievals between dark and bright albedo regimes, with bright RMS values most weighted by the highest AERONET AOD at BBM. However in the dark and dry regime, at Tamanrasset and Saada, there is a cluster of points which reveal a distinct subset in the aerosol retrieval from IASI and MODIS. Over these sites we see a slightly positive bias in the IASI retrievals and a substantially negative bias in the MODIS retrievals. Saada may be an anomaly since the site altitude of 420 m is not particularly high, however within the site's area of influence is a grid cell containing part of the Atlas mountains. At an altitude of 1377 m Tamanrasset is the most elevated site used in this study, with the shallowest atmospheric column above it as evidenced by its driest average column moisture. Hence IASI may have a positive bias and MODIS may have a negative bias as described in Section 3.1. It is thus not the albedo itself which is driving this pattern in the IASI and MODIS retrievals, rather it is the associated elevation.

Comparing the statistics between dark and bright points in the moist regime, we find that the SEVIRI product sees no variation with albedo, consistent with the overall picture. Meanwhile both

IASI and MODIS have more negative biases in the bright regime where the dust loadings are highest. The trend in the points is not markedly different between dark and bright points for MODIS, so MODIS' decreased bias may just be a consequence of higher dust loading. For IASI the dark points are closer to and occasionally above the one-to-one line, whereas the bright points are markedly lower. Hence IASI appears to have a negative bias over the brighter surfaces at BBM and Zinder Airport, which also have some of the lowest emissivities (Table 1). IASI's low AODs over these surfaces are consistent with the results of Fig. 6(b). Taken together these results suggest that the general low bias in the IASI retrievals becomes more pronounced when the emissivity is low, as it is in parts of the west African Sahara.

4. Case studies in June 2011

4.1. A heavy dust case over Bordj Badji Mokhtar on 17th June

On 17th June, a large dust storm emanating from the Algeria/Mali/Niger tri-border area passed over the top of Bordj Badji Mokhtar (BBM). All four satellite products observed the area around BBM on this day, and the AERONET site was able to make some successful measurements, especially in the afternoon. Maps of co-located AODs and meteorological conditions, a 'desert-dust' RGB image, and a time-series plot of AOD over BBM, are shown in Fig. 10. As subjective as the interpretation of the RGB rendering may be, it is clear that the surface underneath the dust storm cannot be seen. Hence we might expect that the signal seen by the satellite retrievals will be originating from the dust layer rather than from the underlying surface. Similarly, the AERONET site may have had difficulty seeing the Sun through the dust layer, and so several of the morning Level 1 data points were 'cloud-screened' and hence removed from the Level 1.5 and Level 2 data sets. The satellite retrievals do not detect cloud in

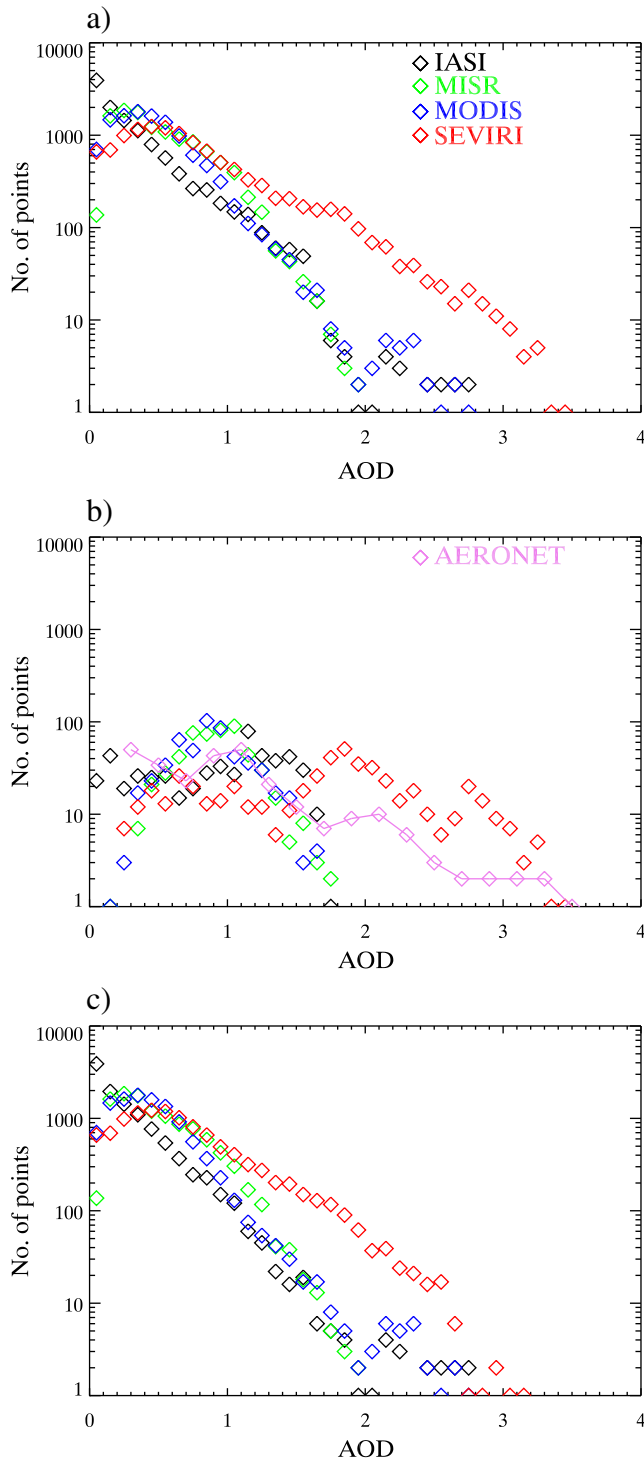


Fig. 8. Histograms of occurrences of AOD values for the four satellite retrievals, for three geographical regions. (a) full domain; (b) Mali/Algeria/Niger border, 17–22°N, 0–5°E; (c) all areas excluding the region plotted in (b). Overplotted in (b) is a histogram from all available half-hourly AERONET data from BBM. It is important to note that the AERONET data are not co-located with the satellite data.

this area until later in the afternoon, so we suggest that the ‘cloud-screened’ Level 1 data may give us appropriate measurements for the dust AOD in the morning.

The cause of this dust event was a convective system further to the south shown in red in the imagery, which formed a haboob that triggered dust emission overnight as it moved northwards. Haboobs are dense dust storms associated with squall lines (e.g. Farquharson,

1937). Haboobs appear to cause approximately half of the Saharan dust uplift in high-resolution models, and a similar fraction at BBM during June 2011, but are largely absent in global models (Marshall et al., 2011, in press). As a consequence of this formation, the dust event is strongly associated with areas of relatively high column moisture (Fig. 10(e)), with a gradient towards lower moisture values towards the leading edge of the dust front, and over BBM. The skin temperature is depressed underneath the dust (Fig. 10(f)). During the day from 0700 to 1600 UTC over BBM the mean column moisture is 17.5 ± 1.0 mm and the skin temperature is 318.9 ± 8.5 K. There is broad agreement between the satellite observations as to the dust spatial distribution and to the position of the leading edge of the dust front in the north. There is also agreement about the position of a smaller individual dust storm further north in central Algeria, at 26°N. However, SEVIRI is most able to capture the magnitude of this dust event, as shown by Fig. 10(g). Where there are simultaneous Level 1 AERONET and SEVIRI measurements, the mean AERONET AOD is 2.99, and the mean SEVIRI AOD is 2.62. For afternoon Level 2 measurements the mean AERONET AOD is 2.35 and the mean SEVIRI AOD is 2.60. By contrast, the IASI overpass gives an AOD of 1.50 while the simultaneous Level 1 AERONET AOD is 3.38, MISR gives 0.90 while the Level 1 AERONET AOD is 3.80, and MODIS gives 1.13 (MODIS Collection 5.1 gives just 0.19) while the Level 2 AERONET AOD is 3.32. The AOD values provided by SEVIRI are very large here (which might be regarded as suspect), however so are the AERONET values, which supports our earlier inference that of the four satellites products, SEVIRI's AOD retrievals are most reliable at high dust loading.

4.2. Falcon aircraft observations on 20th and 21st June

On 20th June, the Falcon 20 carried out a triangular flight across northern Mauritania and northern Mali to survey the Saharan atmospheric boundary layer as well as document the dust uplift in the region of the intertropical discontinuity to the south of the Saharan heat low over Mali (flight F21). F21 took place between 1322 and 1700 UTC, with the Falcon 20 flying at 11 km above mean sea level (amsl). Ten dropsondes were released along the flight track. On 21st June the Falcon 20 performed two flights (F22 and F23). On this day, convection over the Atlas Mountains had initiated a density current which moved southwestward over the northern Sahara during the morning. During the first Falcon 20 flight (F22), a dust front associated with the density current was observed over Mauritania, with older dust overlying it. During the afternoon flight (F23), airborne observations revealed that the dust layers were mixed together as a result of the developing Saharan convective boundary layer. F22 and F23 took place between 0718 and 1035 UTC, and 1313 and 1630 UTC, respectively. Nine dropsondes were released during each flight.

Observations from the Falcon give us a greater spatial range of local AOD measurements than does AERONET, and these are taken over a greater range of surface types. We use the LIDAR as the ‘best estimate’ due to the LIDAR's insensitivity to moisture and surface albedo, such that it is only sensitive to the aerosol loading, a result of its active remote sensing technique. Located on an aircraft the LIDAR also has the highest intrinsic spatial resolution. Fig. 11 shows the dust activity and conditions along the Falcon flight tracks. MISR retrievals are not included in this analysis due to the lack of any spatial matching on any day during the Falcon's flight campaign. The start of the LIDAR measurements on both days is at the north-westernmost extremity of the flight tracks. On the 20th there is coincidence in the locations of high column moisture and albedo, with a particularly strong gradient in moisture as shown in Fig. 11(c); by contrast the atmosphere on the 21st is consistently dry, the aircraft traverses an area of generally lower, but spatially varying albedo.

For both flight F21 (20th) and flight F23 (21st) IASI and SEVIRI agree on the spatial distribution of dust with dominant dust presence in the

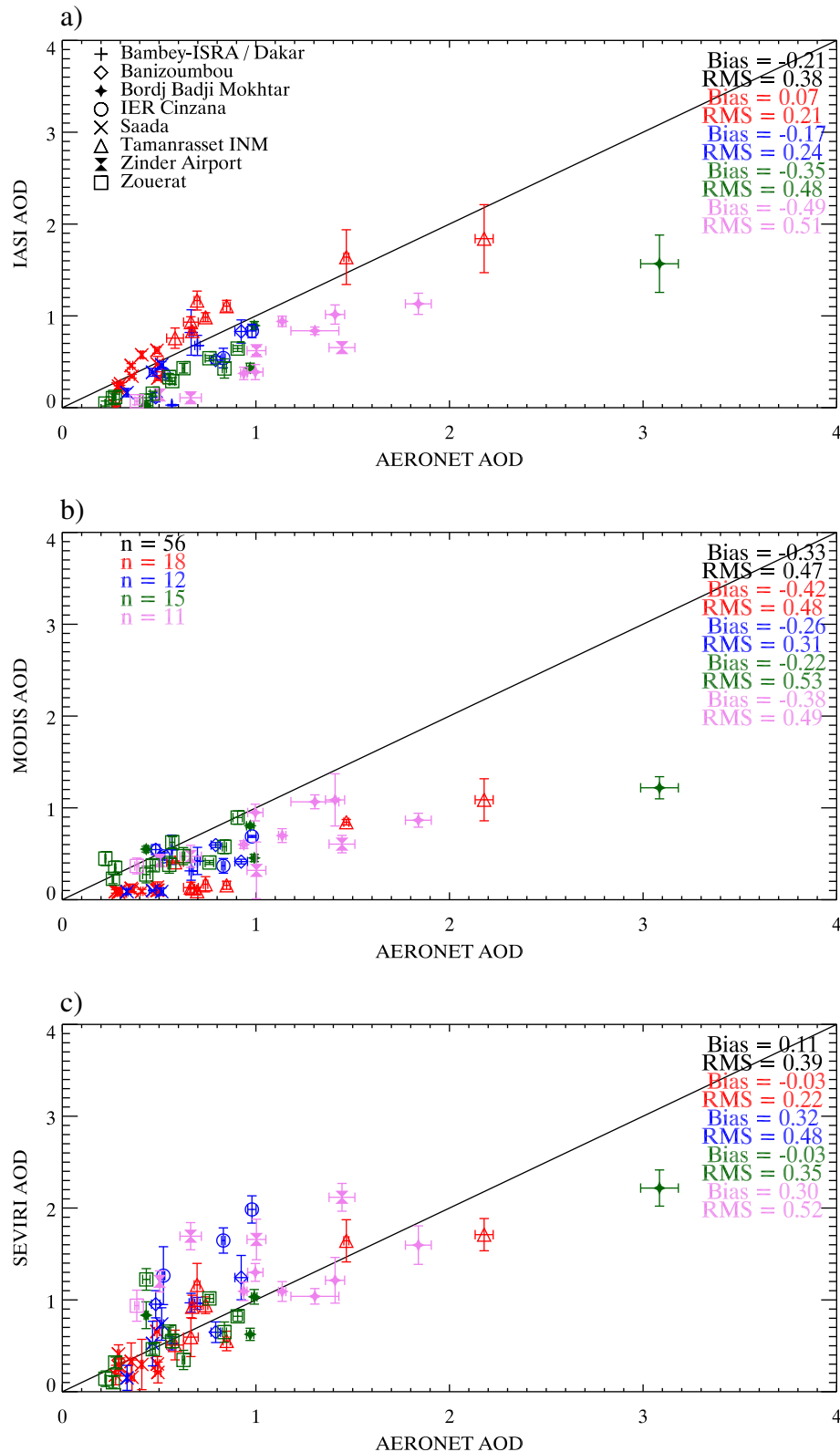
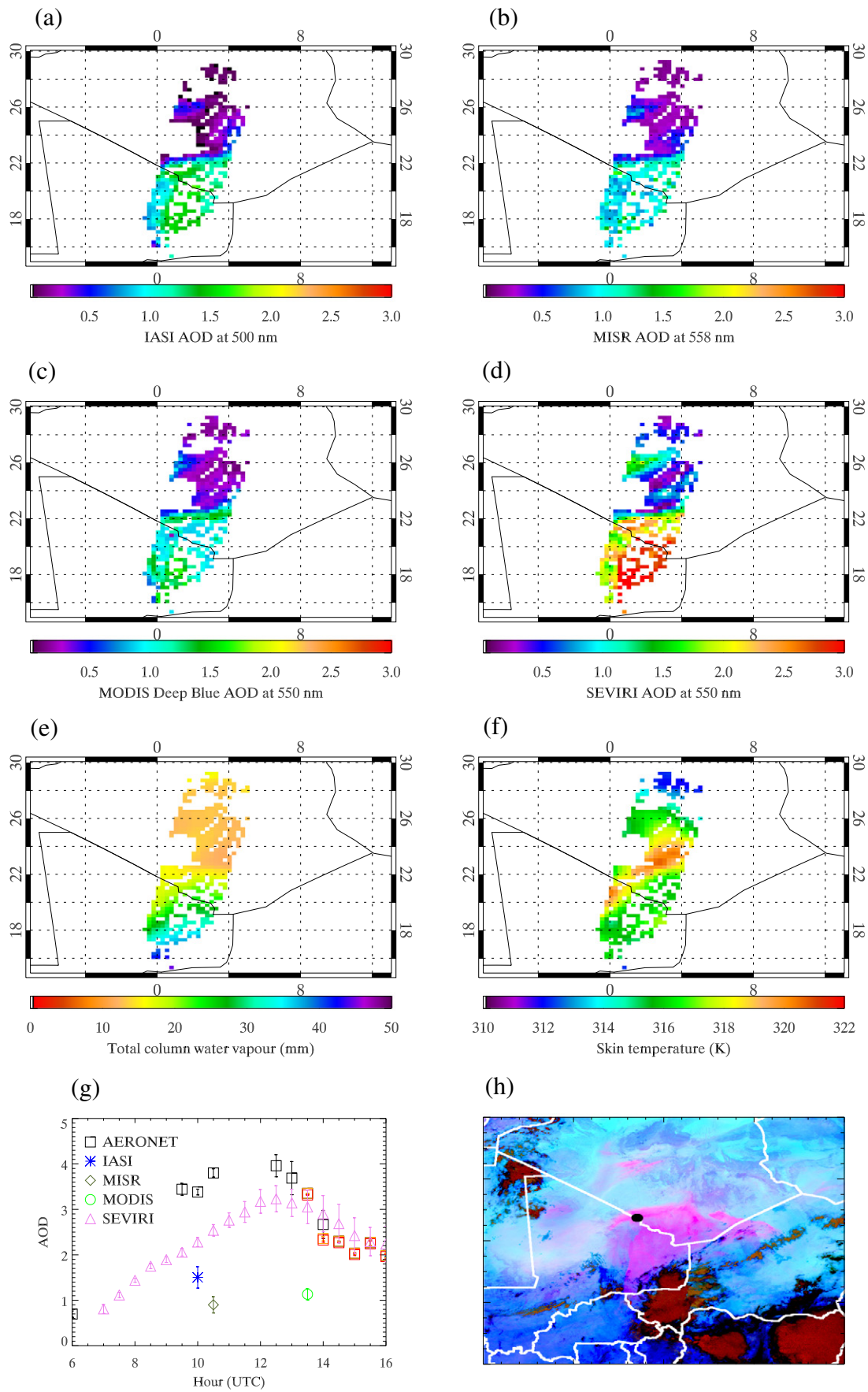


Fig. 9. Scatterplots of Level 1.5 AERONET against satellite retrieval data for June 2011: (a) IASI; (b) MODIS; (c) SEVIRI. Individual sites are marked by varying shapes, and the different moisture and albedo regimes are marked as red (dry/dark), blue (moist/dark), green (dry/bright) and purple (moist/bright). The albedo threshold is 0.3. The number of points (total and by regime) is identical for each panel, and is indicated in panel (b). For AERONET the error bars indicate the standard deviation of the mean of the measurements within three hours of the IASI overpass, while for the satellite products the error bars represent the spatial standard deviation of the mean of the measurements within 25 km of the AERONET sites for the relevant scene viewed.

north, as does MODIS on the 21st, in Figs. 11(e) and 11(f). MODIS does not see this high northern dust loading at the start of F21 (Fig. 11(e)): the reason for this is unclear but one possibility is that the retrieval

has encountered a surface albedo regime over the bright desert surface where the TOA reflectance is not sensitive to AOD (e.g. Seidel & Popp, 2012). Looking more specifically at F21, from ~1430 UTC to ~1540



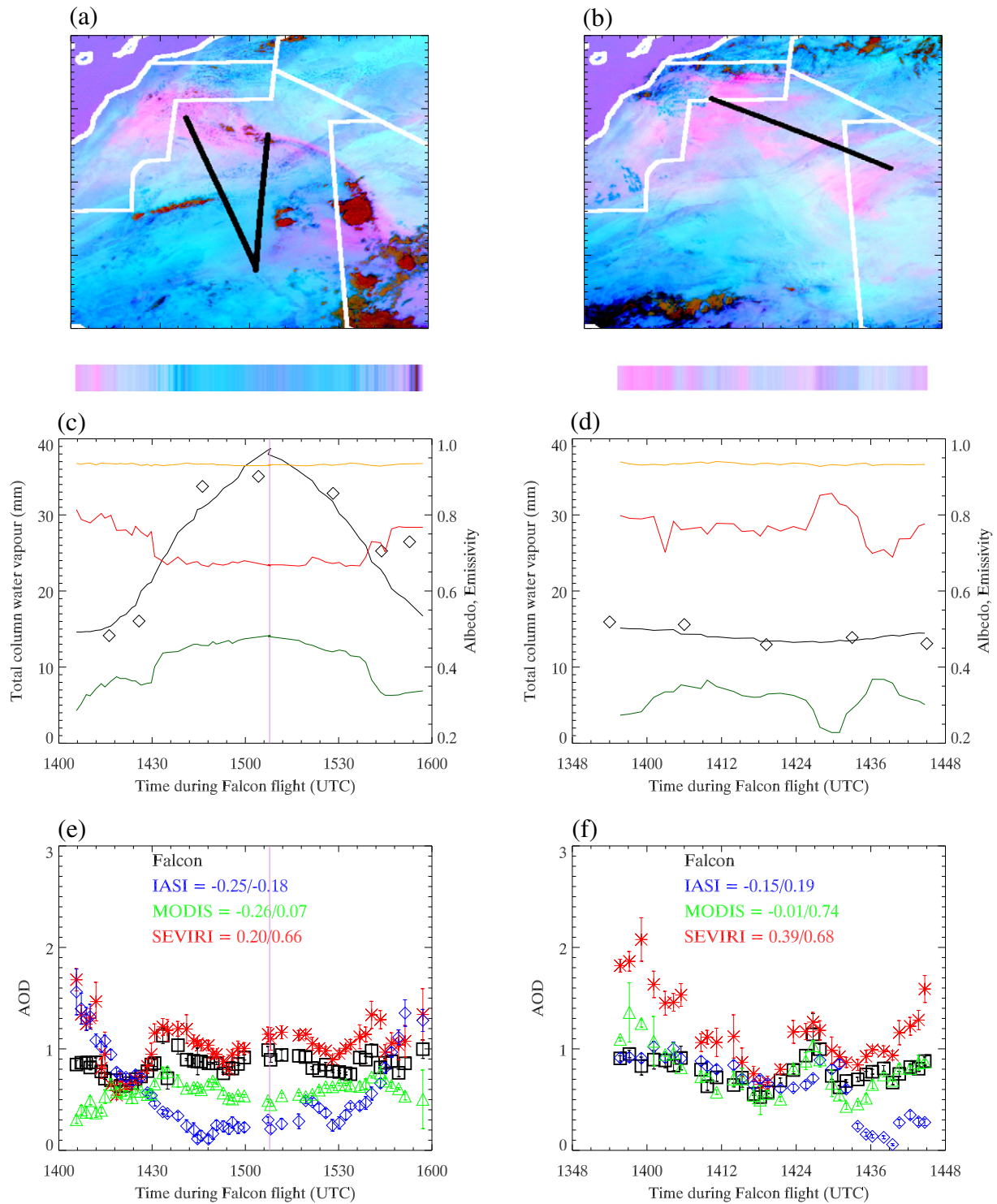


Fig. 11. Dust observations and conditions along the Falcon flight track, on the 20th, flight F21 (left), and the 21st, flight F23 (right). (a,b) SEVIRI RGB images on the 20th (1500 UTC) and the 21st (1415 UTC), included are the flight tracks in black, and below are the RGB colours along the tracks; (c,d) along-track column moisture from ERA-Interim (black line) and from the Falcon dropsondes (black diamonds), albedo (green line), emissivities at 8.7 and 10.8 μm (red and orange lines), and on the 20th the vertical purple line indicates the change in flight direction; (e,f) along-track AODs from the Falcon LIDAR, IASI, MODIS and SEVIRI, with biases/correlations with respect to the Falcon. The error bars indicate the standard deviation of the mean of the AOD measurements within the grid cells along the flight track.

Fig. 10. Dust activity and meteorological conditions over BBM on the 17th June. (a) IASI AOD; (b) MISR AOD; (c) MODIS AOD; (d) SEVIRI AOD; (e) total column water vapour; (f) skin temperature; (g) time-series of AERONET and satellite retrieved AODs during the day (black squares are Level 1 AERONET, orange are Level 1.5, and red are Level 2); (h) RGB 'desert-dust' image from SEVIRI at 1030 UTC (dust appears pink, thick cloud is red, and BBM is the black oval on the Algerian/Malian border). The AERONET error bars are derived from the standard deviation of the mean of the measurements made within ± 15 min of each time slot, while the satellite product AODs are derived from the standard deviation of the mean of the retrievals made within 25 km of BBM. The error on the MISR retrieval is $0.2 \times \text{AOD}$ as discussed in Section 2.1, since there is only one pixel with a successful retrieval.

UTC MODIS and especially IASI are negatively biased against, and weakly correlated with the LIDAR where the aircraft was overflying the region of high albedo and low emissivity. This is consistent with the findings of Fig. 9. IASI's more negative bias in moist conditions may also contribute to its very low values at the southern end of the flight track. Over darker and more emissive surfaces (at either end of flight F21, and along most of the flight F23) IASI is apparently better able to retrieve the AODs that the LIDAR observes. MODIS performs very well during flight F23 with the highest correlation with the LIDAR, under constant dry conditions and over moderately varying albedos. For this flight SEVIRI has a high positive bias against the LIDAR observations, even under dry conditions.

The conditions encountered on flight F23 and at the northern ends of flight F21 are analogous to the conditions generally found at Zouerat, i.e. a dry atmosphere over a semi-bright surface. Set in this context, SEVIRI's high bias against the LIDAR AODs during F23 is consistent with some of the dry/bright SEVIRI/AERONET comparisons at Zouerat seen in Fig. 9(c), at low AODs where SEVIRI is biased high. Hence, while moisture may be a significant driver of anomalously high SEVIRI AOD, this factor is not exclusive. IASI tends to be negatively biased against AERONET at Zouerat while MODIS retrieves AODs either side of the AERONET one-to-one line, consistent with what we see in the LIDAR/satellite product comparisons. Meanwhile no AERONET site is closely analogous to the conditions found at the southern end of flight F21 which has a moist atmosphere similar to that found over the Sahel, but has a very bright surface with an albedo peaking above 0.45. The most analogous sites would be BBM, which has the highest site albedo (0.39), and Zinder Airport, which also has a fairly bright surface (0.34) and a typically moist atmosphere. Both IASI and MODIS are biased somewhat lower over these sites than over Zouerat, especially IASI, which is also borne out by the LIDAR comparisons. SEVIRI is biased high against AERONET observations at Zinder Airport, but is biased slightly low against AERONET at BBM in moist conditions. Again, this is consistent with the LIDAR comparisons.

Correlating the AODs with the various conditions for the two flights, we find that the LIDAR AODs indicate no significant correlation. MODIS and SEVIRI to an even lesser extent have marginal anti-correlations with moisture and albedo/emissivity: for example, MODIS has a correlation with albedo of -0.30 . In contrast, IASI shows a more marked relationship with both column moisture (correlation of -0.58) and $8.7 \mu\text{m}$ emissivity (correlation of 0.73). Especially at low emissivities, the infrared IASI retrieval may be less able to discriminate between the background sand and the lofted dust, and indeed it is at the lowest emissivities that IASI has the strongest negative bias. Moisture may amplify this effect over surfaces of low emissivity, as seen in Fig. 6(b). The RGB imagery extracted along the flight tracks tends to confirm this interpretation. Under dry conditions (Fig. 11(b)) there is a strong relationship in the degree of 'pinkness' to the retrieved SEVIRI AODs. Under more moist conditions (Fig. 11(a)) the pattern corresponds more closely to that seen in the IASI retrievals with enhanced moisture masking the dust signal as measured by the LIDAR. This behaviour is consistent with theoretical expectations (Brindley et al., 2012).

This analysis of the aircraft observations indicates that while broad judgements about the effectiveness of the satellite retrievals under various regimes of conditions can be made, the picture remains a complicated one, with subtle interconnections among retrieved AODs, the meteorological conditions, and the underlying surface properties.

5. Conclusions

By comparing the dust aerosol retrievals of IASI, MISR, MODIS, and SEVIRI under varying conditions during the Fennec campaign period in June 2011 at the peak of the yearly cycle of dust activity in the Sahara, we can learn more about the conditions under which they are most reliable. Spatial agreement between the satellite products

is good. Under heaviest dust loadings ($\text{AOD} > 1$) it appears that SEVIRI is most able to capture the best estimate of the AOD as measured by ground-based and aircraft instrumentation, whereas the other satellite products retrieve much lower values. Out of the mean AODs for each instrument, SEVIRI has the greatest fractional contribution of high AODs to the monthly mean, with values of 0.22 for IASI (from 5% of the number of points), 0.18 for MISR (8%), 0.13 for MODIS (5%), and 0.47 for SEVIRI (22%). Here the fractional contribution is defined as the sum of the high AODs divided by the sum of all AODs. On the other hand, SEVIRI does not perform so well at lower dust loadings where it can significantly overestimate the AOD, especially where the atmospheric water vapour content is also quite high ($>20 \text{ mm}$). Under these conditions the other satellite products appear better able to capture the dust loading. Under moist conditions IASI retrievals also show a noticeably low bias with respect to the 'best estimate', so we may also have more confidence in the IASI retrievals made under drier conditions. MODIS has consistent statistics between dry and moist conditions and, while we have not evaluated MISR explicitly with the 'best estimate' because of a lack of coincident overpasses, satellite product inter-comparisons show that it has a similar response to MODIS. Hence as might be expected, MISR and MODIS seem to be least affected by the atmospheric water vapour content, and so would be the most trustworthy in sharply varying meteorological conditions given low dust loading and suitable surface conditions.

Surface type also plays a role in the effectiveness of the retrievals. Over elevated surfaces MODIS reports very low AODs, and is unable to retrieve the magnitude of the dust loading that the other satellite products and AERONET observe, while IASI appears to retrieve the most realistic AODs. On the other hand over brighter (albedo > 0.3), less emissive surfaces ($\epsilon < 0.84$) it is IASI which most underestimates the AOD with a negative bias of -0.41 with respect to the relevant AERONET sites. This behaviour is also seen in the comparisons with the Falcon LIDAR observations. As shown by Fig. 6, over these surfaces MISR retrieves higher AODs, although these tend to be smaller than those retrieved by SEVIRI, which has a positive bias against AERONET of 0.11. Hence over bright surfaces SEVIRI and MISR should be the preferred instruments, while over elevated surfaces IASI may instead be preferred.

Overall then, SEVIRI performs well at high dust loading, but at lower AODs it is biased high at high moisture content ($>20 \text{ mm}$). These results suggest also a slightly high bias at low dust loadings under dry conditions. IASI performs well at high elevation but has a tendency to under-estimate the dust loading, and is negatively correlated with water vapour and positively correlated with surface infrared emissivity. The sensitivity of the SEVIRI and IASI retrievals due to moisture may arise from the (perhaps insufficiently constrained) corrections each of these infrared instruments must make in order to account for changes in brightness temperature due to water vapour. MODIS struggles particularly at high elevation, underestimating the AOD, but is generally unaffected by moisture. MISR has the most consistent retrievals, with no large variations in any moisture/albedo regime, but is unable to retrieve the magnitude of the largest dust events: at high dust loading with a homogeneous 'surface' of airborne dust, the advantages of MISR's multi-angle observations at minimising the radiance contribution from variable desert surfaces are reduced. These conclusions are summarised in Table 4.

These findings indicate the surface types, the meteorological conditions, and the dust loadings for which each of the satellite products is most capable of retrieving the appropriate values of the AOD, as assessed during the summer maximum in dust activity in June 2011. Observations made during the Fennec campaign have provided new information as to the dust size distributions (Ryder et al., 2013) and the dust layer distributions (McQuaid et al., 2013), for example. Such precise observations of the nature of the dust and of its activity may help to inform our understanding of the scenes that the satellite

Table 4

Conditions under which each product is most capable of retrieving accurate AOD values. Dashes indicate factors to which the specific retrieval algorithm appears relatively insensitive.

Instrument	Dust loading	Moisture	Emissivity	Elevation
IASI	Low	Low	High	High
MISR	Low	–	–	–
MODIS	Low	–	–	Low
SEVIRI	High	Low	–	–

products are trying to make retrievals of, and so it would be of benefit for subsequent studies to also make use of these new measurements when assessing and improving the capabilities of the satellite products for dust retrievals.

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