IMPROVING THE RETRIEVAL OF DOWNWELLING SURFACE SHORTWAVE FLUXES USING DATA FROM GEOSTATIONARY SATELLITES

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Doutoramento em Ciências Geofísicas e da GeoInformação (Detecção Remota) 2012
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Tese orientada pelo Professor Doutor Carlos da Camara

2012
Acknowledgements

First of all, thank you to Carlos da Camara, a.k.a. CC. Only he knows how to put things in perspective and guided through this difficult time.

A most special thanks to Teresa and Celia, the wonderful good friends I needed to take me to the "end of this tunnel".

I would like to thank my french supervisor, Jean-Louis Roujean and all my colleagues at Météo-France for giving me a daily support, especially Bernhard Geiger for the needed advices at the right time.

I would also like to thank all the colleagues from the LSA SAF project for all the fruitful discussions.

A special thanks to all my colleagues in the Physics Department, especially Ricardo Trigo and Pedro Soares.

I would also like to thank my very special friends Tanoska and Maggy for their moral support helping to get through the end of this work.

Last but not least, a very special thanks to my Portuguese and my Dutch families.

The Portuguese Foundation of Science and Technology (FCT) supported this research under the PRAXIS programme (Grant PRAXIS SFRH/BD/2769/2000).
Abstract

Shortwave radiation is a key quantity to estimate the surface radiation budget which has a close relationship with the climate of a given region. Shortwave radiation is affected by aerosols and clouds. Aerosols modify the Earth’s radiation budget and boundary layer meteorology by reflecting sunlight to space and absorbing radiation in the atmosphere. Clouds modulate the vertical and horizontal distributions of solar radiative heating, latent heat, and cooling by thermal radiation that drive the atmospheric circulation. The main objective of this thesis is to analyze in detail the methodology presently used to derive the Downwelling Surface Shortwave Flux (DSSF) based on information from geostationary satellites. The study is closely related to operational activities developed within the framework of the Satellite Application Facility on Land Surface Analysis (LSA SAF).

An already existing operational DSSF algorithm, developed within the framework of the Ocean and Sea Ice (O&SI) SAF, is tested and improved for clear and cloudy sky conditions. In the case of clear sky, the parameterisation for atmospheric absorption accounts for the variation of the concentration of the atmospheric components. In the case of cloudy sky, radiation interactions are more complex and, besides the interaction with the atmosphere, the parameterisation scheme accounts for cloud albedo and relies on a predefined value characterizing the absorption by clouds. Both methodologies are analyzed and two parameterizations are proposed; for cloudy sky pixels the new parameterisation takes cloud types into account whereas, in the clear sky case, diffuse radiation is explicitly included in the DSSF model, based on information about aerosol optical thickness. Model performance is significantly improved and for both methodologies an approach to their integration in an operational environment is proposed.

Keywords: shortwave flux, cloud parameterisation, aerosol parameterisation, meteosat-8,
surface radiation budget
Resumo

A elaboração de cenários do clima futuro pressupõe um conhecimento sólido do estado do clima, quer do passado, quer do presente. O Sol é a fonte primária de energia do sistema climático, estando na origem das circulações oceânica e atmosférica que modulam as interacções entre a atmosfera e a hidrosfera, bem como entre estas e as restantes componentes do Sistema Climático, nomeadamente a criosfera, a litosfera e a biosfera. Os ciclos hidrológico e do carbono constituem exemplos de tais interacções e o seu conhecimento afigura-se crucial para que se possam antecipar possíveis comportamentos do clima no futuro.

No contexto acima descrito, o conhecimento do balanço radiativo à superfície do solo é fundamental em inúmeras aplicações, tais como na previsão numérica do estado do tempo e na gestão de recursos naturais. Em particular, revela-se essencial possuir um conhecimento aprofundado das interacções da energia solar com a atmosfera e com a superfície do solo a fim de que se possa dar resposta a um leque vasto de questões relacionadas com a evolução do clima actual. Assim é, por exemplo, que o facto de a absorção de pequeno comprimento de onda ter vindo a ser subestimada, seja em condições de céu limpo, seja de céu nublado, tem implicações profundas para o balanço energético nos modelos de circulação global. Nesta conformidade, uma maior precisão na estimativa da radiação de pequeno comprimento de onda deverá ter repercussões positivas na caracterização do clima e na elaboração de cénarios do clima futuro.

Do ponto de vista da gestão de recursos naturais, a interacção da radiação solar com
os constituintes atmosféricos tem vindo a ser objecto de numerosos debates, devendo mencionar-se, pela sua importância, os processos relativos aos gases com efeito de estufa (e.g. dióxido de carbono e metano) devido ao seu papel no aquecimento global. Com efeito, os gases com efeito de estufa (sejam naturais, sejam de origem antropogénica) não se opõem à passagem da radiação solar através da atmosfera, mas absorvem e difundem a radiação infravermelha de que resulta um aquecimento da superfície terrestre. Por outro lado, há ainda que ter em conta o facto de as nuvens afectarem profundamente o clima da Terra na medida em que modulam as distribuições horizontais e verticais do aquecimento solar, do calor latente e do arrefecimento térmico que determinam a circulação atmosférica.

A fim de quantificar a radiação solar que atinge a superfície do Globo torna-se necessário desenvolver modelos capazes de simular, de forma adequada, as interações sofridas pela radiação de pequeno comprimento de onda no seu percurso através da atmosfera até chegar à superfície. Com efeito, assim que a radiação interage com um dado meio (e.g. o topo da atmosfera) têm lugar processos de absorção e de difusão, os quais se traduzem numa atenuação da radiação (directa) que pode, no entanto, ser parcialmente compensada caso ocorram processos de difusão múltipla. De referir, ainda, que as nuvens difundem fortemente a radiação e, devido ao número elevado de acidentes de difusão que têm lugar, podem absorver ou reflectir uma fracção significativa da energia.

Permitindo uma observação das nuvens, da atmosfera e das propriedades da superfície com resoluções espaciais e temporais suficientemente finas, a informação fornecida por satélites geostacionários torna especialmente atractiva a aproximação ao problema do balanço radiativo através da modelação. Com efeito, a formulação de modelos adequados
para determinar o balanço global de energia que atinge a superfície do Globo é facilitada pela disponibilidade de dados apropriados provenientes de satélite, desde que complementados por informação proveniente de uma rede suficientemente densa de observações in situ para validar os modelos. Nas últimas décadas, diversos programas meteorológicos têm vindo a dedicar-se à estimação da irradiação solar e da radiação que deixa a superfície, sendo de citar o programa ERBE (Earth Radiation Budget Experiment). Os projectos CERES (Clouds and the Earth’s Radiant Energy System) e ScaRaB (Scanner for Radiation Budget), que são a continuação do ERBE, têm vindo a disponibilizar fluxos radiativos no topo da atmosfera, tendo o programa mais recente do CERES sido lançado em 2011. Destinado a fazer medições do balanço radiativo, o GERB é o instrumento a bordo do MSG (Meteosat Second Generation) que é actualmente operado pela EUMETSAT, a agência europeia para a exploração de satélites meteorológicos. A este programa seguir-se-á o MTG (Meteosat Third Generation), presentemente operado pela EUMETSAT.

Os satélites da série MSG vêm equipados com o radiómetro SEVIRI (Spinning Enhanced Visible and Infrared Imager), um sensor passivo que fornece imagens cobrindo um disco quase hemisférico, contendo informação radiativa acerca de uma diversidade de meios, tais como nuvens, aerossóis, vapor de água, solo, oceano e vegetação, com uma resolução espacial de 3 km no ponto sub-satellite e uma resolução temporal de 15 minutos. Os canais espectrais do radiómetro SEVIRI são o HRV (High Resolution Visible), três canais no visível e no infravermelho próximo, sete canais no infravermelho e dois canais na janela do vapor de água. A importância da elevada resolução temporal no estudo das nuvens merece ser sublinhada dada a sua grande variabilidade no tempo (e.g., os cúmulos podem
O objectivo principal da presente tese é o de contribuir para um conhecimento mais aperfeiçoado dos problemas relacionados com a interação da radiação de pequeno comprimento de onda com a atmosfera e as nuvens, as quais constituem os principais moduladores do balanço radiativo à superfície do solo. Nomeadamente, pretende-se com a investigação desenvolvida analisar o impacto das nuvens e dos aerossóis no fluxo radiativo descende de pequeno comprimento de onda à superfície do solo (DSSF, Downwelling Surface Shortwave Flux). Merece salientar que o trabalho aqui desenvolvido se relaciona estreitamente com as actividades operacionais do projecto LSA SAF (Land Surface Analysis Satellite Applications Facility) que integra o segmento de solo da EUMETSAT e cujo programa inclui aplicações com vista à determinação do albedo e da temperatura da superfície do solo, dos fluxos radiativos descendentes de pequeno e de grande comprimento de onda à superfície do solo, entre outros parâmetros biofísicos e biosféricos.

A tese está organizada em cinco capítulos. Seguindo-se a um capítulo de Introdução, de considerações gerais, o Capítulo 2 que contém uma descrição detalhada do algoritmo utilizado na determinação do DSSF, o qual assenta no denominado algoritmo SSI (Shortwave Surface Irradiance), um algoritmo operacional para a determinação do DSSF, originalmente desenvolvido no âmbito do projecto Ocean and Sea Ice Satellite Application Facility (O&SI SAF), que igualmente integra o Segmento de Solo da EUMETSAT.

As parameterizações para céu limpo e céu nublado são derivadas e, em seguida, aplicadas
aos dados de satélite do GOES-8, GOES-12 e Meteosat-7. Os valores modelados de DSSF são verificados através de uma comparação com dados obtidos em estações radiométricas localizadas nos Estados Unidos e na Europa, dando-se particular atenção à relação entre os valores modelados de DSSF para os casos de céu nublado e a sua relação com os tipos de nuvem.

Verifica-se que o modelo de DSSF apresenta pior performance quando aplicado a píxeis contaminados por nuvens, observando-se ainda que a exactidão dos resultados, quando se recorre a dados dos satélites GOES-8, GOES-12 e Meteosat-7, é comparável àquela que se obtém com informação proveniente do Meteosat-8 (que integra a série MSG). Os resultados mostram, assim, claramente que o principal problema na determinação do DSSF se relaciona com a presença de nuvens, devendo-se este facto à simplicidade da parametrização utilizada, que apenas toma em consideração o albedo do topo das nuvens, sendo desprezadas as características microfísicas e macrofísicas das nuvens. Procede-se então a uma análise do problema da absorção de radiação pelas nuvens, concluindo-se que o factor de transmissão das nuvens está relacionado com a tipologia das mesmas.

A avaliação da performance do algoritmo de DSSF aos dados do MSG é efectuada no Capítulo 3. A verificação é estabelecida utilizando-se dados das estações radiométricas de Roissy e Carpentras, ambas localizadas em França. Um ênfase especial é dado à verificação do algoritmo em relação à quantidade e ao tipo de nuvens. A parameterização para o céu limpo é também analisada em detalhe dadas as limitações do modelo de DSSF no que respeita ao efeito dos aerosóis utilizando-se, como case study, a estação de Roissy, que é afectada por aerosóis urbanos.
Os resultados da validação levam então ao desenvolvimento de duas formulações com o objectivo de melhorar a qualidade do modelo de DSSF quando aplicado, respectivamente, a píxeis de céu limpo e contaminados por nuvens. Estas duas formulações são apresentadas no Capítulo 4. No caso de píxeis contaminados por nuvens, recorrendo a modelos lineares com base física, relacionou-se, para os diferentes tipos de nuvens, o factor de transmissão das nuvens com o respectivo albedo do topo das nuvens. Os coeficientes dos modelos lineares, para os diferentes tipos de nuvens, são obtidos por regressão utilizando informação derivada de satélite para estimar o albedo do topo das nuvens e observações in situ para obter o factor de transmissão das nuvens. Os resultados revelam uma melhoria significativa no caso da presença de nuvens médias e opacas altas. A aplicação operacional do método desenvolvido requer, no entanto, a análise de um número elevado de cenas a fim de se elaborar um conjunto apropriado de tabelas de consulta (look-up tables) de coeficientes, sendo ainda de referir a limitação de, no esquema desenvolvido, se considerar apenas uma única camada de nuvens. Esta limitação poderá, no entanto, vir a ser ultrapassada através da incorporação de diversas camadas no modelo mediante uma combinação adequada de informação proveniente de lidar e de radar, na medida em que os dois instrumentos, quando utilizados em sinergia, permitem identificar nuvens finas e nuvens espessas.

No caso de píxeis de céu limpo, e uma vez que o papel desempenhado pela radiação difusa não se encontra explicitamente incluído no modelo de DSSF, procedeu-se ao desenvolvimento de uma metodologia em que, no cálculo da fração de radiação difusa, se considera a contribuição directa desta radiação. Para tal, derivou-se um parâmetro difuso
associado, o qual se mostra estar relacionado com a espessura óptica dos aerossóis a 550 nm, relação esta obtida a partir de observações in situ e validada a partir de simulações efectuadas por meio de um modelo de transferência radiativa. Os resultados revelam uma melhoria significativa na qualidade do modelo de DSSF, sendo de esperar que se possam generalizar a outras regiões e a outros tipos de aerossóis. No entanto, dada a variabilidade dos aerossóis, quer no que respeita a regiões fonte, quer à sua tipologia, uma aplicação operacional da metodologia proposta requer um conhecimento apropriado da distribuição global dos aerossóis, bem como das suas propriedades. Nesta conformidade, é de esperar que as técnicas de detecção remota baseadas em informação lidar de alta resolução espectral virão a proporcionar a informação necessária.

_Palavras-chave_: fluxo de pequeno comprimento de onda, parametrização de nuvens, parametrização de aerossóis, meteosat-8, balanço radiativo à superfície
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Nomenclature

\( a, b, a' \) and \( b' \): coefficients depending on the aerosol type
\( b_{\text{diffuse}} \): diffuse parameter
\( b_{65S} \): diffuse parameter derived from 6S model
\( f_{\text{aniso}} \): anisotropic factor
\( f_{\text{diffuse}} \): fraction of diffuse radiation
\( j \): day of the year
\( st \): scene type
\( t \): transmission function for a given absorbing gas
\( v \): corrective term accounting for the Earth-Sun seasonal variation
\( y_m \): cloud absorption factor

\( A_s \): surface broadband albedo
\( A_c \): cloud albedo
\( A_{cabs} \): cloud absorption
\( A_{\text{TOA}} \): TOA broadband albedo
\( A_{\text{atm}} \): atmospheric albedo
\( A_{\text{ray}} \): Rayleigh albedo
\( A_{\text{min}} \): minimum albedo
\( A_{\text{max}} \): maximum albedo
\( C, C_2, G \) and \( K \): regression coefficients
\( E_0 \): solar constant
\( F_{\downarrow \text{SW, clr}} \): downward shortwave radiation for a clear scene
\( F_{\downarrow \text{SW, cld}} \): downward shortwave radiation for a cloudy scene
\( F_{\downarrow \text{sw, global}} \): total downwelling surface shortwave radiation
\( F_{\downarrow \text{sw, direct}} \): direct downwelling surface shortwave radiation
\( F_{\parallel \text{sw, direct}} \): direct downwelling surface shortwave radiation from ground-based measurements at the surface, measured following the position of the sun
\( F_{\downarrow \text{sw, diffuse atm}} \): diffuse downwelling surface shortwave radiation from the atmosphere
\( F_{\downarrow \text{sw, diffuse atm+surf}} \): diffuse downwelling surface shortwave radiation from the surface and the atmosphere
\( F_{sw, \text{ diffuse}} \): global diffuse downwelling surface shortwave radiation
\( F_{\text{mult.scat.surf.atm diffuse}} \): diffuse downwelling surface shortwave radiation from the scattering between the surface and the atmosphere

\( K \) and \( G \): regression coefficients
\( M \) and \( B \): regression coefficients (Pinker and Laszlo model)

\( R_{bb} \): broadband reflectance
\( R_{erbe} \): bidirectional reflectance computed from tabulation of Suttles [4].
\( R_{\text{model}} \): modelled bidirectional reflectance factor
\( R_{\text{nrb}} \): narrowband reflectance
\( R_{\text{ray}} \): bidirectional reflectance factor due to Rayleigh scattering

\( T_{\text{in}}^a \): clear sky transmittance
\( T_{\text{out}}^1 \): upwelling atmospheric transmission above the cloud
\( T_{\text{in}}^1 \): downwelling atmospheric transmission above the cloud
\( T_{\text{out}}^2 \): upwelling atmospheric transmission below the cloud
\( T_{\text{in}}^2 \): downwelling atmospheric transmission above the cloud

\( T_{ac} \): transmittance above the cloud
\( T_{at} \): total clear sky atmospheric transmittance

\( T_d \): diffusion by the atmosphere
\( T_c \): cloud transmittance

\( T_{cl} \): cloud transmittance encompassing all cloud effects
\( T_{bc} \): transmittance below cloud to account for multiple scattering
\( T_{\text{2top}} \): sun-cloud-satellite atmospheric transmittance
\( T_s \): sun-surface-satellite transmittance

\( U_{\text{h2o}} \): vertically integrated water vapour content
\( U_{o3} \): vertical ozone amount
\( V \): horizontal visibility

\( \alpha' \) and \( \alpha'_1 \): regression coefficients
\( \alpha \) and \( \beta \): regression coefficients
\( \gamma \): scattering angle
\( \lambda \): wavelength
\( \nu_o \): sine of \( \theta_o \)
NOMENCLATURE

\( \nu_o \): sine of \( \theta_o \)

\( \mu \): cosine of \( \theta \)

\( \mu_o \): cosine of \( \theta_o \)

\( \phi \): relative azimuth

\( \omega \): weighting factor (related to Rayleigh scattering)

\( \tau_{550} \): aerosol optical depth at 550 nm

\( \tau_{6S} \): aerosol optical depth at 550 nm used in the 6S model

\( \theta_o \): solar zenith angle

\( \theta \): view zenith angle

\( \Psi \): azimuthal mean reflectance
Acronyms

6S (Simulation of a Satellite Signal in the Solar Spectrum)
AERONET (Aerosol Robotic Network)
AOT (Aerosol Optical Thickness)
ARPEGE (Research Project on Small and Large Scale)
ARM (Atmospheric underline Radiation Measurement)
ASD (Aerosol Size Distribution)
AVHRR (Advanced Very High Resolution Radiometer)
BOMEX (Barbados Oceanographic and Meteorological Experiment)
BRDF (Bidirectional Reflectance Distribution Function)
BSRN (Baseline Surface Radiation Network)
CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations)
CERES (Clouds and the Earth’s Radiant Energy System)
CMS (Centre de Météorologie Spatiale)
CWV (Concentration Water Vapour)
DSSF (Downwelling Surface Shortwave Flux)
EarthCARE (ESA’s Cloud, Aerosol and Radiation Mission)
ECMWF (European Centre for Medium-Range Weather Forecasts)
ERBE (Earth Radiation Budget Experiment)
ESA (European Space Agency)
EUMETSAT (European Meteorological Satellite Organisation)
GCM (Global Circulation Model)
GERB (Geostationary Earth Radiation Budget)
GOES (Geostationary Operational Environmental Satellite)
HRV (High Resolution Visible)
IPA (Independent Pixel Approximation)
IRI (Imaginary part of the aerosol refractive index)
LSA SAF (Land Surface Applications SAF)
MDB (MatchUp Data Base)
METEOSAT (Meteorological Satellite)
MODIS (Moderate Resolution Imaging Spectrometer)
ACRONYMS

MSG (Meteosat Second Generation)
MTG (Meteosat Third Generation)
NWC SAF (Nowcasting and Very Short-Range Forecasting SAF)
NWP (Numerical Weather Prediction)
OCC (Ozone Concentration)
O&SI SAF (Ocean & Sea Ice SAF) SAF (Satellite Applications Facility)
SAL (Surface Albedo)
ScaRaB (Scanner for Radiation Budget)
SEVIRI (Spinning Enhanced Visible and Infrared Instrument)
SSI (Surface Shortwave Irradiance)
SURFAD (Surface Radiation) TOA (Top Of Atmosphere)
TOMS (Total Ozone Mapping Spectrometer)
WRCP (World Climate Research Programme)
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Chapter 1

Introduction

The understanding of the Earth’s climate, past and present, is fundamental for building up reliable scenarios of the climate in the future. The solar energy coming from the Sun and the rotation of the Earth are at the basis of the oceanic and atmospheric circulations that modulate the interactions between the atmosphere and the hydrosphere as well as among the other components of the climate system, namely the cryosphere, the lithosphere and the biosphere. Examples of such interactions include the global hydrological and carbon cycles whose understanding is crucial to anticipate the possible behaviour of future climate.

In the above-described context, a better understanding of the interactions of the solar energy with the atmosphere and the surface of the Earth has revealed to be extremely important to answer a large number of questions related with the evolution of present climate. For instance, the fact that the shortwave absorption, either in clear or cloudy sky conditions, has been underestimated [5] has important implications in the overall
energy budget in Global Circulation Models (GCMs). An improved accuracy in the estimation of shortwave radiation is therefore expected to have a positive impact in the characterisation of the current climate and in the prediction of climatic changes.

The shortwave radiation is one of the key quantities that are required to estimate the surface radiation budget which has a close relationship with the climate of a given region [6]. A deep knowledge of the Earth radiation budget is therefore of fundamental importance in a number of applications in a wide range of domains that include meteorology, climatology, and more general environmental studies [7]. From the point of view of management policies, climatic change has been the object of several debates [8]. In particular, in the last few decades the topic of greenhouses gases (e.g. carbon dioxide, methane, nitrous oxide) has originated great concern because of their role in the gradual rise of the Earth’s temperature. Greenhouse gases (either natural or anthropogenic) do not hinder the sunlight to enter the atmosphere, but they absorb and scatter infrared radiation warming up the surface. Furthermore aerosols can significantly modify the Earth’s radiation budget and boundary layer meteorology by reflecting sunlight to space and absorbing radiation in the atmosphere [9]. Clouds, on the other hand, affect the Earth’s climate by modulating the vertical and horizontal distributions of solar radiative heating, latent heat, and cooling by thermal radiation that drive the atmospheric circulation [10]. For instance, according to [11], the earth radiation budget depends strongly on the areal coverage of thin cirrus clouds relative to that of thick cirrus clouds.

In order to quantify the solar radiation reaching the surface it is necessary to build up models that are able to properly simulate all the interactions suffered by the shortwave
radiation on its path to the ground. In fact, as soon as radiation interacts with a given medium (e.g. the top of the atmosphere) scattering and absorption processes occur. Both processes translate into an attenuation of radiation (direct), and when multiple scattering effects are important, such attenuation may be partially compensated. Interaction of shortwave radiation with clouds involves understanding the path of solar energy - in the visible and in the near infrared - above and below the same clouds [12]. Clouds scatter radiation strongly (forward) and, because of the high number of scattering events, they may also absorb a significant fraction of the energy. It is therefore not an easy task to study the interaction between solar radiation and the atmospheric system composed of clouds and aerosols.

The improved accuracy of global observations of clouds, atmosphere, and surface properties from satellites makes the modelling approach very attractive [13]. In this respect, the problem of developing adequate models to determine the global energy budget that reaches the surface of the Earth is facilitated by the availability of appropriate satellite data together with an adequate network of ground-based measurements for model evaluation and validation. The satellite-based methods ordinarily relate the outgoing solar radiance at the satellite to the radiative properties of the system and to the surface solar irradiance [14]. In the last decades, several meteorological programs have been devoted to the evaluation of solar irradiance and outgoing radiance. For instance, the global distribution of individual and combined radiative forcing at the top of the atmosphere has been studied extensively during ERBE (Earth Radiation Budget Experiment) [15]. The CERES (Clouds and the Earth’s Radiant Energy System) and the ScaRaB (Scanner for Radiation Budget) projects, which are a continuation of ERBE, keep on providing Top-
Of-Atmosphere (TOA) radiative fluxes [16] with the most recent satellite of the CERES program launched in 2011. Designed to make accurate measurements of the Earth radiation budget, GERB (Geostationary Earth Radiation Budget) is an instrument onboard MSG (Meteosat Second Generation) geostationary satellites that are currently operated by EUMETSAT, the European agency for the exploitation of meteorological satellites. This program will be followed by MTG (Meteosat Third Generation)[17]. Satellites of the MSG series are equipped with the Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer, a passive sensor that provides images covering a quasi-hemispherical disk containing radiative information about a wide variety of media (e.g. cloud, land, ocean, water vapour, vegetation) with a spatial resolution of 3 km at the sub-satellite point and a temporal resolution of 15 minutes [18]. The spectral channels in the SEVIRI instrument include HRV (High Resolution Visible), three channels in the visible and near-infrared, seven channels in the infrared and two channels in the water vapour window. The temporal resolution is of fundamental importance, particularly for the study of the interaction of the shortwave radiation with clouds, given their high variability in time.

The work developed in the present thesis is closely related to the operational activities developed within the framework of the Land Surface Analysis Satellite Application Facility (LSA SAF), whose program includes applications for the determination of the surface albedo, Land Surface Temperature (LST), Downwelling Surface Shortwave Flux (DSSF), Downwelling Surface Longwave Flux (DSLF), among other biophysical and biospheric parameters [19].

The main objective is to contribute to a better understanding of the problems related to
interaction of shortwave radiation with the atmosphere and clouds, the main modulators of the radiation budget over land. In particular, the research performed aims at better understanding the effect of clouds and aerosols on the determination of the amount of solar radiation that reaches the surface using a DSSF algorithm. Developed within the framework of the Ocean and Sea Ice (O&SI) Satellite Application Facility (SAF), the DSSF algorithm was specifically designed to determine the surface shortwave irradiance over water bodies [20], [21]. The methodology is therefore particularly adapted to the spectral, spatial and temporal characteristics of geostationary satellites, namely those of the MSG series. The algorithm comprises two main processing steps; the first step is the determination of DSSF for clear sky conditions and the second step for cloudy sky conditions. Concerning the clear sky case, the main interactions occur by means of reflection, absorption, and transmission by the atmosphere (water vapour, ozone, and aerosols) as well as by means of reflection by the Earth’s surface. For the atmospheric absorption, a parameterisation is used that accounts for the variation of the concentration of the atmospheric components. In the case of cloudy sky, the radiation interactions are more complex and, besides the interaction with the atmosphere, a parameterisation scheme is also necessary to take into account for the cloud albedo and the cloud transmission.

The thesis is organised in five chapters. Following this introduction, Chapter 2 provides a detailed description of the algorithm used in the estimation of DSSF. Parameterisations for clear and cloudy pixels are derived and then applied to satellite data provided by GOES-8, GOES-12 and Meteosat-7. The modelled DSSF values are then verified against several ground-based radiometric sites located in continental Europe and in the United States. Particular attention is given to the relationship between DSSF modelled values
for cloudy pixels and their relation with cloud types.

The application of the DSSF algorithm to MSG data is presented in Chapter 3. Verification is performed using ground-based observations from the radiometric stations of Carpentras and Roissy, both situated in France, in order to assess the performance of the DSSF algorithm with acquired MSG data. A special emphasis is given to the evaluation of the DSSF algorithm in relation with cloud amount and cloud type. The clear sky parameterization is also analysed in detail since, as it will be shown, the DSSF model has inherent limitations in modelling the effect of aerosols with high optical thickness. In this respect, the station of Roissy, which is affected by urban aerosols, is used as a case study to assess the limitations of the model.

Chapter 4 focuses on methodologies aiming to improve the cloud and clear sky parameterisations discussed in the previous chapter. In Section 4.1 a method is proposed to derive DSSF values for cloudy pixels based on a new parameterization for the cloud transmittance factor. This method takes advantage of adequate ground-based measurements and relies on the knowledge of cloud albedo as derived from a physically-based linear relationship between TOA albedo and the cloud transmittance factor. It will be shown that the regression coefficients derived from the linear relationship can be related with the cloud type. The parameterisation is tested for different cloud types verified against ground-based measurements. A parameterisation is then proposed to derive DSSF values for clear sky conditions that explicitly takes into account the impact of the diffuse radiation, the latter linked with the aerosol optical thickness (AOT). The fraction of diffuse radiation is obtained from ground-based measurements and its
dependence against values of the solar zenith angle is investigated. A diffuse parameter is also retrieved and its values are compared against ground-based measurements of the aerosol optical thickness (AOT) at 550 nm. Simulations with a radiative transfer model are then performed in order to verify the validity of the obtained linear relationship. An expression is then derived which permits to include explicitly the contribution of the diffuse irradiance in the DSSF model described in Chapter 2. By using simulated values obtained from a suitable radiative transfer model, it is shown that the linear relationship linking the diffuse parameter with the AOT does have a positive impact on the determination of DSSF. For both approaches, i.e. the new proposed parameterizations for the determination of DSSF for cloudy and clear sky pixels, aspects related to their operational implementation are briefly discussed.

Finally, in Chapter 5 a summary is presented of the performed work, followed by an overall discussion of the main results obtained.
Introduction
Chapter 2

Estimation of DSSF

The balance at the surface between the radiation emitted by the Sun and the radiation emitted by the Earth may be described in terms of flux changes between the atmosphere and the ground. Radiative fluxes quantify the contributions of the shortwave and longwave that are associated to different mechanisms of energy exchange [22], [23]. In this respect, the role of the incident solar radiation flux is especially important over land since it determines, in large part, the surface temperature and the rate of evapotranspiration, with important consequences on atmosphere-surface interactions as well as on the global hydrological cycle [24].

Figure 2.1 provides an overview of the interactions of the shortwave (solar) and longwave (thermal) radiation with the atmosphere, clouds and surface. A non-negligible fraction of solar radiation is absorbed by the clouds and by the atmosphere before being absorbed by the surface. With a value of about 30%, the so-called planetary albedo is the fraction of radiation that is reflected back into space from clouds, particles in the atmosphere, and
land or ocean surfaces.

Figure 2.1: A schematic overview of the Earth’s energy budget and of the interactions of solar (yellow arrows) and thermal (red arrows) radiation with the atmosphere, clouds and surface (source: http://asd - www.larc.nasa.gov/erbe/).

On the other hand the surface albedo (i.e. the fraction of incident electromagnetic radiation reflected by the surface) directly affects the solar energy absorbed by the surface, which in turn modifies, through feedback processes, the various components of the climate system [25]. The land surface albedo is therefore a key variable for characterising the energy balance in the coupled soil-vegetation-atmosphere system [26]. Table 2.1 presents typical values of the surface albedo.
Table 2.1: Range of albedo values in the solar spectral range for several natural features [1].

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Albedo (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid water</td>
<td>5-20</td>
</tr>
<tr>
<td>Fresh snow</td>
<td>75-95</td>
</tr>
<tr>
<td>Old snow</td>
<td>40-70</td>
</tr>
<tr>
<td>Sea ice</td>
<td>25-40</td>
</tr>
<tr>
<td>Soil</td>
<td>5-20</td>
</tr>
<tr>
<td>Desert</td>
<td>20-40</td>
</tr>
<tr>
<td>Sand</td>
<td>30-35</td>
</tr>
<tr>
<td>Forest</td>
<td>10-25</td>
</tr>
<tr>
<td>Grass</td>
<td>16-26</td>
</tr>
</tbody>
</table>

Accurate estimates of space and time variations of shortwave fluxes are of primary importance since the geographic distribution of the differences between the absorbed solar radiation and the outgoing longwave radiation constitutes a main energy source driving the atmospheric circulation [27]. Taking into account that clouds have a dominant influence on the geographic and temporal distribution of the earth radiation budget, global observations of TOA fluxes together with the retrieval of cloud properties are also essential for a correct estimation of the global energy budget of the climate system and therefore to improve climate models [28].

The relationship between satellite observations of reflected TOA solar flux and *in situ* data was studied as early as in 1964 by Fritz *et. al.* [29]. Later, with the help of aircraft measurements, the BOMEX (Barbados Oceanographic and Meteorological Experiment) campaign allowed in 1975 to draw very up-to-date conclusions regarding the effect of clouds on the solar radiation [30]. It was concluded that large cumulus clouds affect in a significant way the solar radiation reaching the surface, either by reflection or
by absorption. As early as 1980, attempts were made to use data from geostationary
satellites to determine the solar irradiance at the surface. For instance, the model
developed by [31], separately considers the cases of clear and cloudy skies to estimate the
solar irradiance at the surface.

A different method to determine the global radiation from satellite data based on
statistical methods was developed in 1985 [32]. Statistical methods were further explored
in 1989 by [33] when developing the Heliosat method making use of geostationary satellite
imagery. An example of a physically and statistically based model is the one developed
by [34], based on atmospheric deterministic models and complex statistical tools such as
neural network techniques and fuzzy logic methods.

2.1 An operational algorithm to estimate DSSF

Information on the shortwave fluxes is needed on a global scale, and therefore, has to be
obtained by remote sensing from instruments carried onboard satellites [35]. Numerical
Weather Prediction (NWP) models constitute a valuable alternative, and analyzed
and forecasted fields of shortwave and longwave fluxes are also widely used for global
applications.

Figure 2.2 presents a schematic overview of an algorithm to retrieve DSSF from TOA
reflectances derived from data provided by SEVIRI, the radiometer on-board Meteosat
Second Generation (MSG) series of satellites. The procedure is currently being opera-
2.1 An operational algorithm to estimate DSSF

An operational algorithm to estimate DSSF is run at the Centre de Météorologie Spatiale (CMS), based at Lannion (France) within the framework of EUMETSAT’s (O&SI SAF) [20].

Throughout the description of the algorithm, the term TOA reflectance will refer to the radiation, reflected from the Earth’s surface, the atmosphere and the clouds, that reach the sensor. The common method to retrieve surface solar irradiance from satellite is based on the so-called independent pixel approximation (IPA) [36]. In case of a clear sky pixel, only the radiation reflected by the Earth’s surface and by the atmosphere have to be taken into account. On the other hand, in the case of a cloudy pixel some of the radiation reflected by the Earth will be reflected back to the surface by the bottom of the cloud and reflected back into space. For both clear and cloudy pixels, the surface albedo plays a very important role since it will control the amount of radiation reflected back into space by the surface.

2.1.1 Brief description of the method

The algorithm (Figure 2.2) is divided into three main parts: Input Variables (input parameters and auxiliary data), Auxiliary Methods and Decision Criteria respecting to the classification of a given pixel as clear sky or cloudy.

A very important step is to decide which part of the algorithm to apply, namely the clear sky or the cloudy sky modules. This is where the cloud mask (Auxilliary Data) determines whether a pixel is cloudy or not. For both cases, the atmospheric correction is made
and for the cloudy case there is an extra correction to parameterize the influence of clouds.

Figure 2.2: Scheme of the DSSF operational algorithm developed at CMS at Lannion (France). The information inside the ovals is common to the DSSF clear and DSSF cloudy sky modules.

### 2.1.1.1 Input variables

Input variables include the solar zenith angle, the surface cover type and albedo, the cloud mask, the atmospheric water vapour content and ozone concentration, aerosol information and reflectance TOA. The cloud mask is required in order to classify the pixel with respect to the presence of clouds, and provide additional information that
may include cloud coverage amount, cloud type, and cloud top height. Information about the land surface albedo is obtained from a static albedo atlas and these values are directionally corrected using the method proposed by [37].

2.1.1.2 Auxiliary methods

The possible existence of a bias on the narrowband to broadband conversion of TOA reflectances on the top of the atmosphere led to designing special experiments whereby observations were taken over the whole solar spectrum [38] providing a better temporal and spatial resolution than the one available with experimental satellite programs like ScaRaB and CERES [39].

It has been found that the most important effects on the narrowband to broadband conversion are 1) scattering and absorption by aerosols throughout the broadband interval; 2) water vapour absorption at selected bands in the near-infrared (0.7-1.0 \( \mu m \)) and infrared (>1.0 \( \mu m \)); and 3) ozone absorption in the visible and ultraviolet [40].

The following conversion for GOES-8 is applied on the DSSF model to transform narrowband into broadband reflectance:

\[
R_{bb}(\theta_o, \theta, \phi) = M \ast R_{nb}(\theta_o, \theta, \phi) + B 
\]  

(2.1)

where \( R_{bb} \) is the broadband reflectance, \( R_{nb} \) is the narrowband reflectance, \( \theta_o \) is the solar
zenith angle, $\theta$ is the viewing zenith angle and $\phi$ is the relative azimuth angle. It may be noted that the conversion respects to the radiometer spectral filter and is defined by means of the linear formula developed by [38] with coefficients fitted for the visible channel.

Values of coefficients used in Eq. (2.1) are shown in Table 2.2 and it may be noted that they were obtained over 4 types of scenes for AVHRR Channel 1 on board NOAA-7 (since the window spanned is close to the one of GOES-8 visible channels). It is worth pointing out that coefficients of the conversion from narrowband to broadband are adapted to the calibration procedure of each satellite and this is done in order to correct the drift during the satellite lifetime.

Table 2.2: Coefficients of the regression model for the narrowband to broadband conversion for different surface types [2].

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>$M$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>0.902</td>
<td>0.01426</td>
</tr>
<tr>
<td>Land</td>
<td>0.804</td>
<td>0.02891</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0.779</td>
<td>0.06831</td>
</tr>
<tr>
<td>Cloud</td>
<td>0.789</td>
<td>0.0504</td>
</tr>
</tbody>
</table>

The conversion of broadband BRDF (Bidirectional Reflectance Distribution Function) into TOA albedo requires the knowledge of the angular properties of the outgoing radiation. The retrieved TOA albedo, $A_{ray}$, [41] is defined by:

$$A_{ray}(\theta_o) = \frac{R_{bb}(\theta_o, \theta, \phi)}{f_{aniso}(\theta_o, \theta, \phi, st)}$$ (2.2)
where $R_{bb}$ is the broadband reflectance and $f_{aniso}$ is the anisotropic factor (BRDF).

The analytical form of the anisotropic factor is derived from the ratio of the modelled bidirectional reflectance $R_{model}$ and the modelled albedo $A_{model}$. Accordingly $R_{model}$ is defined the following way:

$$R_{model} = \omega R_{ray} + \Psi \frac{\Delta R_{model}}{\Psi}$$  (2.3)

with

$$R_{ray} = C_2 \frac{(1 + \cos^2 \gamma)}{(\mu \mu_0)^C_3}$$  (2.4)

$$\Psi = \frac{1}{\pi} \int_0^\pi \Delta R d\phi$$  (2.5)

$$\frac{\Delta R_{model}}{\Psi} = \frac{1 + K(G + \cos \gamma)^2}{1 + K(G^2 - 2G \mu_0 \mu + (\mu_0 \mu)^2 + 0.5(\nu_0 \nu)^2)}$$  (2.6)

and

$$\mu_0 = \cos \theta_o, \ \mu = \cos \theta, \ \nu_0 = \sin \theta_o, \ \nu = \sin \theta, \ \cos \gamma = \nu \nu_o \cos \phi - \mu \mu_o$$  (2.7)

$$\Delta R = R_{erbe} - R_{ray}$$  (2.8)
where $R_{ray}$ is the bidirectional reflectance due to Rayleigh scattering, $\gamma$ is the scattering angle, $\omega$ is the weighting factor describing the reduction in the Rayleigh scattering effects due to increased cloudiness, $R_{erbe}$ is the bidirectional reflectance computed from tabulation of Suttles [4], $\Psi$ is the azimuthal mean reflectance (expressed by regression) and $G, K$ are fitting coefficients. The TOA albedo is defined as:

$$A_{TOA} = \omega A_{ray} + \Delta A \quad (2.9)$$

with

$$\Delta A = \frac{2H}{\mu_o} + 2J \mu_o [1 + \mu_o - 2 \mu_o \ln(1 + \mu_o) + 2 \mu_o \ln \mu_o - \frac{\mu_o^2}{1 + \mu_o}] \quad (2.10)$$

where $J$ and $H$ are regression coefficients. The pre-defined coefficients of this model are related to different kind of scenarios, i.e. desert, vegetation, clear sky over vegetation, partly cloudy sky, mostly cloudy sky and overcast.

### 2.1.2 Downwelling surface flux parameterisations

#### 2.1.2.1 Clear sky flux model

The key issue to estimate downwelling shortwave irradiance in the case of clear skies relies primarily on the knowledge of the physical atmospheric transmission processes. These processes depend on the chemical constituents of the atmosphere such as water vapour...
2.1 An operational algorithm to estimate DSSF

content and ozone concentration as well as on visibility, by means of the optical depth, type of scattering (Mie or Rayleigh) and main type of aerosol (maritime or continental). It may be noted that the transmittance function $t_{i\lambda}$ for a given absorbing gas $i$ may be modelled as:

$$t_{i\lambda} \approx e^{-\left[\alpha_{i\lambda}\left(U_i^*\cos\theta_o\right)^{\beta_{i\lambda}}\right]}$$

(2.11)

where $U_i^*$ is the vertically integrated absorber amount, suitably scaled to account for the temperature and pressure dependence of absorption, $\alpha_{i\lambda}$ and $\beta_{i\lambda}$ are coefficients either derived from experimental measurements or calculated theoretically [3] and $\theta_o$ is the solar zenith angle.

As schematically shown in Figure 2.3, DSSF (denoted here as $F_{\downarrow SW, clr}$) is given by the following relationship:

$$F_{\downarrow SW, clr} = E_o \cdot v(j) \cos \theta_o T_a^{in} + F_{diffuse \ mult.scat.surf.atm}$$

(2.12)

where $E_o$ is the solar constant or TOA solar irradiance at mean Earth-Sun distance (1365 Wm$^{-2}$), $v(j)$ is the corrective term accounting for the Earth-Sun seasonal variation, $j$ is the day of the year, $\theta_o$ is the solar zenith angle, $T_a^{in}$ is the atmospheric transmission parameterisation and $F_{diffuse \ mult.scat.surf.atm}$ represents the multiple scattering between the surface and the atmosphere.
The first term on the right hand side of Equation 2.12 is the direct downward surface irradiance (including the diffuse radiation) and the second term is the multiple scattering between the atmosphere and the surface. It may be noted that the diffuse downward shortwave radiation (scattering by the atmosphere) at the surface is considered part of the atmospheric transmittance parameterisations for clear sky, i.e.

\[ F_{SW, clr}^{↓} = E_o \, v(j) \cos \theta_o \, T_{a, in}^{m} + E_o \, v(j) \cos \theta_o \, T_{a, in}^{m}[\sum_{n=1}^{\infty} (A_s \, A_{atm})^n] \] (2.13)

where \( A_s \) is the surface albedo and \( A_{atm} \) is the albedo from the atmosphere. The second term on the right hand side of the previous equation represents the contribution of multiple scattering of all orders \([n=1...\infty]\) between the surface and the atmosphere. Gathering the

![Diagram showing solar radiation interactions](image)

**Figure 2.3:** Schematic description of the interactions between solar radiation and a system composed by cloud-free atmosphere and land surface.
first and the second terms leads to:

\[ F_{SW, clr}^{↓} = E_o \ v(j) \ \cos \ \theta_o \ T_a^{in} \left[ \sum_{n=0}^{\infty} (A_s A_{atm})^n \right] \]  

(2.14)

Noting that the last term on the right handside of Eq. (2.14) is a convergent power series, i.e.:

\[ \sum_{n=0}^{\infty} (A_s A_{atm})^n = \frac{1}{1 - A_s A_{atm}} \]  

(2.15)

and setting \( F_{direct} = E_o \ \cos \ \theta_o \ v(j) \ T_a^{in} \), Eq. (2.13) becomes:

\[ F_{SW, clr}^{↓} = F_{direct} \left[ \frac{1}{1 - A_s A_{atm}} \right] \]  

(2.16)

In the clear sky method [14], and according to Eq. (2.11), the total transmittance parameterisation, \( T_{at} \), depends on the water vapour (\( \tau_{h_2o} \)) and ozone (\( \tau_{o_3} \)) optical depths, as well as on the Rayleigh scattering (\( \tau_{sc} \)) i.e.:

\[ T_{at} = T_a^{in} \left[ \frac{1}{1 - A_s A_{atm}} \right] \]  

(2.17)

where

\[ T_a^{in} = e^{-\tau_{h_2o}} e^{-\tau_{o_3}} e^{-\tau_{sc}} \]  

(2.18)

and

\[ T_d = \frac{1}{1 - A_s A_{atm}} \]  

with \( A_{atm} = (a' + \frac{b'}{V}) \)  

(2.19)
with

\[
\tau_{h2o} = 0.102\left(\frac{U_{h2o}}{\mu_o}\right)^{0.29} \quad \tau_{o3} = 0.041\left(\frac{U_{o3}}{\mu_o}\right)^{0.57} \quad \tau_{sc} = \frac{(a + bV)}{\mu_o}
\]  

It may be noted that, in the previous expressions, \(T_a\) is the clear sky atmospheric transmittance, \(T_d\) is the contribution of scattering by the atmosphere and surface, \(U_{h2o}\) is the vertically integrated water vapour content [g cm\(^{-2}\)], \(U_{o3}\) is the vertical ozone amount [atm.cm], \(V\) is the horizontal visibility [km] set to a constant climatological value of 12 km, \(a, b, a', b'\) are coefficients depending on the aerosol type, \(\mu_o\) is the cosine of the solar zenith angle, \(A_s\) is the surface broadband albedo and \(A_{atm}\) is the albedo from the atmosphere. Table 2.3 shows the parameterisation coefficients \(a, b, a'\) and \(b'\) for Rayleigh scattering in the case of maritime and continental aerosols.

<table>
<thead>
<tr>
<th>Aerosol Type</th>
<th>(a)</th>
<th>(b)</th>
<th>(a')</th>
<th>(b')</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maritime</td>
<td>0.059</td>
<td>0.359</td>
<td>0.089</td>
<td>0.503</td>
</tr>
<tr>
<td>Continental</td>
<td>0.066</td>
<td>0.704</td>
<td>0.088</td>
<td>0.456</td>
</tr>
</tbody>
</table>

The DSSF for clear sky conditions is therefore given by:

\[
F^{SW}_{clr} = E_o \, v(j) \, \cos \theta_o \, T_{at}
\]  

\[\text{(2.21)}\]

### 2.1.2.2 Cloudy sky flux model

In the case of cloudy sky pixels, the algorithm utilises the information in the auxiliary data, namely the cloud mask, which includes the cloud amount (or cloud fraction)
2.1 An operational algorithm to estimate DSSF

that represents the amount of cloud occupying a specified pixel, usually defined as the percentage of a given horizontal area covered by cloud [42].

The cloud amount is classified into three main categories; partly covered sky, mostly covered sky and overcast sky. The classes that define the previously mentioned categories are empirically based. It may be noted that since no minimum of cloud cover is defined for a given pixel to be classified as clear, a pixel classified as clear sky may still be contaminated by a small amount of clouds.

For a cloudy scene, the parameterisation of the system clouds/atmosphere is more complex since clouds provoke a high number of radiative interactions with solar radiation. According to [43], the solar radiative fluxes in the clouds are strongly affected by their spatial structure. Cess [44] provides evidence that low clouds enhance total solar absorption whereas high clouds cause less absorption than clear sky. One possible reason is that when clouds are high and thick, especially the convective ones, the level of absorption is high and there is still a large amount of interaction with the atmosphere under the cloud, leaving less solar radiation available to reach the surface [45].

A high (low) value of net solar flux at the surface is consistently accompanied by a low (high) value of cloud optical thickness, and therefore by a low (high) value of reflected solar flux at the satellite altitude [14].

According to Schmetz [46], a higher surface albedo enhances multiple reflection between
surface and atmosphere, which in turn increases the photon path length and hence atmospheric absorption. Model calculations performed by [46] show that the effect is marginal for optically thick clouds since little radiation penetrates the cloud and reaches the surface. This fact points out the importance of accounting for multiple scattering and explains why the optical depth of clouds is directly related with the amount of radiation that reaches the surface.

Since each pixel in the satellite image is treated as independent, one may neglect differences in the horizontal flux between different columns caused by the 3-D variability of the atmospheric constituents. This is the rationale of the above-mentioned Independent Pixel Approach (IPA) where the radiative properties of each pixel are treated independently by using standard parallel calculations preserving the scale-invariance. As pointed out by [36] and [47] the IPA approximation is appropriate for large enough horizontal scales (e.g. averages over several tens of kilometers) and for homogenous skies meaning that a given pixel is not "contaminated" by the neighbouring ones. Moreover, if the radiation fields are averaged spatially then the impact of the "contamination" by the neighbouring pixels may be considered as negligible and the pixel may be treated as independent.

Based on the method applied by Brisson et. al. [20], the cloud transmittance $T_c$ may be expressed in the following way:

$$T_c = 1 - A_c - A_c^{abs} \quad \text{with} \quad A_c^{abs} = y_m A_c \cos \theta_o \quad (2.22)$$

where $A_c^{abs}$ is the cloud absorption, $y_m$ is the cloud absorption coefficient, $A_c$ is the
2.1 An operational algorithm to estimate DSSF

cloud albedo and $\theta_o$ is the solar zenith angle. The term $A_c$ expresses the reflective component of the cloud whereas $A_c^{abs}$ represents the absorbing potential of the cloud. The cloud absorption coefficient, $y_m$ remains constant, i.e. it is independent of the cloud type and amount of cloud cover. It is worth emphasizing that although not derived from first principles, parameter $y_m$ has been adjusted by matching the final flux estimates with the help of a validation database [48]. This parameter therefore mainly serves for absorbing the methodological approximations and uncertainties, rather than for quantifying the physical cloud properties [49] and will be analysed in more detail in Section 2.2.5.

Since DSSF for cloudy sky, $F_{\downarrow}^{SW, cld}$, is mostly controlled by the direct radiation and the multiple scattering by the system surface/cloud/atmosphere, the scattering by the atmosphere may be neglected (see Figures 2.4 and 2.5).

Figure 2.4: As in Figure 2.3 but respecting to the interactions between solar radiation and a system composed by atmosphere with clouds and land surface.
Accordingly, the DSSF for cloudy sky is given by:

\[ F^\downarrow_{SW, cld} = F_{direct}T_c + F_{direct}T_c A_s A_c T_{\text{out}}^2 T_{\text{in}}^2 \]  

(2.23)

where \( F_{direct} \) is the direct component of solar radiation, \( T_c \) is the cloud transmission, \( A_s \) is the surface albedo, \( A_c \) is the cloud albedo, \( T_{\text{out}}^2 \) is the upwelling atmospheric transmission and \( T_{\text{in}}^2 \) is the downwelling atmospheric transmission. The second term on the right hand side represents the first order scattering between the clouds and the surface. If we consider infinite reflections between the cloud and the surface, the second term on the right side

Figure 2.5: Schematic description of the interactions between solar radiation, the top and bottom layer of a cloud and land surface.
of Eq. (2.23) may be rewritten as:

\[ F_{SW, cld}^i = E_o v(j) \cos \theta_o T_a^{in} T_c + E_o v(j) \cos \theta_o T_a^{in} T_c \left[ \sum_{n=1}^{\infty} (A_s A_c T_2^{out} T_2^{in})^n \right] \] (2.24)

where \( F_{direct} = E_o v(j) \cos \theta_o T_a^{in} \), \( T_a^{in} = T_1^{in} T_2^{in} \) and \( T_2^{out} \) is such that \( T_a^{out} = T_1^{out} T_2^{out} \) and where \( E_o, v(j) \) and \( \theta_0 \) have the same meaning as in Eq. (2.12).

As in the case of clear sky, the previous equation may be rewritten as:

\[ F_{SW, cld}^i = E_o v(j) \cos \theta_o T_a^{in} T_c \left[ \sum_{n=0}^{\infty} (A_s A_c T_2^{out} T_2^{in})^n \right] \] (2.25)

Computing the sum on the right side of Eq. (2.25):

\[ \sum_{n=0}^{\infty} (A_s A_c T_2^{out} T_2^{in})^n = \frac{1}{1 - A_s T_2^{out} A_c T_2^{in}} \] (2.26)

we obtain

\[ F_{SW, cld}^i = E_o v(j) \cos \theta_o T_a^{in} T_c \left[ \frac{1}{1 - A_s T_2^{out} A_c T_2^{in}} \right] \] (2.27)

Since the cloud transmittance factor \( T_{cl} \) is defined as:

\[ T_{cl} = T_c \left[ \frac{1}{1 - A_s T_2^{out} A_c T_2^{in}} \right] \] (2.28)

Eq. (2.27) may be rewritten as:

\[ F_{SW, cld}^i = E_o v(j) \cos \theta_o T_a^{in} T_{cl} \] (2.29)
The cloudy sky atmospheric transmittance [20] may be considered as the product of two transmittances, \( T_{a^{in}} \) and \( T_{cl} \), where \( T_{a^{in}} \) is the clear sky transmittance and \( T_{cl} \) represents the cloud atmospheric transmittance plus multiple scattering between cloud and surface (cloud factor). Therefore, \( T_{a^{in}} \) and \( T_{cl} \) are respectively given by:

\[
T_{a^{in}} = e^{-\tau_{ho}} e^{-\tau_{o3}} e^{-\tau_{sc}} \quad \text{(above and below the cloud)} \tag{2.30}
\]

\[
T_{cl} = \frac{T_{c}}{1 - T_{bc} A_{s} A_{c}} \quad \text{with} \quad T_{bc} = T_{2}^{out} T_{2}^{in} \tag{2.31}
\]

where \( T_{bc} \) is the transmittance below the cloud that accounts for multiple scattering.

It is worth recalling that, in this method, the TOA reflectance is an input variable that has to be converted into TOA albedo \( (A_{toa}) \) by means of an angular dependence model (see Eq. (2.9)). Therefore \( A_{toa} \) may be written in terms of the molecular albedo \( (\text{Rayleigh albedo}, \ A_{ray}) \), followed by the first order reflection of solar radiation from the top of the cloud, given by \( T_{1}^{in} A_{c} T_{1}^{out} \), followed by the first order reflection of the solar radiation that crosses the cloud and is reflected by the surface (surface albedo given by \( A_{s} \)), followed in turn by the second order reflection, and so on, i.e.

\[
A_{toa} = A_{ray} + T_{1}^{in} A_{c} T_{1}^{out} + T_{1}^{in} T_{c} T_{2}^{in} A_{s} T_{2}^{out} T_{c} T_{1}^{out} + T_{1}^{in} T_{c} T_{2}^{in} A_{s} (T_{2}^{out} A_{c} T_{2}^{in} A_{s}) T_{2}^{out} T_{c} T_{1}^{out} + .......... + T_{1}^{in} T_{c} T_{2}^{in} A_{s} (T_{2}^{out} A_{c} T_{2}^{in} A_{s})^{n} T_{2}^{out} T_{c} T_{1}^{out} + ...
\tag{2.32}
\]

or
2.1 An operational algorithm to estimate DSSF

\[ A_{\text{toa}} = A_{\text{ray}} + T_1^{\text{in}} A_c T_1^{\text{out}} + T_1^{\text{in}} T_c T_2^{\text{in}} A_s \sum_{n=0}^{\infty} (T_2^{\text{out}} A_c T_2^{\text{in}} A_s)^n T_2^{\text{out}} T_c T_1^{\text{out}} \] (2.33)

Taking into account that the last term on the right hand side of Eq. (2.33) includes a convergent power series, we have:

\[ A_{\text{toa}} = A_{\text{ray}} + T_1^{\text{in}} A_c T_1^{\text{out}} + T_1^{\text{in}} T_c T_2^{\text{in}} A_s T_2^{\text{out}} T_1^{\text{out}} \frac{1}{(1 - T_2^{\text{out}} A_c T_2^{\text{in}} A_s)} \] (2.34)

The previous equation may be further re-written as:

\[ A_{\text{toa}} = A_{\text{ray}} + T_{2\text{top}} A_c + \frac{A_s T_2 T_c^2}{1 - T_{bc} A_s A_c} \] (2.35)

where \( A_{\text{toa}} \) is the TOA albedo, \( A_{\text{ray}} \) is the Rayleigh albedo, \( T_{2\text{top}} = T_1^{\text{in}} T_1^{\text{out}} \) is the sun-cloud-satellite transmittance and \( T_2 = T_1^{\text{in}} T_2^{\text{in}} T_2^{\text{out}} T_1^{\text{out}} \) is the sun-surface-satellite transmittance. As in Eq. (2.22) the total transmittance by the cloud is given by:

\[ T_c = 1 - A_c - A_c y_m \mu_o \] (2.36)

Replacing Eq.(2.36) into Eq.(2.35), we are led to the following quadratic equation on \( A_c \):

\[ A_{\text{toa}} = A_{\text{ray}} + T_{2\text{top}} A_c + \frac{A_s T_2 (1 - A_c - A_c y_m \mu_o)^2}{1 - T_{bc} A_s A_c} \] (2.37)

It is worth mentioning that, as pointed out by [50], the parameterization developed for
Estimation of DSSF

cloudy sky is not applicable either for large values of the solar zenith angle, $\theta_o$, or for large values of the viewing zenith angle, $\theta$, and should therefore be restricted to $\theta_o < 80^\circ$ and $\theta < 75^\circ$.

It may be also noted that Eq. (2.35) allows estimating both the minimum TOA albedo ($A_{\text{min}}$) and the maximum albedo $A_{\text{max}}$. In fact, by setting $A_c = 0$ and $T_c = 1$ on Eq. (2.35), we obtain:

$$A_{\text{min}} = A_{\text{ray}} + A_s T_2$$

which is equivalent to the condition of clear sky.

On the other hand, setting $T_c = 0$ on Eq. (2.35), which is equivalent to the existence of a completely opaque cloud, and taking Eq. (2.22) into consideration, we obtain:

$$A_{\text{max}} = A_{\text{ray}} + \frac{T_{\text{top}}}{1 + y_m \mu_o}$$

Values of $A_{\text{min}}$ and $A_{\text{max}}$ may therefore be used as control variables of the algorithm.

Figure 2.6 provides a detailed overview of the presented schemes for clear and cloudy sky conditions.
2.2 Verification of the DSSF algorithm

In this section we present the application of the DSSF algorithm [49], for clear and cloudy pixels, using satellite data from GOES-8, GOES-12 and Meteosat-7. The performance of the DSSF model will then be assessed against DSSF ground-based measurements.
2.2.1 Match-Up Data Base (MDB)

Meteosat-7, GOES-8 and GOES-12 radiances are part of the Match-Up Data Base (MDB) which was built in order to allow an easy access to satellite data and associated meteorological fields for purposes of validation. The MDB used in this study was kindly provided by the Centre de Météorologie Spatiale (CMS) in Lannion (France) and contains data for several stations in the US (Figure 2.7) and in France (Figure 2.8). The data used are scaled radiances, i.e. scaling factors were applied to the true radiance values that are converted into TOA reflectances with the appropriate conversion coefficients. The MDB also includes the angular information of the satellite (zenith and relative azimuth angles) and the solar zenith angle. MDB further incorporates a cloud mask providing the information on the cloudiness of the pixel. It is also worth mentioning that the MDB includes coincident pyrgeometer measurements, satellite derived cloud types and model outputs (surface air temperature and humidity). The cloud types are determined at the IR pixel scale on a hourly basis from the GOES-8 imagery using the method developed by [51]. Ground based measurements, performed at 3 minute intervals, are integrated over 1 hour, centered on the local time of the satellite measurement. The cloud types are extracted over a $5 \times 5$ IR pixel box centered on the pyrgeometer station. The NWP model outputs are derived from the ARPEGE global forecasts produced on a $1.5^\circ$ grid. In addition to this basic information, a range of complementary data are included e.g. in situ meteorological observations. The paper by [52] constitutes a good example of the usefulness of the MDB.

The MDB data used in the following sections cover the period from 2000 up to 2004
2.2 Verification of the DSSF algorithm

and correspond to hourly data for the following variables: monthly surface albedo [%] (monthly climatological values), satellite azimuth angle, phase angle, satellite zenith angle, solar zenith angle, amount of cloud coverage [tenths], day and time of the year, DSSF as computed by CMS (control) [Wm$^{-2}$], DSSF ground-based (see Sec. 2.2.2) [Wm$^{-2}$], land and water masks, ozone concentration [dobson units], water vapour concentration [g cm$^{-3}$], scaled radiance, surface type and visibility [km].

2.2.2 Ground network

The ground-based data were obtained from three observing networks, ARM and SURFRAD in the US (see Figure 2.7), and BSRN in Europe (see Figure 2.8).

![Geographical distribution of radiometric stations](image)

Figure 2.7: Geographical distribution of radiometric stations in the field of view of the GOES-8 East satellite (Continental US).
The Atmospheric Radiation Measurements (ARM) network aims at improving the performance of Global Circulation Models (GCMs) and gives special emphasis to the analysis of clouds and radiation physics related with climate modelling. The ARM acquires measurements of aerosol properties, atmospheric profiles, clouds, radiation, surface fluxes and meteorological data. The radiometric data corresponding to a subset of US stations in the MDB were retrieved with instruments within the ARM measurement program [53].

The Surface Radiation (SURFRAD) program [54] incorporates observing networks (from mid to eastern parts of the US) that measure upwelling, downwelling (direct and diffuse) solar and infrared radiation, photosynthetically active radiation, UVB, spectral solar radiation and meteorological data. The main objective of this ground network is to support climate research with reliable measurements of the radiation budget in the continental US. Data from these observations, as well as those from the ARM program, have been widely used in a number of fields, like weather prediction and climate modelling and have proven to be useful to validate the satellite-based estimation of the surface radiation. A number of stations included in the MDB were also part of the measurement program of SURFRAD.
2.2 Verification of the DSSF algorithm

Figure 2.8: As in Figure 2.7, but for the METEOSAT-7 satellite.

The World Climate Research Programme (WCRP) Baseline Surface Radiation Network (BSRN) [55] has been operating as a network of surface radiation monitoring observatories for over 10 years. The aim of this network is to provide data for calibrating satellite-based estimates of the surface radiation budget (BSRN) and radiation transfer through the atmosphere and monitor regional trends in the radiation fluxes at the surface (see Figure 2.8 for the radiometric stations in Europe).

2.2.3 Verification of the TOA albedo model

As explained before, one of the fundamental input variables in the model is TOA reflectance and in particular the information on the reflectance of clouds. An angular model is suitable for the purpose of determining TOA albedo through TOA reflectance.
In particular the TOA albedo as derived from the Manalo-Smith method (see Section 2.1.1.2) can be verified against GERB data. The GERB instrument is a broadband sensor on board MSG satellites. The purpose of GERB is to accurately measure the Earth Radiation Budget (ERB), i.e. the balance between incoming radiation from the Sun (shortwave) and outgoing radiation from the Earth (longwave) in order to better comprehend the variability of the climate system. Measurements are made of the whole Earth disc from geostationary orbit at 0°176’N, 0°176’E with a nadir resolution of 50km, in wavebands from 0.32 to 4.0μm and from 0.32 to 30 μm to cover shortwave and total radiation bands. The instrument accumulates images of the disc of the Earth every 15 minutes, providing the first consistent hourly measurements of clouds and simultaneous measurements of the radiation balance.

Examples of the verification undertaken are presented in Figure 2.9 and 2.10, which show a comparison between TOA fluxes as determined from the Manalo-Smith and GERB data for two days in February (top panels) and two days in March (bottom panels) in Figure 2.9 and for four days in March in Figure 2.10, for the pixel of Carpentras. The overall agreement is rather good providing confidence on the application of the proposed TOA albedo model. It may be however noted that the data points do not coincide in time and therefore the comparison is just qualitative.
2.2 Verification of the DSSF algorithm

Figure 2.9: Comparison between TOA fluxes as determined from the Manalo-Smith model and TOA fluxes from the GERB instrument for the station of Carpentras. The two top panels refer to the 7th and 14th of February respectively, and the two bottom panels refer to the 13th and 18th of March 2004. Stars correspond to the output of the Manalo-Smith model whereas diamonds correspond to GERB data.
Figure 2.10: As in Figure 2.9, but for the 20th, 21st, 22nd and 24th of March 2004 (from left to right and top to bottom).
2.2 Verification of the DSSF algorithm

2.2.4 DSSF model versus ground based measurements

Figure 2.11 to 2.13 show the results of application of the DSSF algorithm for both clear sky pixels (i.e. $F_{SW, clr}$ as obtained from Eq. (2.21)), and cloudy sky pixels, (i.e. $F_{SW, cld}$ as obtained from Eq. (2.29)) for a set of selected ground based stations and for GOES-8 data. Figure 2.11 provides a comparison between DSSF modelled and DSSF ground-based for the pixel of Bondeville during the month of July 2000 (left panel) and for the pixel of Goodwin Creek during the month of August 2001 (right panel).

![Figure 2.11: Comparison between DSSF modelled (GOES-8) and DSSF ground-based measurements for Bondeville during July 2000 (left panel) and for Goodwin Creek during August 2001 (right panel). Clear pixels are represented by (×) and cloudy pixels by (△).](image)

It is well apparent that, in general, the modelled values of DSSF tend to match DSSF ground-based measurements. It may be further noted that results for clear sky (represented by ×) are especially good considering that a fixed value of 12 km was used for the visibility, and not a more realistic estimate e.g. derived directly from the aerosol optical
depth. In the case of cloudy sky the results show higher dispersion.

A similar comparison is presented in Figure 2.12 for the pixel of Bondeville during the month of August 2000 and for the pixel of Tallahassee during the month of August 2001. Results for the model closely follow the measurements and, as before, there is less dispersion for clear sky values than for cloudy sky. On the other hand, for Tallahassee, there is slight higher dispersion for cloudy sky values.

Results respecting to the pixel of Ashton during the months of July and August are presented in Figure 2.13. This is a particularly good case, especially for clear skies where a high percentage of values fall in the 1:1 line. Again the dispersion is larger in the case of cloudy sky. More results are presented in Appendix A.

Figure 2.12: As in Figure 2.11 but for Bondeville during August 2000 (left panel) and for Tallahassee during August 2001 (right panel).
2.2 Verification of the DSSF algorithm

Figure 2.13: As in Figure 2.11 but for Ashton during July 2000 (left panel) and August 2000 (right panel).

Table 2.4 presents the statistics obtained by comparing ground-based observations of DSSF versus modelled values of DSSF with data from GOES-8. Results refer to seven radiometric stations (Bondeville, Goodwin Creek, Ashton, Sterling, Oak Ridge, Madison and Tallahassee) for all-sky (i.e. clear and cloudy), clear sky and cloudy pixels. The best results, as expected, are found for clear sky, with the best agreement obtained for the station of Bondeville.

The lower values of $R^2$ for the cloudy sky pixels in comparison with the all-sky statistics are also worth being noted. For all the stations there is also a negative bias, i.e., the model is underestimating the values measured in the radiometric stations. As expected the $rmse$ values for cloudy sky are higher than for the cases of clear sky, as well as when all pixels are included in the validation. These results point out the fact to be ex-
expected that the DSSF for cloudy pixels is more difficult to retrieve than for clear sky pixels.

Table 2.4: Statistics respecting to obtained DSSF results for the GOES-8 stations (all sky, clear and cloudy pixels). $R^2$ is the coefficient of determination, $\sigma$ is the standard deviation of the errors in $W m^{-2}$ and $rmse$ is the root mean square error in $W m^{-2}$. For the corresponding Figures see Appendix A.

<table>
<thead>
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</table>
2.2 Verification of the DSSF algorithm

In Figure 2.14 a comparison is provided between DSSF modelled and DSSF ground-based for the pixel of Carpentras during the months of August 2002 (left panel) and of March 2004 (right panel) for METEOSAT data. Again the results show a good agreement between modelled and measured values of DSSF. These results are comparable with those obtained for GOES-8, i.e., there is a good relationship between modelled and ground based measurements with an underestimation by the model (see Table 2.5).

Figure 2.14: As in Figure 2.11 but respecting to the comparison between DSSF modelled (METEOSAT) and DSSF ground-based measurements for Carpentras during August 2002 (left panel) and March 2004 (right panel).

Figure 2.15 shows the comparison between DSSF modelled and measured for the station of Carpentras and Nantes, for June 2002 and February 2004, respectively. The underestimation of the DSSF modelled values, particularly for cloudy sky, is again worth being noticed.
Estimation of DSSF

Figure 2.15: As in Figure 2.14 but for Carpentras during February 2004 (left panel) and Nantes during June 2002 (right panel).

Figure 2.16: As in Figure 2.14 but for Bordeaux during June 2002 (left panel) and for Strasbourg during September 2002 (right panel).
2.2 Verification of the DSSF algorithm

Figure 2.16 shows the comparison between DSSF modelled and measured for the station of Bordeaux during June 2002 (left panel) and of Strasbourg during September 2002 (right panel). Results for these two radiometric stations present a similar behaviour as the previous ones.

Table 2.5 presents the statistics obtained when comparing DSSF ground-based observations and modelled values of DSSF. Results refer to several radiometric stations (Bordeaux, Carpentras, Dijon, Lyon, Nantes, Pau, Strasbourg and Trappes) for all-sky (i.e. clear and cloudy), clear sky and cloudy pixels. There is in general the same trend as those shown for GOES-8 (see Table 2.4). In particular, the $R^2$ values for the clear pixels are higher than the corresponding values in Table 2.4, and the values of $rmse$ are lower. For cloudy sky the values for Europe are slightly better for $R^2$, bias and rmse. To notice that, when considering all-sky pixels, values are again very similar, with slightly better results when comparing measured and modelled DSSF values for the stations in the US.

Results presented in Tables 2.4 and 2.5 are to be expected, with the DSSF model performing better for clear than for cloudy sky pixels. In fact, according to [56], further improvements in estimating the global radiation require methods to monitor the aerosol optical depth with greater temporal and spatial resolution like the ones provided by MODIS as well as the knowledge of the vertical structure of the atmospheric column that cannot be assessed by passive instruments. In fact the larger variability on the value of DSSF that may be observed for cloudy pixels, raises the need to analyse the results with respect to water vapor content as well as to cloud coverage and cloud type.
Table 2.5: As in Table 2.4, but respecting to DSSF results for the METEOSAT-7 stations (all sky, clear and cloudy pixels). For the corresponding Figures see Appendix A.

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<td>June 2002</td>
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<td>August 2002</td>
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<td><strong>All stations</strong></td>
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<td>-5</td>
<td>71</td>
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</tbody>
</table>
2.2 Verification of the DSSF algorithm

According to [57], disagreements between satellite values retrieved by model-based algorithms and surface measurements may arise from different sources which include (1) errors in the surface measurements due to calibration and angular dependence errors, (2) improper parameterisation of the water vapour and the aerosol effects, (3) errors in the retrieval of the cloud properties and (4) the treatment of the effect of clouds by the retrieval algorithm. For instance, a 10% of error in water vapour or ozone columns may lead to DSSF errors of about 1 \( W m^{-2} \) [58].

A sensitivity analysis of the DSSF model to variations in water vapour was therefore undertaken by prescribing input errors ranging from 5% to 200% in the water vapour used as input in the DSSF model. Obtained results that are shown below, confirm that errors up to 25% in the water vapour (25% less than the MDB water vapour values) have indeed a very small impact on the determination of the DSSF values, for both clear and cloudy skies, especially for clear sky values, whereas for water vapour values of 200% (200% more than the MDB water vapour values) the impact is larger. For cloudy skies, it is more difficult to assess the impact solely due to the water vapour.
Figure 2.17: Measured versus modelled values of DSSF at the pixel of Bordeaux (August, 2002). Left panel refers to clear sky and right panel refers to cloudy sky. Squares represent results obtained when using the water vapour amounts measured at the radiometric stations whereas triangles and crosses indicate those obtained when increasing the water vapour amount by 25% and 200%, respectively.

Figure 2.18: As in Figure 2.17, but for Dijon (August, 2002).
2.2 Verification of the DSSF algorithm

Figure 2.19: As in Figure 2.17, but for Strasbourg (June, 2002).

The mean absolute and the mean relative errors for Bordeaux, Dijon and Strasbourg, respectively, are shown in Figures 2.20 and 2.21. Results indicate that the model slightly underestimates the contribution of the water vapour. In any case we can consider that the water vapour is taken correctly into account by the DSSF model.
Figure 2.20: Mean absolute and mean relative errors for Bordeaux (left panel) and Dijon (right panel) for August (2002) all sky. Blue symbols correspond to water vapour 25% (from the nominal value) and pink symbols to water vapour 200% (from the nominal value).
The modulating effect of clouds on DSSF may be assessed by looking at the daily cycle of DSSF as a function of cloud types. An example is shown in Figure 2.22 that respects to daily cycles of modelled DSSF during the month of August 2003 for the station of Sterling. Corresponding cloud types are represented by means of the codes described in Table 2.6. However DSSF values for a completely covered sky may correspond to several cloud types.
Figure 2.22: Daily cycles of modelled DSSF respecting to the station of Sterling during August 2003. Numbers from 1 to 6 indicate corresponding cloud types according to the codes defined in Table 2.6.

Figure 2.23 provides a comparison between DSSF model results and DSSF ground-based measurements for the same data presented in Figure 2.22. As expected the best agreement with the ground-based measurements corresponds to clear sky scenes (identified by the symbol "1" according to Table 2.6). It is also well apparent that larger discrepancies, as given by the differences between modelled and measured values (Figure 2.24), tend to occur when thin and thick cirrus are present.
Figure 2.23: Comparison between DSSF modelled and DSSF ground-based respecting to hourly observations for Sterling during August 2003. Numbers (from 1 to 6) indicate cloud types according to the codes defined in Table 2.6.
Figure 2.24: As in Figure 2.23 but respecting to differences between DSSF model and DSFF ground-based (anomalies) versus DSSF ground-based hourly observations.
Table 2.6: Codes for cloud types.

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<th>Cloud Description</th>
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<tr>
<td>1</td>
<td>no cloud</td>
</tr>
<tr>
<td>2</td>
<td>low</td>
</tr>
<tr>
<td>3</td>
<td>medium</td>
</tr>
<tr>
<td>4</td>
<td>high thick</td>
</tr>
<tr>
<td>5</td>
<td>thin cirrus</td>
</tr>
<tr>
<td>6</td>
<td>thick cirrus</td>
</tr>
<tr>
<td>7</td>
<td>broken clouds</td>
</tr>
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</table>

The main results consist in the fact that cloud type 4 (high thick clouds) corresponds, on average, to the lowest values of DSSF and cloud type 5 (thin clouds) corresponds, on average, to the highest values of DSSF for cloudy pixels. For types 2 (low clouds) and 6 (high thin clouds) results have a more scattered behaviour, a result that might be expected since thick clouds are prone to absorb more radiation than thinner clouds.

2.2.5 Cloud transmittance

As discussed in the previous section, the DSSF model revealed a less good performance in the case of cloudy pixels, for both groups of radiometric stations located in the US and in Europe. In this section a simple analysis is performed in order to assess the role of cloud transmittance, $T_c$, in modelling the cloud effects on DSSF, for this particular DSSF model. Considering Eq. (2.22), the cloud transmittance is given by the following expression:
\[ T_c = 1 - A_c - y_m A_c \mu_o \] (2.40)

where \( A_c \) is the cloud albedo, \( y_m \) is the cloud absorption factor and \( \mu_o \) is the cosine of the solar zenith angle.

According to the study performed by [59], there is a dependence of the cloud optical depth on \( \mu_o \) and therefore a dependence of \( T_c \) on \( \mu_o \) is also to be expected. Figures 2.25 and 2.26 present a plot of \( T_c \) versus \( \mu_o \) (left panels) and \( T_c \) versus \( A_c \) (right panels) for Sterling, with GOES-12, during the month of August 2003.

In Figure 2.25 the two top panels correspond to cloud type 2 (low cloud) and the two bottom panels correspond to cloud type 4 (high thick cloud). Figure 2.26 is similar to Figure 2.25, but respects to cloud type 5 (thin cirrus) and cloud type 6 (thick cirrus), respectively.
2.2 Verification of the DSSF algorithm

Figure 2.25: Cloud transmittance, $T_c$, versus $\mu_o$ (left panels) and versus cloud albedo $A_c$ (right panels) for GOES-12 data (August 2003), for Sterling, for cloud type 2 (low cloud, top panels) and cloud type 4 (high thick, bottom panels). The colour in the symbols correspond to cloud coverage (from a minimum in green up to a maximum in red).
Although it is well apparent that thicker clouds transmit less than thinner clouds and that low values of cloudiness correspond to higher transmission values, no relationship may be found between $T_c$ and $\mu_o$. For all types of clouds, the relationship between $T_c$ and $A_c$ is almost linear and for $A_c$ values higher than 0.4, especially for cloud type 4, the third term
2.2 Verification of the DSSF algorithm

in Eq. (2.22) has very low impact. There seems to be an indication of correlation for type 4 for the station of Madison (Figure 2.29) but the feature is not so strongly observed for the cases of Bondeville (Figure 2.27) and Goodwin Creek (Figure 2.28).

Figure 2.27: Cloud transmittance, \( T_c \), versus the cosine of the solar zenith angle (GOES-12 data August 2003), \( \mu_o \), for Bondeville. The colour in the symbols correspond to cloud coverage (from a minimum in green up to a maximum in red). Top left panel (low cloud), top right panel (high thick cloud), bottom left panel (thin cirrus cloud) and bottom right panel (thick cirrus cloud).
For types 2, 3 and 6 results indicate no correlation between $T_c$ and $\mu_o$, and similar results may be found in Figures 2.28 and 2.29 for Goodwin Creek and Madison, respectively.

A closer look to Eq. (2.40) may explain the features observed in Figures 2.27, 2.28 and 2.29. Since the third term is a product of three quantities less than 1, its impact on
Figure 2.29: As in Figure 2.27, but for Madison.
$T_c$ will be much lower than the impact of $A_c$ and therefore $T_c \approx 1 - A_c$, which is not physically correct. Although the model is expected to perform adequately in the case of high values of $A_c$ (allowing the third term to have an impact on $T_c$), this will not be the case for low values of $A_c$. This feature suggests analysing the impact of varying $y_m$ on the DSSF model for the different cloud types. The current value used in the DSSF operational algorithm is $y_m=0.11$ [49].

The impact of the cloud absorption factor $y_m$ (that was set to 0.04 and 0.11) on the retrieval of DSSF is illustrated in Figures 2.30 and 2.31 that represent, for different cloud types, DSSF anomalies (defined as departures of DSSF modelled from measured values) versus DSSF modelled at Sterling and Bondeville during August 2003.
Figure 2.30: Anomalies versus modelled values of DSSF for two values of the cloud absorption factor, $y_m$, respectively 0.04 (stars) and 0.11 (diamonds) for the pixel of Sterling during August 2003 with GOES-12 data. Each panel respects to a cloud type namely, cloud type 2 (upper left), cloud type 4 (upper right), cloud type 5 (lower left) and cloud type 6 (lower right).
Figure 2.31: As in Figure 2.30, but for the radiometric station of Bondeville.
2.2 Verification of the DSSF algorithm

Table 2.7 shows the bias and standard deviation of DSSF anomalies at several stations and for several cloud types. It is well apparent that changing $y_m$ from 0.04 to 0.11 has a very low impact on the standard deviation for most cloud types analysed. However the standard deviation varies significantly for the station of Bondeville for cloud types 5 and 6.

Table 2.7: Bias, standard deviation ($\sigma$) and root mean square error $rmse$ (all in in W m$^{-2}$) of DSSF anomalies for several GOES-8 stations when applying two different values of $y_m$.

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<th>$\sigma$</th>
<th>rmse</th>
<th>$y_m$</th>
<th>bias</th>
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<td>82</td>
<td>84</td>
<td>-6</td>
<td>83</td>
<td>83</td>
<td>83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penn State</td>
<td>14</td>
<td>97</td>
<td>98</td>
<td>26</td>
<td>93</td>
<td>94</td>
<td>94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sterling</td>
<td>20</td>
<td>116</td>
<td>118</td>
<td>31</td>
<td>115</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Type 6</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Bondeville</td>
<td>0.11</td>
<td>-23</td>
<td>-4</td>
<td>23</td>
<td>102</td>
<td>100</td>
<td>142</td>
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<td></td>
</tr>
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<td>Goodwin Creek</td>
<td>0.04</td>
<td>-13</td>
<td>99</td>
<td>100</td>
<td>0</td>
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<td>Madison</td>
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<td>111</td>
<td></td>
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<tr>
<td>Penn State</td>
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<td>90</td>
<td>90</td>
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</tr>
<tr>
<td>Sterling</td>
<td>-24</td>
<td>91</td>
<td>94</td>
<td>-5</td>
<td>91</td>
<td>91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Furthermore non-negligible variation in the bias may be observed for most cases. Since in the present DSSF algorithm the value of \( y_m \) is kept constant (independently of the cloud type), an alternative approach should be envisaged with the aim of "mimicking" the improvements, shown here, particularly regarding the bias.

In summary, given that the value attributed to \( y_m \) is dependent on the calibration of the sensor [48] a parameterization will be suggested in Chapter 4 that takes into account the cloud types, independently of parameter \( y_m \).
Chapter 3

Impact of cloud and aerosol effects on the DSSF retrieval

3.1 The LSA SAF

The primary role of the Land Surface Analysis Satellite Application Facility (LSA SAF) is to develop algorithms that will allow for a more effective and synergetic use of satellite data for research on interactions among land, atmosphere and biosphere, and related applications [60], [61]. The LSA SAF aims at reaching a broad range of research and application fields that include environmental management, agriculture and forestry, as well as climate modelling. Within the framework of the LSA SAF, a DSSF product has been developed which is generated from satellite observations provided by the SEVIRI instrument on board the geostationary MSG satellites [62]. The method implemented in the LSA SAF closely follows the approach adopted by the O&SI SAF that was described in the previous chapter.
With respect to the input data the DSSF algorithm requires 1) radiometrically and geometrically calibrated scaled radiances, as provided by MSG, in the spectral bands centred at 0.06 µm (visible), 0.08 µm (near-infrared) and 0.16 µm (shortwave infrared); 2) land/sea and cloud masks as derived from software developed by the EUMETSAT Satellite Application Facility on Support to Nowcasting and Very Short Range Forecasting (NWC SAF) [63], 3) view azimuth and zenith angles as well as solar azimuth and zenith angles provided by the LSA SAF system, 4) total column water vapour as provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), 5) ozone content from Total Ozone Mapping Spectrometer (TOMS) climatology [64] and 6) surface albedo.

Figure 3.1 (left panel) shows the first results obtained when the developed DSSF algorithm was applied to MSG data and respects to the 17th of July 2003 at 12:00 UTC. It may be observed that values of DSSF range from 100 to 10,000 W m⁻² and are consistent with results obtained in the previous chapter. For instance, in the case of clear pixels over South Africa and South America, it is well apparent that the solar zenith angle modulates the amount of radiation reaching the surface. A qualitative validation of DSSF may be performed by comparing the results obtained against the respective cloud mask as obtained from NWC SAF products (Figure 3.1, right panel). The lowest values of DSSF are obtained for pixels where very high opaque clouds (types 13 and 14) are present. In the case of high transparent clouds (types 15, 16, 17 and 18) as well as of high opaque clouds (types 11 and 12) values of DSSF are higher but still low when compared with the values for clear sky. Finally, it is worth noting that, over Southern Europe, the high values around 900 W m⁻² are consistent with what is to be expected
during the summer season in the Northern Hemisphere.

In the present chapter a systematic comparison will be performed of retrieved DSSF from MSG data against in situ values as observed in two radiometric stations. The aim is not to perform a validation of the algorithm (for which two stations would be a too small number), but instead to identify examples of situations where the proposed DSSF model reveals a poor performance. This information will then be used to design operational ways to circumvent the problems, leading to improved results.

![Diagram](image)

Figure 3.1: DSSF at 12:00 UTC on the 17th of July 2003 as obtained from MSG/SEVIRI (left panel) and corresponding cloud types as identified using the software developed by NWC SAF (right panel).
3.2 Observational versus modelled data

Observational data were mainly obtained from the Baseline Surface Radiation Network (BSRN) that integrates ground-based radiometric measurements, synoptic meteorological observations and upper air observations for a wide variety of regions of the globe. DSSF values over MSG pixels as obtained from the developed algorithm were compared against DSSF ground-based data as acquired in the stations of Roissy and Carpentras, the latter being part of the above-mentioned BSRN network [65]. Since DSSF ground-based data are provided with a 1 minute temporal resolution, averages of 15 minutes were made centred on the time of data acquisition by the satellite. The satellite-derived data are presented with a 30 minute temporal resolution and a quality flag is also provided, encompassing the following cases:

1. Clear sky, when the clear sky method (for clear sky pixels) is selected by the algorithm;
2. Cloudy sky, when the cloudy sky method (for cloudy pixels) is selected by the algorithm;
3. Cloudy sky, with $A_{\text{toa}}$ below $A_{\text{min}}$ (see Eq. (2.38));
4. Cloudy sky, with $A_{\text{toa}}$ above $A_{\text{max}}$ (see Eq. (2.39)).

The two first cases are associated to good quality flags whereas the two latter ones are assigned bad quality flags. Figures 3.2 to 3.5 provide a comparison between the daily cycles of DSSF, i.e. modelled and measured data for a series of days at the station of Carpentras during the month of October 2004. Figure 3.2 respects to a
3.2 Observational versus modelled data

set of four consecutive days, from the 12th to the 15th of October, which are mostly dominated by clouds and this feature reflects in the lower values of DSSF for some periods of the day; however the model shows a close agreement with the diurnal cycle of the ground-based measurements. Problems raising when the model simulates cloudy pixels are especially apparent on the 14th of October (bottom left panel). In particular the three time slots (represented by red symbols) where the $A_{\text{toa}}$ value exceeds $A_{\text{max}}$ have led to bad quality flags in the product. In fact $A_{\text{toa}}$ albedo may exceed $A_{\text{max}}$ in cases when the cloud absorbs more than what is imposed by the model (see Eq. (2.39)) and it may be recalled that we are using a constant cloud absorption factor, $y_m$.

Similar cases are shown in Figure 3.3, where the higher discrepancies are found on the 16th (top left panel, represented by the green symbols), but still the algorithm attributes to these values a good quality flag. As previously, the model closely follows the diurnal cycle presented by the measurements in particular on the 20th (bottom left panel) and on the 22nd (bottom right panel). Similar results are shown in Figure 3.4, for another four consecutives days in October. It may be noted that the 24th of October (top left panel) is dominated by clear sky and, when the clear sky method (identified by the blue symbols) is applied, the results of the model match quite well the ground-based measurements. It is worth pointing out that despite the use of a constant value of visibility, this does not seem to have a strong influence on the obtained results. On the 27th of October (bottom right panel), and despite the predominance of cloudy conditions, the DSSF model is able to reproduce with fair accuracy the daily cycle of ground-based observations.

Finally, Figure 3.5 respects to the last three days of October. On the 28th (top left panel)
and 29th (top right panel) problems arise when the model is applied to cloudy pixels leading to differences between modelled and measured values that may be higher than 100 W m$^{-2}$. On the other hand, on the 30th of October (bottom left panel), mostly a clear sky day, it may be observed that the values of DSSF are well reproduced during most of the day, the exception occurring during the period around 12 am when the cloudy sky method was applied.
3.2 Observational versus modelled data

Figure 3.2: Comparison between DSSF ground-based and DSSF obtained from the operational algorithm (DSSF MSG) for the pixel of Carpentras on the 12th, 13th, 14th and 15th of October 2004. Colour of symbols indicate the method used; clear sky method (blue), cloudy sky method (green), cloudy sky method $[A_{toa} \text{ above}]$ (red) and cloudy sky method $[A_{toa} \text{ below}]$ (orange).
Figure 3.3: As in Figure 3.2 but respecting to the 16th, 19th, 20th and 22nd of October 2004.
3.2 Observational versus modelled data

Figure 3.4: As in Figure 3.2 but respecting to the 24th, 25th, 26th and 27th of October 2004.
Figure 3.5: As in Figure 3.2 but respecting to the 28th, 29th and 30th of October 2004.
3.2 Observational versus modelled data

Figure 3.6 presents results obtained for four days of November 2004. On the 2\textsuperscript{nd} (top left panel), a day dominated by cloudy pixels, there is a good agreement between model and measurements only for a low number of pixels. On the 3\textsuperscript{rd} (top right panel) the morning is dominated by clouds and there are a few clear sky pixels in the afternoon. In the case of clear sky pixels a good agreement may be found between observed and modelled values, but there is a degradation in quality along the afternoon, with differences between model and measurements reaching up to 150 \textit{W m}\textsuperscript{-2}. The two time slots (represented by red symbols) where the $A_{\text{toa}}$ value exceeds $A_{\text{max}}$ led to bad quality flags in the DSSF product. On the 9\textsuperscript{th} of November (bottom left panel), the day is dominated by cloudy skies and the ground-based measurements tend to be adequately reproduced by the model. On the 16\textsuperscript{th} (bottom right panel) the second half of the day is dominated by clear skies with a general good agreement between model and measurements. In Figure 3.7, the four days shown are dominated by clear sky pixels.

The common feature for these two cases is that the whole day is dominated by clear sky pixels and it may be noted that the observed measurements are well reproduced by the model, despite the increase in negative deviations that takes place in the afternoon. Such an increase in bias could be attributed to the presence of strongly absorbing aerosols but this possibility was ruled out based on the fact that AERONET data indicated that aerosol concentration was too small to have a substantial influence on modelled DSSF values. A more likely possibility is the existence of a lag between the time of acquisition of the image by the satellite and the time of acquisition of the DSSF radiometric measurements, a feature that is particularly difficult to cope with when modelling cloudy pixels.
Finally, two consecutive days are shown in Figure 3.8. On the 25th, in spite of the good agreement between model and measurements, available data just cover a small fraction of the daily cycle. The 26th (right panel) corresponds to a complete cloudy sky day and it may be noted that the observed daily values of DSSF are well reproduced by the algorithm when the cloudy sky method is applied to all pixels.

In summary, results shown in Figures 3.2 to 3.8 provide a good indication that the algorithm has in general a good performance. In the case of cloudy pixels results may be not as good in some cases, but in most of the remaining ones differences between modelled and measured values are within the required accuracy of 5% [66],[49]. In the next section, a comparison will be made between the quality of results obtained with MSG and those already obtained in Chapter 2 when the algorithm was applied to Meteosat-7 and GOES-8 data.
Figure 3.6: As in Figure 3.2 but respecting to the 2nd, 3rd, 9th and 16th of November 2004.
Figure 3.7: As in Figure 3.2 but respecting to the 17th, 18th, 23rd and 24th of November 2004.
3.2 Observational versus modelled data

It is also useful to analyse the contribution of the several components of the radiation to the total amount. Figures 3.9 and 3.10 show the global, direct, diffuse and longwave components for Carpentras on the 15\textsuperscript{th} October 2004 (see corresponding Figure 3.2, bottom right panel) and for the 16\textsuperscript{th} November 2004 (see corresponding Figure 3.7, top left panel). In Figure 3.9 it is clear that the main contributor for the shortwave global radiation comes from the direct component, the diffuse contribution being negligible. In contrast (Figure 3.10) the diffuse radiation plays an important role especially in the second half of the day. This is confirmed in Figure 3.7 where, for this particular day, the afternoon is dominated by clear sky pixels (more results may be found in Appendix B).

Figure 3.8: As in Figure 3.2 but respecting to the 25\textsuperscript{th} and 26\textsuperscript{th} of November 2004.
Figure 3.9: Global radiation (top left panel), direct radiation (top right panel), diffuse radiation (bottom left panel) and infrared radiation (bottom right panel) for the 15th October 2004.
3.3 Statistical analysis

Figures 3.11 and 3.12 present the results of validation of DSSF as obtained from a sample covering the months of October and November 2004, for all-sky conditions (top left panel) as well as restricted to clear sky (top right panel) and to cloudy sky conditions (bottom left panel). Values of the coefficient of determination \( R^2 \) respecting to DSSF
modelled versus DSSF measured are also indicated in the figures, together with the total number of processed observations. In the case of all sky conditions the value of $R^2$ is about 77% for the month of October and 90% for the month of November. Presenting the higher values in October, the dispersion is nevertheless within the range of values shown in Figures 2.12 and 2.13. The DSSF model is able to reproduce the main features of the ground-based data but it is worth noting that the dispersion is not negligible, the value of absolute errors between DSSF model and ground-based measurements reaching 400 Wm$^{-2}$.

When the analysis is restricted to clear sky conditions (top right panel) there is a notorious improvement in the agreement between observed and modelled data, for both months, which translates in the larger values of the respective coefficients of determination, that reach 98% and 96%, respectively, and in the fact that a large amount of data points lie very close to the 1:1 line (represented by the thick black line). There seems to be however a systematic deviation from the 1:1 line (see Figure 3.12) that may be attributed to the already mentioned possible lag between the time of acquisition of the data by the satellite and the time when the radiometric measurements were made (see Figure 3.7).
Figure 3.11: Comparison between DSSF from MSG (DSSF MSG) and DSSF from ground-based measurements (DSSF Carpentras) for the pixel located at Carpentras based on a sample covering October 2004. The number of observations (Nobs), the coefficient of determination ($R^2$) between DSSF MSG and DSSF Carpentras and the best fit line (thick black line) are also shown. Results respect to all sky (clear + cloudy) conditions [top left panel], as well as to restrictions of the sample to clear sky [top right panel] and cloudy sky [bottom left panel] conditions. In the case of cloudy sky, the purple (light blue) dots indicate cases when $A_{\text{lea}}$ is above the maximum (below the minimum).
Figure 3.12: As in Figure 3.11, but for the month of November 2004.
3.3 Statistical analysis

Table 3.1 presents a statistical overview of the above-described results of validation. As expected the magnitude of bias is much lower than the one of standard deviation and is particularly higher in the case of clear sky conditions, reflecting the already mentioned existence of a possible lag between satellite observations and ground measurements for a few days of the month of November. The standard deviation is especially high in the case of cloudy sky pointing out the need for an in-depth look into the effects on DSSF of cloud types and cloud amounts. In what respects to the accuracy (last column in the table), the comparison between DSSF modelled and measured, for the month of November, are within the 5% \([66],[49]\), even for cloudy sky cases. In what concerns the month of October results results are less good, where the 5% accuracy is only reached for the clear sky cases, where for cloudy skies the absolute error can reach up values of 400 \(Wm^{-2}\).

Table 3.1: Statistics of deviations of ground-based measurements at Carpentras from corresponding values of DSSF obtained from MSG data (DSSF MSG - DSSF Carpentras) for the selected sample of data covering the months of October and November 2004. Statistics presented are the bias, the standard deviation (\(\sigma\)), the root mean square error (\(rmse\)), all in \(Wm^{-2}\) and the accuracy (\%).

<table>
<thead>
<tr>
<th>Conditions</th>
<th>bias</th>
<th>(\sigma)</th>
<th>(rmse)</th>
<th>accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clear sky</td>
<td>15</td>
<td>33</td>
<td>36</td>
<td>4.5</td>
</tr>
<tr>
<td>cloudy sky</td>
<td>18</td>
<td>105</td>
<td>106</td>
<td>9.7</td>
</tr>
<tr>
<td>all sky</td>
<td>17</td>
<td>101</td>
<td>102</td>
<td>8.9</td>
</tr>
<tr>
<td>November</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clear sky</td>
<td>-11</td>
<td>38</td>
<td>40</td>
<td>4.0</td>
</tr>
<tr>
<td>cloudy sky</td>
<td>-3</td>
<td>81</td>
<td>81</td>
<td>1.7</td>
</tr>
<tr>
<td>all sky</td>
<td>-5</td>
<td>62</td>
<td>62</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Since no information was available on cloud coverage and cloud type for the whole month of November 2004, we have selected, for the radiometric stations of Carpentras
and Roissy, a set of 24 days during 2004 and 2005 where the cloud products from the SAF NWC were available. Figure 3.13 shows results of the comparison between modelled values of DSSF and corresponding ground-based measurements, together with information about the amount of cloud coverage.

Figure 3.13: DSSF from MSG versus respective ground-based measurements at the radiometric stations of Carpentras (left panel) and Roissy (right panel), as obtained from 24 days of observations during 2004 and 2005. The colour of symbols indicates the amount of cloud coverage (as obtained from SAF NWC) according to the vertical colour bar, ranging from clear sky (black) up to totally overcast sky (red). The coefficient of determination ($R^2$), the bias ($\text{bias}_{\text{anom}}$) and the standard deviation ($\text{stdev}_{\text{anom}}$) are also shown.

The overall agreement between modelled and measured values of DSSF is worth being noted in both radiometric stations, the obtained values of the coefficient of determination being as high as 97% in Carpentras (left panel) and still reaching 82% in Roissy (right panel), and the bias being as low as 2.6 $W m^{-2}$ in Carpentras and -10 $W m^{-2}$ in Roissy.
3.3 Statistical analysis

The magnitude of dispersion is, in turn, considerably larger than that of systematic deviations, the value of the standard deviation reaching $59 \, Wm^{-2}$ in Carpentras and more than doubling in Roissy, where the value of $134 \, Wm^{-2}$ was obtained. It is also worth noting that deviations between modelled and measured values tend to be more pronounced when the pixels start to get overcast.

Figure 3.14 shows the comparison between modelled and measured values of DSSF when the data are restricted to clear sky conditions. Values of the coefficient of determination are especially high, reaching 99% and 93% for Carpentras (left panel) and Roissy (right panel). The case of Carpentras is especially conspicuous, with almost all data points falling very close to the 1:1 line, a feature that translates into the obtained very low values of $5 \, Wm^{-2}$ for bias and $40 \, Wm^{-2}$ for the standard deviation. It is however worth noting that the agreement between modelled and measured values is not as good in the case of Roissy, the bias of $-15 \, Wm^{-2}$ having a magnitude three times larger than that of Carpentras and the standard deviation reaching $88 \, Wm^{-2}$, being considerably larger than the value obtained at Carpentras for cloudy sky conditions ($59 \, Wm^{-2}$). This apparent degradation in performance of the DSSF algorithm when applied at Roissy for clear sky conditions may be attributed to the fact that atmospheric conditions at Roissy are highly affected by urban (anthropogenic) aerosols. The cases of Carpentras and Roissy illustrate the complexity of dealing with fully cloudy pixels. More examples are provided in Appendix C.
Figure 3.14: As in Figure 3.13 but when the data are restricted to clear sky conditions.

Figure 3.15: As in Figure 3.13 but when the data are restricted to low clouds in Carpentras (left panel) and high opaque clouds in Roissy (right panel).
3.3 Statistical analysis

Results obtained point out that deriving a relationship between DSSF values and cloud characteristics is not an easy task. Since DSSF depends on both cloud type and cloud amount, the identification of the sources of error is especially difficult, in particular when the microphysical characteristics of the clouds are not known and simplistic approximations are used for cloud parameterisation. In the next Chapter an alternative approach will be proposed that allows dealing with this issue.

It may be also noted that, in the DSSF model, the scattering by the atmosphere is embedded in the parameterisations of clear sky transmittance and therefore not explicitly described. However, according to the analysed cases, it seems that retrieved values of DSSF in the case of clear sky pixels still have a good level of accuracy, even if comprehensive information about aerosols is not explicitly incorporated in the algorithm. Nevertheless, it may be noted that DSSF for clear skies in Roissy presents a standard deviation two times higher than the one obtained for Carpentras (Figure 3.14). As already pointed out this may be attributed to the fact that the station of Roissy may be contaminated by the presence of urban aerosols and this issue will be also analysed in the next chapter. For this purpose, a parameterisation will be developed that takes into account the scattering properties of the atmosphere by means of aerosol optical properties.
Impact of cloud and aerosol effects on the DSSF retrieval
Chapter 4

Towards an improved DSSF scheme

4.1 The role of clouds in DSSF

Besides emitting in the longwave domain, clouds are an important absorbing agent of solar radiation. Because of their high spatial and temporal variability, the diversity of their typology and the strong interaction they have with short and longwave radiation, clouds are by far the strongest modulator of the 3-D radiation field [36]. For instance, and despite the fact that a cloudy sky generally implies a lower quantity of shortwave radiation reaching the ground, broken clouds may locally increase solar radiation instead of reducing it [67], [68] as a result of side reflections from clouds, which generate fluxes higher than those of clear sky [69]. In this respect, it is worth mentioning that, according to [70], situations in which surface irradiance exceeds the expected clear sky values mainly occur under broken clouds when the direct component of solar radiation is nearly unaffected, while the diffuse radiation is increased in comparison to clear-sky values. On the other hand, as pointed out by [31], the incident solar radiation is mostly attenuated by stratiform low and
middle clouds. An a priori knowledge of cloud characteristics and, in particular, of their optical properties, is therefore of primary importance for an adequate estimation of DSSF.

According to [10], optically thin clouds, like cirrus or cumulus, have only a small effect on either TOA upward or surface downward shortwave fluxes, whereas optically thick clouds, like nimbostratus, have a larger effect. Low, thick clouds primarily reflect solar radiation and cool the surface of the Earth, whereas high, thin clouds primarily transmit the incoming solar radiation. At the same time, the latter types of clouds trap some of the outgoing infrared radiation emitted by the surface and radiate it back downwards, thereby warming the surface of the Earth. The larger discrepancies in the determination of the surface solar irradiance are therefore to be expected in the presence of thick rather than in the presence of thin clouds and one may accordingly anticipate that the fraction of cloud cover will play a major role in the case of optically thick clouds.

However, as discussed in the previous chapters, the DSSF model that is currently operational in the O&SI and the LSA SAFs relies on a simple cloudy sky parameterization scheme that just incorporates information about cloud top albedo, $A_c$. No other cloud characteristics, either microphysical or macrophysical, are taken into account. Information on cloud albedo is nevertheless not sufficient, in general, to distinguish among the different types of clouds. For instance, the albedo of thick clouds (e.g. cumulo nimbus) may vary from 30 to 90% whereas the albedo of thin clouds (e.g. cirrus) may lie between 20 and 70%.

Since knowledge of $A_c$ is in general not sufficient to estimate the impact of a given cloud
type on DSSF, an alternative cloudy sky parameterisation scheme is proposed using a simple procedure that takes into account the cloud transmittance for different cloud types.

4.1 The role of clouds in DSSF

4.1.1 Parameterisation of the cloud transmittance factor

As discussed in Chapter 2, the cloud transmittance factor, \( T_{cl} \) is given by:

\[
T_{cl} = \frac{T_c}{1 - T_{bc} A_s A_c}
\]  \hspace{1cm} (4.1)

where \( A_s \) and \( A_c \) are respectively the surface and the cloud albedos, \( T_{bc} = T_{2\text{out}} T_{2\text{in}} \) is the transmittance below the cloud (\( T_{2\text{out}} \) and \( T_{2\text{in}} \) being respectively the upwelling and the downwelling atmospheric transmissions of the layer below the cloud) and \( T_c \) is the cloud transmittance which is in turn given by:

\[
T_c = 1 - A_c - A_c^{abs}
\]  \hspace{1cm} (4.2)

where \( A_c^{abs} = y_m A_c \mu_o \) is the cloud absorption (\( y_m \) and \( \mu_o \) being respectively the cloud absorption coefficient and the cosine of the solar zenith angle).

Rewriting Eq. (4.1) in terms of \( A_c \) and taking Eq. (4.2) into account one obtains:

\[
A_c = \frac{1 - T_{cl}}{1 + y_m \mu_o - A_s T_{bc} T_{cl}}
\]  \hspace{1cm} (4.3)
Taking into account that $T_{cl} \sim 10^{-1}$, Eq. (4.3) may be approximated by expanding it in a Taylor series in $T_{cl}$ up to the first order:

$$A_c \approx \frac{1}{1 + y_m \mu_o} [1 + (-1 + \frac{A_s T_{bc}}{1 + y_m \mu_o}) T_{cl}]$$  \hspace{1cm} (4.4)$$

As shown in Eq. (2.34), the TOA albedo, $A_{toa}$, is given by:

$$A_{toa} = A_{ray} + T_{ac} A_c + T_{bc} T_c A_s \frac{1}{1 - T_{2out} A_c T_{2in} A_s}$$ \hspace{1cm} (4.5)$$

where $A_{ray}$ is the Rayleigh albedo and, as shown in Eq. (2.35), $T_{ac} = T_{2top} = T_{1out} T_{1in}$ is the transmittance above the cloud ($T_{1out}$ and $T_{1in}$ being respectively the upwelling and the downwelling atmospheric transmissions of the layer above the cloud).

Neglecting multiple scattering (i.e., the last term on the right hand-side of Equation 4.5) and introducing Eq. (4.4) into Eq. (4.5), one is led to the following equation:

$$-A_{toa} + A_{ray} + \frac{T_{ac}}{1 + y_m \mu_o} - \frac{T_{ac} (1 + y_m \mu_o - A_s T_{bc})}{(1 + y_m \mu_o)^2} T_{cl} = 0$$ \hspace{1cm} (4.6)$$

Solving the previous equation in order to $T_{cl}$, one is finally led to the following linear relationship between $T_{cl}$ and $A_{toa}$:

$$T_{cl} = \alpha'_o + \alpha'_1 A_{toa}$$ \hspace{1cm} (4.7)$$
4.1 The role of clouds in DSSF

where:

\[
\alpha'_o = \frac{A_{ray}(1 + y_m\mu_o)^2}{T_{ac}(1 + y_m\mu_o - A_sT_{bc})} + \frac{1 + y_m\mu_o}{1 + y_m\mu_o - A_sT_{bc}} \tag{4.8}
\]

and:

\[
\alpha'_1 = -\frac{(1 + y_m\mu_o)^2}{T_{ac}(1 + y_m\mu_o - A_sT_{bc})} \tag{4.9}
\]

Values of \(\alpha'_o\) and \(\alpha'_1\) may be estimated by means of regression analysis applied to pairs \((T_{cl}, A_{toa})\) as obtained from the DSSF model using satellite information as input. An example is given in Table 4.1 where a list of coefficients is presented for different cloud types as obtained from GOES-8 respecting to the station of Bondeville during August 2002.

Table 4.1: Coefficients \(\alpha'_o\) and \(\alpha'_1\) as obtained from the cloud transmittance model applied to Bondeville (August 2002) in the case of cloud type 2 (low cloud), cloud type 4 (high thick cloud), cloud type 5 (thin cirrus cloud) and cloud type 6 (thick cirrus cloud) (see Table 2.6 for the cloud types description).

<table>
<thead>
<tr>
<th>Bondeville</th>
<th>(\alpha'_o)</th>
<th>(\alpha'_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 2 (low)</td>
<td>1.41</td>
<td>-2.05</td>
</tr>
<tr>
<td>type 4 (high thick)</td>
<td>1.40</td>
<td>-2.14</td>
</tr>
<tr>
<td>type 5 (thin cirrus)</td>
<td>1.40</td>
<td>-2.07</td>
</tr>
<tr>
<td>type 6 (thick cirrus)</td>
<td>1.41</td>
<td>-2.10</td>
</tr>
</tbody>
</table>

Obtained values of both \(\alpha'_o\) and \(\alpha'_1\) do not change with cloud type up to the first decimal place. This behaviour suggests that the physical model is not sensitive to cloud type, a problem that was already pointed out in Section 2.2.5. In the following section a method is proposed that attempts to capture the variability of the cloud type by exploring the linear relationship between \(A_{toa}\) and \(T_{cl}\) using ground-based measurements together with the corresponding satellite data.
4.1.2 Implementation of the new method

From Eq. (4.7) one may consider the following linear model:

\[ T_{cl} = \alpha_o + \alpha_1 A_{toa} \]  

(4.10)

where the cloud transmittance factor, \( T_{cl} \), may be obtained from ground-based measurements of \( F_{SW, cld} \) since:

\[ T_{cl} = \frac{F_{SW, cld}}{E_{\partial T^m} \alpha T_{a}} \]  

(4.11)

Regression coefficients \( \alpha_o \) and \( \alpha_1 \) may therefore be obtained from time series of ground observations of \( F_{SW, cld} \) and concurrent satellite-derived estimates of \( A_{toa} \).

Table 4.2 presents obtained values of regression coefficients for six stations in the US using ground based values of \( F_{SW, cld} \) and GOES-8 derived values of \( A_{toa} \) during the month of July 2000. It may be noted that values of \( \alpha_o \) and \( \alpha_1 \) now change appreciably from cloud type to cloud type. It is worth stressing that the positive (negative) signs of \( \alpha_0 \) (\( \alpha_1 \)) based on Equation 4.10 are in agreement with the corresponding positive (negative) signs of \( \alpha'_0 \) (\( \alpha'_1 \)) that were derived from the theoretical model based Equations 4.7, 4.8 and 4.9; however the empirically derived values (\( \alpha_0 \) and \( \alpha_1 \)) have now a much larger variability than the corresponding theoretical ones (\( \alpha'_0 \) and \( \alpha'_1 \)).
4.1 The role of clouds in DSSF

Table 4.2: Coefficients obtained from Eq. 4.10 and respective averages corresponding to 6 stations for GOES-8 (2000 07). Type 2 (low cloud), type 4 (high opaque cloud), type 5 (thin cirrus cloud) and type 6 (thick cirrus cloud).

<table>
<thead>
<tr>
<th>𝑎_0^type</th>
<th>Bondeville</th>
<th>Madison</th>
<th>Goodwin Creek</th>
<th>Ashton</th>
<th>Tallahassee</th>
<th>Sterling</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 2</td>
<td>1.1</td>
<td>1.4</td>
<td>0.9</td>
<td>1.2</td>
<td>1.4</td>
<td>1.3</td>
<td>1.28</td>
</tr>
<tr>
<td>type 4</td>
<td>1.0</td>
<td>1.1</td>
<td>0.6</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.04</td>
</tr>
<tr>
<td>type 5</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
<td>1.2</td>
<td>1.18</td>
</tr>
<tr>
<td>type 6</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>𝑎_1^type</th>
<th>Bondeville</th>
<th>Madison</th>
<th>Goodwin Creek</th>
<th>Ashton</th>
<th>Tallahassee</th>
<th>Sterling</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 2</td>
<td>-1.6</td>
<td>-2.1</td>
<td>-0.9</td>
<td>-1.6</td>
<td>-2.4</td>
<td>-1.9</td>
<td>-1.92</td>
</tr>
<tr>
<td>type 4</td>
<td>-1.3</td>
<td>-1.6</td>
<td>-0.7</td>
<td>-1.5</td>
<td>-1.2</td>
<td>-1.5</td>
<td>-1.42</td>
</tr>
<tr>
<td>type 5</td>
<td>-1.7</td>
<td>-1.7</td>
<td>-1.3</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-1.8</td>
<td>-1.54</td>
</tr>
<tr>
<td>type 6</td>
<td>-1.7</td>
<td>-1.5</td>
<td>-1.4</td>
<td>-1.6</td>
<td>-1.4</td>
<td>-1.9</td>
<td>-1.62</td>
</tr>
</tbody>
</table>

Table 4.3 presents obtained values of regression coefficients for 7 stations in France using ground based values of $F_{SW, cl}$ and Meteosat-7 derived values of $A_{tota}$ during the month of August 2002.

<table>
<thead>
<tr>
<th>𝑎_0^type</th>
<th>Bordeaux</th>
<th>Lyon</th>
<th>Nancy</th>
<th>Pau</th>
<th>Dijon</th>
<th>Trappes</th>
<th>Strasbourg</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 3</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.14</td>
</tr>
<tr>
<td>type 5</td>
<td>1.1</td>
<td>1.0</td>
<td>1.3</td>
<td>1.3</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
<td>1.16</td>
</tr>
<tr>
<td>type 7</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
<td>1.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>𝑎_1^type</th>
<th>Bordeaux</th>
<th>Lyon</th>
<th>Nancy</th>
<th>Pau</th>
<th>Dijon</th>
<th>Trappes</th>
<th>Strasbourg</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 3</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.4</td>
<td>-1.4</td>
<td>-1.4</td>
<td>-1.5</td>
<td>-1.4</td>
<td>-1.44</td>
</tr>
<tr>
<td>type 5</td>
<td>-0.9</td>
<td>-1.0</td>
<td>-2.1</td>
<td>-1.8</td>
<td>-1.4</td>
<td>-0.9</td>
<td>-1.8</td>
<td>-1.41</td>
</tr>
<tr>
<td>type 7</td>
<td>-1.5</td>
<td>-1.6</td>
<td>-2.1</td>
<td>-2.2</td>
<td>-2.0</td>
<td>-1.8</td>
<td>-2.5</td>
<td>-1.96</td>
</tr>
</tbody>
</table>
The same consistency may again be observed in what respects to the signs of the obtained regression coefficients and to their larger variability. The stability of the values of $a_0$ is also worth being noticed, in particular in the cases of type 3 (medium clouds) and type 7 (broken clouds).

It may be observed that broken clouds (type 7) tend to have the largest positive values of $\alpha_o$ together with the largest negative values of $\alpha_1$. Medium clouds (type 3) and thin cirrus clouds (type 5) have similar values of $\alpha_o$, between 1.1 and 1.2, but the latter type tends to have higher negative and more variable values of $\alpha_1$.

The performance of the developed linear model was verified by means of a process of cross-validation which consisted in applying the regression coefficients $\alpha_0$ and $\alpha_1$ to an independent dataset and then studying the deviations of modelled values of DSSF from corresponding ground-based measurements. In the cross-validation process, the following equation was accordingly used:

$$DSSF(T_{cl}^*) = E_o \cos \theta_o T_{a}^{\text{in}} (\alpha_{o}^{\text{type}} + \alpha_{1}^{\text{type}} A_{t_o})$$  \hspace{1cm} (4.12)$$

where $\alpha_0$ and $\alpha_1$ coefficients are the averages of estimates obtained for each cloud type over a set of stations analyzed (last columns of Tables 4.2 and 4.3).

An example of results obtained during the verification process is given for Bondeville (Figure 4.1) and for Tallahassee (Figure 4.2), both stations during August 2011 and for high opaque clouds (type 4). Both figures show the comparison between the new
4.1 The role of clouds in DSSF

method (in orange) and the baseline one (in black) against the respective ground-based measurements.

Figure 4.1: Modelled DSSF values with the new method ($T^*_cl$ orange asterisks) and with the baseline method ($T_{cl}$ black diamonds) versus ground-based DSSF measurements at Bondeville during the month of August 2001 and for high opaque clouds (type 4) using GOES-8 data.

In the case of Bondeville (Figure 4.1), there is a clear improvement in the agreement between modelled and measured DSSF values when applying the new method. The absolute differences between the baseline and the new method may reach up to 100 $Wm^{-2}$. In general the modelled values obtained with the new method agree rather well with the measured values.
In the case of Tallahassee (Figure 4.2) there is again an improvement in the agreement between modelled and measured DSSF values when applying the new method. The absolute differences may reach up to 200 $Wm^{-2}$, namely for high measured values of DSSF. As in the previous case, the mean values obtained with the new method agree rather well with the ground-based measurements with the values obtained from the baseline staying around 100 $Wm^{-2}$ lower than ground-based measurements. Similar results for cloud type 4 were found in the stations of Ashton and Sterling (Figure 4.3), as well as of Goodwin Creek and Madison (Figure 4.4), respecting to GOES-8 data.
4.1 The role of clouds in DSSF

Figure 4.3: As in Figure 4.1, but at Ashton (left panel) and Sterling (right panel) during the month of August 2001 for high opaque clouds (type 4) using GOES-8 data.

Figure 4.4: As in Figure 4.1, but for Goodwin Creek (left panel) and Madison (right panel).
An assessment on the performance of the baseline and the new methods was then performed based on the statistical analysis of the deviations of modelled results with each method from the respective in situ observations. Table 4.4 presents an overview of obtained results from the statistical analysis which covers the period of August 2001 and respect to all stations listed in Table 4.2. It may be noted that the data analysed are represented in Figures 4.1 to 4.4. The station of Goodwin Creek was however excluded from the validation study as the obtained regression coefficients in the calibration stage (July 2000) were not consistent with the ones obtained with the other stations.

As shown in Table 4.4, results are grouped according to cloud types and it may be noted that the sample length is reasonably long, ranging from 502 for low thick clouds (type 2) up to 954 for thick cirrus (type 6). For all four analysed cloud types the root mean square error of the new method is lower than the one for the baseline method.

Table 4.4: Statistics respecting to the comparison of the new method and the baseline one during August 2001 (GOES-8). For each cloud type, information includes the number n of cases, bias of the new method (bias<sub>new</sub>), bias of the baseline (bias<sub>bas</sub>), standard deviation of the new method (σ<sub>new</sub>), standard deviation of the baseline (σ<sub>bas</sub>), root mean square error of the new method (rmse<sub>new</sub>) and root mean square of the baseline (rmse<sub>bas</sub>). Values shown are in W m<sup>-2</sup>.

<table>
<thead>
<tr>
<th>cloud type</th>
<th>bias&lt;sub&gt;new&lt;/sub&gt;</th>
<th>bias&lt;sub&gt;bas&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;new&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;bas&lt;/sub&gt;</th>
<th>rmse&lt;sub&gt;new&lt;/sub&gt;</th>
<th>rmse&lt;sub&gt;bas&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 2 (n = 502)</td>
<td>9.0</td>
<td>-10.8</td>
<td>266</td>
<td>304</td>
<td>267</td>
<td>304</td>
</tr>
<tr>
<td>type 4 (n = 561)</td>
<td>-0.8</td>
<td>-1.2</td>
<td>189</td>
<td>223</td>
<td>189</td>
<td>223</td>
</tr>
<tr>
<td>type 5 (n = 721)</td>
<td>6.7</td>
<td>7.4</td>
<td>257</td>
<td>278</td>
<td>257</td>
<td>278</td>
</tr>
<tr>
<td>type 6 (n = 954)</td>
<td>-3.3</td>
<td>-5.3</td>
<td>217</td>
<td>243</td>
<td>217</td>
<td>243</td>
</tr>
</tbody>
</table>
It may be further observed that in both cases the bias is one order of magnitude smaller than the standard deviation of errors and therefore the observed decreases in the root mean square error reflect corresponding decreases in the standard deviation. In fact, when comparing, for each cloud type, the observed decrease in standard deviation if the new method is used instead of the baseline one, decreases in standard deviation range between 8% in the case of thin cirrus (type 5) and 15% in the case of high thick clouds (type 4), with the remaining two types, thick cirrus (type 6) and low clouds (type 2) presenting decreases of 11 and 13%, respectively.

Figure 4.5: As in Figure 4.1, but respecting to a set of seven stations (listed in Table 4.3) during the month of September 2002 for medium clouds (type 3) using METEOSAT-7 data.

The validation exercise was further carried out with data covering the period of Septem-
Towards an improved DSSF scheme

ber 2002 and respecting to all stations listed in Table 4.3. The statistical analysis was restricted to cloud type 3 (medium clouds) which formed a very long sample (11 283 values) because the remaining cloud types did not lead to adequate samples for statistical analysis. Regression coefficients were those from the calibration period of August 2002 (Table 4.2). The data are shown in Figure 4.5 and statistical analysis is provided in Table 4.5. The observed decrease in root mean square error when using the new method instead of the baseline one is even more dramatic than in the preceding four cases analysed. Such decrease results again from a corresponding decrease in standard deviation which now reaches 27%.

Table 4.5: As in Table 4.4, but for September 2002 (METEOSAT-7).

<table>
<thead>
<tr>
<th>cloud type</th>
<th>bias&lt;sub&gt;new&lt;/sub&gt;</th>
<th>bias&lt;sub&gt;bas&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;new&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;bas&lt;/sub&gt;</th>
<th>rmse&lt;sub&gt;new&lt;/sub&gt;</th>
<th>rmse&lt;sub&gt;bas&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 3 (&lt;em&gt;n = 11283&lt;/em&gt;)</td>
<td>0.12</td>
<td>0.35</td>
<td>177</td>
<td>242</td>
<td>177</td>
<td>242</td>
</tr>
</tbody>
</table>

Obtained results provide a strong indication that the relationship between <em>T<sub>cl</sub></em> and <em>A<sub>toa</sub></em> is sensitive to the cloud type, a particularly important aspect given that e.g high opaque clouds (type 4) are very difficult to model in shortwave flux models and medium-low clouds are a quite frequent type. This conclusion is reinforced when a similar procedure was applied to the amount of cloud coverage (instead of cloud types). In this case obtained coefficients were neither stable nor consistent.
It may be finally noted that the proposed methodology may be operationally implemented by using the respective information on the cloud mask which in the case of the operational DSSF is available along with the radiance values. As a first step, estimates of $a_0$ and $a_1$ should be retrieved from long enough time series in order to ensure stable values, which would be used to build a look-up table (of coefficients $a_0$ and $a_1$) for the different cloud types. Regression coefficients are to be derived from a larger database (of both satellite and ground-based information) and more complex cloudy scenes are to be considered in order to take into account as much variability as possible. Having the information on the cloud type and the corresponding coefficients for each cloud type, this method could be applied operationally.

### 4.2 Diffuse irradiance model

Aerosols have a strong impact on the radiation budget and they play therefore a major role in the Earth’s energy budget. Special attention must be paid to the different ways aerosols interact with radiation in order to develop parameterisation schemes that account for these interactions in radiative transfer computations. Aerosols in the atmosphere are associated to the emission of pollutant gases such as sulphur dioxide, nitrogen dioxide and volatile organic compounds as well as to dust and to biomass burning [71]. Aerosols have their main absorbing band in the visible spectral region. The attenuation of shortwave radiation by aerosols varies considerably with time and location and is one of the most difficult factors to estimate [72]. Two competing and interacting effects may occur when the aerosol is embedded in a cloud [73]: aerosol absorption is
Towards an improved DSSF scheme

increased because multiple scattering within the cloud increases the absorption path, whereas it is reduced through reflection of shortwave radiation by the cloud, which in turn reduces the amount of radiation that is available to be absorbed. Absorbing aerosols may also increase clear sky atmospheric absorption by an amount that may be even larger than under cloudy conditions [9].

In the previous chapter, DSSF was estimated using a fixed value for visibility related with a fixed value for the aerosol loading in the atmosphere. The impact on quality of retrieved DSSF that results from such simplified aerosol parameterization have been addressed in recent LSA SAF validation reports [74] that explicitly refer to plans on parameterizing the direct and diffuse contributions separately. Since an increase of total or partial aerosol loading reduces the solar energy available at the ground level [75], it is important to have a characterisation of the aerosols in order to assess their true impact on DSSF. Besides, as noted by [72], the insolation is more strongly reduced by increased aerosol scattering at large solar zenith angles than around midday. Moreover, according to [76], the diffuse downward shortwave irradiance arises from scattering of radiation by molecules and aerosols.

The aim of the present section is to improve the modelling of the global radiation budget by introducing a more realistic impact of the aerosols. We begin by addressing the relation between diffuse radiation and aerosol loading, particularly at high solar zenith angles. We then investigate how the contribution of the diffuse radiation to the global radiation budget may be parameterised.
4.2 Diffuse irradiance model

In order to understand the actual contribution of the diffuse radiation to the solar global radiation, an analysis is performed of ground-based measurements of the downwelling surface shortwave diffuse radiation and of aerosol optical properties. It is worth noting that global or diffuse solar radiation fluxes at the Earth’s surface are measured by means of pyranometers, which integrate hemispherically the radiation impinging on a horizontal receiver surface, whereas the direct solar flux is measured by means of pyrheliometers, which point to the Sun with a narrow viewing angle [77]. Particular attention will be devoted to the ratio between the diffuse radiation and the global radiation, hereafter referred to as the diffuse parameter.

Since the solar zenith angle has an important effect upon the direct radiative effect of aerosols [78], the variation of the diffuse parameter as a function of the solar zenith angle will be analysed. It may be noted that, according to [79], in the absence of an identified absorber or process there is a relationship between the Aerosol Optical Thickness (AOT) and the diffuse irradiance at the surface under cloud free conditions. Moreover, according to a study performed by [80], the diffuse irradiance provides vital information concerning aerosol scattering properties. Hence the motivation to develop a methodology that allows retrieving a diffuse parameter (from ground-based measurements) by relating it with the respective ground-based measurements of AOT. This relationship will be established by comparing values (with a sampling interval of approximately 30 minutes) of the diffuse coefficient and AOT at 550 nm. We will then rely on simulations from a radiative transfer model to consolidate, on a physical basis, the relationship empirically found between ground-based measurements of the diffuse parameter and ground-based measurements of AOT.
Towards an improved DSSF scheme

It may be finally noted that besides being important to correct the directional surface albedo, the diffuse irradiance may also have an impact on the modelling of the downward global surface shortwave radiation given its dependence on AOT. In fact, according to [81], discrepancies between modelled and measured values of global downwelling surface shortwave irradiance could be caused by the complex dependency of the solar radiation on aerosol optical depth and water vapour. Furthermore, as shown by [82], radiative transfer calculations confirmed the correlation between aerosol and radiative properties. Accordingly, by means of ground-based measurements and radiative transfer simulations we will develop a statistically valid diffuse irradiance model based on values of AOT at 550 nm.

4.2.1 Shortwave radiation ground-based measurements

The downwelling shortwave global radiation, $F_{sw,\,global}^\downarrow$, measured at the surface level depends on $i$) the direct radiation, $F_{sw,\,direct}^\downarrow$, which reaches the ground (without interacting with the clouds or the atmosphere), $ii$) the diffuse downward radiation, $F_{sw,\,diffuse_{atm}}^\downarrow$, i.e. the radiation that is scattered by the atmosphere, and $iii$) the radiation that is $n$ times scattered between the surface and the atmosphere, $F_{sw,\,diffuse_{atm+surf}}^\downarrow$:

$$F_{sw,\,global}^\downarrow = F_{sw,\,direct}^\downarrow + F_{sw,\,diffuse_{atm}}^\downarrow + F_{sw,\,diffuse_{atm+surf}}^\downarrow \quad (4.13)$$

The diurnal variation of different contributions of the three terms on the right hand side
of Eq. (4.13) may be assessed using ground-based measurements. For this study we have relied, through the BSRN network, on pyranometric measurements as obtained from the radiometric station at Carpentras (44°5’N, 5°3’E) located in the South of France. The data used comprise basic measurements of global, direct and diffuse sky radiation acquired at the surface with a temporal resolution of one minute. A sequence of five clear days in July 2003 was chosen by visual inspection, based on the behaviour of the global radiation during the solar period. An example of ground based measurements of global, diffuse and direct shortwave downward radiation is shown in Figure 4.6, for a clear day.

![Figure 4.6: Downwelling surface shortwave radiation on the 4th of July 2003 for the station of Carpentras. Downwelling global surface shortwave (black), downwelling direct surface shortwave (green) and downwelling diffuse surface shortwave (orange).](image)

The minor contribution of the diffuse radiation (around 10% in the present situation during most of the day) to the global budget with respect to the contribution of the direct radiation is worth being noted.
4.2.2 Retrieval of the fraction of diffuse radiation from ground based measurements

The quantity to be studied is the so-called fraction of diffuse radiation, denoted by $f_{\text{diffuse}}$, and defined as:

$$f_{\text{diffuse}}(\theta_o) = \frac{F_{\text{down, diffuse atm}} + F_{\text{down, diffuse atm+surf}}}{F_{\text{down, global}}}$$  \hspace{1cm} (4.14)

where $\theta_o$ is the solar zenith angle. From radiative transfer simulations, we have confirmed that the contribution of $F_{\text{down, diffuse atm+surf}}$ to $F_{\text{down, global}}$ is very small when compared with the contribution of $F_{\text{down, diffuse atm}}$ and therefore the assumption that $F_{\text{down, diffuse}} \approx F_{\text{down, diffuse atm}}$ is a valid one. Accordingly Eq. (4.14) may be rewritten as:

$$f_{\text{diffuse}}(\theta_o) = \frac{F_{\text{down, diffuse}}(\theta_o)}{F_{\text{down, global}}(\theta_o)}$$  \hspace{1cm} (4.15)

According to [83], the total irradiance measured by the unshaded pyranometer should be equal to the total irradiance which is obtained by adding the direct irradiance (i.e. the direct-measured normal irradiance multiplied by the cosine of the solar zenith angle) as measured by the pyrheliometer, with the diffuse irradiance, as measured by the shaded pyranometer. Therefore Eq. (4.15) may be written as:

$$f_{\text{diffuse}}(\theta_o) = \frac{F_{\text{down, diffuse}}(\theta_o)}{F_{\text{down, diffuse}}(\theta_o) + F_{\text{down, direct}}(\theta_o) \cos \theta_o}$$  \hspace{1cm} (4.16)
where $F_{sw, direct}$ is the direct downwelling surface shortwave irradiance from ground-based measurements at the surface measured following the position of the sun.

Eq. (4.16) may be re-written as:

$$f_{diffuse}(\theta_o) = \frac{F_{sw, diffuse}^4(\theta_o)}{F_{sw, direct}^\parallel(\theta_o)} \frac{F_{sw, diffuse}^\parallel(\theta_o)}{F_{sw, direct}^\parallel(\theta_o)} + \frac{F_{sw, direct}(\theta_o) \cos \theta_o}{F_{sw, direct}^\parallel(\theta_o)}$$

(4.17)

By introducing the diffuse parameter, $b_{diffuse}$, defined as:

$$b_{diffuse} = \frac{F_{sw, diffuse}^4(\theta_o)}{F_{sw, direct}^\parallel(\theta_o)}$$

(4.18)

the fraction of diffuse radiation in Eq. (4.17) may be written in the following simplified form:

$$f_{diffuse}(\theta_o) = \frac{b_{diffuse}}{b_{diffuse} + \cos \theta_o}$$

(4.19)
Figure 4.7: Variation of the fraction of diffuse radiation measurements, $f_{\text{diffuse}}$, with the solar zenith angle ($\theta_o$) [black stars]. The coloured lines represent the range of theoretical values of $f_{\text{diffuse}}$ calculated according to Eq. (4.19) with constant $b_{\text{diffuse}}$ as indicated by the coloured values. Data sets correspond to the station of Carpentras (composite of five clear sky days that were selected during the month of July 2003).

Figure 4.7 shows the results of a sensitivity study aiming to determine the optimal value of $b_{\text{diffuse}}$ to be used in Eq. (4.19) based on values of $f_{\text{diffuse}}$ as derived with Eq. (4.15) using five clear sky days that were collected during July 2003 in the station of Carpentras. The set of curves shown in the figure corresponds to the different tested values of $b_{\text{diffuse}}$ and the black stars indicate the values derived from ground-based measurements. The strong dependence of $f_{\text{diffuse}}$ with the solar zenith angle ($\theta_o$) is well apparent and it may be noted that this dependence is more pronounced for $\theta_o$ larger than 60°. In this particular case, obtained results suggest using a value between 0.05 and 0.10 for $b_{\text{diffuse}}$. 
Combining Eqs. (4.15) and (4.19) we obtain:

\[ f_{\text{diffuse}}(\theta_o) = \frac{b_{\text{diffuse}}(\theta_o)}{b_{\text{diffuse}}(\theta_o) + \cos \theta_o} = \frac{F_{\downarrow}^{\text{sw, diffuse}}(\theta_o)}{F_{\downarrow}^{\text{sw, global}}(\theta_o)} \] (4.20)

Since Eq. (4.13) may be written in the following approximated form:

\[ F_{\downarrow}^{\text{sw, diffuse}} \approx F_{\downarrow}^{\text{sw, global}} - F_{\downarrow}^{\text{sw, direct}} \] (4.21)

then by replacing the previous expression in Eq. (4.20) we obtain:

\[ \frac{F_{\downarrow}^{\text{sw, global}}(\theta_o)}{F_{\downarrow}^{\text{sw, direct}}(\theta_o)} \approx (1 + \frac{b_{\text{diffuse}}}{\cos \theta_o}) \] (4.22)

Defining \( D_{\text{diffuse}} \) as the quantity on the right hand side of Eq. (4.22), the previous equation may be simply written as:

\[ F_{\downarrow}^{\text{sw, global}}(\theta_o) \approx D_{\text{diffuse}} F_{\downarrow}^{\text{sw, direct}}(\theta_o) \] (4.23)

It is worth noting that Eq. (4.23) may be viewed as a simplified model that allows determining the global downward surface radiation once the diffuse contribution is known. Accordingly we will now investigate the possibility of deriving an expression for \( D_{\text{diffuse}} \) based on information about the AOT at 550 nm.
4.2.3 Aerosol optical properties from ground-based measurements

Information about the aerosol optical thickness at the radiometric stations of Avignon (43°93’N, 43°84’E) and Carpentras was obtained via the AErosol Robotic NETwork (AERONET). It may be noted that, for the selected time period of study, no ground based measurements of AOT at 550 nm were available at the site of Carpentras. However, because of the proximity of this site to the radiometric station of Avignon, we have investigated whether the atmospheric conditions were similar enough to allow estimating AOT (550 nm) at Carpentras from concurrent data measured at Avignon. Figure 4.8 shows a scatter plot of the AOT at 550 nm, at Carpentras versus Avignon, for a selection of clear days during the year of 2003.

Figure 4.8: Scatter plot of the aerosol optical thickness (AOT) at 550 nm measured at Avignon versus Carpentras.
Values of AOT at both sites are well correlated but there is a marked bias between the two series, values in Avignon tending to be higher than those at Carpentras. AOT as derived at Avignon was therefore used to estimate AOT at Carpentras.

### 4.2.4 Diffuse Parameter versus Aerosol Optical Thickness

With the purpose of analysing the relationship between the diffuse parameter $b_{\text{diffuse}}$ (Eq. (4.18)) and AOT at 550 nm (denoted hereafter as $\tau_{550}$), we have built up a database with $\tau_{550}$ and $b_{\text{diffuse}}$ as derived from ground-based measurements. The data used in this analysis (clear days) covered the months of June, August and September (2000), June, July, August and September (2001) and July, August and September (2002).

![Comparison between the values of $\tau_{550}$ and $b_{\text{diffuse}}$, respectively for Avignon (left panel) and Carpentras (right panel). Obtained regression coefficients, i.e. $a$ (slope) and $b$ (intercept), are also shown as well as the respective regression lines.](image)

Figure 4.9: Comparison between the values of $\tau_{550}$ and $b_{\text{diffuse}}$, respectively for Avignon (left panel) and Carpentras (right panel). Obtained regression coefficients, i.e. $a$ (slope) and $b$ (intercept), are also shown as well as the respective regression lines.
As shown in Figure 4.9, time series (sampled approximately every 30 minutes) of $\tau_{550}$ and of $b_{\text{diffuse}}$ at Avignon (left panel) and at Carpentras (right panel) are fairly correlated ($\rho = 0.89$ for Avignon and $\rho = 0.97$ for Carpentras), suggesting building up the following linear models:

\begin{align*}
    b_{\text{diffuse}} &= 0.53\tau_{550} + 0.04 \quad \text{for Carpentras} \\
    b_{\text{diffuse}} &= 0.74\tau_{550} + 0.02 \quad \text{for Avignon}
\end{align*}

which will be verified by means of simulations with a radiative transfer model, as described in the next Section.

### 4.2.5 Simulations with a Radiative Transfer Model

In order to consolidate, on a physical basis, the results obtained in the previous sections, a radiative transfer model was used to produce simulated values of diffuse and global radiation, and therefore of $f_{\text{diffuse}}$ using Eq. (4.15).

For this purpose we have relied on 6S (Second Simulation of the Satellite Signal in the Solar Spectrum), a radiative transfer model which allows simulating the interaction of near infrared and visible radiation with the atmosphere [84]. This radiative transfer code was designed to simulate the reflection of solar radiation by a coupled atmosphere-surface system for a wide range of atmospheric, spectral and geometrical conditions. The model applies successive orders of scattering and is the basic code for the calculation of look-up tables in the MODIS atmospheric correction algorithm [85].
The 6S model is also used to derive aerosol related products for GOES visible imagery [86].

Table 4.6 presents the input values to the 6S model for a set of 16 simulations for a day in July with the same geographic location of Carpentras.

Table 4.6: Input parameters for the set of 21 simulations by 6S. Assigned values of Aerosol Size Distribution (ASD), Aerosol Optical Thickness (AOT) and Imaginary part of the aerosol refractive index (IRI) are given in the 2nd, 3rd and 4th columns of the table. Values of Surface ALbedo (SAL), Ozone Concentration Content (OCC), and Concentration of Water Vapour (CWV) were kept constant in all simulations and were defined as follows: SAL = 0.1; OCC = 0.3 cm.atm and CWV = 2 gcm$^{-2}$.

<table>
<thead>
<tr>
<th>Simulations</th>
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<th>IRI</th>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>0.3</td>
<td>0.030</td>
</tr>
<tr>
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<td>0.4</td>
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<tr>
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<tr>
<td>8</td>
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<td>0.1</td>
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</tr>
<tr>
<td>9</td>
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</table>

4.2.5.1 Results

Figure 4.10 (left panels) presents the obtained dependence of $f_{\text{diffuse}}$ on the solar zenith angle for two different cases, namely when $f_{\text{diffuse}}$ is obtained from ground-based
measurements (black curves) and when $f_{\text{diffuse}}$ is derived from Eq. (4.19) (green curves) using values of $b_{\text{diffuse}} = 0.2$ (for $\theta_o \approx 20^\circ$) for the 23rd of July 2002 (upper left panel) and of $b_{\text{diffuse}} = 0.09$ (for $\theta_o \approx 20^\circ$) for the 29th of July 2003 (lower left panel). Figure 4.10 (right panels) presents the dependence of $f_{\text{diffuse}}$ on the solar zenith angle as obtained from the set of 16 6S simulations (dashed curves) using the input values shown in Table 4.6. Curves in green are those that were derived from Eq. (4.19) using the values of $b_{\text{diffuse}}$ that provided the best fit to the ground-based observations. Results obtained for the 23rd of July 2002 (top right panel) indicate that simulation #12 is the one that presents the best agreement with the results based on Eq. (4.19) and it may be noted that for this particular simulation run, a value of $\tau_{650} = 0.3$ was used (see Table 4.6). For the 29th of July 2003 (right bottom panel) the best agreement was obtained in the case of simulation #8 corresponding to $\tau_{650} = 0.1$ (see Table 4.6).
4.2 Diffuse irradiance model

Obtained results strongly suggest investigating the relationship between $b_{diffuse}$ and $\tau_{550}$ (AOT at 550 nm). Accordingly, a large set of values of $b_{diffuse}$ was obtained from 1500 simulations, which will be denoted by $b_{diffuse}^{6S}$. The latter quantities were then compared...
Towards an improved DSSF scheme

against the respective values of $\tau_{550}^{6S}$. The obtained result is shown in Figure 4.11 and it is well apparent that there is the same kind of linear relationship than the one depicted in Figure 4.9. For values up to 0.2, the good correlation between the diffuse coefficient and the AOT at 550 nm is worth being emphasised. However, beyond this threshold, there is an increasing disagreement between the two quantities. In this respect, it may be noted that values shown in red correspond to desert aerosols that are less likely to be found in the radiometric stations used in this study, unless in the occurrence of exceptional synoptic conditions, e.g. associated to Saharan dust events.

Figure 4.11: Comparison between $b_{\text{diffuse}}^{6S}$ and $\tau_{550}^{6S}$ for the 6S simulations. Symbols in red (black) correspond to desert (other types of) aerosols.
4.2 Diffuse irradiance model

Given the availability of separate components of the downwelling flux in the 6S simulations
the relationship in Eq. (4.18) was also tested. Figure 4.12 shows the obtained variation
of $b_{\text{diffuse}}^6$ with the solar zenith angle, $\theta_s$, and it is worth emphasising that, for common
aerosol types (black curves), values of $b_{\text{diffuse}}^6$ remain constant with $\theta_o$, showing a very
slight increase for values of $\theta_o$ higher than 80°.

![Figure 4.12: Variation of $b_{\text{diffuse}}^6$ as function of $\theta_o$ for the set of 6S simulations. Symbols in red (black) correspond to desert (other types of) aerosols.](image)

However, in the case of desert aerosol particles (red curves), there is a sharp increase of
$b_{\text{diffuse}}^6$ for values of $\theta_o$ above 60°. We may therefore conclude that the relationship given
by Eq. (4.18) is valid for certain types of aerosols, but more detailed 6S simulations
would still be required before generalising the proposed relationship for a wide range of
aerosol types.
The gain in performance that is expected to be obtained when parameterizing the
diffuse radiation using the proposed methodology was finally assessed by comparing the
following results that were obtained from a set of 6S simulations (as described in Table
4.6):

1. Simulated DSSF when the diffuse component by is neglected (i.e. following the
baseline method);

2. Simulated DSSF when the diffuse component is parameterized using the
proposed methodology based on AOT (i.e. following the new method);

3. Simulated DSSF when the contribution of aerosols is explicitly taken into
account based on radiative transfer computations (i.e. following a physically-based
approach).

An overview of obtained results is provided in Figure 4.13 where simulated values of
DSSF as computed following the baseline method (black diamonds) and following the new
method (orange diamonds) are plotted against the true values using the physically-based
approach. For reference purposes, true values are also plotted against themselves (green
diamonds), naturally following along the 1:1 line.

The observed shift towards the 1:1 line that is obtained when using the new method
translates into the gain in performance to be expected and provides a sound indication
4.2 Diffuse irradiance model

that diffuse radiation by aerosols should not be neglected.

Figure 4.13: Simulated values of DSSF using the baseline method (black diamonds) and the new method (orange diamonds) versus simulated DSSF values based on radiative transfer computations. All simulations were performed using 6S (see Table 4.6). For reference purposes, DSSF values based on radiative transfer computations are also plotted against themselves (green diamonds).

Given that AOT (and aerosol type, etc) may be potentially retrieved globally [87],[88], then by using the 6S model (with adequate inputs) the value of $f_{\text{diffuse}}$ could also be derived globally via Equation 4.19. As shown in Figure 4.12, the relationship fails for certain types of aerosols (namely the desertic ones), but this aspect requires further investigation, since for a large part of the desertic aerosols there is a very good
relationship between $b_{\text{diffuse}}^{6S}$ and $\tau_{550}^{6S}$.

We may therefore conclude that a simple parameterization scheme based on the relationship between diffuse radiation and the aerosol optical thickness may be used, within certain limitations, to model appropriately the contribution of the diffuse radiation to the global budget. Given the knowledge of certain properties of aerosols, the proposed methodology provides a correct assessment of the impact of the diffuse radiation. In this respect, it is worth emphasising that although based on data respecting to the station of Carpentras, may be extended to other sites, when affected by a wide range of aerosols not including the desert ones.
Chapter 5

Conclusions

The availability of correct estimates of downwelling surface shortwave radiation (DSSF) has become more and more important in a wide range of domains that include weather forecast, climate monitoring, and environmental studies. In particular, such correct estimates are a crucial requirement for a proper diagnosis of the global energy budget of the climate system. The present thesis focused on the analysis and improvement of a pre-existing algorithm (hereafter referred to as the baseline algorithm) that aims at retrieving DSSF on an operational basis using information from geostationary satellite data. The baseline algorithm relies on a model originally developed within the framework of the Ocean and Sea Ice Satellite Application Facility (O&SI SAF) to derive DSSF over the ocean in case of either clear sky or cloudy pixels. The baseline algorithm includes therefore parameterizations for the interaction of the solar radiation with the atmosphere as well as with clouds. Performance of the baseline algorithm was first evaluated using data from geostationary satellites, namely GOES-8, GOES-12, Meteosat-7 and, finally, Meteosat-8 that integrates the current Meteosat Second Generation (MSG) series.
Results obtained from the baseline model were verified against ground-based measurements located in the US and Europe. The verification process pointed out that the major issue regarding the determination of DSSF is related to the presence of clouds. In the case of pixels contaminated by clouds, verification has shown that absolute differences between estimates of DSSF as determined with the baseline model and ground based measurements can reach values as high as $200 \, Wm^{-2}$, stressing the fact that clouds are indeed a modulating factor on the derivation of DSSF values. Results further pointed out that certain cloud types, namely very low, high opaque and medium clouds, are associated to the highest discrepancies between modelled DSSF and ground-based measurements. Verification of the DSSF model with Meteosat-8 data was also performed against ground based measurements for two radiometric stations located in France where the associated information on cloud cover and cloud types was available. Obtained estimates of DSSF were consistent with results previously obtained but the availability of information about clouds contributed to putting into evidence on more solid grounds the limitations of the baseline algorithm for certain cloud types.

The baseline algorithm was improved by means of a simple parameterization scheme that relies on a physically-based linear relationship between the cloud transmittance factor (used in the baseline DSSF model) and top-of-atmosphere (TOA) cloud albedo for different cloud types. Coefficients of the linear model, for different cloud types, were estimated by means of linear regressions between satellite derived information for the cloud albedo at the top-of-atmosphere and ground-based measurements (GOES-8 and Meteosat-7 validation stations). Results obtained revealed a significant improvement in
the quality of retrieved DSSF particularly when medium and high opaque clouds were present.

An operational application of the developed method nevertheless requires the analysis of a high number of scenes that would allow building up an appropriate set of look-up tables for the different cloud types and geographical regions. In this respect, it is worth stressing that ground-based measurements are an essential tool for validating this type of models and therefore it is especially important to establish a solid and concise database that will allow for a proper and systematic validation, and, if possible, global validation of the DSSF models, particularly for cloudy pixels. On the other hand, and despite the obtained improvements, it is worth noting that there is still a limitation related with the fact that cloud type and cloud coverage should not be analysed independently against DSSF estimates; however this may only be achieved with sophisticated data analysis techniques, that for operational purposes, could be too computationally expensive. It is also important to bear in mind that we are considering a single cloud layer above the pixel under consideration, and this could be improved in the near-future by incorporating several cloud layers in the model using active sensors, that are able to identify the location of the top layer of thin and thick clouds. In fact the inclusion of such information may be easily incorporated in the DSSF model given that each cloud is treated as a homogeneous and independent layer in the atmosphere. The DSSF model has the flexibility of including two or more cloud layers without increasing the complexity of the equations.

In the case of clear sky pixels, and despite the limitations of the baseline model regarding
the contribution of the diffuse radiation to the overall budget, namely due to the presence of aerosols, the retrieval of DSSF led to estimates within the required user accuracy of 5%. Bearing in mind the limited number of cases analyzed, it seems that, even if comprehensive information about aerosols is not explicitly incorporated, retrieved DSSF for clear sky has still an acceptable level of accuracy. Nevertheless, in the event of aerosols with a high optical thickness, e.g. in the cases of urban ground validation stations (case of the ground-based station of Roissy) or of validation stations influenced by desert dust, the resulting effects may be non-negligible as suggested in [74].

In case of clear sky pixels the DSSF baseline model takes into account the effect of aerosols by means of a very simple approach via a fixed visibility parameter. Since the role of the diffuse radiation is not explicitly included in the DSSF baseline model, a methodology aiming at mitigating this problem was proposed based on the analysis of the diffuse radiation from ground-based stations that were also measuring the aerosol optical thickness (AOT). The analysis allowed establishing a relationship between the diffuse parameter and AOT. The relationship was then validated by means of radiative transfer simulations. Results obtained indicated that information on AOT may be used to assign more realistic values to the diffuse parameter leading to better estimates of DSSF. However, given the variability of aerosols in terms of source regions and typology, the operational application of the proposed methodology would require a proper knowledge of the global distribution of aerosols as well as of their properties. It is expected that, in the near future, such information may be obtained in an operational environment thanks to the advances on the retrieval of the aerosol optical depth at a global scale using remote sensing techniques based on active sensors currently being
developed. Knowledge about the stratification of aerosols is also an important factor to consider. In this respect, it is worth mentioning that ground stations allow identifying one type of aerosol in the layer closest to the surface and appropriate techniques may be used to identify the scattering properties of the aerosol present in the layers above.

It may be finally noted that some of the above-mentioned issues cannot be addressed based only on information derived from passive remote sensing instruments. Results obtained in the present thesis demonstrate that the horizontal variability of radiative properties is an essential aspect when modelling DSSF, but it is also clear that knowledge related to the stratification of clouds and aerosols could improve the performance of DSSF models. An in-depth knowledge on the microphysical properties of both clouds and aerosols is indeed a key issue and improvement in quality of retrieved values of DSSF is therefore to be expected by combining active and passive remote sensing data.
Appendix A

This Appendix contains part of the results that are presented in Subsection 2.2.4 (Tables 2.4 and 2.5). Comparisons are presented between DSSF modelled (GOES-8 and Meteosat) and DSSF ground-based measurements for stations in the US and Europe for the central pixel. The clear pixels are represented by \( \times \) and cloudy pixels by \( \triangle \). The radiometric stations of Sterling, Oak Ridge, Madison, Goodwin Creek and Bondeville are located in the US and those of Strasbourg, Pau, Nantes, Lyon, Dijon, Bordeaux and Trappes are located in Europe.
Figure A.1: Sterling August 2000 (top left panel), Sterling June 2001 (top right panel), Sterling August 2001 (bottom left panel) and Oak Ridge July 2000 (bottom right panel).
Figure A.2: Oak Ridge June 2001 (top left panel), Oak Ridge August 2001 (top right panel), Madison August 2000 (bottom left panel) and Madison June 2001 (bottom right panel).
Figure A.3: Madison August 2001 (top left panel), Goodwin June 2001 (top right panel), Goodwin August 2001 (bottom left panel) and Bondeville August 2000 (bottom right panel).
Figure A.4: Strasbourg June 2002 (top left panel), Strasbourg August 2002 (top right panel), Pau June 2002 (bottom left panel) and Pau August 2002 (bottom right panel).
Figure A.5: Nantes August 2002 (top left panel), Nantes September 2002 (top right panel), Lyon August 2002 (bottom left panel) and Lyon September 2002 (bottom right panel).
Figure A.6: Dijon June 2002 (top left panel), Dijon August 2002 (top right panel), Dijon September 2002 (bottom left panel) and Bordeaux August 2002 (bottom right panel).
Figure A.7: Bordeaux September 2002 (top left panel), Trappes June 2002 (top right panel), Trappes August 2002 (bottom left panel) and Trappes September 2002 (bottom right panel).
Appendix B

This Appendix shows ground-based data respecting to the Global Radiation, Direct Radiation, Diffuse Radiation and Infrared Radiation which correspond to the DSSF comparisons presented in Section 3.2 for the stations of Carpentras during the months of October and November 2004.
Figure B.1: Global radiation (top left panel), Direct radiation (top right panel), Diffuse radiation (bottom left panel) and Infrared radiation (bottom right panel) for the 12th October 2004.
Figure B.2: As in Figure B.1, but for the 16th October 2004.
Figure B.3: As in Figure B.1, but for the 19th October 2004.
Figure B.4: As in Figure B.1, but for the 17th November 2004.
Figure B.5: As in Figure B.1, but for the 18th November 2004.
Figure B.6: As in Figure B.1, but for the 23rd November 2004.
Appendix C

This Appendix completes the results that are presented in Section 3.3 for the stations of Carpentras and Roissy and include other cloud types.
Figure C.1: DSSF from MSG versus respective ground-based measurements for the radiometric station of Carpentras, as obtained from 24 days of observations during 2004 and 2005. The colour of symbols indicates the amount of cloud coverage (as obtained from SAF NWC) according to the vertical colour bar, ranging from clear sky (black) up to totally overcast sky (red). The results are shown considering only very low (top left panel), medium (top right panel), high opaque (bottom left panel) and high semi-transparent thin (bottom right panel) clouds.
Figure C.2: As in Figure C.1, but for high semi-transparent meanly thick (top left panel), high semi-transparent thick (top right panel), high semi-transparent above low or medium (bottom left panel) and fractional (top right panel) clouds.
Figure C.3: As in Figure C.1, but for the radiometric station of Roissy.
Figure C.4: As in Figure C.3, but for high semi-transparent meanly thick (top left panel), high semi-transparent thick (top right panel), high semi-transparent above low or medium (bottom left panel) and fractional (top right panel) clouds.
Bibliography


