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

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E pur si muove
Phrase attributed to Galileo Galilei

Perhaps some day in the dim future
it will be possible to advance the computations
faster than the weather advances and at a cost
less than the saving to mankind due to
the information gained. But that is a dream.
Lewis Fry Richardson

Compartirem misteris i desigs
d'arrel molt noble i secreta, en l'espai
de temps que algú permetrà que visquem.
Compartirem projectes i neguits,
plaers i dols amb dignitat extrema,
l'aigua i la set, l'amor i el desamor.
Ara mateix. Miquel Martí i Pol

Declaration of authorship

I hereby certify that the thesis I am submitting is entirely my own original work except where otherwise indicated. I am aware of the University's regulations concerning plagiarism, including those regulations concerning disciplinary actions that may result from plagiarism. Any use of the works of any other author, in any form, is properly acknowledged at their point of use.

Alex Montornès Torrecillas

Agraïments

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Resum

El transport radiatiu a l'atmosfera és la font d'energia principal del sistema climàtic, que determina l'estructura tèrmica de l'atmosfera i, per tant, la dinàmica. Així doncs, la representació d'aquests processos físics esdevé un component essencial dels models numèrics de predicció del temps (NWP) i dels models climàtics de predicció (NCP).

Tanmateix, el transport radiatiu no pot ésser resolt de forma explícita en els models atmosfèrics per dos motius: i) el tractament complet de l'equació de transport radiatiu (RTE) requereix una quantitat de recursos computacionals elevada i ii) el camps del transport radiatiu, com ara el gruix òptic, no són una solució explícita de les equacions d'Euler i, per tant, hom els ha de parametritzar mitjançant els camps meteorològics. Com a conseqüència, hom simplifica els processos físics relacionats amb la radiació i els aproxima en els esquemes físics.

En el cas particular de la radiació solar, l'ús d'aquestes parametritzacions en els models es va reduir durant anys a la representació del cicle dia/nit. En aquest context, la precisió dels esquemes solars quedava relegada a un segon pla i hom prioritzava els recursos computacionals. Aquest enfocament era suficient per a la majoria de les aplicacions meteorològiques més comunes (ex. predicció meteorològica) en les quals altres fonts d'errors, com la mida del pas de malla o les condicions inicials, eren més rellevants.

Amb el creixement de la indústria solar durant la darrera dècada s'ha produït un canvi de paradigma. Ara, la irradiància solar (i.e. horitzontal global GHI, horitzontal directa DHI i difusa DIF) esdevé un producte important, tant per a l'avaluació del recurs com per al pronòstic.

L'objectiu principal d'aquesta tesi és la identificació i quantificació de les fonts d'error que tenen una contribució directa o indirecta en la precisió dels esquemes solars, particularment, en aquells disponibles en el model Weather Research and Forecasting (WRF-ARW), àmpliament emprat en el sector.

En primer lloc, la tesi presenta una revisió del conjunt d'aproximacions considerades en sis parametritzacions disponibles en el model WRF-ARW: Dudhia, Goddard, New Goddard, Rapid Radiative Transfer Model for General Circulation Models (RRTMG), Climate Atmospheric Model (CAM) and Fu-Liou-Gu (FLG). Aquesta discussió inclou una comparativa de la representació dels processos físics (ex. absorció per ozó o dispersió per gotetes de núvol), així com una anàlisi de les discrepàncies entre els articles originals i l'algoritme finalment implementat.

A continuació, s'introdueix una discussió sobre les fonts d'error que contribueixen a la imprecisió dels resultats en els esquemes solars. S'identifiquen dues contribucions: i) les fonts d'incertesa i ii) les fonts d'error. D'una banda, les fonts d'incertesa són aquells factors externs a les parametritzacions solars que produeixen resultats negatius. De l'altra, les fonts d'error són limitacions en la representació del transport radiatiu com a conseqüència del conjunt d'aproximacions assumides per cada esquema. En aquesta tesi hi ha tres fonts d'error que són analitzades: i) l'error degut a la discretització vertical de l'atmosfera en un conjunt d'estrats que s'assumeixen homogenis (error de truncament, ϵ_{trun}), ii) l'error com a resultat d'una representació insuficient de l'estrat entre el cim del model (TOM) i el cim de l'atmosfera (TOA), anomenat error de TOM ϵ_{tom}, i iii) l'error degut a les simplificacions i a les parametritzacions físiques de l'RTE, definit com a error físic, ϵ_{phys}.

Per tal d'evitar la incertesa introduïda pels altres components del model, el codi font de

cadascun dels sis esquemes solars ha estat separat del model i adaptat per treballar amb perfils verticals 1-dimensionals. Mitjançant aquest mètode, les habilitats dels esquemes solars poden ésser analitzades sota condicions d'entrada idèntiques.

Els estudis de l'error de truncament i del TOM es realitzen mitjançant perfils verticals ideals considerant quatre escenaris: una atmosfera seca, una atmosfera humida amb vapor d'aigua, una atmosfera amb un núvol baix d'aigua i una atmosfera amb un núvol alt de gel.

El resultats per l'ϵ_{tom} mostren que pel rang típic de valors de TOM en aplicacions de mesoscala (i.e. ~10 hPa), l'error respecte a una columna atmosfèrica completa és menor al 0.5% i, per tant, hom pot negligir l'error del TOM. L'FLG i el Dudhia són els esquemes més sensibles perquè consideren un estrat transparent, mentre que la Goddard, la New Goddard i l'RRTMG són les parametritzacions més independents. La CAM és un cas entremig.

L'anàlisi de l'ϵ_{trun} revela que la sensibilitat dels esquemes solars a la configuració vertical (i.e. nombre de nivells verticals i la seva distribució) es troba directament relacionada amb el mètode emprat per a la integració vertical dels processos de multidispersió. El Goddard, el New Goddard i l'RRTMG són els esquemes amb la menor dependència a la configuració vertical, mentre que el Dudhia i l'FLG mostren variacions importants en els resultats quan el nombre de nivells verticals és menor a 100. Per les configuracions de mesoscala típiques, l'ϵ_{trun} en condicions de cel serè es troba al voltant de l'1.1%, el 0.9% i el 4.9% per la GHI, DHI i DIF, respectivament. En els dos escenaris amb núvols, l'ϵ_{trun} augmenta significativament, essent més important en el cas de núvols alts.

L'anàlisi de l'ϵ_{phys} es realitza en condicions de cel serè mitjançant dades de radiosontatges reals provinents de l'Integrated Global Radiosonde Archive i comparant les sortides dels esquemes amb les mesures del Baseline Solar Radiation Network. Amb l'excepció de la Dudhia, el comportament de totes les parametritzacions és el mateix. Una gran sobreestimació de la DHI juntament amb una gran infraestimació de la DIF que porta a un biaix proper a zero per la GHI. L'RRTMG mostra els resultats més precisos en les estimacions de la GHI i la DHI , seguida de la CAM i de la New Goddard. Els pitjors resultats els obtenen la Goddard i l'FLG. Per regions, les estacions polars (i.e. atmosfera neta amb un contingut d'aigua baix) mostren els errors més petits amb un MAE mitjà del 2.1%, el 5.2% i el 3.7% per la GHI, la DHI i la DIF, respectivament. Per contra, les estacions situades a latituds mitges obtenen els pitjors resultats amb un MAE mitjà del 3.4% en la GHI, de l'11.6

A part de les irradiàncies, la tesi mostra una discussió de les altres sortides radiatives que tenen un impacte en el model com són els perfils verticals dels fluxos (cap a baix i cap a dalt) i de la velocitat d'escalfament associada a la radiació d'ona curta.

El conjunt d'estudis desenvolupats en aquesta tesi porten a concloure que l'RRTMG és la parametrització amb les millors característiques per a les aplicacions d'energia solar.

Abstract

The radiative transfer in the atmosphere is the main energy source of the climate system shaping the thermal structure and hence, the dynamics of the atmosphere. Consequently, the representation of these physical processes becomes an essential component of the numerical weather prediction (NWP) and numerical climate prediction (NCP) models.

However, the radiative transfer cannot be explicitly resolved in the atmospheric models for two reasons: i) a full treatment of the radiative transfer equation (RTE) requires a high amount of computational resources and ii) the radiative transfer fields such as the optical thickness are not a direct solution of the Euler equations and hence, they must be parameterized in terms of the meteorological fields. Consequently, the physical processes related with radiation are simplified and approximated in physical schemes.

In the particular case of the solar radiation, the use of these parameterizations were reduced for many years to represent the day/night cycle inside the model. Therefore, the accuracy of the solar schemes was left in the background and the computational resources were prioritized. This approach was enough for most of the common meteorological applications (e.g. weather forecasting) in which other sources of error such as the grid size or the initial conditions were more important.

With the growth of the solar energy industry during the last decade, a paradigm shift has occurred. Now, the solar irradiance (i.e. global horizontal GHI, direct horizontal DHI and diffuse DIF) become an important product for resource assessment as well as for forecasting applications.

The main objective of this thesis is the identification and quantification of the sources of error that have a direct or an indirect contribution to the accuracy of the solar schemes, particularly, in those available in the Weather Research and Forecasting (WRF-ARW) model, widely used in the sector.

First, the thesis presents a review of the set of physical approximations considered in six solar parameterizations available in the WRF-ARW model: Dudhia, Goddard, New Goddard, Rapid Radiative Transfer Model for General Circulation Models (RRTMG), Climate Atmospheric Model (CAM) and Fu-Liou-Gu (FLG). This discussion includes a comparison of the representation of the physical processes (e.g. ozone absorption or cloud droplets scattering) as well as an analysis of the discrepancies between the original papers and the implemented algorithm.

Then, the sources of error that contribute to the inaccuracy of the solar scheme results are discussed. Two contributions are identified: sources of uncertainty and sources of error. On the one hand, the sources of uncertainty are the external aspects to the solar parameterization that lead to bad skills. On the other hand, the sources of error are limitations in the representation of the radiative transfer as a consequence of the set of approximations assumed by one scheme. In this thesis three sources of error are analyzed: i) errors due to the vertical discretization of the atmosphere in a set of layers that are assumed to be homogeneous (truncation error), ii) errors due to the misrepresentation of the layer between the top of the model (TOM) and the top of the atmosphere (TOA), called TOM error and iii) errors due to the physical simplifications and parameterizations in the RTE, named physical error.

In order to avoid the uncertainty introduced by the other components of the model, the source code of each one of the six solar schemes has been separated of the model and adapted for working with 1-dimensional vertical profiles. Under this approach, the skills of the solar schemes can be analyzed under identical input conditions.

The studies of the truncation and TOM errors are performed by using ideal vertical profiles under four scenarios: a dry atmosphere, a wet cloudless sky atmosphere, an atmosphere with a low water cloud and an atmosphere with a high ice cloud.

The results for the ϵ_{TOM} show that for the typical range of TOM values in mesoscale applications (i.e. ∼10 hPa), the error with respect to a full atmospheric column is less than 0.5% and hence, the TOM error can be neglected. FLG and Dudhia are the most sensitive schemes because they consider a transparent layer, while Goddard, New Goddard and RRTMG are the most independent parameterizations. CAM is an intermediate case.

The analysis of the ϵ_{trun} reveals that the sensitivity of the solar schemes on the vertical configuration (i.e. number of vertical levels and their distribution) is directly related with the method used for the vertical integration of the multiscattering processes. Goddard, New Goddard, CAM and RRTMG are the schemes with the lower dependence on the vertical settings while Dudhia and FLG show important variations in the results when the number of vertical levels is less than 100. For the typical mesoscale configurations, the ϵ_{trun} under clear-sky conditions is determined around 1.1%, 0.9% and 4.9% for the GHI, DHI and DIF, respectively. In both cloudy scenarios, the ϵ_{trun} increase significantly, being more important for the high clouds.

The ϵ_{phys} is analyzed under clear-sky conditions using real soundings from the Integrated Global Radiosonde Archive data-set and comparing the irradiance outcomes with the Baseline Solar Radiation Network measurements. With the exception of Dudhia, the behavior for all the parameterizations is the same. A large overestimation of the DHI with a large underestimation of the DIF that leads to a near-zero bias for the GHI. The RRTMG shows the most accurate results for the GHI and DHI estimations followed by CAM and New Godard. The worst results are obtained by Goddard and FLG. By regions, polar sites (i.e. clean atmosphere with low water vapor amount) show the lowest errors with a mean MAE of 2.1%, 5.2% and 3.7% for GHI, DHI and DIF, respectively. By contrast, midlatitude sites show the worst results with a mean MAE of 3.4% in GHI, 11.6

Beyond the irradiances, the thesis shows a discussion of other radiative outcomes that have an impact on the model such as the vertical fluxes profiles (downward and upward) and the shortwave heating rate.

The set of studies developed in this thesis lead to conclude that RRTMG is the parameterization with the best skills for solar energy applications.

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List of Acronyms

AER	Atmospheric and Environmental Research
AERONET	Aerosol Robotic Network
AOD	Aerosol Optical Depth
BSRN	Baseline Surface Radiation Network
CAM	Community Atmosphere Model
CFC	Chlorofluorocarbon
CKD	Correlated K-Distribution
CONUS	Continental US
CPU	Central processing unit
CSP	Concentrating Solar Power
DCS	Dry Clear-Sky
DHI	Direct Horizontal Irradiance
DIF	Diffuse Horizontal Irradiance
DISORT	Discrete Ordinates Radiative Transfer for a Multi-Layered Plane-Parallel Medium
DNA	Deoxyribonucleic Acid
DNI	Direct Normal Irradiance
ECMWF	European Center for Medium-Range Weather Forecast
FLG	Fu-Liou-Gu
GCM	General Circulation Model
GEOS	Goddard Earth Observing System
GFDL	Geophysical Fluid Dynamics Laboratory

GFS	Global Forecasting System
GHI	Global Horizontal Irradiance
GPU	Graphics Processor Unit
GSFC	Goddard Space Flight Center
HITRAN	High-Resolution Transmission Molecular Absorption
HWRFRA	Hurricane WRF Radiation
IASI	Infrared Atmospheric Sounding Interferometer
ICA	Independent Column Approximation
IGRA	Integrated Global Radiosonde Archive
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISA	International Standard Atmosphere
IWC	Ice Water Content
LBL	Line-By-Line
LBLRTM	Line-bBy-Line Radiative Transfer Model
LCL	Lifting Condensation Level
LES	Large Eddy Simulations
LSM	Land Surface Model
LWC	Liquid Water Content
Meso-NH	Meso Non-Hydrostatic
MICA	Monte Carlo Independent Column
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model
MODTRAN	Moderate Resolution Atmospheric Transmission
MOSAIC	Model for Simulating Aerosol Interactions and Chemistry
NAM	North American Mesoscale
NASA	National Aeronautics and Space Administration
nBias	Normalized Bias
NCAR	National Center of Atmospheric Research
NCP	Numerical Climate Prediction
nMAE	Normalized Mean Absolute Error
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NWP	Numerical Weather Predictor
OPAC	Optical Properties of Aerosols and Clouds

PAR	Photosyntetic Active Region
PBL	Planetary Boundary Layer
PIFM	Practical Improved Flux Method
RMSE	Root Mean Square Error
RRTM	Rapid Radiative Transfer Model
RRTMG	Rapid Radiative Transfer Model for GCM
RTE	Radiative Transfer Equation
SARAH	Surface Solar Radiation Data Set – Heliosat
SBDART	Santa Barbara DISORT Atmospheric Radiative Transfer
SCM	Single Column Model
SsiB	Simplified Simple Biosphere
SURFRAD	Surface Radiation Network
TES	Technology Experiment Satellite
TKE	Turbulent Kinetic Energy
TOA	Top of the Atmosphere
TOM	Top of the Model
TPW	Total Precipitable Water
TSO	Transmission System Operator
UCAR	University Corporation for Atmospheric Research
UTC	Coordinated Universal Time
UV	Ultraviolet Radiation
WCS	Wet Clear-Sky
WMO	World Meteorological Organization
WPS	WRF Preprocessor System
WRF	Weather Research and Forecasting
WRF-ARW	WRF-Advanced Research WRF
WRF-CHEM	WRF-Chemistry

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