IMPLEMENTATION AND VALIDATION OF WEATHER RESEARCH AND FORECASTING MODEL FOR MAINLAND PORTUGAL

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Abstract

Since 2002, the research group of Instituto Superior Técnico, MARETEC, has implemented the MM5 weather forecast model for mainland Portugal and provides daily numerical weather forecast, available at http://meteo.tecnico.ulisboa.pt. In addition, the outputs of the MM5 serve as a basis for other numerical models, namely MOHID, and for research purposes in various areas of environmental engineering. However, in 2008 MM5 was discontinued and replaced by its successor, the WRF.

The WRF model is a complex model and has a very diverse set of physical parameterization schemes, which allows, on one hand, to be able to choose and thus allow to adapt the outputs of the model to the real conditions of the domain and the period in study, but on the other hand, makes it difficult to choose the best subset from the universe of possibilities

The present work aims to implement the WRF version 3.9.1 for mainland Portugal and its validation, choosing the parametrization that best adapts to the real conditions, in order to replace the MM5.

Based on the calculation of statistical variables, it was implemented a methodology that allowed to validate the model and to choose the parametrization that best adapts to the real data, from a subset of options, previously selected. The comparison tests were carried out based on the data obtained from 10 SNIRH meteorological stations, distributed homogeneously throughout the territory of mainland Portugal. On one side, the results obtained allowed to choose the best parametrization, but on the other side, they showed that it is necessary to consider a larger set of parametrizations for analysis in order to adjust the model outputs to the observed data as best as possible.

Keywords: meteorology, numerical weather prediction, WRF, parametrization, validation.

1 INTRODUCTION

A critical step in applying a numerical weather prediction model is the selection of the proper parameterization setup that will produce the best results. While certain combination of parameterizations are generally accepted as best performing, each model configuration must be tested and evaluated before using it for long term simulations. This becomes compelling as numerical weather prediction models continues to move to increasingly higher-resolution forecasts, which are computational costly (Skamarock 2004). In this study we examine the performance of WRF (Weather Research and Forecast model) model by performing six experiments using different parameterization schemes before using it for long term high-resolution simulations.

The WRF is a numerical modelling system oriented to atmospheric phenomena research and mesoscale weather forecasting. Its development began in the 90s and continues to this day as the result of a partnership between various research groups and US government agencies. Designed to be a leading edge in the art of atmospheric, flexible, portable and efficient simulation across multiple computing platforms, the WRF system is an open source software and available free of charge. The code was written in fortran with routines in C, perl and Bash, and part of the code comes from the MM5 model and some Advanced Regional Prediction System (ARPS) functions. The WRF is a non-hydrostatic dynamic regional model, which has the capacity to have multiple embedded domains, data assimilation in four dimensions (x, y, z and t), portability in several computational platforms and various physical parametrization options. The parametrizations are specific models that relate the physical processes to the prognostic variables into the dynamic equations. Its coupling to a dynamic numerical model translates into calculation schemes that serve to estimate the effect of a certain physical process on the variables solved, in the first instance, by the dynamic model. Its effect is to modify the current values of these variables at regular intervals of time. Although an atmospheric model is based on its dynamic core, parametrization is an important factor when it comes to realistically simulating weather phenomena.

One of the most important and difficult tasks in numerical modelling is the validation of model solutions. The validation seeks to increase the credibility of the model, producing results that represents, as close as possible, the behaviour of the real system. The method of validating the solution of an atmospheric model to different parametrization schemes of a particular physical process is not trivial in the sense that it is not always possible to draw general conclusions about the effect of the modification tested. Any new embodiment of the model that includes the variation of another constituent part may alter the results of the first test. This aspect is, in the first analysis, a consequence of the interaction between physical processes, with feedback mechanisms whose effects are impossible to predict analytically.

The methodology adopted consisted of varying six combinations of the possible options of the WRF v3.9.1 physical schemes, comparing the resulting predictions with a set of local observations of some surface atmospheric variables. This study reports to the month of May 2016 and to a geographic domain centred in Portugal, coordinates 40 ° N, 8 ° W, with simulations extended to the Iberian Peninsula. The need to impose boundary conditions from a larger scale model, a characteristic feature of limited area models, raises the problem of domain sensitivity and other aspects related to the nesting of higher resolution domains.

Choosing between different options of different processes makes it difficult to choose a subset of the universe of possible combinations. In this work, we intend to evaluate the performance of WRF in the prediction of some atmospheric parameters of surface, air temperature, relative humidity, wind speed and precipitation, and to determine which parametrization best adapts to the real conditions in Portugal, using statistical parameters and a set of ten surface meteorological stations for comparison with the model results.

2 WRF MODEL: DATA AND METHODOLOGY

Initially it is necessary to make several decisions regarding the implementation of the model. From the choices made, all will have direct or indirect effects in solving the dynamic equations of the model. The sensitivity tests allow us to determine the effect of the choices made for the implementation of the model and its results. However, it is certain that less correct choices in the parametrizations determine worse results in the values of the output variables of the model.

2.1 WRF CHARACTERIZATION

Version 3 of the WRF supports a variety of capabilities, including real-world data simulations and idealized simulations, multiple boundary condition options, complete physical options, multiple filtering options, data assimilation, regional and global applications. The model is divided into 4 main groups: organization and preparation of external data, pre-processing of input data (WPS), model core (WRF) and output data post-processing. The WRF needs external data that characterize the domain's involvement in time and space, namely terrestrial data of topography, land use, land cover, albedo, etc. and meteorological variables that allow to define the initial and boundary conditions. Figure 1 shows the WRF data flow.

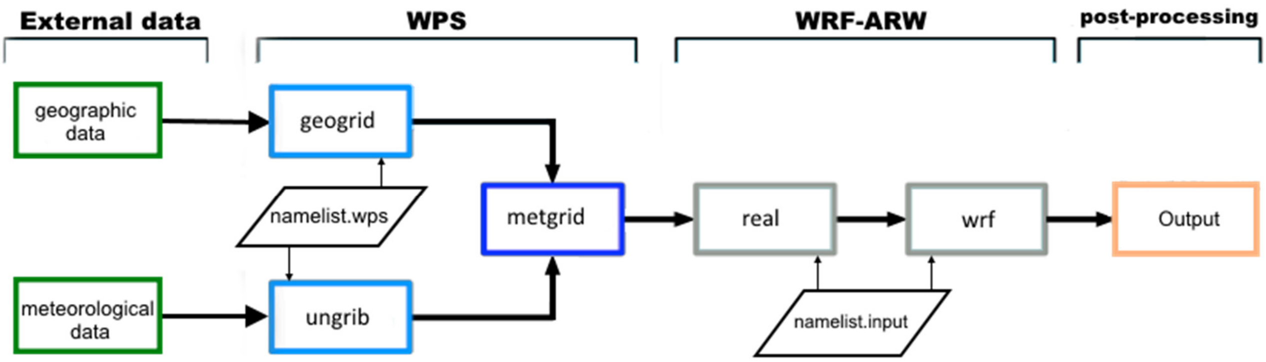


Figure 1 - WRF model data flow

2.2 DOMAIN

The domain is the rectangular physical space represented by a three-dimensional mesh in the model space of calculation. The mesh spacing (which in the model is equal in both directions, $\Delta x = \Delta y$) and the number of nodes determine their dimensions. The position of the mesh in the earth globe can be defined by the coordinates of longitude and latitude of the geometric centre of the domain or by another point of the mesh. The precise orientation of the domain is defined by the meridian that must be aligned with the y-axis in a given position x of the mesh.

The WRF has 4 projections whose choice depends on the domain latitudes: Mercator; Lambert Conformal Conic; Polar Stereographic; and Regular Latitude-Longitude.

The domain is fixed to increase the resolution for a given area, where more precise meteorological information is needed, for example in an area with irregular topography, stocks of many lakes, etc. For these areas, the distance between mesh cells must be reduced and therefore more calculation points are available. For other areas with regular topography, such as oceans or areas of lesser interest, such as deserts, high resolution calculation is usually very expensive and the use of global models is sufficient. On the other hand, the domain is embedded in a larger domain that provides the initial and boundary conditions for the calculation.

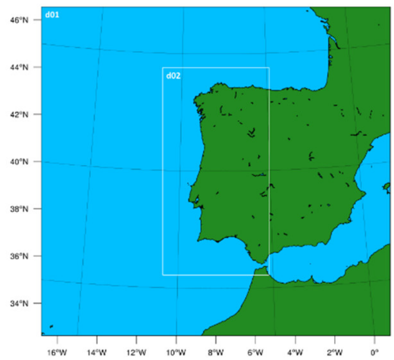


Figure 2 – Domains used in the simulations

Following a telescoping logic in the choice of simulation domains, the nest domain, which theoretically allows greater spatial resolution, has been defined to cover the territory of Portugal, but considers the border a little far away so that phenomena of predictions that are only solved at the finer scales, have time to develop through their interaction with the terrain. Thus, the parent domain was defined for an area encompassing the entire Iberian Peninsula and an extensive surrounding maritime range. Both domains are centred at 40 ° N, 8 ° W coordinates (**Figure 2**).

2.3 Vertical and Horizontal Discretization

The vertical description is defined by levels and for each level is defined a value of the vertical coordinate sigma, σ, in turn defined in relation to the hydrostatic pressure component, proportional to the mass of the air column that extends from the level to the upper boundary of the model, divided by the mass throughout the column, *ie* mass from the surface of the terrain to the upper limit of the model. Thus, the vertical coordinate system is of the terrain-following type and considers the top of the atmosphere a constant pressure surface.

The coordinate σ allows the lower atmosphere layer of the model to be represented, for each point of the mesh, by a horizontal step to follow the contour of the terrain for all types of topographic regions. This coordinate is defined by the following expression (Skamarock, *et al*., 2008):

$$\sigma = \frac{P_h - P_{htop}}{P_{hsup} - P_{htop}} \tag{2-1}$$

where P_h is the hydrostatic component of the pressure, P_{hsup} is the surface pressure and P_{htop} is the constant pressure value at the top of the model.

The horizontal discretization is done by means of outdated meshes in the space of type Arakawa C, whose components u, v and w of the wind are solved in the boundary points of the mesh. In turn, the thermodynamic variables are defined in the centre of the mesh.

The mesh size of the parent domain is 24 km [(70X) × (66Y)] and that of the nest domain is 8 km [(64X) × (124Y)]. The number of vertical levels (equal in both domains) was set at 35. In order to discriminate as best as possible the lowest layers of the atmosphere, the vertical sigma levels of the WRF were set manually between 0 and 1, giving a smaller spacing, in the first layers, adjacent to the surface, and larger in the intermediate layers.

2.4 Temporal Discretization

The WRF uses a time integration scheme described by Wicker and Skamarock (2002), where a time-split type integration is used, in which low frequency modes are integrated using the 3rd order Runge-Kutta scheme, while the horizontal high-frequency modes are integrated with a forward-backward scheme and the vertical high-frequency modes with an implicit vertical scheme using Δt of the high-frequency waves.

As it is impractical from a time point of view to carry out many WRF simulations over a long time period, it was necessary to make a prior selection of a limited number of simulation days. Assuming that a regional scale model should be able to reproduce the windings of the meteorological time, it was decided to simulate the month of May 2016, due to its variable weather conditions. During this period of time there were large thermal amplitudes, relative humidity and wind speed also presented variable values and, also, the occurrence of strong precipitation.

2.5 Initial and Boundary Conditions

In real applications, either in the weather forecast or in the past time simulation, the WRF, as a limited area model, requires boundary conditions that represent, as best as possible, the state of the surrounding atmosphere over the integration time of the dynamic equations. These conditions are provided from the output values of a global model, which considers the entire globe. The initial state is defined from the analysis values at the vertices of the global mesh. On the other hand, the global forecast allow the advance of forecasts made by the limited area model. Since the interest of a mesoscale model begins where another larger scale model is unable to solve the equations with the desired detail, it is natural that the regional model has a much more refined mesh than the model that gives it conditions. However, the difference between resolutions should not be too pronounced, given the problem of spatial and temporal definition of boundary conditions. For reasons of numerical optimization, the difference of 1/3 of the resolution proves to be the correct choice to fit between models.

Even if the meteorological data is the only one that comes from a global model, the refinement operated by the limited area models relies on two improvements:

a) The improvement of the dynamic equations;
b) A better representation of the terrestrial surface, achieved at the expense of a higher resolution of the topography and other physiographic parameters, such as the albedo, the type and use of the soil, the land cover, etc.

The detailed description of the interaction between the orography and the atmosphere and the non-hydrostatic formulation of the dynamic equations are considered as two key aspects for the success of the fine mesh models.

The performance of the WRF can be improved by a system of data assimilation that allows to optimize the calculation of the initial state and, consequently, to obtain a final solution closer to reality.

Climate Forecast System version 2 (CFSv2) 6-hourly reanalyses (0.2° × 0.2° lat.-long.) are employed as initial and boundary conditions of the coarse domain. NCEP (National Centre for Environmental Prediction) provides the SSTs at a horizontal increment of 0.083° × 0.083°. SSTs are kept fixed throughout the forecast. All simulations were initialized every two days at 0h hours with a spin up of 12h (Yang *et al.*, 2011) and the forecast horizon was defined in 48 hours.

2.6 Physical Parameters

In WRF, physical processes parametrization schemes are implemented in separate modules, organized in five main blocks: (i) MP - cloud microphysics; (ii) CP - convective processes; (iii) PBL - exchange and turbulent transport in the planetary boundary layer; (iv) LW and SW - radiation processes and (v) SL and LSM - soil-surface interaction (Skamarock *et al.*, 2005). The relationship between them is shown in Figure 4.

Use several physical parametrization together with the type of initial conditions and combining multiple numerical models is an interesting option to try to optimize the prediction system. In addition, it is a viable solution to verify the best combination of parametrizations to be used in operational models.

In general, it is not possible to decide the best combination of parameterizations by the performance indexes, since there is a great variation according to the meteorological event, domain region, season of the year and initial conditions.

The range of parameterizations offered by the WRF is enormous which makes its use increasingly complex from the point of view of calibration. For a qualitative description of the characteristics of the various schemes and for a list of fundamental descriptive articles see chapter 5 of the ARW User's Guide Version 3.

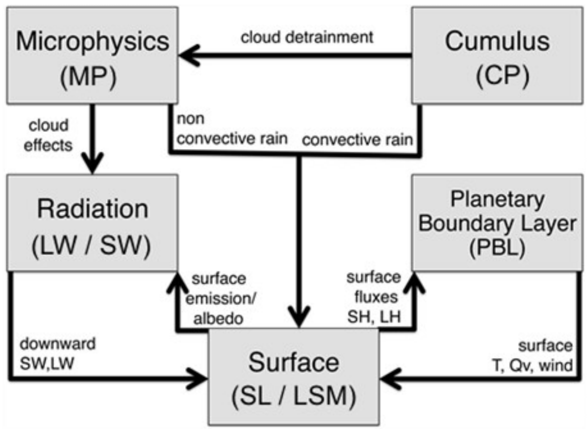


Figure 4 – Physical parameterizations interactions in WRF model

Table 1 shows the physical schemas selected for testing. For reasons of time, we opted to keep MP, LSM, LW and RW constant, varying only CP and PBL / SL.

Table 1 - Physical configurations in test

	MP	CP			PBL / SL		LSM	LW	SW
	WSM6	KF	BMJ	GF	YSU / MM5	MYJ / Eta	Noah	RRTM	Dudhia
P1	•	•			•		•	•	•
P2	•		•		•		•	•	•
P3	•			•	•		•	•	•
P4	•	•				•	•	•	•
P5	•		•			•	•	•	•
P6	•			•		•	•	•	•

2.7 Ground Data

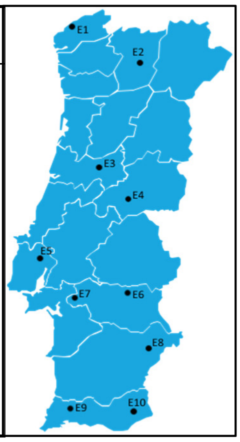
Topography, albedo, soil category, soil use, land cover, among others, were taken from the NCAR databases, using a fine-resolution data of 10’ resolution for the major domain and 2’ minutes resolution for the nest domain.

2.8 Statistical Evaluation

Statistical evaluation has been performed, using 10 available meteorological stations of the National System of Water Resources Information Network (SNIRH) which are located in the wider area of Portugal (Table 2).

Table 2 - Location of the SNIRH stations used for the evaluation

Site		SNIRH Code	Latitude	Longitude	Altitude
Vila Nova de Cerveira	E1	02E/02GC	41,939º	-8,737º	102 m
Vila Pouca de Aguiar	E2	05L/02C	41,4638º	-7,5898º	853 m
Penacova	E3	12G/05C	40,305º	-8,183º	182 m
Proença-a-Nova	E4	15J/01UC	39,748º	-7,929º	502 m
Alenquer	E5	19C/04C	39,14º	-9,084º	164 m
Santiago do Cacém	E6	26F/02C	37,841º	-8,622º	108 m
Vendas Novas	E7	22F/03C	38,5841º	-8,6164º	41 m
Serpa	E8	26M/01C	37,9481º	-7,4324º	223 m
Monchique	E9	30F/01C	37,3228º	-8,5946º	792 m
Picota	E10	30K/02C	37,174º	-7,68º	140 m



The fields of air temperature (ºC), relative humidity (%), wind speed (m/s) and precipitation (mm/h) were selected for analysis.

The mean square value of the error (RMSE) was calculated and translates the distance between the observed values and the simulated values:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\Phi_i^2} \quad \textbf{(2-2)}$$

where $\Phi_i = x_i^o - x_i^p$ represents the deviation between an individual forecast value (x_i^p) and an observed value (x_i^o), at the same location and at the same time, and N is the total number of checks performed.

Statistical analysis was performed separately for the sets of observations and for the period under review (May 2016). Since the study period has 31 days, a total of 7440 comparisons were made, per parameter and per parametrization. Assuming that the lowest error value represents the best compatibility between the simulated values and the observed values, the RMSE was used to determine the best parametrization.

3 Results and Discussion

More realistic forecasts means a lower RMSE in absolute value whereas the reverse is also true. The following tables show the calculated RMSE computed using aggregated values of the difference between forecasts and observations, for each parametrization under study. For each location, the parameterization with the lowest error is represented by the green color.

Table 3 - RMSE values for air temperature (° C)

Station	Air Temperature					
	P1	P2	P3	P4	P5	P6
E1	2.3	2.2	2.1	2.4	2.3	2.2
E2	1.8	1.8	1.5	2.0	1.9	1.7
E3	2.7	2.7	2.5	2.6	2.7	2.5
E4	1.8	1.9	1.7	2.0	2.0	1.8
E5	1.8	1.7	1.7	2.1	2.2	2.0
E6	2.0	1.9	1.9	2.3	2.3	2.2
E7	2.4	2.4	2.4	2.5	2.5	2.4
E8	1.9	1.9	1.8	1.8	1.8	1.7
E9	4.6	4.7	4.5	4.8	5.0	4.6
E10	1.6	1.6	1.5	1.9	1.9	1.8
Total	1	3	**9**	0	0	3

Table 4 - RMSE values for relative humidity (%)

Station	Relative Humidity					
	P1	P2	P3	P4	P5	P6
E1	11.5	11.4	11.0	12.0	11.5	11.8
E2	11.6	10.9	11.6	13.1	12.1	13.3
E3	14.7	15.3	14.2	13.3	14.3	13.5
E4	8.9	9.3	8.9	10.8	10.2	10.9
E5	10.8	11.1	10.7	11.0	11.4	11.0
E6	11.9	12.3	12.2	11.6	12.0	11.7
E7	16.2	16.8	16.4	14.3	15.0	13.9
E8	12.5	12.8	12.8	10.0	10.0	10.0
E9	13.5	14.8	13.3	12.5	13.9	12.2
E10	11.3	11.6	11.2	13.4	13.0	13.2
Total	1	1	**4**	3	1	3

Table 5 - RMSE values for wind velocity (km/h)

Station	Wind Velocity					
	P1	P2	P3	P4	P5	P6
E1	10.8	11.1	10.6	13.5	13.7	13.2
E2	10.4	10.8	10.4	12.9	13.2	12.5
E3	7.5	7.6	7.2	9.6	10.1	9.7
E4	10.9	11.7	10.8	14.3	15.0	14.1
E5	13.3	13.7	12.7	16	16.2	15.2
E6	16.0	16.1	15.6	18.5	18.5	17.8
E7	15.4	16.0	15.0	17.7	18.1	17.0
E8	13.9	14.4	13.4	15.6	15.9	14.9
E9	8.0	8.3	7.9	10.4	10.6	10.1
E10	16.4	16.9	16.1	18.8	19.2	18.2
Total	1	0	**10**	0	0	0

Table 6 - RMSE values for precipitation (mm/day)

Station	Precipitation					
	P1	P2	P3	P4	P5	P6
E1	9.4	7.9	6.1	8.1	6.6	7.1
E2	10.6	9.9	9.8	12.1	12.1	12.3
E3	7.3	3.3	5.7	9.5	4.3	5
E4	9.1	3.8	4.6	8	4.4	7.9
E5	6.2	8	5.4	6.2	7.6	7.1
E6	4.6	5.1	6	3.8	4.3	3.8
E7	10.8	6.5	4.6	8.2	8	5.9
E8	12.8	5.5	8.8	8.6	6.4	9.1
E9	3.4	6.4	15.1	3.3	6.5	10
E10	10	4	5.1	8.3	3.4	4.8
Total	0	3	**4**	2	1	1

Table 7 - Summary table with the number of times the RMSE was lower, for each meteorological variable and for each parametrization

	P1	P2	P3	P4	P5	P6
Air Temperature	1	3	9	0	0	3
Relative Humidity	1	1	4	3	1	3
Wind Velocity	1	0	10	0	0	0
Precipitation	0	3	4	2	1	1
Total	**3**	**7**	**27**	**5**	**2**	**7**

From the parametrizations under study, the parametrization P3 is the one that most frequently obtains the lowest RMSE, showing the parametrization that best adapts to the observed values (Table 7)

4 Conclusions

The work carried out allowed to demonstrate that WRF is a complex model and needs to be tested for its implementation in order to find the set of options which allows to obtain a solution of the model as close to reality. On the other hand, testing with the greatest number of parameters combinations available in the WRF becomes a rather complex work from a limited time.

When gathering comparisons of several places it was intended to give a reasonable representation, as far as possible of Portugal territory. However, the climate has important variations from North to South and from the coast to the interior. A geographically detailed study would potentially be more informative and typified weather conditions should be studied. It would be useful to extend the same type of regional tests to other variables such as mean sea level pressure and solar radiation. Increase of the study period with the incorporation of warmer periods (summer) and colder periods (winter) would be an added advantage to find the parameterization that best suits the meteorological conditions of Portugal.

In the hypotheses considered for the study, the parameter set CP GF and PBL/SL YSU/MM5 (Parameterization 3) showed to be the one that obtains the solution of the model closest to the observation values, for the period under study. Although we have found the parameterization that allows to maintain the best performance of the WRF, more tests should be performed, varying the remaining physical schemes (MP, LSM, LWR and SWR) and maintaining those that previously presented better results. Not having been the subject of this work, the assimilation of data should also be considered, for an improvement in the performance of the model.

Because further testing is possible, this work should be considered as a first step towards achieving the objectives initially proposed.

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