A surface reflectance DAtabase for ESA's earth observation Missions (ADAM)

Executive Summary Report

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Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ADAM	A surface reflectance DAtabase for ESA's earth observation Missions
ADAM-FDS	ADAM input reflectance products over land relying on the FondsDeSol processing chain
ADAM-GA	ADAM input reflectance products over land relying on the GlobAlbedo processing chain
AMF	Air Mass Factor
AMF_{trop}	Tropospheric Air Mass Factor
API	Application Programming Interface
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATBD	Algorithm Theoretical Basis Document
BBDR	BroadBand spectral Directional Reflectances
BRDF	Bidirectional Reflectance Distribution Function
CYCLOPES	Carbon cYcle and Change in Land Observational Products from an Ensemble of SatelliteS
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DOAS	Differential Optical Absorption Spectroscopy
ENVISAT	ENVIronmental SATellite
EO	Earth Observation
ESA	European Space Agency
GOME	Global Ozone Monitoring Experiment
GUI	Graphical User Interface
HDF	Hierarchical Data Format
IGBP	International Geosphere-Biosphere Programme
IFREMER	Institut Français de Recherche et d'Exploitation de la MER
LER	Lambert-equivalent reflectivity
LOA	Laboratoire d'Optique Atmosphérique
LSCE	Laboratoire des Sciences du Climat et de l'Environnement
MERIS	MEdium Resolution Imaging Spectrometer
MISR	Multiangle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics & Space Administration
NDVI	Normalized Difference Vegetation Index
NetCDF	Network Common Data Form
NIR	Near Infrared
NRT	Near Real Time
OMI	Ozone Monitoring Instrument
OMLER	OMI-LER data product

PARASOL	Polarisation et Anisotropie des Réflectances au sommet de l'Atmosphère, couplées avec un Satellite d'Observation emportant un Lidar
POLDER	POLarization and Directionality of the Earth's Reflectances
QuickScat	Quick Scatterometer
RT	Radiative Transfer
SACURA	Semi-Analytical CloUd Retrieval Algorithm
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY
SeaWiFs	Sea-viewing Wide Field-of-view Sensor
SNR	Spectral Normalised Reflectance
SPOT	Satellite Pour l'Observation de la Terre
SU	Swansea University
SWIR	Short Wave Infrared
UB	University of Bremen
UCL	University College London
USGS	U.S. Geological Survey
UV	ultra-violet
VCD	Vertical Column Density
VGT	VEGETATION sensor

References

[RD1]	NOV-3895-NT-11143	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 1: Literature survey of ESA's EO missions needs for surface reflectance information.
[RD2]	NOV-3895-NT-11144	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 2: Identification of suitable existing surface reflectance datasets for the generation of ADAM.
[RD3]	NOV-3895-NT-12008	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 3: Definition of the database design, products and product content and graphical user interface.
[RD4]	NOV-3895-NT-12121.	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 4: Improvement and/or expansion of existing surface datasets Algorithmic Theoretical Basis Document.
[RD5]	NOV-3895-NT-12228	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 5: Structure of the ADAM input surface database and output products
[RD6]	NOV-3895-NT-12229	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 6: Verification of the ESA EO Surface Reflectance Database
[RD7]	NOV-3895-NT-12402	NOVELTIS and ADAM partners (2012). A surface reflectance DAtabase for ESA's earth observation Missions (ADAM). Technical Note 7: Needs for an operational NRT surface reflectance service
[RD8]		http://modis-land.gsfc.nasa.gov/MODLAND_grid.html
[RD9]		CYCLOPES (Carbon cYcle and Change in Land Observational Products from an Ensemble of SatelliteS), M. France, Editor. 2006. p. 11.
[RD10]		https://lpdaac.usgs.gov/products/modis_products_table/surface_reflectance/8_day_l3_global_500m/mod09a1

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1. Introduction

1.1. Context of the study

An important input to radiative transfer modelling, retrieval and validation, of optical satellite-based Earth Observation (EO) measurements, is the good knowledge of the expected surface reflectivity for any given wavelength range, illumination and viewing angles. This is important for the estimation of the expected radiance of the surface reflected signal, which is again decisive for the retrieval of the atmospheric absorption and for an estimation of signal-to-noise ratio of the retrieved data products. Examples of atmospheric remotely sensed products where the accuracy of the surface reflectance largely influences their accuracy include NO_2 and water vapour total column, aerosol optical thickness and cloud top pressure retrievals. Also for the estimation of future climate scenarios, it is important to include a good estimate of the expected (change of) surface reflectance. Surface reflectance information is also important for the estimation of surface heat fluxes and the Top Of the Atmosphere (TOA) radiation in Numerical Weather Prediction (NWP) and climate modelling. This is, furthermore, used to determine feed-back mechanisms as a function of changes in local vegetation.

Both in the preparatory and exploitation phase of the ESA's Earth Observation missions, there is a constant need for accurate *a priori* surface reflectances in the wavelength ranges used for radiative transfer modelling, retrieval, and validation activities. Several databases of surface reflectance at various wavelengths already exist, but not all of them are easily available. Koelemeijer *et al.* (2003) shows an example of such a database but at very low spatial resolution (1º x 1º) for 5 years of monthly values based on GOME (Global Ozone Monitoring Experiment, on-board the ESA ERS-2 platform) observations. In the GOME database, Lambertian Equivalent Reflectances (LER) are provided, which are not representative over vegetation, snow and oceans where directional effects can cause errors of up to 30-50% in retrievals of surface properties (Diner *et al.*, 1998). The use of a Lambertian assumption for retrieving surface reflectance can cause non-negligible impacts on spectral surface retrievals (Wang *et al.*, 2010). A further concern is the temporal variability of the surface, and any surface reflectance database will therefore need to be at a sufficiently coarse resolution both temporally and spatially to try to minimise noise due to vegetation phenology effects (Moody *et al.*, 2008).

High quality spectral BRDF and integrated albedo databases (both "black-sky" and "white-sky", see Schaepman-Strub *et al.*, 2006, for definitions) have been available from NASA instruments such as MODIS (Schaaf *et al.*, 2002) and MISR (Martonchik et al, 1998) on a 1km grid since 2000 and from POLDER (Bicheron and Leroy, 2000) intermittently on a 6.7km grid since 1997.

In the ESA GlobAlbedo project (http://www.GlobAlbedo.org), broadband BRDFs and integrated albedos for the visible, NIR+SWIR and total shortwave, are being produced by combining BBDR (BroadBand Directional Reflectances) derived from the ESA ENVISAT MERIS with the SPOT-4 & 5 VEGETATION spectral channels after being corrected for aerosol atmospheric effects. The database is global, providing monthly mean values climatology for a period of 14 years 1998-2011). Gaps in the GlobAlbedo product are filled from a 10-year (200 – 2009) MODIS Collection 5 dataset called "Priors", which estimates the error in the BRDFs from the Obit (quality flag). In addition (as compared to GlobAlbedo), there is a need for more narrow-band surface reflectance products tailored for the use of end-to-end simulation activities as well as atmospheric remote sensing retrievals from 300 nm to 4 μm. The creation of such a tailored database is the scope of this activity.

ADAM (A surface reflectance DAtabase for ESA's earth observation Missions) has been defined to fit the present and planned Earth Observation mission products and retrieval needs. This includes both land and ocean surface reflectances.

Such a centralized and validated narrow-band spectral BRDF database aims at supporting the preparation and exploitation of optical ESA Earth Observation missions. It would, furthermore, be a valuable contribution to the science community which currently use albedo and LER information in atmospheric radiative transfer calculations and retrievals of atmospheric parameters.

The ADAM is a project funded by ESA involving seven partners:

- NOVELTIS http://www.noveltis.com/
- University College London (UCL) http://www.ucl.ac.uk/mssl/imaging
- Laboratoire des Sciences du Climat et de l'Environnement (LSCE) http://www.lsce.ipsl.fr/
- Laboratoire d'Optique Atmosphérique (LOA) http://www-loa.univ-lille1.fr/
- Universität Bremen (UB) http://www.iup.uni-bremen
- Swansea University (SU) http://www.swan.ac.uk/
- Freie Universität Berlin (FUB) http://www.fu-berlin.de/

1.2. Objectives of the study

The objective of the ADAM project is to generate narrow-band Earth surface reflectances over the spectral domain ranging from 300 nm to 4000 nm and given any observation or illumination geometry.

This is achieved thanks to the building of:

- a dataset of gridded 10 x 10km monthly climatologies of:
  - normalized reflectances in the seven spectral bands of the MODIS instrument **over land**,
  - chlorophyll concentration and wind speed **over ocean;**
- a web interface for the accessing of the database, free of charge, by scientists from all over the world via a Graphical User Interface;
- a stand-alone calculation package that allows the computation of the Earth surface reflectance (over land – vegetation/soil, and snow - and ocean) in any narrow-band/observation geometry using the datasets described above as input.

The generated products can used by current and future passive and active Earth Observation missions from Ultra Violet (UV), Visible (VIS), Near-Infra-Red (NIR) and Short-Wave-Infra-Red (SWIR) with the scope of improving radiative transfer simulations and inversions and assessing new sensor performances.

The ADAM input dataset has been obtained and validated based on various EO mission products which have been interpolated and extrapolated in order to cover the UV-SWIR range at fine spectral resolution and translated into different viewing geometries thanks to suitable BRDF models. The ADAM products (input database, calculation tools, and output data) are available from a dedicated web interface (Figure 1-1).

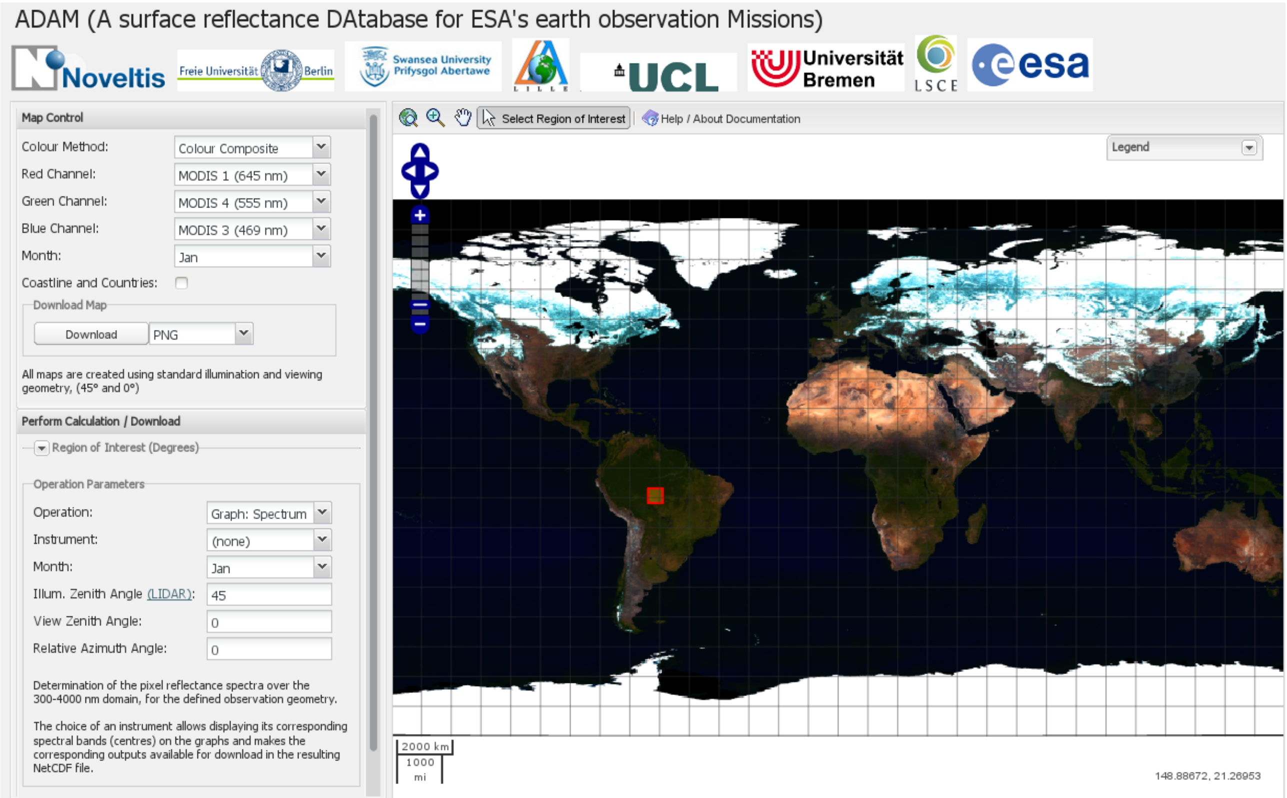

Figure 1-1. ADAM GUI interface showing a false colour composite of MODIS Normalised Reflectance for January 2005 and the location (red box) over Amazonia used to calculate the statistics of spectral NR for the whole of 2005.

1.3. Logic of the study performed in the ADAM project

Task 1 of the ADAM project addressed the **requirements for a surface reflectance database**. The outcome of the literature review is reported in Technical Note 1 (NOV-3895-NT-11143 [RD1]).

Task 2 identified appropriate satellite database and ancillary information to derive the surface component of the ADAM database. This is described in Technical Note 2 (NOV-3895-NT-11144 [RD2]).

Task 3 specified the **design of the database and specified the data as well as the web interface (GUI)** of the ADAM database for accessing and visualizing the products. This specification work is described in Technical Note 3 [RD3].

In task 4 the various input datasets were prepared and used as an input to a tailored ADAM processing chain in the following way:

1) the **existing datasets that are used as an input of the main ADAM calculation tools** were improved (with a focus on the pre-processing of the input reflectance products over land surfaces that is undertaken by the FondsDeSol processing chain),

2) the **stand-alone ADAM toolkit** were developed, that allow the computation of the Earth surface reflectances over the <u>300-4000 nm spectral range</u> (with a <u>spectral resolution of 1nm</u>) and <u>in any observation geometry</u>.

The various input datasets that are used as an input of the ADAM processing chain are described in Technical Note 4, along with the corresponding Algorithm Theoretical Basis Document (ATBD) [RD4].

Task 5 was dedicated to the **compilation of the database** within the dedicated Graphical User Interface Web site, and the **description of its content and its access using the GUI functionalities**. The ADAM products structure and formats, as well as their access through the ADAM GUI, are documented in a dedicated Technical Note 5 [RD5], which is basically an updated and completed version of the Technical Note 3, and serves as a **Data User Manual**. The ADAM user-oriented documentation has been produced within this task, and is available through the ADAM Web page 'Help/About Documentation' section. It includes:

- **On-line User manual** for web interface and Application Programming Interfaces (API),
- The Data User Manual, providing description of Product structure and format [RD5].
- The **ATBD** describing the data sources, data processing steps and quality control [RD4].

Task 6 was dedicated to the **validation of the ADAM database**, including:

- The comparison of the ADAM products with dedicated reflectance databases specifically derived for this exercise (a land surface database derived for the globalbado processing chain, and a fonddesols land surface dataset for a different year);
- The assessment of the impact of ADAM database on the retrieval of NO_2;
- Comparison of ADAM generated BRF products of Top of Canopy (ToC) from MISR.

These validation exercises are presented in a Technical Note 6 [RD6].

Task 7 addressed the **sensitivity of the retrieval of atmospheric parameters with respect to rapid changes in the surface reflectance** (for instance, snow, vegetation, ocean colour) and established **the needs for a NRT service**. This is reported in the corresponding Technical Note 7 [RD7].

The Final Report package is made of the seven Technical Notes described above, together with the present document, summarizing the ADAM project. The ADAM web interface (http://adam.noveltis.com/) is available and will be fully operational and accessible at the conclusion of the contract execution in order to allow users to easily and freely access the ADAM products.

Detailed developments, results and conclusions, are given in each Technical Note. The next section provides an executive summary of main results of the project. The last section describes the over-arching conclusions and lists a set of recommendations as well.

2. Summary of main results and conclusion of the ADAM project

2.1. Task 1: Literature survey of ESA EO missions needs for surface reflectance information

A survey has been given of the requirements of current and planned ESA EO missions for *a priori* spectral albedo, BRDFs, and/or LERs.

This literature survey has identified current or future ESA missions requiring knowledge of the surface reflectance for generating reliable satellite products for atmospheric retrieval. Many active and passive missions perform or will perform measurements in the solar domain, from the UV domain up to the SWIR (4µm), and consequently retrieval algorithms have to account for surface reflectance as well as directional effects, since several sensors perform multi-angle measurements. Furthermore, for precise measurements of faint signals such as fluorescence, accurate knowledge of surface reflectance is mandatory. **Several publications have shown that uncertainties of surface reflectance can induce significant errors on retrieved parameters especially for low albedos**. For example, Boersma et al. (2004) found a 5% change in NO_2 VCDs for a surface albedo change of 2% at 440 nm for clean cases, a 8% change for polluted cases, and a 15% change for heavily polluted cases. **Therefore, the better the reflectance characterization, the better the accuracy on retrieved parameters**. To date, several remote sensing retrieval schemes use surface reflectance information provided by LER climatologies with variable spectral resolutions and 1° x 1° (GOME LER) or 0.5° x 0.5° (OMLER) spatial resolution. There is a need for an improvement of this knowledge. In particular, Popp et al., (2011) have demonstrated that a spectral database from the ESA MERIS AlbedoMap project had a substantial impact on Oxygen A-band cloud retrievals as well as trace gas retrievals, especially when compared with GOME-LER data. Based on this, **the target specifications for ADAM for trace gas, climate gas, clouds and aerosol retrievals are the provision of directional reflectance data on a spectral and spatial scale better than 5 nm and 10 km, respectively.**

The temporal variations of surface reflectance have also to be considered since the order of magnitude of these reflectance values can be high, especially in high latitude areas that are affected by snow and in regions where vegetation exhibit strong seasonal cycles. This implies that information on the inter-annual variation of the surface reflectance is necessary. For applications with a low sensitivity to the surface reflectance variability, the knowledge of the seasonal reflectance variation is sufficient. For retrievals with a large sensitivity, the instantaneous value of the surface albedo from near-real-time measurements would be necessary. The latter need cannot be served by the use of a climatology, but would instead call for a NRT surface BRDF product. Such applications will not be served by the outcome of this project, but are discussed further in chapter 2.7. Based on the assessment presented here, **the provision of monthly maps of the surface albedo variation from one year of data together with the monthly variations from a 10-year dataset from MODIS is taken as the baseline specification for ADAM**. This is a substantial improvement upon currently available OMLER climatological dataset with 23 specific wavelengths over a three-year time period (Kleipool et al., 2008).

Finally, any forward atmospheric radiative transfer model (and whatever the implemented RT algorithm) requires knowledge of the surface reflectance in order to generate accurate signal simulations at the sensor level. In regions where the surface reflectance is rapidly changing, because of flood, burnt scars and snowfall, a temporal resolution sufficient to represent these changes is necessary. Furthermore, due to the many applications of the atmospheric RT models to various remote sensing missions, **a surface reflectance model as a function of viewing and illumination angle for various types of surfaces found around the globe is both sufficient and necessary. This calls for the delivery of spectral BRDF information in addition to currently available climatological albedo or LER products**. Increasingly 3D RT is recognised as critical to represent the natural complexity in the atmosphere-land-ocean surface interactions.

As a consequence, providing accurate and up-to-date surface directional reflectance products via a dedicated portal is of the highest importance for improving atmospheric retrievals and surface characterization, as well as for feasibility studies in the framework of mission preparation.

ADAM addresses the needs of different applications for improved retrieval of land and ocean surface properties, aerosols and cloud characteristics. There is no "one size fits all" set of requirements as they are specific to the application requirements. Application requirements and climate needs are reported in Technical Note 1 [RD1], along with the specification for the surface reflectance accuracy. The surface reflectance requirements were listed in Table 2-1 (TN1 [RD1]) as follows:

Table 2-1: Accuracy requirements for an *a priori* surface reflectance database regarding atmospheric retrievals. (*)Personal communication

Atmospheric constituent (troposphere)	**Accuracy requirement for an a priori surface reflectance knowledge** SR: surface reflectance	**Albedo / LER / BRDF knowledge**	**Wavelength range and spectral resolution**	**Spatial and temporal resolution** G … Goal T … Threshold	**Viewing** (VZA) **and illumination** (SZA) **angle**
NO_2 **(*A. Richter)**	<2% for SR<0.1 <5% for SR<0.3 <10% else	BRDF required	420 – 500 nm Spectral res.: 5 – 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 60° SZA: 0 – 85°
BrO **(*A. Richter)**	<2% for SR<0.1 <5% for SR<0.3 <10% else	BRDF required with the exception of snow/ice covered regions	330 – 370 nm Spectral res.: 5 – 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 60° SZA: 0 – 80°
HCHO **(*F. Wittrock)**	<3% for SR<0.2 <5% for SR>0.2	BRDF required	330 – 360 nm Spectral res.: 5 – 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 60° SZA: 0 – 75°
CHOCHO **(*F. Wittrock)**	<3% for SR<0.2 <5% for SR>0.2	BRDF required	430 – 460 nm Spectral res.: 5 – 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 60° SZA: 0 – 75°

Atmospheric constituent (troposphere)	Accuracy requirement for an a priori surface reflectance knowledge SR: surface reflectance	Albedo / LER / BRDF knowledge	Wavelength range and spectral resolution	Spatial and temporal resolution G … Goal T … Threshold	Viewing (VZA) and illumination (SZA) angle
O_3 **(*M. Weber)**		Albedo usually a fitting parameter (e.g. WF – DOAS) or as a priori information in standard DOAS method	325 – 337 nm Spectral res.: 5 – 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 40° SZA: 0 – 80°
XCO_2 **(*M. Reuter)**		Albedo usually a fitting parameter (e.g. WMF – DOAS)	1555 – 1595 nm 750 – 780 nm (O_2) Spectral res.: 5 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 40° SZA: 0 – 80°
XCH_4 **(*M. Buchwitz, O. Schneising)**		Albedo usually a fitting parameter (e.g., WMF – DOAS)	1630 – 1670 nm 750 – 780 nm (O_2) Spectral res.: 5 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 40° SZA: 0 – 80°
Aerosols **(*W. von Hoyningen-Huene)**	1% for SR<0.1 <1% for SR>0.1 (VIS 412 nm)	BRDF required	412 – 670 nm (land) 412 – 885 nm (ocean) Spec. res.: 10 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 55° SZA: 0 – 80°
Clouds **(*V. Rozanov, L. Lelli)**	Over land (except snow, ice) <10% for 0.0 < SR < 0.2 <5% for 0.2 < SR < 0.4 Over ocean <15% Cirrus clouds: 1% for SR<0.1 <1% for SR>0.1	BRDF required for cirrus clouds and COT retrieval LER for cloud altitude (using O_2 A-band)	758 – 772 nm (oxygen A-band) Spec. res.: 1 nm	1 x 1 km^2 (G) 10 x 10 km^2 (T) NRT (G) weekly maps (T)	VZA: 0 – 60° SZA: 0 – 80°

2.2. Task 2: Identification of suitable existing surface reflectance datasets for the generation of ADAM

A literature and www search was performed in order to identify existing datasets suitable for the generation of ADAM input products. These datasets are classified into three main categories:

- Satellite products providing surface reflectances at a global scale;
- Specific products for the generation of the spectro-directional land surface reflectances (BRDF modelling from directional measurements, spectral datasets);
- Products for the generation of the ocean reflectances (chlorophyll and wind climatologies).

2.2.1. Satellite products

It was originally intended to use the product from either MERIS or SeaWiFs for ocean surfaces (chlorophyll concentration) and the similar products as those used in the GlobAlbedo project for land surfaces: MERIS, VGT and POLDER products, along with MODIS priors in order to fill in the spectral gaps and to provide an estimate of the reflectance variability. Compared to GlobAlbedo, the land products would have been used to compute the reflectance in narrow spectral bands instead of broad bands. The FondsDeSol database was foreseen to be used in Task 6 for direct validation of the ADAM output reflectance products.

Since Task 2, the choices have been refined:

- **FondsDeSol** (improved) is used to provide the input dataset of **land surface reflectances** (Gonzales et al., 2010)**;** in order to ensure representativity of the database, a typical year 2005 has been chosen, and 3 additional years of MODIS data have been used for gap filling;
- **SeaWiFs** is used to provide the input dataset of **chlorophyll content over ocean**;
- **QuickScat** is used to provide the input dataset of **wind speed over ocean**.

A processed MODIS prior estimation dataset based on the MODIS spectral BRDF dataset which is employed for GlobAlbedo retrievals of MERIS & VEGETATION was computed for the 7 MODIS spectral bands. These are now used for direct validation in Task 6 (section 2.6)

2.2.2. Datasets for land surfaces

2.2.2.1. Top of canopy directional reflectances

We recommended that the ADAM reflectance database over land surfaces be developed using the linear kernel model of Ross-Li improved by Maignan *et al.* (2004) to account for the "hotspot" effect.

We recommended a processing of the land surface reflectance database using a priori BRDF 'shapes', given the Ross-Li-Maignan model, to correct the directional effect and hence provide a normalised spectral reflectance product (in standardised view zenith - 0º - and solar zenith - 45º - angles) at MODIS wavebands. There has been some evolution during the project and we now use a BRDF shape that varies with the vegetation cover (quantified by the NDVI) rather than the surface type.

Forthe baseline version, it was intended to use MODIS normalised reflectances derived from FondsDeSol (with uncertainties based on the spatial variance from upscaling from the 500m MODIS resolution to the 10km ADAM target resolution) to get ADAM up and running quickly for evaluation based on atmospheric chemistry retrieval. This initial ADAM version was further improved to produce the final ADAM-FDS product (see §2.4) that is one of the main input of the ADAM calculation tools.

It was originally intended to use a land cover classification and *a priori* BRDF 'shapes' in order to perform the directional extrapolation and hence compute the land surface reflectance in any observation geometry with the ADAM calculation tools. This processing was replaced by a simpler and "as accurate" approach that scales the a priori BRDF 'shapes' as a function of NDVI (not relying on any a priori assumption of the land surface type).

2.2.2.2. High resolution spectral datasets for spectral interpolation

Based on the analysis of available spectra datasets, it was intended to use two sources of data:

- The USGS spectral archive, with a focus on bare soil and snow (http://speclab.cr.usgs.gov/spectral.lib06/ds231/datatable.html);
- The DLR spectral archive with a focus on vegetated scenes (http://cocoon.caf.dlr.de/intro_en.html).

In addition, the dataset has been expanded thanks to the ASTER spectral library (http://speclib.jpl.nasa.gov/) that has a higher spectral coverage (300 nm up to 14 µm).

The databases were acquired either from CD-ROM or through ftp. The spectra were provided as text files with metadata. The steps required for their use were: included 1) selection and extraction of a limited set of spectra representative of the variability of natural targets; 2) cleaning-up some of the spectra over spectral domains with large atmospheric absorption; 3) merge of some of the spectra to obtain reflectance estimates outside the nominal spectral range of most of the data [0.3-2.5] µm.

For future work, it is recommended that effort be focused on the UV part of the spectrum as the requirement in Table 2-1 indicates a greater interest in the UV than for the SWIR and thermal infrared.

2.2.2.3. Directional reflectance shapes for directional interpolation

As described above, it was intended to use typical BRDF shapes, derived from PARASOL data, for directional interpolation. The BRDF shapes were developed at LSCE and were readily available for the project. They are provided in the form of the two coefficients of a BRDF model for a set of spectral bands and surface types. Although they have been demonstrated to be mostly appropriate (they were used for the processing of the FondsDeSol products) one drawback is the potential discontinuity at surface types boundaries. Another drawback is the lack of evolution with changing vegetation cover. During the ADAM project development, new work at LSCE led to an alternative. Rather than using typical shapes that depend on the vegetation type, one uses a model that depends on the NDVI [Bréon and Vermote, 2012]. This alternative approach is used in the ADAM tool. Note that snow surfaces show a very different reflectance directional signature than other land surfaces and require, therefore, a specific directional/spectral model.

2.2.3. Datasets for oceans

2.2.3.1. Water chlorophyll content climatology datasets

Based on an analysis of both SeaWifs and MERIS available products, it was concluded that SeaWifs was better suited to ADAM objective. We used monthly mean fields to derive a global monthly climatology at 0.5° resolution, and did some gap-filling over cloudy or absence of daylight areas (high latitudes). The gap-filled data are indicated in a data quality index.

2.2.3.2. Wind speed climatology datasets

As for the wind speed climatology, it was intended to build a monthly mean product based on the Quickscat dataset available at IFREMER. From the data, it was possible to average the available monthly data and generate a climatological wind speed at a monthly temporal resolution, and at a spatial resolution of 0.5 degree.

2.2.4. Recommendations for dataset improvements

The ADAM consortium recommended the provision of uncertainties associated with the land surface reflectances in each spectral band. This was originally foreseen in the GlobAlbedo processing scheme, by employing the GlobAlbedo optimal estimation (GA-OE) approach which employs a 10-year MODIS prior for the 7 spectral bands chosen. Another approach suggested during the project was to assess a representative error based on the spatial variance of the 500 m MODIS resolution measurements, when upscaled to 10km. The choice of the FondsDeSol database (with a lower temporal coverage: one typical year plus three additional years for gap filling) for the definition of the input ADAM reflectance products over land has led the consortium to use the second approach. Nevertheless, within the project, we made a comparison between the uncertainties derived from the GA processing (based on uncertainties at each step of the processing) and those from the FDS processing (based on the spatial variability of the measured reflectances). The latter uncertainties are much smaller than the former..

Concerning the ocean part of ADAM, the wind speed climatology is provided on a monthly basis. The user should be aware that these climatological values may be very different than the actual wind speed at a given moment as the wind speed is a highly variable quantity.

As for the chlorophyll concentration that is necessary to compute the water column reflectance, the SeaWiFs and MERIS products appeared to fulfil the requirements, although some data processing was needed to generate a climatology dataset at the appropriate spatial and temporal resolution [RD4].

As for the spectral signatures, we have been able to access and use a large number of reflectance spectra measured in-situ or in the laboratory. These spectra appear suitable for an interpolation/extrapolation of the MODIS narrowband measurements within the visible and mid-IR spectral range (0.4 to 2.3 µm). There is however an insufficient number of suitable measurements in the UV (<0.4 µm) and the shortwave infrared (>2.3 µm). The few available spectra indicate that the reflectance in the UV is small (smaller than in the blue range) and has low variability. As for the SWIR (from 2.3-4 micron), there is a rather large atmospheric absorption as well as increasing longer wavelength emission that makes this spectral range ill-suited for space-borne remote sensing of the surface. There is nevertheless a need to improve the representativeness of the datasets over these spectral ranges.

2.3. Task 3: Specification of the database design, products, product content and graphical user interface

The third task focused on the database design, the data specifications and the web interface (GUI) of the ADAM database for accessing and visualizing the products. The structure of the ADAM database was defined. Then the data and tools that are part of the ADAM products delivered to the user were specified.

The web interface and its functions for displaying the global map of ADAM data and for performing quantitative analysis over a region of interest (e.g. display of the reflectance spectra over the 300-4000 nm domain, BRDF, or time series) have been specified, as well as the downloading functions of all or part of the ADAM products. Finally, the various calculations (mainly, for an area of interest: computation of the surface reflectance spectrum in the user required observation geometry, BRDF in a particular plane transect or over the upper hemisphere for a given waveband, or reflectance time series in given waveband and observation geometry) involved in the interactive analysis from the web interface or from the tools available to the user to process the ADAM products have been detailed in a step-by-step manner.

Technical Note 3 [RD3] provides a detailed description of these specifications, which have been used and improved to implement the ADAM database processing, products, and GUI, as detailed in tasks 4 and 5. The main functionalities of these are as follows:

- access to the whole or part of the ADAM input climatologies over land (normalised MODIS reflectances in seven bands) and ocean (chlorophyll concentration and wind speed) surfaces at 0.1°x0.1°;
- compute dynamically, for an area of interest:
  - reflectance spectra of the corresponding pixels from 300 up to 4000nm (1nm spectral resolution), given the observation geometry and the month of interest (user choices);
  - directional variation of the surface reflectance (BRDF) in a particular transect plane or in 3D, given the illumination angle, waveband, and month, of interest (user choices)
  - temporal variation (time series) of the surface reflectances, given the observation/illumination geometry and wavebands.

  with a specific treatment depending on the surface type (vegetation/soil, ocean, snow)
- display the result on a calculation on a window and allow the user to download them via .png figures and NetCDF4/HDF5 files.

2.4. Task 4: Improvement / expansion of existing surface datasets and generation of the ADAM database

2.4.1. ADAM processing chain

The ADAM processing chain uses existing input datasets to compute the ADAM Earth surface reflectances over the 300-4000 nm spectral range with a spectral resolution of 1nm and in any observation or illuminaton geometry. It is based on:

1) A pre-processing for the improvement of existing datasets in order to provide intermediate datasets that are used as an input of the main ADAM calculation tools;
2) The stand-alone ADAM calculation tools, the so-called API tools of the ADAM interface that performs the spectro-directional calculations of the Earth surface reflectance over the 300-4000 nm spectral range and given any user-specified observation geometry, based on the previous intermediate datasets.

A schematic diagram of this processing chain is shown in Figure 2-1 below.

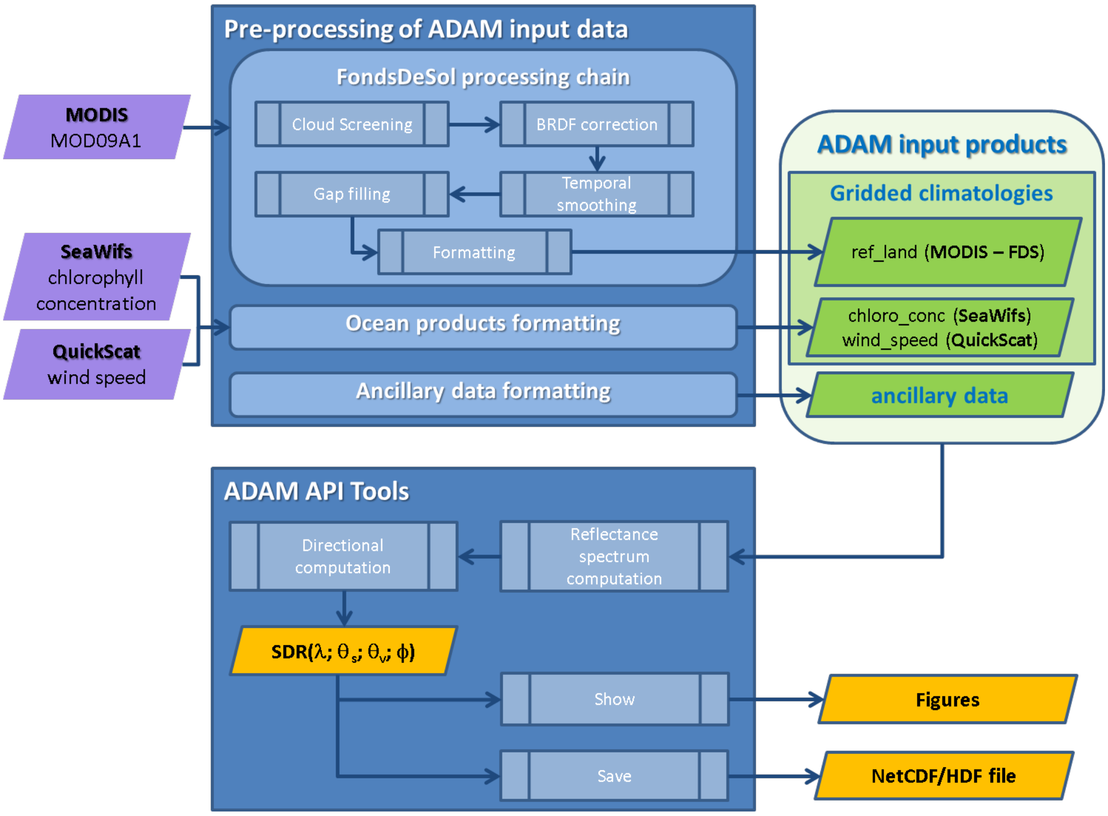

Figure 2-1: Flowchart of the main processing tasks operated in the pre-processing of the ADAM input data (with a focus on FDS processing) and by the ADAM API Tools.

The first pre-processing step provides ADAM intermediate products (further referred to as ADAM input products). The main intermediate inputs consist of gridded monthly climatologies of land and ocean products, including their relationship to different surface types. They are provided in the form of gridded data at 0.1° spatial resolution (Plate Carre projection) for different 12 months, provided in NetCDF files. They are available for the user through the ADAM web interface:

- **Over ocean:**
  - Monthly chlorophyll concentration derived from SeaWiFs. It is used to compute the water column reflectance which shows large spectral variations but is significant only in the visible spectral range;
  - Monthly wind speed derived from QuickScat. It is used to estimate the sun-glint and the foam contributions ;

- **Over land:**
  - The input dataset for ADAM over land surfaces is derived from MODIS observations for the year 2005, chosen as a typical year in order to ensure the representativeness of the ADAM database The data processing of the sensor measurements, as part of the FondsDeSol processing chain, generates a database of monthly surface reflectances in a normalised observation geometry (satellite view zenith 0º nadir, sun at 45° zenith angle). They are the main inputs of the spectral interpolation/extrapolation procedure that generates a reflectance spectrum over the 300-4000 nm spectral range;
  - Uncertainty variance-covariance matrix for the 7 spectral bands associated with the normalized surface reflectance. They are used by the spectral interpolation procedure to derive the spectral variation of the uncertainty on the land surface reflectance.

In addition, some ancillary data are used by the ADAM API tools to perform the spectro-directional reflectance calculations, depending on the surfaces.

- **Land surfaces:**
  - For the spectral interpolation and extrapolation from the MODIS narrowband measurements, we have collected several hundreds of land surface spectra at high (1 nm) resolution (as described in §2.2.2.2). We have selected those that correspond to natural surfaces and performed a statistical analysis on the spectra. The interpolation/extrapolation method is then based on the hypothesis that the spectral shape variability is limited and can be described by a few eigenvectors. The elements defining **Empirical Orthogonal Functions (EOF)** are derived for further use as input of the ADAM API Tools so as to perform the spectral extrapolation of the reflectance and of the associated uncertainty.
  - Snow was deliberately excluded from the statistical analysis of land surface reflectance spectra because its reflectance range and spectral signature is highly different from those of the other spectra which would have had a very large impact on the eigenvectors. **Thus, a specific model for snow pixels is used**. The **imaginary part of the refractive index of ice** is required to determine the spectral and directional variations of snow pixels.
- **Ocean surfaces:**
  - The computation of the glint reflectance depends on the wind speed (to determine the wave slope distribution) and on the Fresnel reflectance which is a function of the incidence angle and of the **refractive index of water**.
  - The foam reflectance is a function of wind speed and wavelength. Its spectral dependence is due to water absorption that increases with wavelength. In ADAM, the dependence of the foam contribution with wavelength is modelled as a function of the **water absorption coefficient**.
  - The computation of the water column component of the ocean reflectance is based on a simple model that relies on **6 typical ocean reflectance spectra** over 300-800 nm with the associated chlorophyll content values.

The final ADAM products describe the Earth surface reflectances over a wide spectral domain (300-4000nm) while the MODIS instruments monitors the Earth at relatively high spatial and temporal resolutions in only a few narrow spectral bands. Among the MODIS spectral bands (http://nsidc.org/data/docs/daac/modis_v5/spectral_bands.html), the most useful ones are for bands 1 to 7 that span from 470 to 2130 nm with a spectral width of between 20 to 50 nm. Therefore, the ADAM API tools include spectral interpolation and extrapolation procedures based on the narrowband measurements that are available, in order to derive the land surface reflectances over 300-4000nm, with a spectral resolution of 1 nm. In addition, ADAM aims at providing realistic values for any reasonable observation geometry. This is implemented by the ADAM API Tools that allows the extrapolation of the input reflectance from the reference geometry to any other set of sun/view angles. The main tasks of the ADAM API tools are:

1. **Initialisation**

   a. **Reading of the user defined configuration.**

   Either from the web interface or with manual scripts, the user may define various parameters controlling the analysis: area, wavebands, period of interest, observation geometry, type of graphs, etc.

   b. **Loading of the ADAM input data for the requested area and period, with determination of the land/sea/snow mask**

2. **Computation of the reflectance spectrum over 300-4000nm for each pixel within the area of interest, for the normalized observation geometry**

   The processing differs depending on the pixel type: soil and vegetation/snow/ocean.

3. **Computation of the directional reflectances, for each pixel:**

   a. Surface Directional Reflectance if only one view direction is required,

   b. Bidirectional Reflectance Directional Function is multiple view directions are requested.

4. **Display of the results via figures** (Figure 2-2 and Figure 2-3) **and preparation of result file (HDF5/NetCDF4) for downloading**

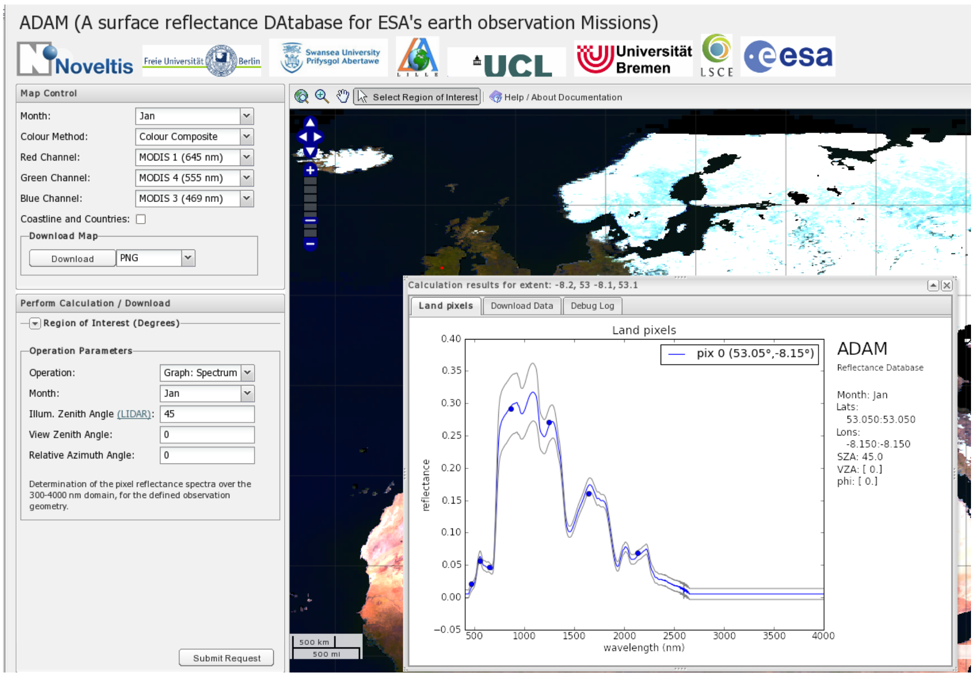

Figure 2-2: Spectral reflectance over 300-4000nm (and associated uncertainty) for a land pixel in Ireland (red dot above the plot) in January, superimposed on a display of the ADAM database over Europe.

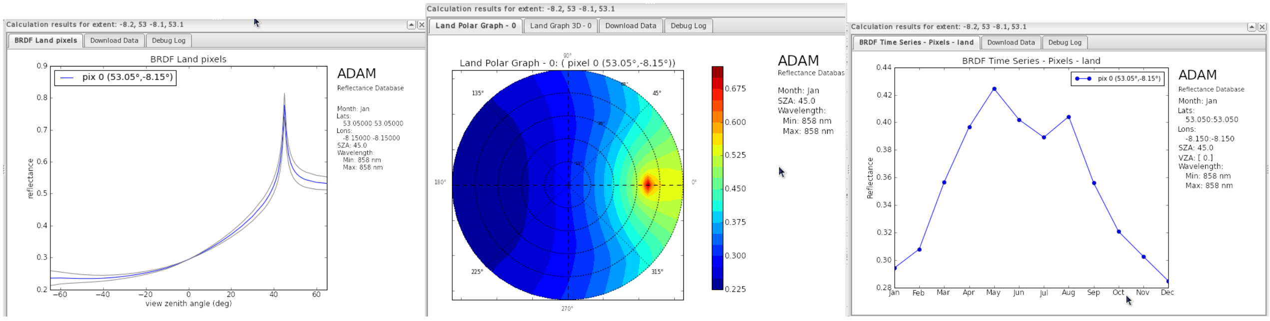

Figure 2-3: For the same pixel than in Figure 2-2 and at 858nm: BRDF in the principal plane (left), BRDF as a polar plot representation (middle), time series variation over a particular set of view / solar angles over the year (right).

2.4.2. Uncertainty quantification

For the ADAM project, uncertainties have been specifically addressed **for the land products** (except for snow). The FondsDeSol processing chain has been modified in order to estimate the variance-covariance matrix between the seven MODIS bands for each 0.1°x0.1° pixel (approximately 10 km) (for each month). For each 0.1°x0.1° pixel, the monthly error covariance matrix between the 7 spectral bands has been determined from the variability of the reflectance values of each 500 m encompassed in the 0.1°x0.1° pixel. This information is used to compute the uncertainty on the reflectance spectrum of land pixels, with a 1nm spectral resolution.

Additionally, a procedure has been implemented to compute the uncertainty associated to the BRDF for pixels over land (except snow).

2.4.3. Product Verification / Functional validation

Various verifications have been performed on the ADAM processing chain and on products.

The final FondsDeSol products derived for ADAM are mainly based on a single year (2005) of retrieved surface reflectances from observations made by MODIS. The ADAM FDS product has been compared against pre-existing FondsDeSol products for year 2006. The main difference between the two versions is that 2006 was based on data sets of MOD09A1 products (collection 4) over 1 year of data, while ADAM FDS for year 2005 is based primarily on data from 2005 with some adjacent years used for gap filling from on a 4-year data set (collection 5). Another aspect was the introduction of a MODIS snow cover product (MOD10A2) to help the cloud/snow discrimination. The MOD10A2 contains data fields for maximum snow cover extent over an 8-day compositing period and a chronology of snow occurrence observations. This new construction has a significant impact on the Northern Earth regions in wintertime. The last important change was the use of a MODIS land classification product (MCD12Q1) at 500m resolution instead of the global IGBP 1km product, used for reflectance normalization.

A dedicated quantitative analysis has been performed to validate the spectral interpolation approach over the land surface. A validation exercise against an independent set of reflectance spectra confirms that the method does reproduce well the measured spectra. Overall, the difference between the "true" and "reconstructed" spectra is smaller than - or of the order of magnitude of a few percent within then 440-2000 nm spectral range and up to 0.1 (10%) for longer wavelength (mid-IR). The reconstructed spectra should be seen as "realistic", i.e. represent observations that may be measured by a space-borne sensor, although they are likely to deviate slightly from the true spectrum over a particular pixel. The reflectance values for the longer wavelength in the SWIR should be treated with caution as the input narrowband reflectances do not provide the necessary constraints to evaluate the reflectances in this spectral range.

2.4.4. Quality control

It should be well understood that the ADAM Tools do not attempt to generate exact value for any given day and time, but only typical values of the Earth's surface reflectances (and associated errors for the land surfaces). Indeed, the use of monthly climatologies (using some gap filling procedures) excludes the possibility of correctly accounting for finer temporal variations of the surface state.

2.4.4.1. Ocean spectral reflectance

The modelling approach based on the chlorophyll concentration to simulate the spectral variation of water column reflectance assumes a constant value in the UV, based on the reflectance at 400 nm.

2.4.4.2. BRDF modelling for snow mixed pixels

The modelling of the spectral BRDF for mixed pixels composed of snow and non-snow elements (vegetation and soil) is complex and has received little attention in the literature so far. The scattering properties of snow and vegetation/soil surfaces are very different: for soil/vegetation, the BRDF is strongly anisotropic with maximum reflectance observed in the retro-solar direction, while it is more isotropic for snow. To our knowledge, no simple model exists in the literature that can be implemented in the ADAM processing tools for treating any combination of snow/vegetation/soil elements.

Therefore, we have considered two cases for modelling the BRDF of snow pixels:

- for pixels exhibiting high reflectance values in the visible, close to those of "pure" snow, we have considered that the non-snow elements can be neglected. Therefore state-of-the-art snow model is applied;
- otherwise the surface behaves like a Lambertian surface with constant reflectance values independent of the viewing direction.

2.4.4.3. Observation geometries

- There is no control that the observation geometry (either the default one proposed in the web interface, or the one chosen by the user) may correspond to a physically realisable observation configuration for the pixel/period considered. In particular, there is no relation between the value of the sun zenith angle and latitude/time.
- In ADAM API Tools, the range of variation for the view zenith angle is set to [-65°; and 65°]. Beyond these values, the BRDF models that are used are not validated and are likely to provide unphysical reflectance values.
- The user has however the possibility to change this variation interval by modifying the standard ADAM configuration file, but all responsibility for any subsequent results rests entirely in the user's hands as described in the registration process (note that hard limits are imposed on the web interface to avoid computations beyond the domain of validity of the models used).
- For the same reason, the maximum value of the illumination zenith angle is limited to 70°. However, the user may control the behaviour of ADAM outputs when going beyond this threshold value:
    - either all reflectance outputs associated to out of range illumination directions are set to 0,
    - or all reflectance outputs associated to out of range illumination directions are set to NaN,
    - or all reflectance outputs associated to out of range illumination directions are set to the reflectance value that corresponds to the threshold sun zenith angle.

2.4.4.4. Quality flags

The quality flag have been generated in the frame of CCN1. They are associated with the gridded input data is in order to indicate when a pixel has been gap filled:

- 0 indicates no gap-filling;
- 1 indicates gap-filling for **chloro_conc** data only;
- 2 indicates gap-filling for **wind_speed** data only;
- 3 indicates gap-filling for **chloro_conc** and **wind_speed** data;
- 4 indicates gap-filling for **ref_land** data.

2.5. Task 5: Description of the input and output products of the ADAM database, and of their use through GUI

The compilation of the ADAM input database used by the API tools and the dedicated Graphical User Interface Web site, and the description of its content and its access using the GUI functionalities, has been performed in task 3 (see summary description in section 2.3 above).. The user-oriented documentation has been produced within this task, and is available through the ADAM Web page help section. This documentation includes which follows:

- The ADAM products structure, content and formats, as well as their access through the ADAM GUI, is documented in the dedicated Technical Note 5: structure of the input ADAM database (gridded climatologies and ancillary data), means for accessing ADAM products (input or output data resulting from the ADAM computations), structure and format of the ADAM output products.

- User manuals for web interface and Application Programming Interfaces (API), is part of the On-Line documentation in the ADAM Web Site. We provide below some high-level description of this documentation.

The user's manuals for the web site and for the API are available online through the ADAM Web page 'Help/About Documentation' section. The proposed structure of the documentation is the division into 3 Sections: Project ('About ADAM'), Website ('Using the Website') and API ('Using the API').

'About ADAM' provides basic information on the ADAM project's purpose and metholodology, and links to the technical notes. It provides in particular the ATBD (Technical Note 4 [RD4]) and the ADAM User Manual (Technical Note 5 [RD5]).

The section **'Using the Website'** provides all the useful information relating to the use of the web site, including the management of the maps, launching of calculations, and downloading of data, in the form of an online user manual. The structure is as follows:

- Commented screen shot of Website use, in step by step for
  - Use of the maps,
  - Launching computation,
  - Downloading of the data,
  - Use of the website via command line.

'Using the API' gives the detailed information on the API: purpose and overview, and a link to a dedicated ADAM API documentation for expert users (the User Manual, TN5 [RD5]). The structure of the API documentation is as follows:

- Introduction;
- What is API?
- Examples;
- Modules Documentation.

2.6. Task 6: Scientific evaluation of the ADAM product

The verification of the ESA EO surface reflectance database ADAM has been addressed by a direct as well as an indirect validation/assessment part. A twin-track approach was chosen for a direct inter-comparison of different versions of ADAM (the version based on 2005 MODIS FondsDeSol (FDS) versus the version based on 2005 GlobAlbedo (GA-MODIS)), which have both been derived from the MODIS surface reflectance dataset but through completely independent processing algorithms, as well as a comparison of ADAM with the MISR independent dataset. In addition, we presented an indirect validation (with DANDELION campaign data) and assessment (using remote sensing data only) of the ADAM database by investigating the impact of ADAM BRDF products on the retrieval of atmospheric NO_2 from SCIAMACHY measurements. Moreover, a sensitivity study regarding clouds was carried out in order to evaluate the impact of the surface reflectance on the retrieved cloud parameters.

2.6.1. Direct validation

In general, there is excellent agreement between surface reflectance estimates of the ADAM FDS and ADAM GA databases. Overall, the two datasets show similar values for areas not contaminated by aerosols/clouds and over snow/ice. For CEOS cal/val sites such as DOME-C over Antarctica and Libya-4 they show very similar behaviour and for transects at 18ºE, results are also very similar.

However, there are also significant differences on the reflectance values between the two datasets for some specific conditions:

1) The largest reflectance values (between 0.8 and 1) correspond to snow covered pixel in the visible (bands 1-4). The largest fraction of these pixels is found over Antarctica and Greenland. For these pixels, there is a clear difference between the two datasets, ADAM GA being lower than FDS. These differences are confirmed over the Dome C site, and are expected to be due to differences in the BRDF models used. For such fully snow covered pixel, the reflectance is expected to be close to 1 in the visible, and the ADAM GA value appears lower. However, the realism of the respective GA and FDS values are under discussion with respect to recent references.
2) The other large differences in reflectance values are found were ADAM FDS is low, while GA shows much larger values. These differences can be associated with residual aerosol/cloud contamination in GA which have not been eliminated in the 10 years of MODIS BRDF values. This might be explained by the impact of poorer surface reflectance retrievals in the inputs for the BRDF retrieval which are not properly screened in the resultant 16-days BRDF retrieval in ADAM GA. These poorer quality reflectance retrieval are eliminated in ADAM FDS.

There are also clear differences between the uncertainties in ADAM FDS and GA. This appears to reflect the different nature and source of the uncertainties. ADAM FDS uncertainty comes from spatial variability, while ADAM GA uncertainty comes from the uncertainties in the Qbit (Quality bit) from the original MODIS BRDF product. These are driven solely by the number of directional surface reflectances in each 16-day input and the weights of determination in the retrievals. If there is large-scale contamination of pixels by aerosol/clouds and they are not correctly identified as such in the original surface reflectances, the Qbit might not register these. However, experience has shown that where this Qbit indicates poor quality the uncertainties are likely to be at least as large as the mean. Aerosol and cloud retrievals over snow by MODIS are very poor so the uncertainties are likely to be high. Over tropical forests where there are persistent clouds, the Qbit is likely to reflect very high uncertainties. This is what is demonstrated in the products..

The methods of uncertainty calculation lead to largely different error estimates. However, as suggested from a preliminary global assessment and by some case analyses like a North-South transect over tropical Africa, the error reported in GA is significantly larger than the one's initial expectation of uncertainties on NR values (as suggested, e.g., by significantly lower differences between the FDS and GA datasets).

In addition, Comparison with the MISR Level-3 0.5º x 0.5º monthly Land DHR (Directional Hemispherical Reflectance) dataset has been performed using a simulated set of spectral land DHRs derived from the ADAM-FDS and ADAM-GA datasets for the same spectral responses as those from MISR using the spectral extrapolation tools within ADAM.

MISR provides multi-angle ToA radiances in 4 spectral bands (blue, green, red, NIR) at 9 different angles up to ±70º. These ToA radiances are employed to simultaneously retrieve surface BRFs (using aerosol AODs calculated within the retrieval algorithm) at each of the 9 angles for all cloud-free regions on the Earth's land surface. These BRFs are then used to retrieve a BRDF for each cloud-free observation at 1.1km from which the DHR "black-sky" albedo is retrieved. For all spectral land DHR observations (maximum of ≈30 month at high latitudes and 4 at the equator), statistical monthly summaries are produced, as described by Braverman and Di Girolamo (2002).

ADAM Earth surface DHRs have been computed at 0.5x0.5° using the same wind speed and chlorophyll concentration climatology over oceans, and the GA and FDS normalized reflectance products over land.

Three approaches were taken for this inter-comparison: 1) correlation analysis of MISR vs FDS and MISR vs GA; 2) triple collocation analysis of all 3 datasets as described in, e.g., Caires and Sterl, 2003; 3) comparisons of ADAM simulated BRFs with individual BRFs measured by MISR instantaneously. In the first approach all land spectral DHRs for all bands were employed to derive a statistical correlation. Results indicates that the GA data has slightly higher correlation with MISR than FDS, due mainly to the much higher values of the DHR from FDS for albedos>0.8 and a band of FDS values for the same MISR DHR. The triple collocation analysis indicates that most of the residual variance is in the northern hemisphere for FDS and GA due most likely to ephemeral snow and the variance is highest in the MISR dataset due to underlying issues in the MISR level-3 dataset. The underlying variance structure of FDS and GA are similar but the MISR is very different as it appears to come from a data sampling with statistically significant differences. Without a "truth" dataset, an objective conclusion is not possible from this analysis.

2.6.2. Indirect validation with respect to NO_2 retrieval

2.6.2.1. Using remote sensing data

Accurate knowledge of the spectral surface reflectance is crucial for trace gas retrievals in the UV-VIS range, especially if the trace gas densities peak in the troposphere. Since retrieval of nitrogen dioxide using the so-called DOAS method has been found to be very sensitive to prior surface reflectance knowledge, we selected NO_2 as the representative trace gas for the indirect assessment of ADAM-FDS and ADAM-GA. For the global inter-comparison we computed different sets of Air Mass Factors (AMFs needed to convert the slant column density into a Vertical Column Density (VCD) in the context of the DOAS method) for SCIAMACHY observations in 2005 based on the currently used GOME LER database (June 1995 until December 2000) and the newly derived ADAM database, respectively. The impact of the surface reflectance has been analysed with respect to the modelled AMFs using SCIATRAN RTM and consequently, regarding the retrieved NO_2 VCD by means of the DOAS technique. The results of this assessment have been presented as seasonal maps (spring: March - May, summer: June - August, fall: September - November, and winter: December - February) for SCIAMACHY AMFs and NO_2 VCDs, respectively, on a global scale for the year 2005.

When comparing the AMFs based on GOME LER and ADAM BRDF, respectively, we found large differences where GOME LER is inaccurate. Overall, that is related to regions covered by snow and ice, areas characterized by persistent clouds (GOME LER product might be influenced by residual cloud contamination in these areas), and water surfaces exhibiting a significant amount of phytoplankton. Furthermore, large differences are visible in regions where BRDF effects play an important role, such as arid regions (deserts) and vegetation (woods). In addition, significant differences are noticeable where spatial resolution is relevant, such as mountains and along coastlines. Over land, the AMFs based on the GOME LER are generally higher compared to the AMF based on the ADAM BRDFs due to the fact that GOME LER leads to a stronger contribution of surface reflection to the TOA radiance and hence, results in a higher AMF. Over water, both AMF datasets show similar values except in regions of significant phytoplankton concentration.

When comparing the results of NO_2 VCDs using AMFs based on GOME LER and ADAM BRDF, respectively, **we found large differences in regions where the Lambertian assumption differs significantly from the BRDF model** (as mentioned above). Therefore, the higher AMF values in the case of GOME LER lead to smaller NO_2 VCDs. Moreover, considerable differences are visible in areas where large concentrations of tropospheric nitrogen dioxide are found close to the surface (e. g., urban agglomerations). Additionally, large solar zenith angles (i. e., at high latitudes during winter) also lead to clear differences between GOME LER and ADAM BRDF based NO_2 VCDs. However, from this inter-comparison we are not able to draw the conclusion that the BRDF effect is solely responsible for these large differences in AMFs and hence, NO_2 VCDs, because the compilation of both needs to be taken into account for a fair comparison. The GOME LER climatology is based on 5.5 years of GOME observations, while ADAM BRDF databases (FDS and GA) are compiled on the basis of MODIS surface reflectance.

In addition, we presented relative differences of SCIAMACHY AMFs (left column) and NO_2^{trop} VCDs (right column) based on ADAM-FDS and ADAM-GA for May and June 2005, in order to evaluate the indirect impact on our results due to the two different ADAM versions. Over water we found a good agreement between FDS and GA based AMFs and thus, NO_2 VCDs. However, over land significant differences are visible almost everywhere. We conclude that the origin of the differences between the two ADAM products might be explained by the higher quality of the cloud filtering in FDS (and the associated gap-filtering) that removes contaminated pixels that are still present in GA (mainly in the visible).

2.6.2.2. Using in situ DANDELIONS campaign

Furthermore, an indirect validation of NO_2 retrieval results was carried out in the framework of the DANDELIONS campaign, which took place at Cabauw (The Netherlands) from May to June 2005. Judging from this preliminary comparison, **the new ADAM data set leads to a better agreement of the SCIAMACHY retrievals with the ground-based validation measurements than the GOME LER data**.

However, more detailed analysis is needed to investigate the reasons for the larger than expected (in the range of 30%) deviations between ground based and space borne results. Possible reason might be related to:

- spatial inhomogeneities;
- comparison of point measurements with observations obtained from the large SCIAMACHY science pixel (60 km x 30 km) using a 100 km radius as the co-location criteria;
- cloud contamination;
- inappropriate a priori NO_2 profile (i. e. not polluted enough) derived from the coarse spatially resolved OSLO CTM (2.8 x 2.8 degrees);
- underestimated aerosol load.

These are reasonable arguments for explaining the expected deviations. However, they cannot fully explain the large deviations encountered in this indirect validation, i. e. the retrieved SCIAMACHY nitrogen dioxide vertical columns are generally too low. A detailed analysis of each co-location would be necessary in order to discuss these large differences. The sensitivity of the satellite observations to NO_2 in the lower atmosphere decreases towards the ground if the surface is dark as it usually is in the spectral region of NO_2 retrievals. The details of the resulting averaging kernels (AVK) depend on the surface spectral reflectance and on assumptions made for aerosol as well as cloud contamination. We demonstrated that the AVK changes by more than a factor of 3 over the lowest 4 km in the atmosphere for a typical shape of an AVK for a measurement over Cabauw assuming GOME LER. Therefore, good knowledge of the NO_2 vertical distribution is an important prerequisite of the retrieval. Over polluted regions, assumption of a sharp maximum in the boundary layer is usually a good approximation, but deviations from the a priori shape taken from the model calculations can easily lead to uncertainties of the order of 30% and more. While the sensitivity of the observations to a given number of NO_2 molecules decreases with altitude as reflected in the AVK, it should be pointed out that in combination with a typical NO_2 profile in a polluted area (large concentrations close to the ground), the overall effect is that the NO_2 signal observed by the satellite is dominated by the NO_2 close to the surface.

2.6.2.3. Assessment of the impact of the surface reflectance on the retrieval of cloud parameters

In the last part of the indirect assessment of ADAM we investigated the influence of the spectral surface reflectance on cloud parameters, such as cloud optical thickness (cloud albedo) and cloud top height, retrieved with the Semi-Analytical CloUd Retrieval Algorithm (SACURA). In the framework of a sensitivity study, five distinct ground scenes are selected, which are believed to be representative for typical surface reflectivities, seasons, geo-locations, and geometries. Then, we computed two different sets of synthetic top-of-atmosphere (TOA) reflectances, at SCIAMACHY nominal spectral specifications in the range from 758 to 772 nm (oxygen A-band), based on the ADAM BRDF and GOME LER surface datasets, respectively. For each generated dataset three cloud layers, with a cloud-top height of 2 km (low-level cloud), 4 km (mid-level), and 9 km (high-level) for three different optical thicknesses (10, 20, and 50) were chosen for this study. Overall 60 different spectra were calculated. We can conclude that the accuracy of retrieval of cloud parameters over water and vegetation does not appreciably change, if a BRDF-surface base model is substituted by a LER based surface. For other scenes (mixed, desert, and snow) LER and BDRF display differences for thin and low-level clouds. In particular, while COT relative errors reveal a substantial stability, CTH retrieved values are more affected. Light reflected by the surface undergoes multiple scattering throughout the cloud and oxygen absorption is enhanced inside the cloud itself. While this holds for all clouds over almost dark and moderately bright ground pixels, this is not true for bright pixels and low-level thin clouds. In this situation clouds do not screen the surface anymore and the LER assumption is not appropriate. In the context of global operational perspective and statistics, we conclude that the introduction of an angle-dependent surface model should not significantly impact the derived cloud products since water and vegetation surfaces are abundant and the absolute global mean cloud optical thickness is about 20 for cloud top heights between 3 km and 6 km. Nevertheless, a BRDF database like ADAM is definitely advantageous for studying specific scenes (e. g., snow, ice, and arid regions) on a pixel basis considering measurements obtained from different satellite platforms. Lastly, it is important to mention that any required accuracy in cloud remote sensing relies on the approach deployed in the algorithm and on the spectral sensitivity of the instrument. Different spectral coverage and spectral/spatial resolutions enable the capture of different cloud property ranges, which might mask the benefit of the BDRF usage.

2.7. Task 7: Identification of NRT information needs and the potential of an operational delivery service of surface properties

Existing trace gas retrievals use low resolution (1º x 1º) Lambertian Equivalent Reflectances (LER) derived from old (pre-2000) EO data. Few studies have examined the impact of using higher spatial resolution and spectral BRDF information instead of LER. Even if additional work is necessary for demonstration and quantification, the implication is clear that higher spatial resolution and spectral BRDF wrt LER produces improve retrievals.

The sensitivity of the retrieval of atmospheric parameters with respect to rapid changes in the surface reflectance (for instance, snow, vegetation, ocean colour) has been assessed, in order to derive needs for operational NRT service delivering surface reflectance information.

The ADAM database has been used to assess what typical variations exist for spectral reflectance for areas with different land cover. Preliminary analysis of monthly time series of Spectral Normalised Reflectances

(SNR) on specific area over Siberia clearly demonstrate the large variations in SNR for Blue (between 0.02 and 0.8) and NIR (between 0.1 and 0.8) and smaller ones for SWIR (between 0.15 and 0.6) due to the spectral NR behaviour of snow.

In general, whenever the actual surface condition differs significantly from its representation by a climatological database, we have to expect large difference in trace gas and aerosol retrieval products. For instance, the change of land (e. g., deforestation and desertification) and sudden snowfall not covered in a climatological data set will lead to large errors in the retrieval results. It should be noted that most studies do not address the impact of natural changes in spectral reflectance on trace gas retrievals, except in so far as the differences for snow-free surface between summer and winter months. In that case, for summer months changes appear to be minimal in terms of their impact when comparing different sources of BRDF or spectral LERs. For winter months impacts are dramatically different between different datasets. It is therefore expected that once the relevant changes in spectral reflectances over snow/ice surfaces can be taken into account, these large changes will produce dramatic changes in retrievals.

This example suggests that a climatology derived from 10 or more years of MODIS data may not be sufficient to improve trace gas retrievals enough in snow-covered regions. However, it has also been clearly demonstrated that monthly mean directional reflectance information largely improve retrievals w.r.t. currently used LER climatologies. The investigation into the possibility for NRT surface reflectance products would require a specific study.

The monthly time series results from ADAM suggest that there is a need for NRT surface reflectance knowledge, which operates on time-scales of less than a month. Snow cover can change dramatically over very short time periods of less than a day. However, given that only polar orbiting satellites (MODIS, MERIS, Sentinel 3 in the near future) have sufficient spectral and latitudinal coverage at present (e.g., SEVIRI on MSG is not much use as the Geostationary coverage is not sufficient to cover most regions with ephemeral snow), this suggests that a few days' updates would be sufficient to meet the needs of the impact of snowfalls. Also, as there is cloud cover during snowfall it may take several days for clouds to clear to reveal the underlying surface. **Given the distribution of locations of high amounts of NO_2 (and other trace gases associated with greenhouse gas precursors), an operational service to create daily updates should have beneficial effects.**

It shall be mentioned that (even if most studies reported to date do not cover this particular aspect) pioneering studies on the sensitivity of trace gas retrievals to spectral reflectance accuracy requirements indicates, for the case of NO_2 retrieval at resolutions of 8 x 8km, very high accuracy requirements on DHR (black sky albedo) for NRT applications, at 0.017 (total column NO_2 and and 0.005 for tropospheric columns). This will be very difficult to achieve unless using much higher resolution measurements (<<1km) and are available requiring the use of aggregation to achieve this accuracy.

3. Conclusions and recommendations

The ADAM consortium has achieved the objective of the project to generate a narrow-band Earth surface reflectance database over the spectral domain ranging from 300 nm to 4000 nm which can be computed for any observation geometry. In order to make the ADAM products manageable for users, the consortium has chosen solutions to reduce the volume of data that can be downloaded:

- The ADAM products is provided as a monthly climatology corresponding to a typical year, and at 0.1°x0.1° (11 x 11 km at the equator, ≈11x8 km at mid-latitude);
- Rather that providing the surface reflectances for all the combinations of spectro-directional configurations that could be accounted for, the ADAM products is made of a restricted number of gridded inputs which, when used with a specifically designed calculation package, allow the derivation of the Earth surface directional reflectance (with a discrimination of vegetation/soil, snow, and ocean, surfaces) at 1 nm spectral resolution over 300-4000nm, and for any observation geometry.

Thus, the main input ADAM products consist of monthly climatologies of:

- Climatological (monthly) chlorophyll concentration over ocean surfaces;
- Climatological (monthly) wind speed over ocean surfaces;
- Normalised reflectances (i.e. Provided in a standard observation geometry) in seven MODIS wavebands over land surfaces (as well as the associated variance-covariance matrix between spectral bands).
- Statistical models for the spectral interpolation/extrapolation from the seven MODIS channels
- Empirical models for the extrapolation from the normalized observation geometry to the user geometry

The companion ADAM calculation package embeds the procedures in order to perform the computation of the surface reflectance in the standard observation geometry (for all surface types), and further the spectro-directional extrapolation into the user requested configuration of observation. Moreover, the ADAM tools also provide the uncertainty associated both to the reflectance spectrum and to the BRDF, for land surfaces.

The datasets that are the most appropriate for the design of the ADAM input products were firstly determined. Over ocean surfaces, climatologies of wind speed (from QuickScat observations) and chlorophyll content (from SeaWiFs observations) have been derived from existing datasets through averaging and gap filling. For the land reflectance products, the FondsDeSol (FDS) processing chain for MODIS observations was strongly improved in the frame of the project. The main improvements concern 1) the use of a land cover classification (required for the BRDF correction) at the same spatial resolution as the MODIS observations (500 m) and 2) the use of three years of data in addition to the target year (2005) in order to provide more realistic land surface reflectance over very cloudy regions.

The ADAM FDS normalised reflectances have been compared with those from the GlobAlbedo (GA) dataset, which was derived from similar MODIS observations, but using additional years of observation, and through a different processing chain. The results show very good agreement between the two products with respect to the surface reflectance values for deserts and most vegetation areas. Over persistent snow covered regions, the FDS reflectance values were generally higher than GA, and ADAM-FDS shows near constant values. This is most likely due to its higher reliance on a model than GA which only uses measurements. On the other hand, the GA products present remaining aerosol/cloud contaminations (mainly visible over the tropics) which are not apparent in FDS. The other differences are attributed to the snow cover dynamics in mid-latitude regions, which is not captured the same way in the two datasets. In addition, there are large differences between the uncertainties reported by ADAM FDS and GA (the latter are much larger), which reflect the different nature and source of the uncertainties: ADAM FDS uncertainty is computed from the spatial variability of the measured reflectances, while ADAM GA uncertainty includes spatial variability, statistics on time variability, and uncertainties associated with cloud or aerosol contamination. ADAM FDS and ADAM GA products have also been compared with MISR and MAIAC independent datasets to provide a consolidated validation. FDS and GA normalised reflectances are very similar except over bright regions where GA is lower (>0.4) and very dark regions, such as tropical forests where FDS is lower. The larger GA uncertainties reflect the poorer BRDF retrievals over areas with persistent cloud cover and/or aerosols from forests fires or the lack of samples due to restrictions in illumination angles at high latitudes. BRF values computed from FDS and GA show similar behaviour when compared against equivalent MISR and MAIAC. GA show closer correlation with MISR than FDS does for a site in the Amazon, Tapajos which is a FLUXNET and AERONET site, while the agreement with MAIAC data is better with FDS than with GA. The Ocean BRDF values have, however, not been validated in this activity.

Indirect validation studies of the ADAM products have been carried out by assessing the impact of the use of ADAM BRDF products as compared to GOMI-LER data on NO_2 retrieval, and demonstrated significant improvements of atmospheric composition retrieval when using ADAM. The findings indicate that the NO_2 retrieval can be strongly affected by the assumption on the surface reflectance as suggested by the large differences in regions where the Lambertian assumption differs significantly from the BRDF model. The preliminary analysis conducted on the data available from the DANDELIONS campaign shows better agreement of the SCIAMACHY retrievals with the ground-based validation measurements when based on the ADAM products than when using the GOME LER data. In addition, a sensitivity study has been carried out in order to evaluate the impact of the surface reflectance on the retrieval of cloud parameters (optical thickness and top height). In the context of global operational perspective and statistics, we conclude that the introduction of angle-dependent surface model should not significantly impact the derived cloud products since water and vegetation surfaces are abundant and the absolute global mean cloud optical thickness is about 20 for cloud top heights between 3 km and 6 km. Nevertheless, a BRDF database like ADAM is definitely advantageous for studying specific scenes (e. g., snow, ice, and arid regions) on a pixel basis considering measurements obtained from different satellite platforms.

ADAM is thus a centralized and validated narrow-band database of land and ocean surface reflectance climatologies providing realistic reflectance values and spatio-temporal behaviour of the Earth surface reflectance on a global scale (0.1x0.1 deg² spatial resolution), which aims at supporting the preparation and exploitation of ESA's optical Earth Observation missions. It will, furthermore, be a valuable contribution to the science community that presently mainly uses albedo information in atmospheric radiative transfer calculations and retrievals of atmospheric parameters. Finally, it constitutes a unique dataset for further improvements in the perspective of NRT operational needs and applications.

The ADAM consortium believes that the following issues are crucial for further improvements and consolidation of ADAM

Improvements of the dataset:

Extensive work has been performed on the land component of the ADAM dataset, in particular working with two different datasets (GA and FDS). Based on these analyses, the ADAM consortium recommends a consolidation of the understanding and characterization of uncertainties associated with the land surface reflectance in each spectral band.

The original approach proposed for the spectral interpolation and extrapolation from the 7 MODIS narrowband measurements is well suited for the visible and mid-IR spectral range (0.4 to 2.3 µm). There is however additional uncertainty for the UV (λ<0.4 µm) and the shortwave infrared (λ >2.3 µm) domains. The MODIS channels do not provide sufficient information to properly constrain the reflectance in those spectral bands, and ADAM recommends to consolidate this issue. For the UV, one way might be to process OMI and integrate the processed reflectances together with the MODIS narrow band reflectances.

Over the ocean, the main limitation is the use of a climatological value for the wind speed. This limitation impacts the direction that is affected by the sunglint with limited additional uncertainty linked to the wave slope distribution. For other directions, a lambertian reflectance has been assumed because there is very limited information on the directional signature of the reflectance generated by the water column and the surface foam. Further work might be needed for a proper evaluation of the BRDF effects over the oceans, but this will impact only the shorter wavelengths. .

It is also recommended to improve ADAM to correctly account for the presence of sea-ice, either temporary or permanent, and possibly not fully covering.

<u>Improvements of ADAM evaluation and demonstration:</u>

Indirect validation results obtained so far suggest some interest of ADAM BRDF, but consolidation is needed to reach a consistent evaluation of the added value for retrieval, both for current and future missions.

- Current missions (e.g., SCIA, GOME, OMI): not easy as large experience, methods and datasets already exist. It is necessary to consolidate users interest, and to show consistency and demonstrate (at least slight) improvement using ADAM BRDF wrt currently used databases.
- Future missions (e.g., CarbonSat, S5-P, S5, S3 (trace gases, aerosols, clouds)) : higher spatial resolution and spectral sampling favour the use of ADAM. It is necessary to show significant improvement and needs for future missions.

More generally, a consolidation of the evaluation of the ADAM database through publications is necessary.

<u>Accessibility and promotion to the users:</u>

The ADAM web site and interface has been designed with a representative team of scientific users, and integrates most of the requested functionalities and facilities, as well as possibilities to improve or adapt the functionalities to specific needs through API tool kit.

From this basis, the main effort to be done is to support a large number of users as well as expand the area that each user can process, and take their feedback on the interface, functionalities, in order to propose necessary improvements. These efforts should be supported by the best possible dissemination and promotion by ESA and the consortium partners.

It is also strongly recommended to put additional effort for the increase the processing speed, and to consolidate more flexible and user-friendly processing tools (e.g., API could evolve into a library, with appropriate documentation and examples of main programs for their use) to enable an easy use of ADAM by the scientific community.

UCL would like to establish a facility at CEMS/ESA Harwell for the exploitation of MODIS spectral BRDF prior at 500m every 8 days over 14 years and would like to be able to work with Noveltis on the use of the Python tools to enable this to take place.

<u>Improvement for NRT applications:</u>

The monthly time series derived from ADAM indicate that there are surface reflectance variations on time-scales of less than a month which suggest the development of an improved version with a temporal period from one day to one week rather than one month. Given the distribution of locations of high amounts of trace gases associated with greenhouse gas precursors, an operational service to create daily updates should have beneficial effects for the monitoring of such products from space. However NRT requirement on spectral reflectance accuracy appears very demanding. Consolidation of the strategy to go from ADAM to NRT application should be addressed. One way of addressing this is through the use of optimal estimation where the underlying concept is that tomorrow is very likely to be similar to today.

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