Numerical Weather Predictions Study of the Hurricane Katrina

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Abstract

The weather research and forecasting (WRF) is a numerical weather prediction (NWP) system designed to serve both atmospheric research and operational forecasting needs. In this project, the results of simulating the Katrina Hurricane event with real data are shown. Different options for parametrizing the problem and for doing multiple domain simulations are discussed and compared. We use 5 meteorological magnitudes to study the hurricane: Potential temperature, pressure and wind's direction, modulus and vorticity. The veracity of the results of the simulation is checked comparing in a qualitative way the real trajectory of the hurricane with the predicted ones. The time evolution of the previously named magnitudes is represented in gif format (see [1]), where we appreciate that both the predicted and the real trajectories are very similar.

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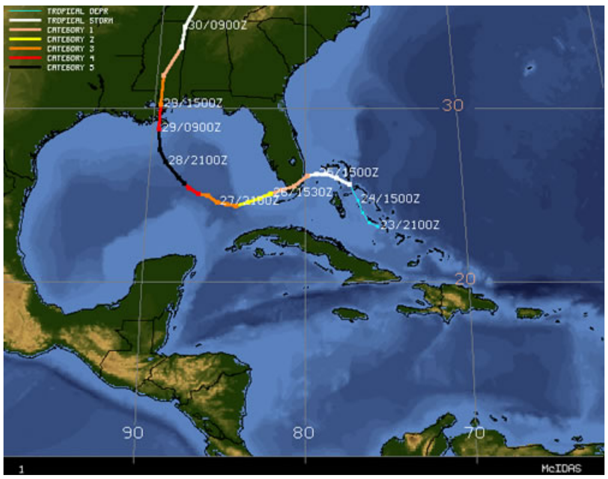
Contents

1 Case of study: the Hurricane Katrina

“Hurricane Katrina was an extremely destructive and deadly tropical cyclone that was one of the costliest natural disasters and one of the five deadliest hurricanes in the history of the United States” [4]. “Katrina first caused fatalities and damage in southern Florida as a Category 1 hurricane on the Saffir-Simpson Hurricane Scale. After reaching Category 5 intensity over the central Gulf of Mexico, Katrina weakened to Category 3 before making landfall, first in Lousiana and then in Mississippi” [5].

On the left of Figure 1.1 we can visualize the complete track that the Katrina’s Hurricane followed from the 23th to the 30th of August of 2005. On the right we see a real satellite image of the Katrina at a point where it was of Category 5 intensity.



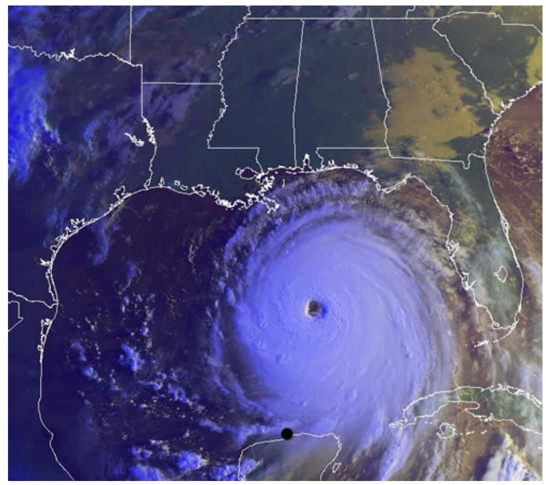


Figure 1.1: Left: Complete track of Katrina. Right: Visible image of Hurricane Katrina on August 28, 2005 at 7:19am as a Category 5 hurricane. Images courtesy of University Of Wisconsin - Madison Cooperative, Institute for Meteorological Satellite Studies [5].

The goal of this project is to run a WRF model with different parametrizations and nesting approaches using real data sets of the Hurricane Katrina for the period `28-08-2005` 00:00 h to `30-08-2005` 00:00 h.

In section 2 we describe the datasets available for our study, both qualitatively and via graphical visualizations. Section 3 is devoted to briefly explain the general procedure we have followed to run the WRF model for various simulations that are introduced in section 4, where we also summarize the basics about parametrizations and nesting concepts. In section 5 we present and discuss the results obtained from the simulations; we use graphical representations of different variables such as the perturbation potential temperature, the pressure and the wind direction and modulus, as well as the vorticity, and do a comparison between the different simulation approaches.

2 The Hurricane Katrina data sets

2.1 Qualitative description of the data sets

The dataset we are going to use for the simulation is from the hurricane Katrina event and it was obtained from the Global Forecast System (GFS). This is a global model that requires some initial conditions given by the observational data from around the world. It can be downloaded in the ARW Online Tutorial for the Katrina case.

The dataset consists in several files which contain information about the event every 6 hours during two days (from 28-08-2005 to 30-08-2005). It has 26 pressure levels (1000-10hPa) excluding the surface and it is a GRIB1 type data (which is seen how to work with later).

With this data we will be able to feed the WRF model with both initial conditions in order to solve the many partial differential equations from the 28-08-2005 and contour conditions, to let the model know what goes in and out of the region to study every several hours (every 6h, to be precise).

Thus, this data allows us to initiate the WRF model at any time (00, 06, 12 and 18h) between the 28th and 30th and run it up to the 30th introducing in it the contour conditions to let the model know what is happening outside from its domain.

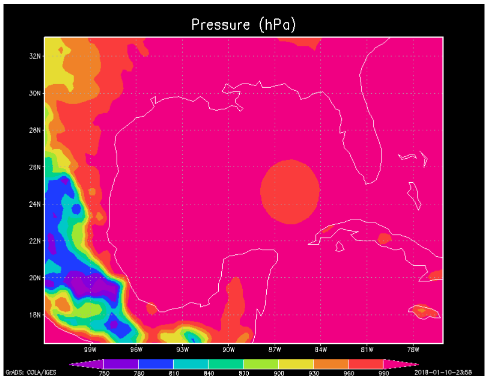
2.2 Data visualization

To familiarize with the data, here we present some interesting magnitudes that we will later refer to when presenting the results of our simulations and forecasts.

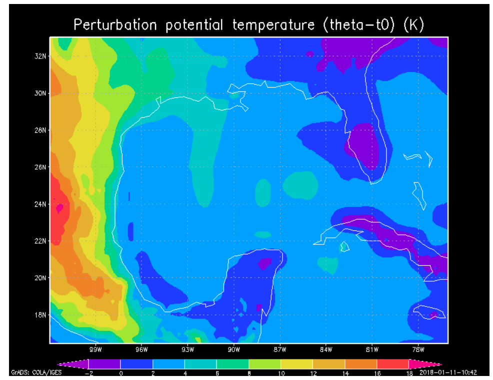
In Figure 2.1 we have displayed the pressure, the perturbation potential temperature, the vorticity and the wind speed modulus for the initial date, 28-08-2005 at 00:00h.

We see that vorticity and wind speed modulus are very helpful to prove the presence of the hurricane at this initial time. With the grid sizes that have been considered it looks like that the vorticity is maximal at the centre of the hurricane and decreases as one moves away from it: it is known that at the centre vorticity must ideally be zero. We will see that using a simulation with nesting these fact will then be observed. On the other hand, we observe that at this initial time the maximum wind speed in modulus occurs near the centre of the hurricane and in the north-west direction (red spot).

Another thing we can visualize is the wind direction by means of arrows, see Figure 2.2. We should have tried to reduce the density of arrows to a better visualization, but if we look at this figure closely, we would appreciate that the arrows near the hurricane are longer (which represents a larger modulus of the wind speed) as one could deduce from figure 2.1d



(a)



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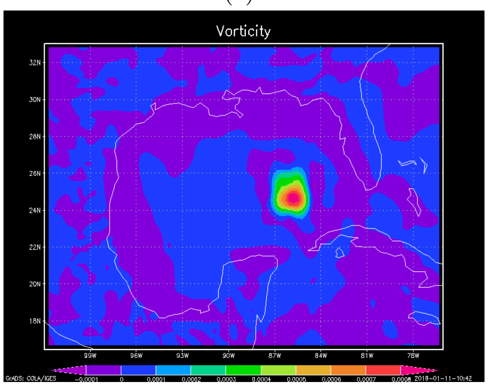
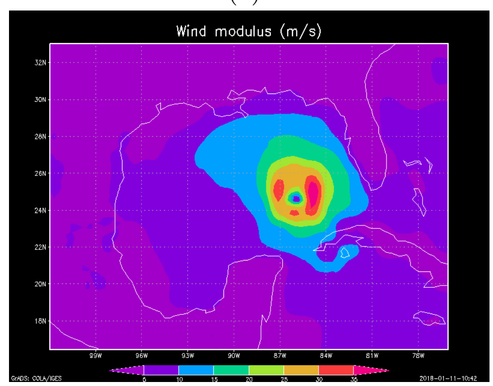


(c)



(d)

Figure 2.1: (a) Pressure in hPa (b) Perturbation potential temperature in Kelvin (c) Vorticity (d) Wind speed modulus in meters per second.

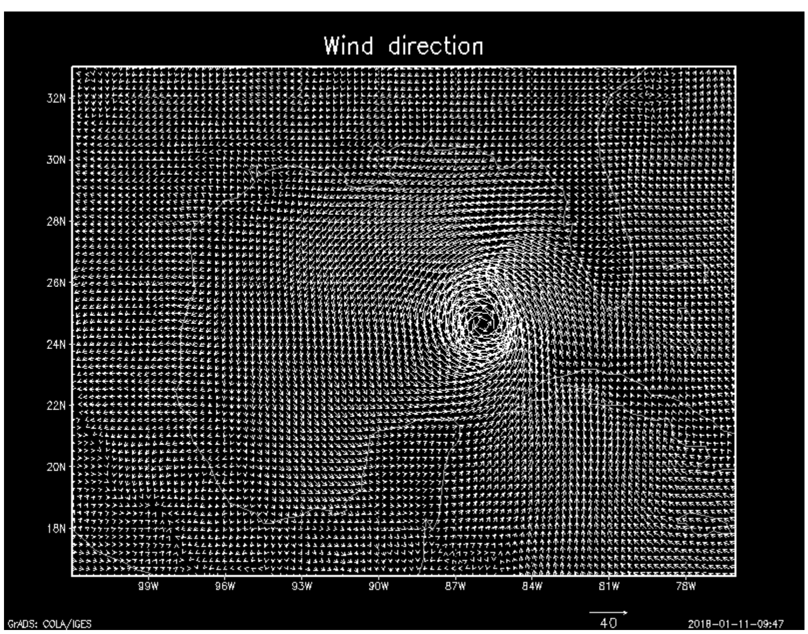


Figure 2.2: Wind directions for the initial date 28-08-2005 at 00:00h.

3 The WRF model: simulation procedure

The Weather Research and Forecasting model (WRF) is a numerical model for predicting weather for atmospheric research and forecasting. The Advanced Research WRF (WRF ARW) model contains several programs for initialization processes (ideal.exe and real.exe), a numerical integration program (wrf.exe) and a one-way nesting executable (ndown.exe). Some of its capabilities consist in performing real-data and idealized simulations, control of physics and boundary conditions options, nesting, among others.

In order to start the simulation process it is necessary to download, compile and install all the required programs and all the libraries that they need for its operation. This procedure (see Figure 3.1) has been performed following the tutorial in [2].

Once all required programs and libraries are installed a dataset to work with has to be downloaded. In this case we will be using the data presented in section 2.

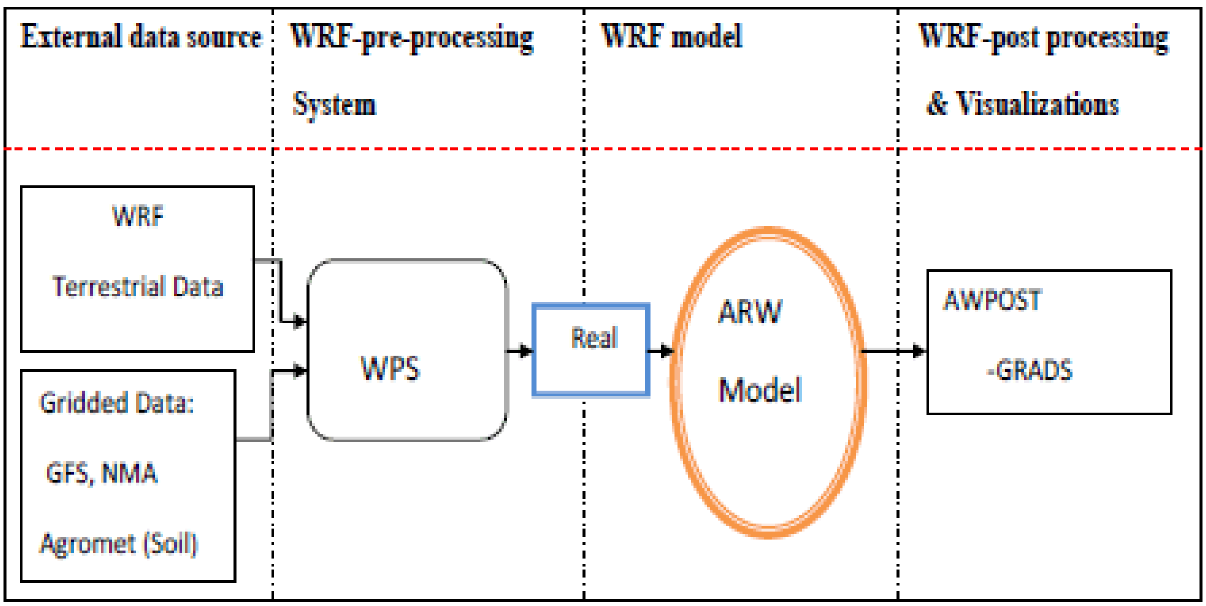


Figure 3.1: Scheme of the WPS ARW model functioning with input data introduction and post-processing.

The first step is to convert the downloaded data to files that the WRF model can understand. To do so, several things have to be done. They basically consist in using `geogrid.exe`, `ungrib.exe` and `metgrid.exe`.

`GEOGRID` defines the simulation domains and interpolates the downloaded terrestrial dataset with the model grid. Such domains are specified by modifying the file `namelist.wps`.

`UNGRIB` unpacks GRIB meteorological data and creates intermediate files. As before, the way the procedure is done is controlled by the user through `namelist.wps`.

`METGRID` interpolates the data obtained in the previous steps and generates files which are ready to be used by the WRF model. Again, it is controlled by the file `namelist.wps`.

Once the data is converted to files which the model can use, we can proceed to run it. It consists in two steps: executing `real.exe` and `wrf.exe`. The first one interpolates the files which were generated in the `METGRID` step and creates boundary and initial conditions files. Afterwards, we generate the model forecast by running `wrf.exe`. Both processes are controlled using the file `namelist.input`, in which we specify some important parameters, such as the total forecasting time, the period of new data inputting, the period of restarting files creation, the physics and dynamics of the forecast, among others. We will focus on some of these parameters when presenting the simulations we have performed in section 4.

Once these programs are executed, a file named `wrfout_d0*`, which contains data predictions for all the previously specified time periods is generated. Other restart files called `wrfrst_d0*` are also generated depending on the specifications in `namelist.input`. This file is almost ready to be post-processed using GrADS. However, it has to be, first, converted through `ARWpost`. `ARWpost` is a Fortran program that reads `WRF` outputs and generates files which are ready to visualize.

4 Characteristics of the simulations

In this project we will be predicting the weather in the same region and interval of time, but we can do this forecast in different ways depending, mainly, on the parametrization chosen, and on if we are doing nesting or not. Now we will explain what is the parametrization and nesting, and we will characterize the different runs of the WRF we have done for the Katrina case.

Parametrization

At the end of the day, what we are doing with WRF is numerically integrate a set of PDEs (Partial differential equations) with respect the time. This system of PDEs represents the time evolution of a physical system. The model from which we obtain these PDEs can have a set of approximations that simplifies the calculations, or make the results more precise. Depending on the conditions of the problem, some approximations may be inaccurate and a source of error, or not doing some approximations, could lead to a computational power inefficiency.

In `namelist.input` there are some variables that can have different values. Depending on the values, the WRF performs different approximations when forecasting the weather. The main parameters, and the ones that we will vary are:

- **Microphysics** (`mp_phsyiscs`): Different models depending on the precipitations. If there is snow, rain, ice, its a cloudy day, there is a mix of precipitations... We should use different values on this parameter.
- **Long wave Radiation** (`ra_lw_physics`): This parameter refers to the interaction between the atmosphere and the long wave radiation coming from the Sun. Depending on the presence of different gases in the region of the atmosphere that we are studying, different approximations will have to be done.
- **Short wave Radiation** (`ra_sw_physics`): The same that the previous one, but with short wave radiation.
- `radt`: minutes between radiation physics calls. In the WRF tutorial it recommends that `radt`=dx in km.

- **Surface layer physics** (`sf_sfclay_physics`): The surface layer is the layer of a turbulent fluid most affected by interaction with a solid surface or the surface separating a gas and a liquid where the characteristics of the turbulence depend on distance from the interface. In meteorology, surface layers are characterized by large normal gradients of the meteorological magnitudes. Different approximations will be performed in WRF relating to the turbulences originated in this area, depending on the value of this parameter
- **Land-Surface physics** (`sf_surface_physics`): The value of this parameter will determine which model WRF uses to take into account the interaction between the land and the atmosphere.
- **Boundary layer option** (`bl_pbl_physics`): The boundary layer is the lowest part of the atmosphere. Its behaviour is directly influenced by its contact with the land surface. On Earth it usually responds to changes in surface radiative forcing in an hour or less. In this layer physical quantities such as flow velocity, temperature, moisture, etc., display rapid fluctuations (turbulence) and vertical mixing is strong. The value of this parameter will determine which model we use to treat this layer of the atmosphere and moreover, it will constrain the value of `sf_sfclay_physics`.
- `bldt`: Minutes between boundary-layer physics calls (0=call every time step).
- **Cumulus physics** (`cu_physics`): Model used in the cumulus physics, the physics of the low altitude clouds formed by atmospheric convection. They are white, have flat bases and can grow in the vertical direction.
- `isftcflx`: Alternative Ck (exchange coefficient for temp and moisture), Cd (drag coefficient for momentum) formulation for tropical storm application.

Depending on the situation and the context of our weather forecast, we should give the appropriate values to these parameters in order to obtain the higher balance between precision/computation cost.

Nesting

With WRF we can do the weather forecast in a given region. WRF divides this region in a grid, and the precision of the calculus is higher as the grid gets narrower. Nests, are regions of the grid with a different precision. Usually, the regions were more complex or interesting meteorological phenomena are nested with higher precision.

There are different ways of nesting in WRF, and we nested in 3 different ways following the WRF tutorial for the Hurricane Katrina case [3]:

a) Two-way nested run, with one input file

b) Two-way nested run, with two input files:

  i) Use all the meteorological and static data for nested domains as input

  ii) Use only the static data for nested domains as input.

In our case, we will nest a region that contains the trajectory of the hurricane, increasing the precision of the simulation in this region.

4.1 Single Model Domain with a first parametrization approach

In these simulations we followed the tutorial step by step: we used the parametrization shown in the tutorial and we did not use any nests. The parametrisation for this run is the following:

- `mp_phsyiscs`=3 → WSM 3-class simple ice scheme: A simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes.
- `ra_lw_physics`= 1 → RRTM scheme: Rapid Radiative Transfer Model. An accurate scheme using look-up tables for efficiency. Accounts for multiple bands, trace gases, and micro-physics species.
- `ra_sw_physics`= 1 → Dudhia scheme: Simple downward integration allowing for efficient cloud and clear-sky absorption and scattering.
- `radt`: 30
- `sf_sfclay_physics`= 1 → Monin-Obukhov Similarity scheme: Based on Monin-Obukhov with Carslon-Boland viscous sub-layer and standard similarity functions from look-up tables
- `sf_surface_physics`= 2 → Noah Land-Surface Model: Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics.
- `bl_pbl_physics`=1 → YSU scheme: A first-order nonlocal scheme, with a counter-gradient term and an explicit entrainment term in the turbulence flux equation.
- `bldt`=0.
- `cu_physics`=1 → Kain-Fritsch (new Eta) scheme: deep and shallow sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale.
- `isfflx`=1 → With fluxes from the surface.
- `ifsnow`=1 → With snow cover effect.
- `icloud`=1 → With cloud effect.
- `num_soil_layers`=4 → Noah land-surface model.
- `sf_urban_physics`= 0 → Activate urban canopy model (in Noah LSM only).

We did not use any nest, it is a single domain model.

4.2 Single Model Domain with a second parametrization approach

From the manual of the WRF we found an specific parametrization for high definition simulations for hurricanes. The parameters that we will change respect the previous model are:

- `mp_phsyiscs`=6 → WSM 6-class graupel scheme: A new scheme with ice, snow and graupel processes suitable for high-resolution simulations.
- `ra_lw_physics`= 4 → RRTMG scheme: Similar than RRTM but better for high precision simulations.

- `ra_sw_physics`= 4 → RRTMG scheme: Similar than RRTM but better for high precision simulations.

- `radt`: 10.

- `cu_physics`=6 → Tiedtke scheme: More precise scheme but more computationally expensive. Takes into account tropical effects.

- `isftcflx`=2 → Donelan scheme for Cd and Garratt scheme for Ck. Model used in tropical storms.

The difference between the first parametrization and this second one, is that now in the parameters we are using more precise models, so we assume that it will be more computationally expensive but accurate. Moreover, now the schemes take into account tropical effects and include possibility of snow, ice and hail (more extreme weather). We will use a single domain model too, so we will not use any nest.

4.3 Nested Model Simulation with the first parametrization approach

We will also do 2 simulations with 2 different nestings. We will nest the central part of the region that we will study, and we will increase the precision there (see Figure 4.1). We do it this way because it is the region where the hurricane stays more time, and it will allow us to study it with more precision. In both nested simulations we will use the first parametrization (parametrization given by default in the tutorial). The two nestings that we are going to do are the two-way nested runs, with two input files:

- Using all the meteorological and static data for nested domains as input. We will call it nesting i

- Using only the static data for nested domains as input. WE will call it nesting ii

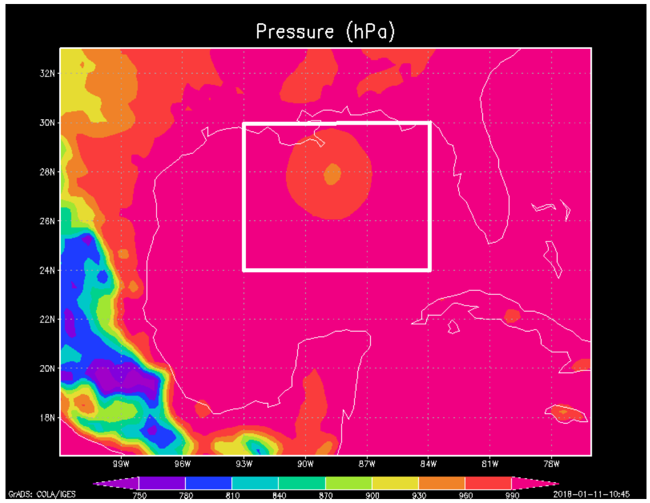


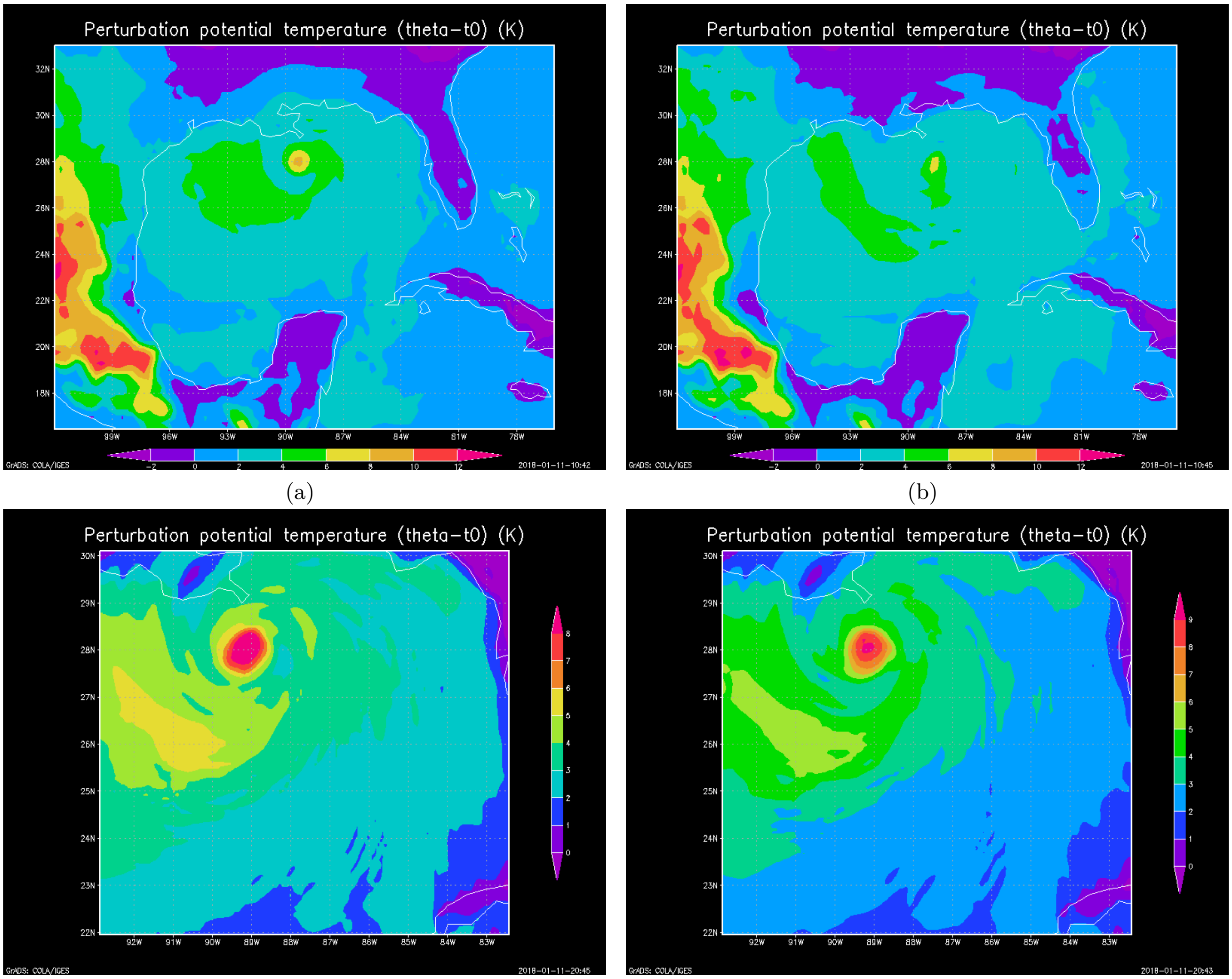
Figure 4.1: Plot of the pressure on a given time, the white box will be the region nested with more precision.

5 Results

In this section we show the results obtained in the simulations described in the previous section, and the comparison between the different characterizations. We will show the results as graphs obtained using the tool Grads. All the results can be visualized as giffs that have been attached to this report, and that can also be downloaded from the GitHub repository of our project [1].

We will divide the results in 5 subsections, and each subsection will be devoted to a different magnitude: perturbation potential temperature, pressure, wind's vorticity, wind's direction and wind's modulus, respectively. For each magnitude we will show plots corresponding to the 29th of august at 6:00h, in order to compare the 4 different simulations. For the nested cases, we will show a plot of the more precise domain.

5.1 Potential Temperature



(a) (b) (c) (d)

Figure 5.1: Plots of the potential temperature the 29th of August at 6:00h for the different simulations: (a) Single domain, first parametrization (b) Single domain, second parametrization (c) Multiple domain, nesting *i* (d) Multiple domain, nesting *ii*.

We plotted the potential temperature of the air, which is is the temperature that the air would attain if adiabatically brought to a standard reference pressure, usually 1000 millibars. Due to the differences of pressure that an hurricane produces, plotting the potential temperature we can observe the profile of the hurricane.

Here we can observe the big differences that are between the four simulations. The nested plots are more precise, and use a different scale. We can note the importance of the nesting and the parametrization on the final result of the simulation, since there exist huge variations around the eye of the hurricane depending on the parameters chosen, and the nesting approach used.

5.2 Pressure

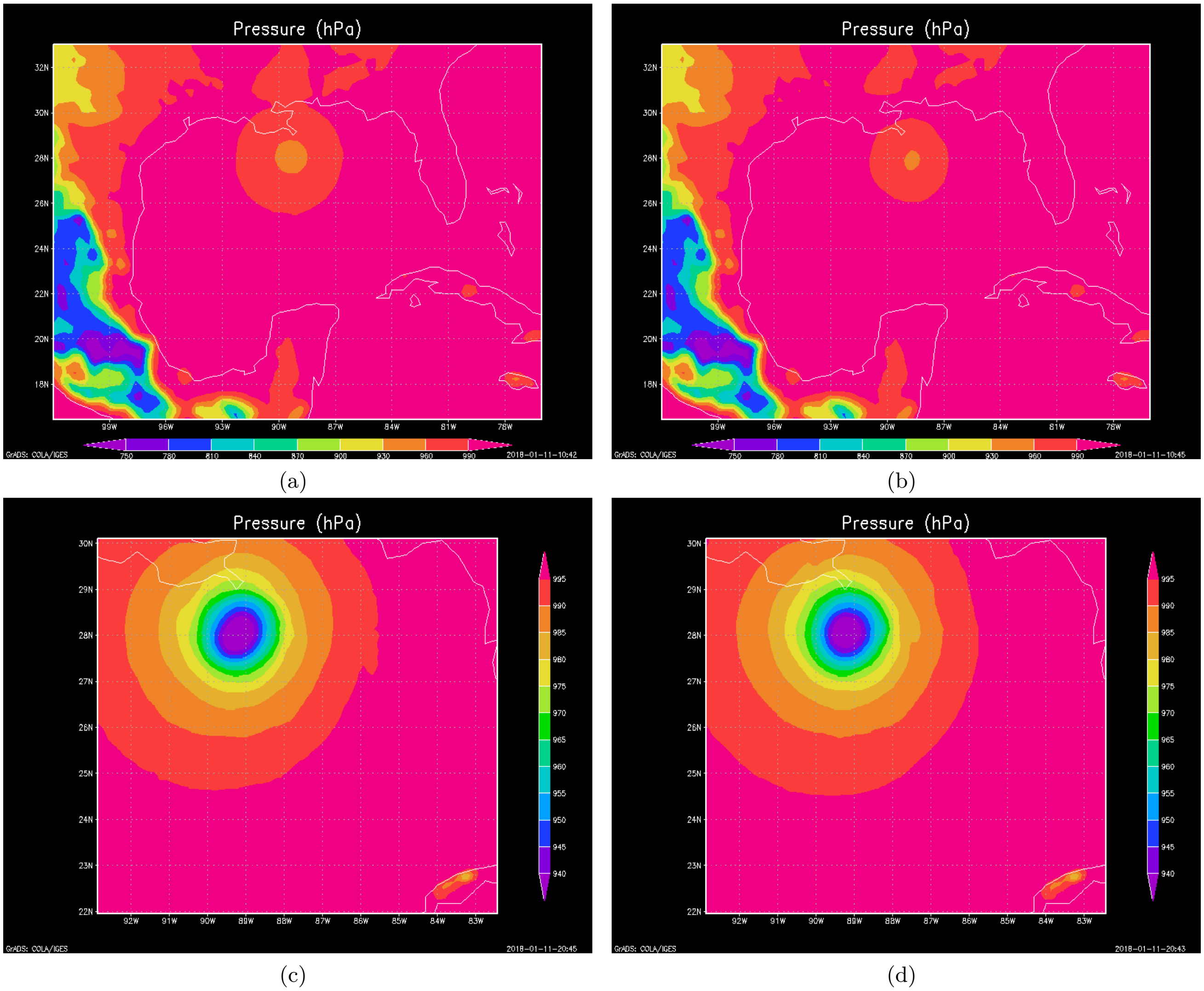


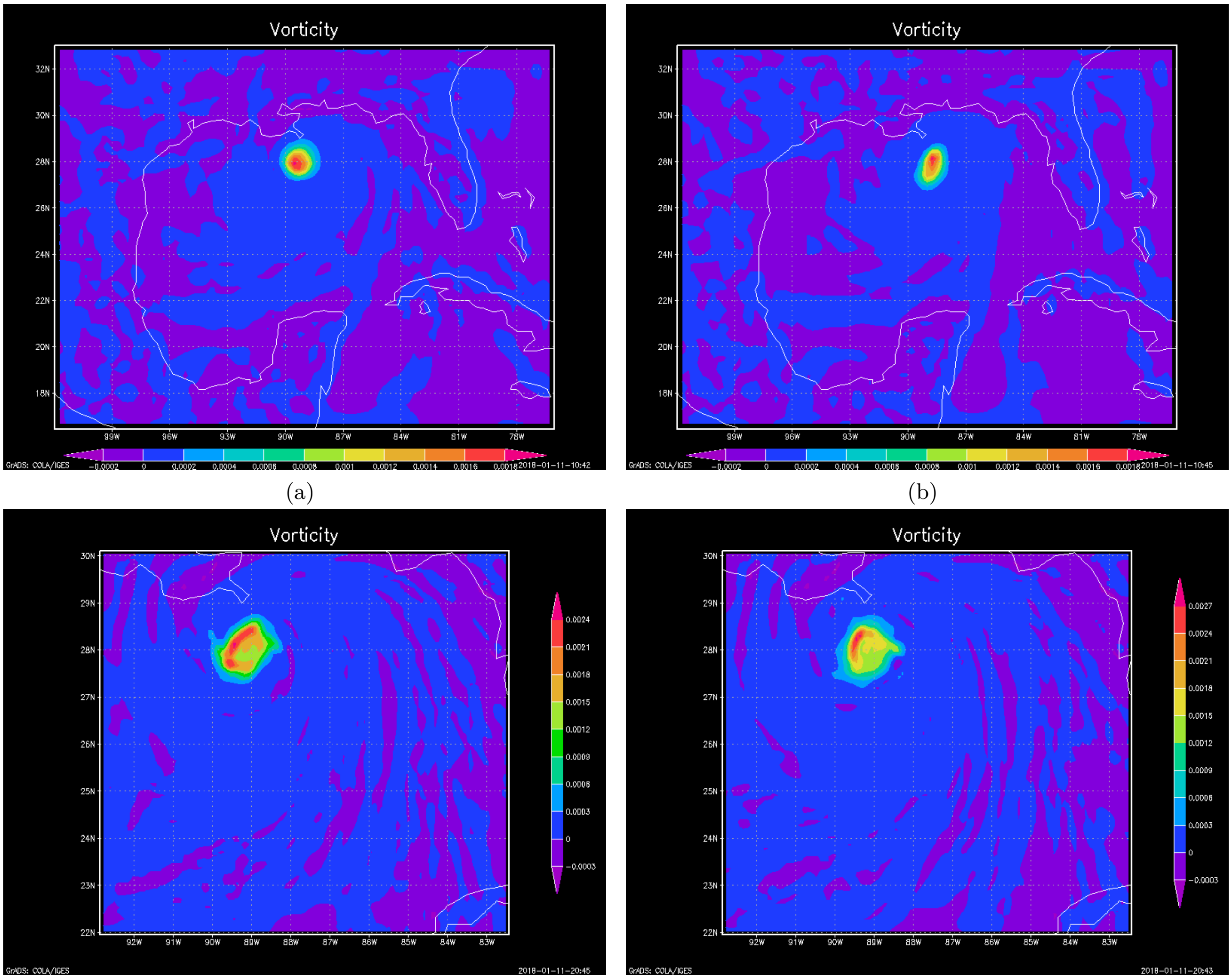
Figure 5.2: Plots of the pressure the 29th of August at 6:00h for the different simulations: (a) Single domain, first parametrization (b) Single domain, second parametrization (c) Multiple domain, nesting *i* (d) Multiple domain, nesting *ii*.

With this plots we can again localize the hurricane, and we can see the difference of pressure that produces its characteristic strong wind. We can observe that using the second parametrization we can localize the hurricane more precisely, and in a bit different position than with the first parametrization.

Checking the nested plots, we can not observe significant differences between them, but we can compute the pressure around the hurricane with more precision, while in the single domain simulations we only have a precision of 30 hPa, in the multiple domain simulations we have a precision of 5 hPa, which allows us to locate with more precision the eye of the hurricane.

We can also see that the centre of the hurricane is placed almost in the same place in the multiple domain simulations, and the single domain simulation with the second parametrization, while it is placed more in the west by the single domain simulation with the first parametrization. This may indicate us that using the second parametrization, we are getting more accurate results.

5.3 Wind's Vorticity

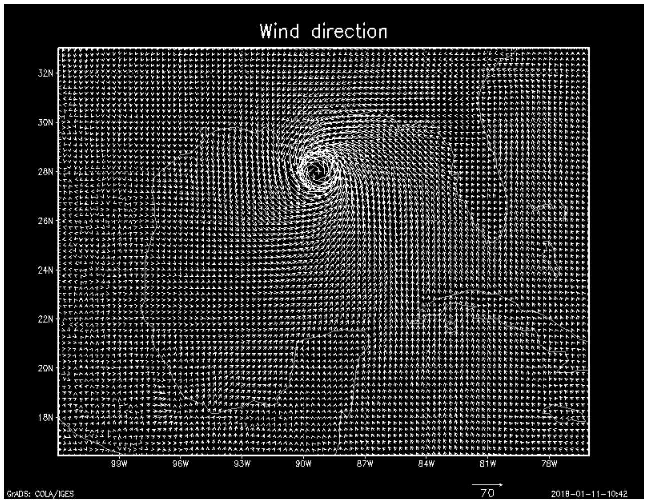


(a) (b) (c) (d)

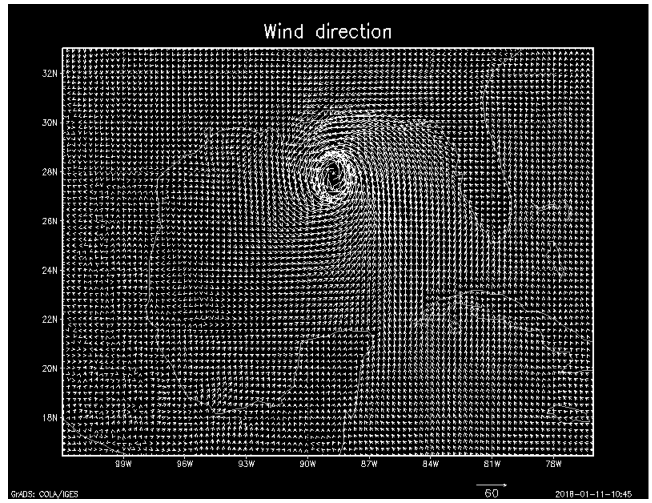
Figure 5.3: Plots of the wind's vorticity the 29th of August at 6:00h for the different simulations: (a) Single domain, first parametrization (b) Single domain, second parametrization (c) Multiple domain, nesting *i* (d) Multiple domain, nesting *ii*.

For this magnitude we can observe some interesting facts. In a hurricane, the vorticity in the centre should be 0, since ideally there is no wind in the eye of an hurricane. However, for the first parametrization without nesting, the maximum of vorticity is in the centre. This is a numerical error. For the second parametrization, we can observe that in the centre of the hurricane there is a spot where the vorticity is lower (so the maximum is not in the centre). In the nested versions, with the first parametrization, we can observe that in the centre of the hurricane that the vorticity is much lower than in the surrounding areas, and we can also see that the vorticity is higher in the direction where the hurricane will advance.

5.4 Wind's Direction



(a)



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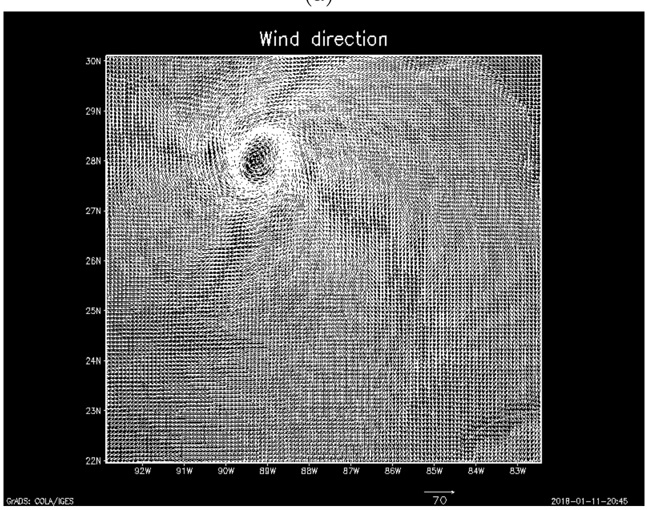
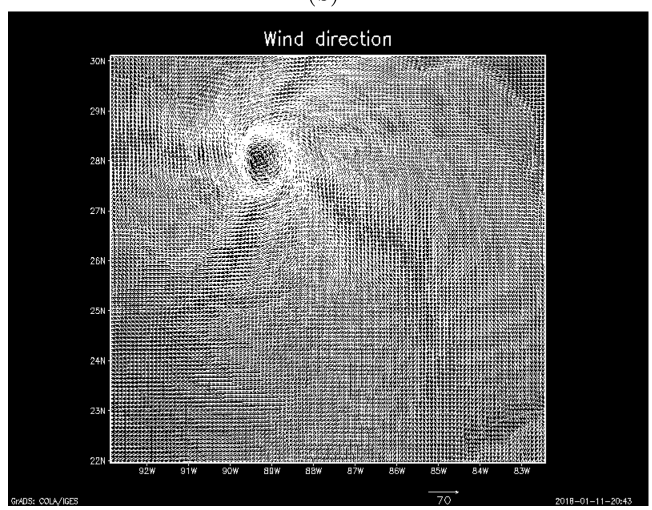


(c)

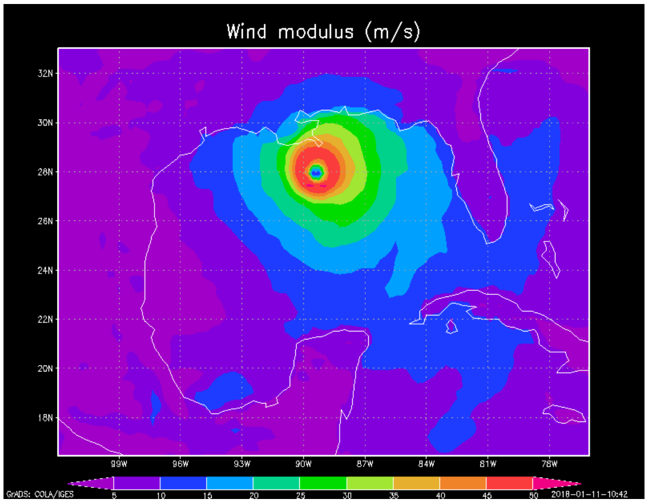


(d)

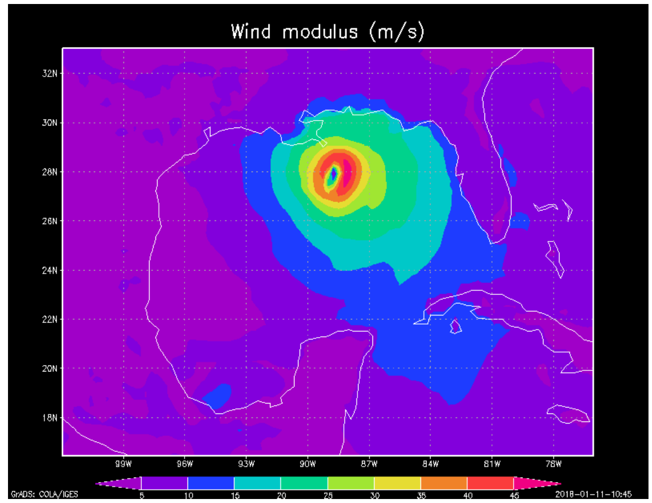
Figure 5.4: Plots of the wind's direction the 29th of August at 6:00h for the different simulations: (a) Single domain, first parametrization (b) Single domain, second parametrization (c) Multiple domain, nesting *i* (d) Multiple domain, nesting *ii*.

We could not make these plots easier to visualize, so there is not much to see. We can only observe that there exists difference between all 4 simulations, and that the wind in all the studied region spins around the eye of the hurricane.

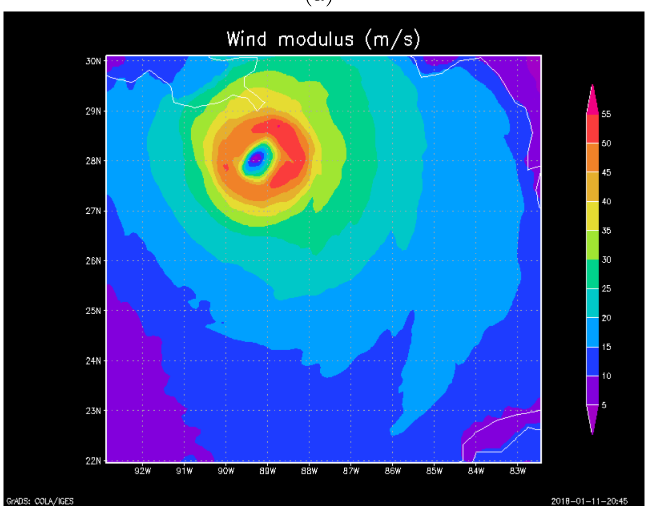
5.5 Wind's modulus



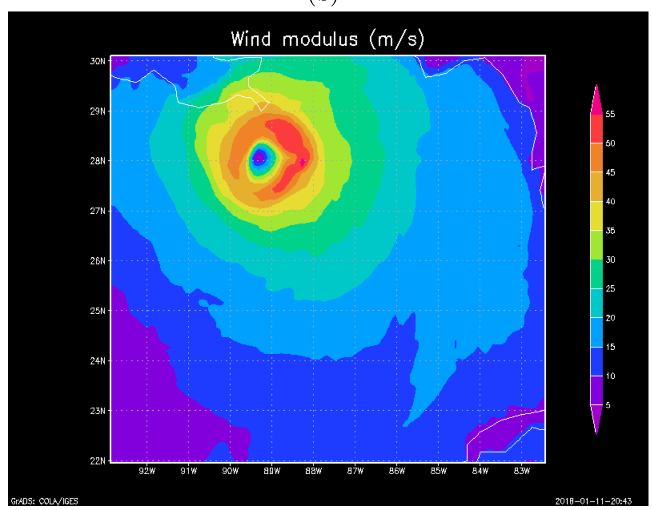
(a)



(b)



(c)



(d)

Figure 5.5: Plots of the wind's modulus the 29th of August at 6:00h for the different simulations: (a) Single domain, first parametrization (b) Single domain, second parametrization (c) Multiple domain, nesting *i* (d) Multiple domain, nesting *ii*.

The wind's modulus, refers to the maximum speed of the air in a given point. Strong and violent winds are the first thing that comes to your mind when you think on a hurricane. We can observe that effectively, in all the plots the maximum of the wind's strength is around the eye of the hurricane, while in the centre of the hurricane the wind is minimum, as expected (in the centre of an hurricane, theoretically, there is no wind).

Comparing the four plots, while in the first parametrization simulation with single domain we see that the wind's modulus is approximately radially distributed around the hurricane's wind, in the other simulations we can see that the wind's modulus at the east of the centre of the hurricane is larger than in the west.

6 Conclusions

After a tedious work on installing the WRF and all the necessary libraries, we “forecasted” the Katrina Hurricane which took place at the ends of August of 2005, using the dataset that we downloaded from the ARW Online Tutorial for the Katrina case [3].

We did 4 different simulations, using single or multiple domains, and changing the parametrizations. We used two different parametrizations: The parametrization given by default in the ARW Online Tutorial for the concrete case of the Katrina Hurricane, and the parametrization that is given in the WRF manual for hurricanes. We also checked the different parameters, looked for their meanings, and explained the differences between both parametrizations. We concluded that the second parametrisation should be more precise and accurate, although it would be more time consuming, as we in fact observed experimentally.

We also did multiple domain simulations, nesting in two different ways: The first one, a two-way nested run with two input files using all the meteorological and static data for the nested domains as input, and the second one, a two-way nested run with two input files, using only the static data for the nested domains.

We did one single domain simulation using both parametrizations, and a multiple domain simulation using both nesting techniques with the first parametrization. From all these simulations, we plotted the potential temperature, the pressure and the wind’s vorticity, direction and strength (modulus) every three hours, from the 00:00h of the 28th of August of 2005, to the 00:00h of the 30th of the same month.

We present all these plots in a giff format, attached to this report and which can be downloaded in our GitHub repository [1], so that one can observe the time evolution of the hurricane during all these days. We qualitatively saw that the trajectory is very similar to the real one: initially going to the west, and then to the north, landing on Luisiana. Hence, we can conclude that our forecast is pretty accurate.

We also plotted all the studied magnitudes, for the 4 different simulations, when the system has evolved for 30 hours, to see the differences between the different models. We concluded that the second parametrization is more precise although is more time consuming, and we also saw that the nested regions were computed with more precision, but again, consuming more time. However, we do not have enough information nor knowledge to determine which technique to do the nesting was better in this case.

As further work, we were interested in doing a comparison between the predicted trajectories of the simulations and the real trajectory followed by the Katrina. This would involve quite tedious image analysis and finding a source with the Katrina’s trajectory in the same coordinates/frame corresponding to the output images we have been considered so far.

References

[1] GitHub repository of the project, https://github.com/dsalgador/NWP-Hurricane-Katrina.

[2] Numerical Weather Predictions slides, Josep Ramon Miró.

[3] WRF OnLine Tutorial, The National Center for Atmospheric Research. http://www2.mmm.ucar.edu/wrf/OnLineTutorial/CASES/index.html.

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