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A study of the shortwave schemes in the Weather Research and Forecasting model

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Chapter 1

Introduction, Motivation and Objectives

As radiation is the main energy source for the earth-atmosphere system shaping the thermal structure and hence, the dynamics of the atmosphere, the representation of the radiative transfer processes is an essential component of the numerical weather prediction (NWP) and of the numerical climate prediction (NCP) models.

Since the first attempt by Richardson (1922) to forecast the future state of the atmosphere by calculating the full partial differential equations proposed by Vilhelm Bjerknes in his Meteorological Manifesto in 1904, the atmospheric modeling field has become increasingly more complex and realistic, often strongly linked with the improvements in the computational resources (Shuman, 1989; Lynch, 2008). There are a number of publications that review the history of atmospheric modeling which include the two previously cited papers as well as the paper of Dudhia (2014) and a large number of books and manuals that present the state of the field such as as Pielke (2002) and Warner (2007). Many of these papers and manuals devote a section or an entire chapter to presenting the common assumptions for coupling the radiative transfer within the atmospheric models. A full reading of these documents and a comparison with the radiative manuals such as Chandrasekhar (1950), Lenoble (1993) or Liou (2002), among others, leads to the conclusion that the radiative transfer processes in NWP and NCP models have been historically enormously simplified. Mainly, three elements explain the reason of these simplifications, which will be described in detail through the next chapters. First, a full treatment of the radiative transfer needs a high amount of computational power, unfeasible for an atmospheric model even with the current hardware resources. Second, the kind of data required for evaluating the radiative variables (i.e. optical properties) are not a solution of the Euler equations and hence, they need to be parameterized as a function of the meteorological fields. Finally, for most of the traditional applications of the NWP models (e.g. weather forecast, extreme events), the radiative fluxes play a secondary role in comparison with the microphysics or the Planetary Boundary Layer (PBL) processes that have a direct impact to the human activities. Under this context, the austerity in the radiative transfer computation was reasonable and necessary.

The development of solar parameterizations for NWP models has occurred in two separate historical periods defined by the dominant applications that have motivated the formulation of the schemes. The time of transition between these two periods is vague but is roughly in the decade of the 2000s.

Before the 2000s, the main interest of the solar parameterizations in the atmospheric models was to include the diurnal cycle, required for a realistic representation of the surface fluxes. As it is explained in Dudhia (2014), the radiative transfer in the earliest models was parameterized in very simple schemes consisting in an integrated column with a rough representation of the atmospheric cooling. With the emergence of the cumulus and microphysics schemes, new algorithms solving the radiative transfer layer by layer and interacting with the atmospheric particles were necessary. The large increase in computational power during the 1980s and 1990s facilitated the development of more realistic schemes, adding new physical processes such as the absorption due to different gas species (e.g. ozone or carbon dioxide), the scattering produced by ice crystals, cloud droplets or aerosols and increasing the spectral resolution, from broadband schemes to parameterizations with few spectral bands. Moreover, as models reached longer forecasting horizons, the radiative schemes became more important because the diabatic term produced by the radiative heating and cooling rates acquires a more significant role as we discussed in Montornès et al. (2015e) and hence, more accurate approaches were necessary.

The growth of the solar energy industry has introduced a change of paradigm during the last decade. Solar energy as well as wind power, hydro power or bio energy are renewable sources of energy that depend directly or indirectly on the atmospheric conditions and thus, the atmospheric modeling is the natural tool for the analysis of the fuel amount. For example, before installing a wind farm in one specific region, the promoter needs a climatic characterization of the wind regimes on the target site, which typically includes the wind speed probability distribution at turbine blade height, the vertical profile of the wind speed as well as other parameters such as the turbulence, shear, wind veer or wind rose. All this information is necessary for assessing the profitability of the projected plant. The same analysis can be performed for the photo-voltaic plants, the water reservoirs and the other renewable, each one with their particularities and relevant meteorological fields. The study of the fuel amount and its conditions is called resource assessment. The main limitation for the studies of resource assessment is the availability of real long period data-sets in the place of interest and hence, NWP models and reanalysis data-sets become a valuable tool. Nevertheless, unlike other renewable sources of energy, the solar resource has a great ally: the products derived from satellite data, as it is outlined in Fig. 1.1.

Satellite data provides a large number of benefits. Under perfect or ideal conditions, this kind of data could provide a global coverage as well as long-term series. Furthermore, satellite data decreases the uncertainty in the estimation of the irradiance because the problem is *reduced*, note the italic typesetting, to infer the surface irradiances from the reflected radiation measured at the top of the atmosphere (TOA) by the sensors assembled in the satellite. This process can be more or less complex (e.g. Lenoble, 1993 presents an introduction of these methods) and it avoids the limitations associated with the simplifications and the predictability of the NWP models such as the approximations used by the microphysics scheme, the determination of the aerosols or the uncertainty in the initial conditions, among others. To put it plainly, let us imagine one cloud. If this cloud is sufficiently large to be detected by the sensor of the satellite, the problem consists in searching the way for inferring the radiation below the cloud based on the reflected radiation at the TOA, that it is not easy at all. On the contrary, an atmospheric model has to simulate firstly the cloud at the correct location and time (i.e. without spatial and temporal biases), and with the appropriated characteristics. Afterwards, it has to compute the radiative fluxes with a simplified algorithm in order to reduce the computational costs. As the microphysical processes are not represented by the dynamic equations, they must be parameterized in microphysics and cumulus schemes, increasing the degree of uncertainty. Therefore, NWP models start out with disadvantages with respect to satellite data-sets.

In practice, the process of preparing the satellite products is more complex than the one idealized described above. Due to the lack of information, some products use data from reanalysis models as, for example, the Surface Solar Radiation Data Set – Heliosat, SARAH, (Müller et al., 2015) that takes atmospheric fields, such as the water vapor, from the ERA-Interim. Moreover, there are different satellites from different missions. Each one of these satellites does not cover the whole globe, at the same time because they have different orbits (i.e. geostationary and polar) and very often their measurements correspond to different periods, not to mention the fact that usually they have different kind of sensors (i.e. instruments, channels) due to distinct technological generations. Consequently, a spatiotemporal homogenization is necessary before providing global solutions, required for the solar resource studies. Therefore, NWP models become an interesting tool to be used as a predictor for calibrating the different sources of satellite data and hence, reliable solar schemes are essential.

As a result of the different treatment of the satellite data, many products, public and commercial, have proliferated providing solutions to the solar resource assessment such as the National Solar Radiation Database (Wilcox, 2012) from the National Renewable Energy Laboratory (NREL), Helioclim (Blanc et al., 2011) from SoDa, Meteonorm or SolarGis (both private companies), among others. An interesting review of these data-sets is presented in Sengupta et al. (2015).

Once the plant is built, the future conditions of the atmosphere are necessary for a large number of applications such as the maintenance of the plant, scheduling the energy market, guaranteeing the stability of the electrical grid and others. For example, if one can forecast that one's solar plant will be covered by clouds during two days in the next week, one can schedule the maintenance of the solar panels for these days instead of stopping the production during the sunny days and thus, minimizing the economic damage. The case of the stability of the electrical grid is more critical because it can have an effect on a whole region or even a country. Some of the renewable energies (e.g. wind and solar) experience a high spatial and temporal variability becoming a problem for the stability of the electrical grid. In the case of the solar energy, the photo-voltaic is more sensitive than the concentrating solar power (CSP) because the thermal inertia of the second one masks the problem (Sengupta et al., 2015). Furthermore, an accurate forecast of the future energy is of utmost importance for the transmission system operator (TSO) that adapts the energy mix against the variations of solar energy availability (Wittmann et al., 2008; Lorenz et al., 2009; Martín et al., 2010; Marquis et al., 2011).

Therefore, depending on the application and the forecast horizon of interest, four types of prediction are defined: intra-hour forecasting, short-term, mid-term and long-term. The methods used vary with the forecasting horizon according to the degree of predictability of the different approaches as it is summarized in Fig. 1.1. The methods for forecasting can also be classified by the number of steps (Chen et al., 2011). On the one hand, the direct methods predict directly the interest field (i.e. solar, wind energy or whatever) while, on the other hand, the two stage approaches forecast the meteorological fields and, after that, they use a plant model for the conversion to energy. As this thesis is not oriented to these methods, we will introduce briefly the forecasting horizons and methods in the following paragraphs in order to show the interest in the NWP models and, consequently, in the solar parameterizations. Further information can be find in Diagne et al. (2013), Inman et al. (2013) or in Sengupta et al. (2015) as well as in other publications that will be referenced in the following paragraphs.

The intra-hour forecasts cover the predictions from tens of minutes to 1 hour ahead with a high frequency of updates. Therefore, this kind of forecast requires good measurements of the plant. Consequently, the intra-hour predictions are obtained by using statistical methods (e.g. Bacher et al., 2009; Wang et al., 2012; Teo et al., 2015) or/and with sky cameras, extrapolating the cloud and irradiance information (Chow et al., 2011; Marquez and Coimbra, 2013; Peng et al., 2015). The first one offers predictions from few minutes to 1 hour ahead, while the second one is used for forecasts from 15 to 30 minutes ahead. In the recent years, a number of providers (e.g. Clean Power Research) have started using satellite-based methods for intra-hour forecasting beyond about 15 minutes. It generally outperforms site-based statistical methods after 15-30 minutes.

The short-term predictions range from 1 hour to few hours ahead. Generally, the forecast in this window is produced using satellite data, extrapolating different products based on

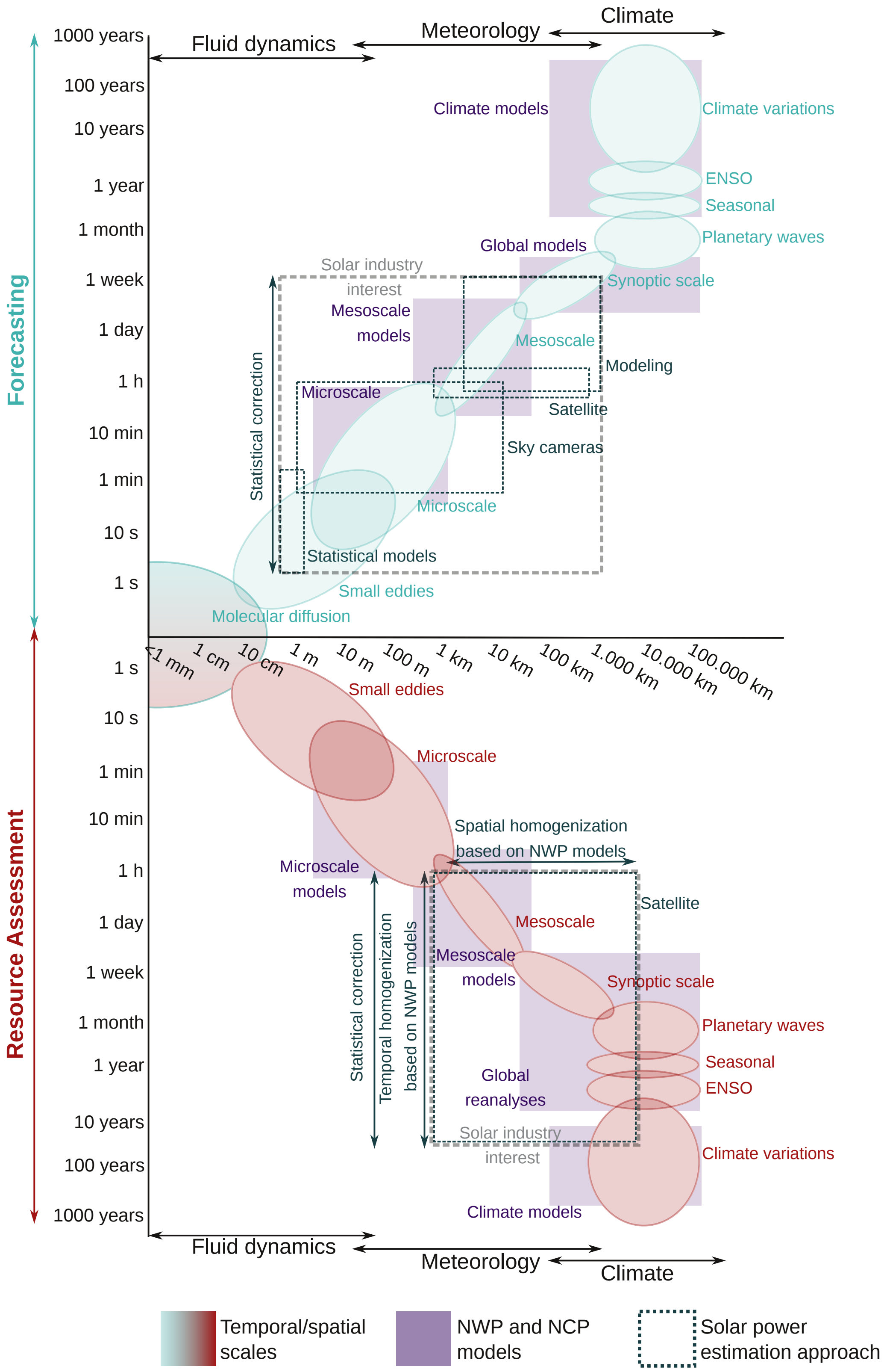

Figure 1.1: Solar resource assessment (below) and forecasting (above) approaches at different spatiotemporal scales. Based on Sengupta et al. (2015) and Montornès et al. (2015c).

subsequent frames (Hammer et al., 1999; Marquez et al., 2013), allowing updates with a high frequency as in the intra-hour case. The progresses in the data assimilation approaches as well as of the rapid update cycle models is improving the skills of the NWP models that are starting to be valuable tools for the short-term forecasting too (Inman et al., 2013).

Finally, the mid-term and long-term forecasts cover periods from some hours to days and weeks ahead. At these scales, the approaches used in the intra-hour and short-term predictions are not longer valid and a full and physical approach considering most of the processes occurring in the atmosphere is fundamental. Therefore, NWP models must be used. In general, these models are improved by using a dynamical or statistical down-scaling and calibrating with on-site measurements (e.g. Diagne et al., 2014).

1.1 Motivation

From this brief description of the methods either for resource assessment or for forecasting, one can conclude that NWP models are an important tool for both and, hence, a good comprehension of the shortwave schemes and of their limitations is necessary. It is at this point where this thesis started in the fall of 2011. In that time, the knowledge about the performance of the mesoscale models for solar applications was mostly focused on extended validations. Zamora et al. (2005) presented some analyses about the performance of the solar schemes showing a great dependence on the atmospheric conditions, particularly, aerosols. Moreover, models such as the Weather Research and Forecasting (WRF) were not optimized to predict ground-based solar irradiance parameters. Mathiesen and Kleissl (2011) evaluated the skills of the Global Horizontal Irradiance (GHI) outcomes from the North American Mesoscale (NAM) Forecast System, the Global Forecasting System (GFS) and the European Centre for Medium-Range Weather Forecast (ECMWF) over the continental US (CONUS) region. The study showed significant biases in the determination of the GHI with 50 Wm^{-2} under clear sky conditions and reaching the 200 Wm^{-2} under cloudy sky situations. Similar results were obtained by Lara-Fanego et al. (2012) that evaluated the performance of the WRF model in the determination of the GHI over Andalusia (south of the Iberian Peninsula). The analysis of the results in different forecasting horizons indicated a high dependence of different metrics with the sky conditions and the season. In the day-ahead, the Root Mean Square Error (RMSE) observed was around 10% and 50% relative to the measurements under clear sky and cloudy sky scenarios, respectively. A good summary of all these studies can be found in Inman et al. (2013).

Moreover, models such as the WRF–ARW were not explicitly oriented to the solar resource field. Three facts exemplify clearly this issue: i) the documentation related to the solar schemes was simple as it can be noted from the WRF User's Tutorial of summer 2011 (Dudhia, 2011), ii) the treatment of the aerosols was extremely simplified by using few climate profiles in some cases and iii) only the GHI was available in the simulation output file, although the direct and diffuse components are evaluated in almost all schemes as a solution of the radiative transfer equation (RTE).

In this context, Dr. Bernat Codina and Dr. John Zack proposed as an initial framework of the thesis to build a better understanding of the solar parameterizations and their limitations. This means to split the total error in the determination of the solar outcomes as the sum of different contributions such as errors from clouds, errors from aerosols, errors from the scheme itself, etc. At the same time, I was working as a Forecasting Specialist in a company called Meteosim Truewind that over the years became AWS Truepower. My tasks were mostly oriented in the statistical methods for improving the wind and solar forecast and I really wanted to recover a more physical oriented research.

One of the indications that the topic of the thesis was of the interest of the scientific community as well as of the industrial sector is the large number of publications and works that have appeared during the development of this thesis by other researchers and groups. Probably, the greatest exponent of this interest is the WRF–Solar program (Jimenez et al., 2016). The WRF–Solar is a project developed by the National Center of Atmospheric Research (NCAR) and other institutions with the idea of improving the solar fields outcomes oriented to the solar industry requirements. Under this umbrella, the treatment of the aerosols and clouds for solar radiative transfer purposes has been improved significantly. Concurrently, new variables such as the direct and diffuse components of the irradiance have been included as an output of the model, after including minor changes in the code. In this sense, the work presented in this thesis has contributed to the development of the WRF–Solar as we will briefly explain in Appendix A and more deeply in other parts of the thesis. The exhaustive work performed by the WRF–Solar group regarding the aerosols and the lack of a common methodology for all the schemes, makes us treat the aerosols in a tangential way in this thesis, focusing to other aspects of the radiative transfer problem.

Following the state-of-the-art, our initial idea was to launch a set of simulations around the world and validate the outcomes against real measurement, searching the physical reasons of the results. Nevertheless, this approach soon met some issues that made us reconsider the project. First, a full simulation presents many degrees of freedom (e.g. microphysics options, initial conditions, among others) that makes a full control of all of them difficult. Second, the analysis of long-period simulations (e.g. 1 year) for a set of sites is interesting from a pragmatic point of view but it diffuses a physical comprehension of the results. In other words, in our understanding, it offers interesting results for a product but it is not pertinent for a thesis project in physics. Finally, solar schemes are not isolated components within the model and hence, they interact with the other modules limiting a systematic comparison of the results of different parameterizations from the perspective of the scientific method.

Therefore, the approach of the thesis was reconsidered and a decision was made to focus upon the solar parameterizations and leave aside the interactions of the schemes with the full NWP model, which will likely be explored in future work or in the development of industry-oriented applications. The first step consisted in reading and learning about the radiative transfer in the atmosphere and its coupling in mesoscale models, particularly, the WRF–ARW model. This model was chosen because it is a state of the art and open source model widely used in research and applications by a broad user community. Furthermore, this model has a large number of active developers that work in new schemes and options for the model. For example, the most recent version of the WRF model (i.e. 3.8.1) at the writing of this document has nine solar parameterization schemes. This point is interesting for the work that will be presented here because it allows a deep analysis of the methods for solving the RTE as well as of the existing parameterizations for the radiative variables as a function of the meteorological fields. Additionally, the WRF–ARW model is widely used for research and applications by a large number of companies and institutions and thus, a better knowledge of the radiative transfer schemes in this mesoscale model can be interesting for improving the accuracy of the final products. Although the above comments suggest that there are many practical applications of the investigation of this topic, the objective of this thesis is not the improvement of a specific product but instead it is the an advancement in the understanding of the physical processes contained in the NWP solar schemes and the limitations of each of the parameterizations.

Under this new research line, we studied the different schemes available in the WRF–ARW model, their approximations, assumptions, parameterizations and range of applicability, from an academia perspective (i.e. analyzing the based papers and reports) and from a more practical point of view (i.e. studying the translation of all these ideas in an algorithm written in Fortran). The thesis is focused on six of the nine solar schemes in the model: Dudhia, Goddard, New Goddard, Rapid Radiative Transfer Model for Global Circulation Models (RRTMG), Community Atmosphere Model (CAM) and Fu-Liou-Gu (FLG). The Geophysical Fluid Dynamics Laboratory

(GFDL) scheme was initially considered, but as the thesis progressed, this scheme was excluded because it is an old parameterization and it is not considered as the main schemes within the model. Although, this can deprive the users of this scheme the benefits of this work, in our understanding, the addition of this parameterization only introduces noise to the discussion without new or interesting results. The Hurricane WRF Radiation (HWRFRA) is omitted due to the low interest for solar resource purposes and because it is a particular version of the GFDL. The new version of the RRTMG, called RRTMG-fast, is not considered such as a separated scheme.

For the purpose of studying the shortwave schemes under the same conditions, we created a tool called *sandbox*. In the software development jargon, a *sandbox* corresponds to a programming environment in which a specific code is isolated from the main program and tested under different conditions. Basically, the idea is an analogy of the sandbox used by a kid, building and destroying sand castles. Following this idea, we separated the source code of the different schemes from the main model and we adapted them for working with 1-dimensional vertical profiles as input data-sets. Once we built this tool, we could design experiments by using ideal profiles (e.g. assuming a standard atmosphere) or real profiles from radiosoundings. The advantage of this approach is that solar schemes become independent of the sources of uncertainty derived from the other schemes of the model such as the microphysics. Consequently, schemes can be analyzed under the same conditions and testing multiple scenarios.

This thesis is conceptually divided into two major blocks. This first block describes the radiative transfer schemes and consists of Chapters 2 and 3. The second block identifies, describes and analyzes of sources of error in the schemes and consists of Chapters 4, 5 and 6.

Chapter 2 presents a brief theoretical introduction to the radiative transfer in planetary atmospheres and the common approximations necessary for coupling it in NWP models. This chapter is not a real contribution but, in our understanding, it is interesting as a summary of the approaches commonly used for building the solar schemes and it has been a part of my work for achieving the knowledge presented in this thesis. Moreover, the knowledge presented in this chapter has been improved with the learning obtained from studying the solar parameterizations. The most experimented researchers in the field can find this chapter superfluous. However, it can be an interesting introduction for new scientists in the field.

Although there are high accuracy methods for solving the RTE, they present important limitations to be coupled in a NWP model for two reasons. First, because a full treatment of the RTE requires a 3-dimensional integration of the scattered light considering the contribution of each particle in the atmosphere together with a high spectral integration of the spectral lines of each molecule. As the RTE must be solved at each grid-point and vertical layer, the process becomes unfeasible for an operational model and consequently, these methods have to be approximated. Second, because the solution of the RTE is expressed in terms of a set of magnitudes called radiative variables that are not a solution of the Euler equations and hence, they must be parameterized as a function of the meteorological fields available in the model by using empirical and/or theoretical relationships.

The different approximations available for solving the RTE and parameterizing the radiative variables lead to a wide range of solar parameterizations, being the literature a good example of this with papers such as Stephens (1984), Slingo (1989), Dudhia (1989), Fu (1991), Briegleb (1992) or Fu and Liou (1993), among others that will be presented later. As one can observe from these works, a great part of the shortwave schemes were developed during the 1980s and 1990s, when the interest of the NWP models was not the analysis of the solar resource. And particularly, it explains the different options available in the WRF model.

These differences are analyzed in Chapter 3. This Chapter describes six solar schemes in the WRF–ARW model. The review includes the theoretical fundamentals of each parameterization and the practical issues once an algorithm is implemented. Generally, the description of the basis of each shortwave scheme is split among a large number of papers and reports.

Moreover, in many cases there are significant differences between the original idea and the final code implementation. Therefore, Chapter 3 can be an interesting handbook for the scientific community for a better understanding of the physical aspects of the solar radiative transfer in the WRF–ARW and it can help to the future developers, as it has helped us to develop this thesis. Furthermore, this chapter presents a general overview of the solar parameterizations with information that only can be derived from the source code.

Afterwards of the description of the solar schemes in the WRF–ARW model, we proceed to discuss their limitations in Chapter 4. We differentiate two sources of inaccuracy in the results: sources of error and sources of uncertainty. The first one corresponds to all these elements that are directly related with the approximations described in Chapters 2 and 3 (e.g. solution of the RTE, parameterizations of the radiative variables), while the second one represents all these elements produced by the other components of the model (e.g. microphysics scheme). This thesis is oriented to the sources of error as an intrinsic limitation of the solar schemes. In addition, this Chapter includes a description of the methodology used for the study of the sources of error.

Finally, Chapters 5 and 6 present the set of experiments and results for the analysis of the sources of error. Further details regarding these chapters will given in the following section where the objectives of the thesis will be detailed.

1.2 Objectives of the Thesis

The main objective of this thesis is the identification and quantification of the sources of error that have a direct or indirect contribution to the accuracy of the shortwave parameterizations coupled in NWP models, particularly, in the WRF-Advanced Research WRF (WRF–ARW) model. The initial idea was to focus on the solar resource applications, this means the GHI, the Direct Horizontal Irradiance (DHI) and Diffuse Horizontal Irradiance (DIF). Nevertheless, the deep analysis of the physical aspects of the solar parameterizations performed in this thesis led to include more fields such as the vertical profile of the shortwave fluxes (i.e. upward and downward) as well as the heating rate profile as a consequence of the atmospheric absorption. This extended analysis of all the fields derived from the radiative transfer broadens the direct relevance of this work beyond the solar industry to larger community of NWP model developers and users.

The main original objective of the thesis was very ambitious. Consequently as the different studies were developed, we noted that we could not cover all the elements and we decided to work in detail in the following ones presented in thesis and leave as a future work the remaining ideas.

- **Documentation of the solar schemes** (Chapter 3): When we started working on the analysis of the solar schemes of the WRF–ARW model in 2011, the documentation related with the approximations of each parameterization was split among many papers and reports. Many of them from the 80s and 90s. The user's manual and the material presented in the tutorials by NCAR related with the solar schemes was simple, only showing a brief description of the main physical processes represented by each scheme. This information has been slightly improved in the last years, partly due to the development of the WRF-Solar project mentioned above.

  Therefore, the first step for understanding the limitations and the physical aspects of each parameterization was to read the related papers and the source code of each parameterization. As a consequence of all these studies, we developed a high amount of notes describing the different equations, approximations and algorithms used by each scheme. It is likely that the description of how the schemes are actually implemented in the WRF software is even more valuable because in many cases there are significant discrepancies between the published descriptions and the actual implementations.

This information was put together and presented in Chapter 3. We expect that this compilation, presented as a handbook, can be a useful contribution of this thesis for future developers or those users interested in more details of the physical approximations assumed by each scheme.

- **Identification of the sources of error** (Chapter 4): Once we understood the physical characteristics of each shortwave parameterization, the next step was to identify the sources of error that contribute to the inaccuracy of the results observed for example in studies such as Mathiesen and Kleissl (2011) or Lara-Fanego et al. (2012), among others. The objective was to identify the sources of error and express them as a linear sum of the individual contribution under the assumption that each is independent of the others.

  We distinguish two kind of contributions: sources of error and sources of uncertainty. The sources of error are limitations due to the set of approximations assumed by one scheme. The sources of uncertainty are those external aspects to the solar scheme that lead to lower overall accuracy in solar radiation forecasts or simulation. For example, if the NWP model has a spatial and temporal bias in the determination of the clouds then, the solar outcomes will show a large error, although it is not a direct problem of the shortwave parameterization.

  This thesis is focused in the analysis and the quantification of the sources of error associated to six solar schemes in the WRF–ARW model: Dudhia, Goddard, New Goddard, RRTMG, CAM and FLG while the sources of uncertainty will be reserved as future work.

  The discussion that will be presented in Chapter 4 leads to define three types of sources of error: i) errors due to the vertical discretization in a set of layers that are assumed as homogeneous (truncation error), ii) errors due to the misrepresentation of the layer between the top of the model (TOM) and the TOA (TOM error) and iii) errors due to the physical simplifications and parameterizations related with the RTE (physical error).

- **Methodology for a systematic comparison between shortwave schemes** (Chapter 4): The first idea for the analysis of the sources of error described in the previous paragraphs was the common approach consisting in running a set of simulations for a set of sites and periods and estimate some metrics. Although this approach is pragmatic for searching the best configuration of the model in real applications, it was not useful for analyzing the real limitations of these physical schemes.

  On the one hand, solar schemes in real simulations interact with the other components of the model by following high non-linear relationships (Montornès et al., 2015b). In other words, two distinct solar schemes under identical atmospheric conditions lead to different results that are propagated through the model leading to different atmospheric conditions at the next call of the solar module that, at the same time, will increase the differences between the respective outcomes. Hence, it is a vicious cycle that breaks down any attempt to perform a systematic analysis. On the other hand, in a full model simulation the different sources of error are more difficult to be isolated because all the atmospheric processes are overlapped.

  In order to avoid this problem, we present a different approach. The source code of each solar scheme is separated from the NWP model and adapted to work with 1-dimensional vertical profile. The advantage of this method is that we can design different experiments under identical and systematic conditions.

- **Analysis of the truncation and TOM errors** (Chapter 5): The study of these sources of error is performed proposing ideal vertical profiles. The reason for using these profiles is to facilitate the testing of the solar schemes under a range of vertical configurations.

  Given these profiles, a discussion about the sensitivity of the results against multiple number of vertical levels (from tens to thousands), different vertical distributions of the levels and a few number of TOM values is addressed. This study is performed under four distinct scenarios: a dry atmosphere following the International Standard Atmosphere of 1976 (ISA-1976), a wet clear-sky atmosphere and a cloudy atmosphere assuming low and high clouds composed of cloud water droplets and ice crystals, respectively.

  The discussion includes an analysis and comparison of the most important outcomes of the shortwave schemes such as the surface irradiances, downward and upward fluxes profiles and heating rate profile.

- **Analysis of the physical errors** (Chapter 6): The characterization of the physical error requires comparing the outcomes from the solar schemes with real measurements. These experiments are performed by using real soundings from the Integrated Global Radiosonde Archive (IGRA) data-set (Elliott and Gaffen, 1991) as input data for the sandbox tool and comparing the outcomes with the measurements from the Baseline Surface Radiation Network, BSRN, (Ohmura et al., 1998). One of the problems of this methodology is that the radiosonde data provides no information about the cloud properties (i.e. liquid water and ice concentrations). After exploring different approaches, it was decided to focus on clear-sky conditions and defer the analysis of the performance of the solar schemes under cloudy conditions to a future work.