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LIMITED AREA MODELS COUPLING ATMOSPHERE (MM5) AND OCEAN (POM) AND ITS APPLICATION IN SOUTHWEST SOUTH ATLANTIC BIGHT

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ABSTRACT

In this study it is presented the methodology to develop a coupled modeling system between atmosphere and ocean. MM5 (Mesoscale Modeling System – 5th Generation) and Princeton Ocean Model (POM) have been used as the basic tools for the proposed methodology. Interpolation routines were created, using Barnes (1964) objective analysis that was used as base method in order to exchange fields between the models. POM has been configured to transfer sea surface temperature to MM5, while it back with momentum flux and solar radiation. Results obtained from Ocean Data Assimilation (ODA) Experiment, developed by the Geophysical Fluids Dynamics Laboratory (GFDL) using the Modular Ocean Model (MOM), have been used as initial and boundary condition for temperature, salinity and horizontal velocity components. In the atmospheric Model the Global Forecast System (National Centers for Environmental Prediction - NCEP) analysis has been used as initial and boundary conditions, updated every six hours. Computational, and some physical aspects, of the coupled system are investigated for the Southwest Atlantic Bight. The results have shown some computational throughputs in interpolation routines when transferring fields between models. Both atmospheric and oceanic models have shown physical reasonable results related to that encountered in that region.

1. INTRODUCTION

The objective of this work is to develop and apply a coupled modeling system between atmosphere and ocean for the Southwest Atlantic Bight, including the region near shore Vitória-Trindade chain extending to Itajaí on 27°S latitude). The southeast area of Brazil shelters about 42% of the Brazilian population being responsible for more than 50% of GDP (Gross Domestic Product). The economy is the most developed and industrialized among the five Brazilian areas, also concentrating most of the Brazilian petroleum. The development and application of a coupled model that it includes this area as study object reaches the economic interests, once application would allow a better understanding of oceanographic and atmospheric features.

Heat, momentum and humidity changes between air and sea have been recognized as fundamental processes in the development of atmospheric features as tropical hurricanes, cyclones, boundary layer jets, coastal fronts, and precipitation systems. Numerical predictions of these features are critically dependent of a good representation of surface flows.

The atmospheric circulation can be influenced by sea surface temperature (SST) nuances. In many parts of the ocean, SST can be approximate as a local and unidimensional balance, where (at least an average of long term) SST is locally adjusted due to sensitive and latent heat lost and the balance between longwave radiation and shortwave radiation. However there are parts of the ocean where the oceanic currents affect SST in a more intensive way. Oceanic currents connect warm areas to those where happens lose of heat; the heat gained from atmosphere can be stored by many years and transported by thousands of kilometers before return to atmosphere. These currents are influenced by the atmosphere through the winds to surface or by the buoyancy effect. However, the atmosphere and the ocean interact strongly, and the coupled system cannot be understood considering those as an isolated system (Stuart and Rintoul, 1998).

Ocean-atmosphere coupled systems have been used mainly in climate studies and seasonal forecasts. For short period forecasts usually two weeks or less, it is considered satisfactory to use climatological SST or observed as initial condition for atmospheric models, and to keep it constant along the integration (Cohen-Solal et al., 1998). The premise for such is that ocean conditions changes occur in timescales larger than atmospheric and the information obtained with initial SST is valid for such period. By the way in cases of shallow and semi-closed waters the properties of the sea can vary quickly in function of the atmospheric variability, as in areas where islands and coast lines cause divergence in ocean top layers. There are oceanic processes that can influence the atmospheric conditions in timescales like a day (Gustafsson et al., 1998).

Some attention has been devoted to interactions with SST probably due it has been widely used as lower boundary condition, regarding the ocean, for atmospheric models. SST and wind surface act as ocean-atmosphere link, influencing the magnitude of the turbulent flows and the longwave net radiation flux (Weller et al., 2004). SST is also modulated by an interrelation of several factors. Among the most important there are the shortwave and longwave radiation, the sensible and latent heat flux, fresh water, and convection through the wind and waves interaction. SST variations can be considered as an effect caused either by atmospheric as oceanic processes (Katsaros and Soloviev, 2004).

2. MODELS

2.1 Fifth-Generation PSU/NCAR Mesoscale Modeling System – MM5

MM5 is the fifth generation of a series of atmospheric limited area models developed in a join effort between Penn State University and National Center for Atmospheric Research (NCAR). The first version documented date from the 70's decade (Anthes and Warner, 1978). Ever since it has been diffused and several versions have been released, with so many improvements and additions of different physical options. No-hydrostatic, with coordinated sigma-p in vertical, it was designed to simulate regional scale and mesoscale atmospheric circulation although it has already been applied even in global domains (Dudhia and Bresch, 2002).

The last version included grid nesting options (one and two-way), parallel processing versions (shared and distributed memory) and four dimensional data assimilation. One of the differentials when compared to other atmospheric models is the number of physical options in the code available through simple changes in the configuration files.

The code of MM5 is extensive possessing more than 200 subroutines and more than 50,000 code lines. It was written with the objective of being portable among the most several computational platforms. The model code was written in standard FORTRAN 77 with use of some FORTRAN 90 resources. It uses a high modular structure.

In the present work was included the microphysics parameterization taking into account the ice phase in the clouds, convection parameterization (Grell, 1993), shortwave and longwave atmospheric radiation, with effect of clouds included, and boundary layer parameterization proposed by Hong and Pan (1996).

2.2 Princeton Ocean Model – POM

The Princeton Ocean Model (POM) was used for ocean modeling. His development was initiate in 1977 by George Mellor (2003). It was developed in Atmospheric and Oceanic Sciences Program of Princeton University in a join effort with Geophysical Fluid Dynamics Laboratory (GFDL) from NOAA (National Ocean and Atmosphere Agency).

POM is a pseudo-three-dimensional with free surface model (vertically integrated) of primitive equations, solved by finite differences in curvilinear coordinates in horizontal and sigma-z in vertical. The prognostic variables are the horizontal components of momentum, free surface, temperature and salinity that join with continuity equation, the hydrostatic equation, the turbulent kinetic energy and the turbulence macroscale, composing model governing equations. It includes turbulence closure model level 2.5 (Mellor, 1982) joint the prognostic equation for the macroscale turbulence in order to obtain coefficients turbulence for heat and momentum.

The model has a free surface and a split time step. The external mode (barotropic) is two-dimensional and uses a short time step based on the CFL condition and the external wave speed. The internal mode (baroclinic) is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed.

Using common memory areas (COMMON BLOCKS), it was written entirely in FORTRAN 77, has simple structure and could be separated in three defined parts:

1 - Physical and mathematics constants definition;
2 - Numeric integration of equations, which calls functions for calculation of boundary conditions and advectives terms calculations;
3 - Model finalization with error analysis, storage of re-initialization information and model memory flush.

3. METHODOLOGY

The joining among models of different systems (atmosphere, lithosphere, hydrosphere, biosphere and cryosphere) can be faced as an alternative to creation of unified modeling systems, partly due the complexity that such code would reach and also to take advantage what already has been developed in each area.

Several joining methods exist among models, standing out the use of couplers, or flux couplers. Couplers are used in the process of information changes among the coupled systems, being included interpolations and grid adjustments when necessary. Some couplers include refinements such flow conservation check during simulation, systems synchronization and specification of when they should happen. Flux couplers are becoming popular as it has been applied and as new features have been included. The method when using the coupler is also known as component method. This one becomes more flexible as the components (models) can be substituted by others in needed.

Couplers have been used mainly in cases where models are global scale due to complexity that these computational systems can reach.

Another method is to merge many computational codes in a single one. This method is dissuaded (Gustafsson et. al., 1998) since it involves a larger effort in code adaptation, as well as in the difficulty in case of change models. In fact it becomes more efficient as the communication among the models is made through subroutines arguments. In this case, it is necessary a model to be in control while other works as a subroutine. One of the inherent difficulties to this method can be how to manager stack memory. It happens as the models can name variables with common names, therefore, subroutines need to be created to intermediate passage parameter among models, increasing the level use of the stack memory.

Coupled models can still be classified about how the information is changed, could be one-way when a model sends information for other, but it doesn't receive anything back, or two-way when the return of information exists; synchronous when the models start at the same time, or asynchronous when one start and at the end of his execution, another is initiate and forced with the fields generated by the first.

Here will be presented an atmosphere-ocean coupled system that works synchronous and two-way. For such was chosen to use the ocean model being a subroutine of the atmospheric model, after a deep code analysis.

Code characteristics revealed to be favorable to use that technique, however it yields the creation series of auxiliary subroutines in order to bring the models together (Figure 1).

Those auxiliary routines are shortly described below:

hold_mm5_momentum – Keep horizontal momentum fields in temporary arrays that can be accessed by both models;
hold_pom_temp – Keep temperature fields from ocean model, it calls interpolation routine and hold interpolated SST;
send_pom_sst – Stores SST in a temporary array that can be accessed by both models;
interp_driver_o2a – Performs calculations of parameters for the interpolation process when change of information happens in ocean-atmosphere way;
barnes_objan2 – Calculates generic parameters of interpolation process;
barnes_weight – Performs interpolation using four neighbors points to smooth;
mm5_hold – Keep SST interpolated at visible array in MM5 memory area;
recv_pom_sst – Transfers SST for MM5 that stores the surface temperature (over land and ocean), just filling out the values when on the ocean;
send_mm5_momentum – Sends horizontal momentum fields for interpolation process;
interp_driver_a2o – Performs calculations of interpolation parameters when the change of information happens in the atmosphere-ocean way;
pom_hold – Keep MM5 horizontal momentum interpolated at visible memory area in POM;
recv_mm5_momentum – Transfers horizontal momentum for POM that stores the 10 meters wind just filling out the values when on the ocean;

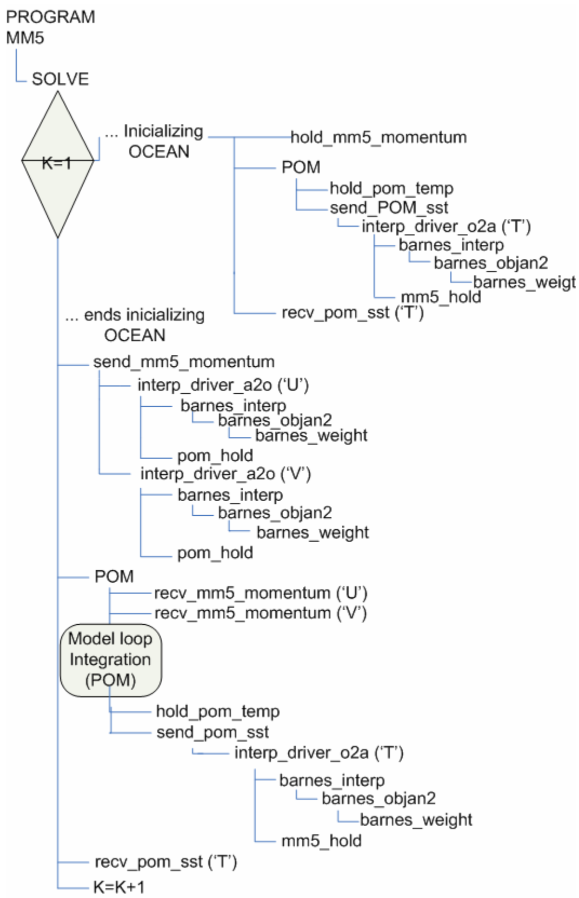


FIGURE 1 - FLOWCHART OF SUBROUTINES CREATED FOR COMMUNICATION K, MM5 STEPTIME AND SOLVE CONTROLS MM5 EQUATIONS SOLUTION.

Once the area of the domain of the models is approximately equal the interpolation is used with two purposes. One would be the necessary fine adjustment in function of the areas have not the same inclusion exactly and in function of the models they use different grid lattices (MM5 B-grid and POM C-grid). Another reason is the need to adjust the grid borders that do not coincide in an exact way, have been used in this case four grid borders points, where interpolation is applied again.

Initially it was just selected the field of close horizontal momentum to 10 meters of MM5 to be transferred to POM and the field of SST to be transferred from POM for MM5.Interpolation results concerning the transferred fields can be evaluated starting from Figure 2 that represents the SST field in Celsius degrees, at POM grid in sigma-z (a) and interpolated for the MM5 grid (b). It is noticed that in the right inferior border, a smaller extension of the values ranging from 22 to 20 degrees Celsius, that occurs due the imposed method in the borders. Another problem emerges at this point that would be distinguishing of what is defined as land, and what is defined as water for each model. In the attempt of solving this problem, when parameter passage among the models happens, mainly from ocean to atmosphere, the land use array, that stores the exact information from where atmosphere model considers a grid element as water to maintain the soil surface temperature over land, and to update just the SST with that received from POM, over ocean. Following this procedure it can guarantee that spurious values that come from interpolation process cannot generate artificial gradients. In case of Figure 2b, the continent is masked exactly by points where the model just considers water, being the gradients observed in the coast (Figure 2b) effects of interpolation from the visualization method.

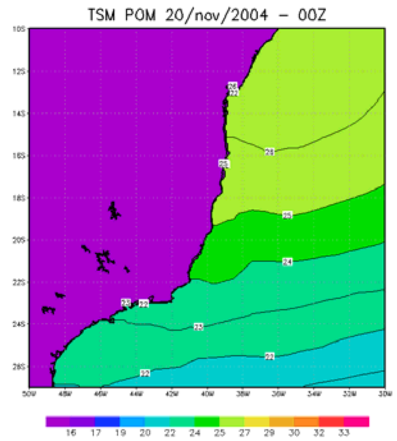


FIGURE 2A – SST USED AS POM INITIAL CONDITION.

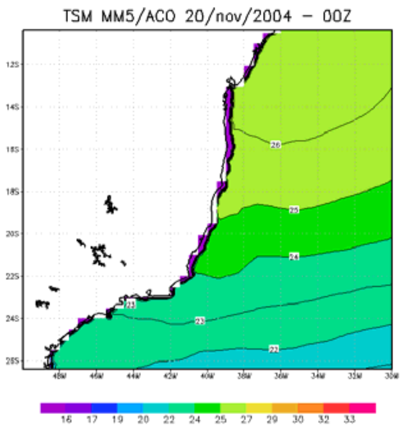


FIGURE 2B - SST USED AS ATMOSPHERIC INITIAL CONDITION INTERPOLATED FOR MM5 GRID.

Aiming to test the coupled model system MM5 was configured with a domain that includes Atlantic South Southwest border, going from Itajaí (~27°S) about 200 Km extending to Salvador (~10°S), with longitudes varying from 50°W to 30°W with 5' degree resolution (~9 Km), and 23 levels defined in vertical, being the first sigma level defined about 9 meters height and the last reaching 13 Km approximately. The period from November 20-25, 2004 was chosen for the simulation, starting at 00Z. NCEP (GFS - Caplan and Pan, 2000) global model fields, with 1° resolution in latitude and longitude were used as initial and boundary condition for MM5.

POM was configured for the same area (approximately) starting from the bathymetry (Figure 3) generated using observational data from LEPLAC (Levantamento da Plataforma Continental Brasileira), of REVIZEE (Levantamento dos Recursos Vivos da Zona Econômica Exclusiva) and from USGS (United State Geological Survey). It was defined 15 sigma levels in vertical, being five for the boundary ocean layer. Monthly average fields obtained from the experiment of ocean data assimilation (ODA) from GFDL (Schneider et al., 2003) for November, 1985, it was interpolated vertically and horizontally for POM grid, actually using temperature, salinity and horizontal momentum fields as initial condition, in the attempt of reducing the spin-up. As north and south boundary condition, it was kept constant along the time integration and a radiation condition was used at the lateral boundary.

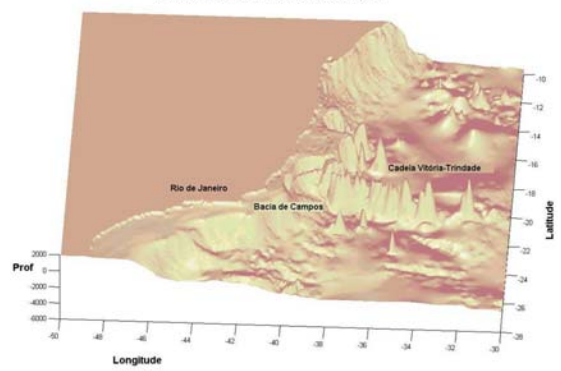


FIGURE 3 –BATYMETRY AREA PERSPECTIVE

Three simulations were accomplished as summarized in the table below (Table 1):

TABLE 1 – SIMULATIONS SUMMARY

	POM	MM5	MM5+POM
SST	MOM	GFS	POM
Period	1-29 Nov	1-20 Nov	20-25 Nov
10m wind	GFS	X	MM5

Coupled model Integration starts with MM5 holding horizontal momentum fields (10m winds) and soon afterwards a call to POM that reads the initialization fields (from MOM initial files) and it returns to MM5 initial SST (without any integration in time). MM5 is integrated one hour using the initial SST and sends the initial momentum to POM that soon afterwards is integrated in the time by one hour. To the end, MM5 receives SST prescribed for one hour and keep momentum fields of this hour for the next call to POM. This outline (Figure 4) stays until the end of the simulation, being the passage of the fields done through the interpolation routines.

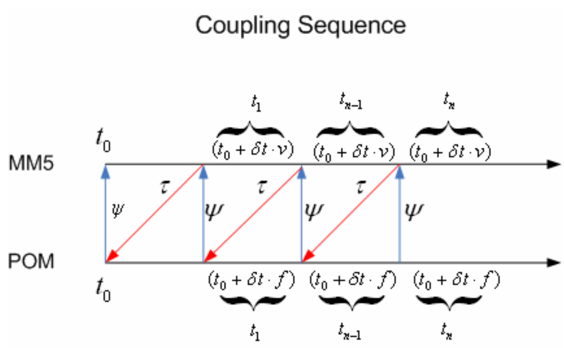


FIGURE 4 - OUTLINE OF CHANGE OF INFORMATION BETWEEN THE ATMOSPHERIC MODEL AND THE OCEANIC MODEL.

In this test case the coupling performed, the couple frequency is the same for the atmosphere as for the ocean $(\nu = f)$ however the timestep of each model differs. MM5 was configured with a 20 seconds timestep while in POM the internal timestep was of 360 seconds, and the external 12 seconds.

A simulation using profilers, in the attempt to reveal computational bottlenecks generated by the routines created specifically for the coupling.

4. RESULTS

Coupled model was executed for all experiments without presenting problems in memory access or disk I/O. These problems would be expected as the codes use different memory access methods and file units that could be coincident.

The code has been analyzed through the CPU total time and the wall clock time, defined here as a sum of CPU time, the process time disk I/O.

A CPU time analysis shows that a high percentage of participation (31%) is used by interpolation process among models grid when compared to others subroutines of the coupled model system (Figure 5) like SOUND.

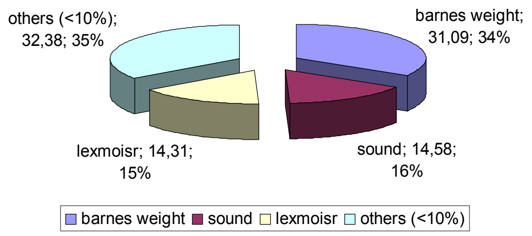


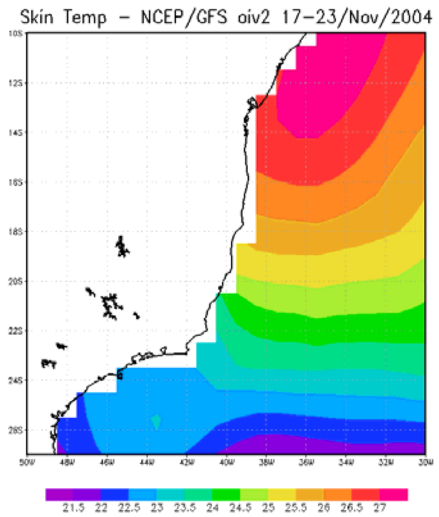
FIGURE 5 - CPU UTILIZATION BY FUNCTIONS

This routine (barnes_weight) is called twice when MM5 transfers the wind horizontal components for POM, and once POM transfers SST for MM5, process that happens in couple frequency, in this case 3600 seconds. It is also used in borders adjust. Analyzing the subroutine call numbers (not shown), can be seen that important subroutines like POM itself has 20 calls and SOLVE 360 calls in a two hour simulation against barnes_weight with 58, and even those do not reach more than 10% of CPU utilization, as can be seen in Figure 5. LEXMOISR subroutine had 86040 calls reaching 15% of CPU utilization, and SOUND got 360 calls and 16%. These results could be associated to neighbor search algorithm showing that it needs a better analysis, as that subroutine does not has so much calls but loads a lot of CPU.

Besides the computational aspects is important to evaluate mathematical and physics process impacts in coupled model system.

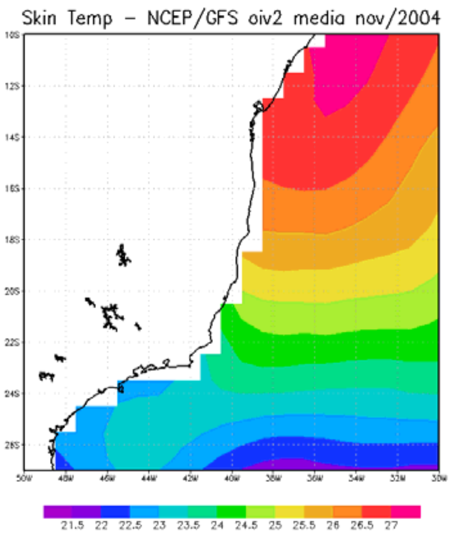
The "**MM5**" simulation uses SST (actually the skin temperature) of GFS/NCEP. The initial SST field from global model GFS, is obtained through the technique proposed by Reynolds (2002). The SST variation in the time is obtained through exponential relaxation (e-folding) applied on month climatology along the simulation (Peter Caplan, NCEP/NOAA, Personal Communication, 2005).

In the Figure 7 is presented the initial SST (a) and the climatology (b). It is possible to notice that the variation, even in a qualitative analysis is smoothed.



(A)

FIGURE 7A - SST (SKIN TEMPERATURE) OPERATIONALLY USED IN NCEP AND HERE AS BOUNDARY CONDITION FOR MM5.



(B)

FIGURE 7B – MONTHLY SST (SKIN TEMPERATURE) OPERATIONALLY USED IN NCEP AND HERE AS BOUNDARY CONDITION FOR MM5.

The "**POM**" simulation was used in attempt to reach spin-up, which can be estimated analyzing the kinetic energy curve obtained with POM (Figure 8), it can be noticed that in the simulation period the model doesn't reach the regime, in other words, it remain in spin-up. In Figure 8, two curves are presented, one for the first level of the model and other for the second level. It is also noticed differences among these curves. The variations are more significant in the first level (level sigma 1), that when closer the surface as it suffers more direct interactions, and fast, with the atmosphere.

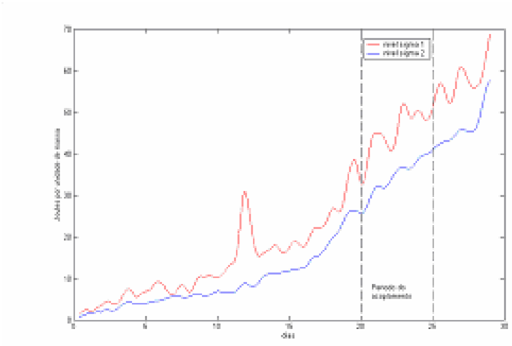


FIGURE 8 – KINETIC ENERGY, LEVELS SIGMA 1 AND 2 (TOP OCEAN) FOR THE 30 DAYS PERIOD. DASHED LINES SHOWS THE SIMULATION PERIOD OF THE COUPLED SIMULATION (MM5+POM).

A discrete Fast Fourier transform was applied to POM kinetic energy time series that was obtained from “**MM5+POM**” simulation (Figure 9). It can be noticed, in the frequency spectrum that a close pick to the cycle corresponding to one hour. This pick could indicate an impact of momentum passage from the atmospheric model to ocean, signaling a POM answer to forcing.

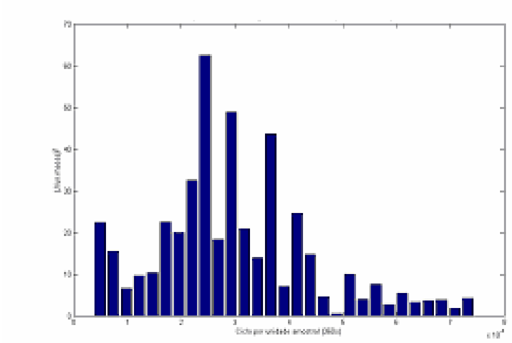


FIGURE 9 - KINETIC ENERGY SPECTRUM FROM “MM5+POM” SIMULATION. HORIZONTAL SCALE IS CYCLE PER AMOSTRAL UNIT (360 SECONDS) FOR 10^{-3}

Time series were extracted from “MM5+POM” and “MM5” simulation, obtaining atmospheric parameters for each timestep of atmospheric model (20 seconds), for 16 points (Figure 10). Point 13 (Figure 10) was selected, due the largest distance from continent, reducing the influence of the interactions with this. It can be noticed in Figure 10 the land use categories used by atmospheric model, as well as an idea of resolution reached by the model close to the coast.

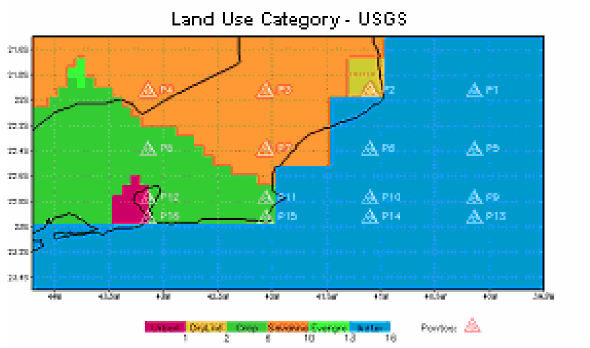


FIGURE 10 – LAND USE CATEGORY FROM USGS POINT 13 WAS USED FOR ANALYSIS

A quick look at kinetic energy curve for “MM5+POM” and “MM5” simulations (Figure 11), it is noticed discrepancies among the curves as well as differences in variations intensity. The larger difference in the intensity happens between November 22 and 23 with a significant loss of energy of the “MM5+POM” when compared to “MM5”.

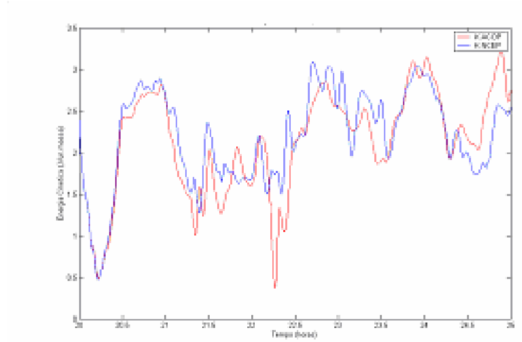


FIGURE 11 - KINETIC ENERGY TIME SERIES FROM POINT 13, “MM5+POM” AND “MM5” SIMULATIONS.

This difference is presented in the Figure 12, in the curve aspect of the absolute value of the difference among “MM5+POM” and “MM5” normalized by the average of both in times. The difference gets to reach the value of 0.6 in relation to the average. Value this that the can be associated some meteorological phenomenon or oceanographic, that it might have happened in the day. Computational and mathematics causes as interpolation processes when exchanging fields and calls to created subroutines, at first would be discarded for the absence of a periodicity, since these processes occurs in intervals with certain period. However more discerning analyses would be necessary to conclude something.

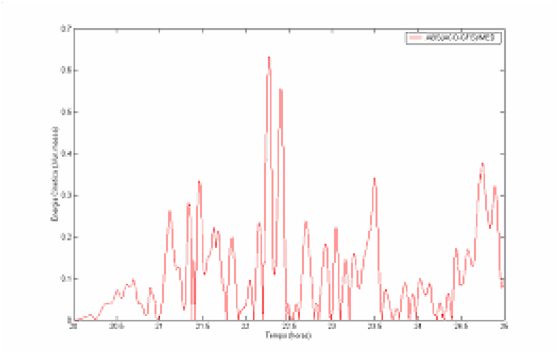


FIGURE 12 - ABSOLUTE DIFFERENCE TIME SERIES AMONG KINETIC ENERGY OF THE MM5+POM AND MM5 SIMULATION NORMALIZED BY AVERAGE OF BOTH.

The latent heat curve (Figure 13) also presents significant variations among 22 and 23, also presenting a discrepancy in the final period of the simulation. This discrepancy can be seen as loss of kinetic energy (Figure 13).

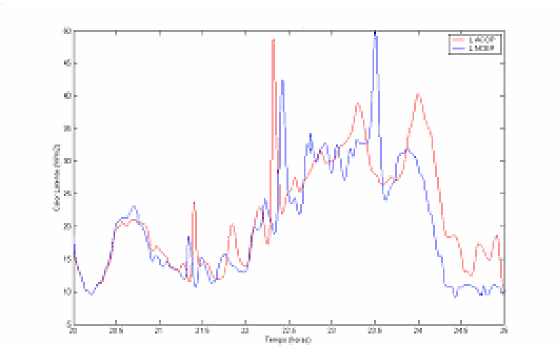


FIGURE 13 - LATENT HEAT TIME SERIES IN THE POINT 13, MM5+POM AND MM5 SIMULATIONS.

This discrepancy at the end of simulation can be related the difference happened on the 22, once this if it turns more visible and evident after pick. For latent heat (Figure 14) that gives idea of amount of heat stored/loss can be had when of the use of the coupled model.

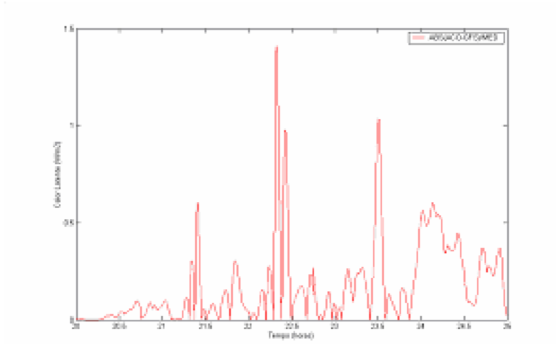


FIGURE 14 - ABSOLUTE DIFFERENCE TIME SERIES AMONG LATENT HEAT OF THE SIMULATION STEEL AND GFS IN RELATION TO AVERAGE OF THE TWO.

5. CONCLUSION

The methodology used for creation of an ocean-atmosphere coupled model was presented. The model has shown a reasonable computational performance, even with auxiliary routines added, however fine tunes are necessary to improve the interpolation process.

The analysis of energy spectrum obtained from POM in the coupled model revealed a pick in close frequency of the change of information among the models (atmospheric and oceanic), indicating to be happening an impact in the updating of the atmospheric momentum fields that force the ocean. It is believed that the use of an interpolation in the time, of the atmospheric fields, could smooth this impact.

Decco (2004) and Fragoso (2004) applied POM oceanic model, using boundary conditions and initialization similar, and concluded that heating of the model can be obtained in three months of simulation.

The coupled model was sensible to SST variations and horizontal momentum, as it could be observed in kinetic energy curves and latent heat. More discerning studies are recommended on the phenomenology involved in the ocean-atmosphere interaction for coupled case, aiming results validation of physical and dynamic features.

A suggestion would be the inclusion of a mechanism to assure surface flows and mass conservation and the addition of new parameters in exchange among the models, as for instance, solar radiation from atmospheric to ocean model.

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