EVALUATING THE IMPACT OF LARGE EDDY SIMULATIONS IN ROCKET EXHAUST MODELING

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Abstract. *In order to estimate the risks associated and the environmental impacts from the launchings (either normal or failed), a modern approach has been developed called "Modelo Simulador da Dispersão de Efluentes de Foguetes" (MSDEF), in Portuguese. The model needs to be provided with surface and sounding wind speed and direction, in addition to other meteorological variables like temperature, radiation and terrain height. For this purpose, we choose to use the Weather Research and Forecasting Model (WRF). However, the highest resolution available in the default version of the WRF model is of 1 km, which is very coarse in terms of the spatial scale of the formation, stabilization and dispersion of the rocket exhaust cloud formed near the ground. So, it is required to run the WRF model using a higher resolution, which enables to run large eddy simulations in WRF (WRF-LES), generating meteorological information with very high resolution (~100m) to input to MSDEF. Thus, this work aims to evaluate the meteorological information simulated by WRF-LES for the Alcântara Launch Center (ALC) and perform a simulation of a rocket launch event using MSDEF with the WRF-LES meteorological dataset as input.*

Keywords: *rocket exhaust cloud; atmospheric dispersion; MSDEF; WRF-LES; Alcântara Launch Center.*

1 INTRODUCTION

An important and singular air pollution problem is related with rocket launches. The burning of rocket engines during the first few seconds prior to and immediately following vehicles launchings results in the formation of a large cloud of hot, buoyant exhaust products near the ground level, which subsequently rises and entrains ambient air until the temperature and density of the cloud reach an approximate equilibrium with ambient conditions. Although such events happen less frequently, they are carried out in places, called space launching centers, where the impact can be outstandingly dangerous if there are nearby populated areas. Some of these space launching centers are located close to populated areas and they may be affected by the gases released during the launchings.

The United States space activities are conducted by the military personnel (Air Force) and civilians (NASA). The US Air Force have 2 rocket launching centers, being one at east coast (Cape Canaveral Air Force Base in Florida) and other one at west part (Vandenberg Air Force Base in California). These launching centers are close to big and populated region/cities that may be affected by the gases released during the launchings. In order to estimate the risks associated and the environmental impacts from the launchings (either normal or failed), a special model named REEDM – Rocket Exhaust Effluent Diffusion Model was developed by (Bjorklund et al., 1982). This model assumes a constant wind profile and Gaussian plume turbulence to access the movement of the clouds derived from the exhausted gases.

Unfortunately, there is no model fully ready to meet these demands in Brazil, or some experimental data dispersion of contaminants related to ALC. Therefore, researches are very important and the developing of a system modeling designed to calculate peak concentration, dosage and deposition (resulting from both gravitational settling and precipitation scavenging) downwind from normal and aborted launchings to use in mission planning activities and environmental assessments, pre-launch forecasts of the environmental effects of launch operations and post-launch environmental analysis in Brazilian site.

The initial problem, whose solution is particularly important for predicting the atmospheric dispersion of gases from static test firings launches, and other hot releases, is defining the source; i.e., the initial distribution of the gases resulting from the buoyancy of the hot exhaust gases. Observation shows that the exhaust gases form a cloud elevated above the surface. A combination of theoretical analysis and empirical observations has been used to create a mathematical model of the cloud and thus to provide a source description for subsequent atmospheric dispersion analyses. In addition to the meteorological parameters, which are the principal factors determining the turbulent diffusivity of the atmosphere, the depth of the surface transport layer or the presence of an inversion layer can profoundly affect the predicted ground-level concentrations of rocket exhaust gases. It is assumed that no transport of effluents occurs across the boundaries of a transport layer; hence, the effluents are trapped within their respective transport layers. Consequently, an interaction exists between the height of the surface transport layer and the height of the exhaust cloud stabilization in determining the downwind ground-level concentrations of exhaust gases. Although the amount of exhaust products contained in the ground cloud is a function of the local meteorology (principally the depth of the atmospheric boundary layer (ABL), it is typically calculated to be that due to approximately the first 20s of burn time of the space shuttle engines. This assumption is arrived at by considering the ground cloud to be formed by the exhaust cloud emitted through the flame trench for the first 10s after ignition plus the column of exhaust products formed during the following 10s.

To this end, the authors are engaged in the development of a modern framework that will allow the modeling of the rocket exhaust clouds that considers the Brazilian site characteristics. The model is based on semi-analytical solution of the time dependent three-dimensional advection-diffusion equation. Furthermore, in the present work we report numerical simulations with MSDEF approach using micrometeorological parameters and wind profile generated by the WRF model in the area around the ALC, using parameterizations that enable the usage of large eddy simulation in WRF for real cases (WRF-LES). This approach has been chosen due to the unique meteorological conditions that appear in the ALC region, as it will be exposed in greater details in the next section.

2 SITE DESCRIPTION

The Alcântara Launch Center is situated on the coast of Maranhão State, in Brazil, as shown in Fig. 1, with geographical coordinates 2° 24 ' S; 44° 24 ' W, 32 km from the capital, São Luiz, and with altitude between 40 and 50 m., There are carried out the launching payloads (satellite and/or scientific experiments), through the satellite launch vehicle (VLS) and/or sounding rockets, such as the VSB-30.

The ALC has a privileged location for the construction of a rocket launch center due to its proximity to the line of Equator (2° S latitude), in which energy is greatly reduced for placing satellites in geostationary orbit, enabling great fuel economy (Silva, 2014).

In relation to the wind, the knowledge of their vertical structure (average profiles and gusts of wind) is important, because the rockets are designed and constructed to bear the action of the wind, and the fact that their trajectory, guidance and control are determined by the wind near the surface profile (Fisch, 1999).

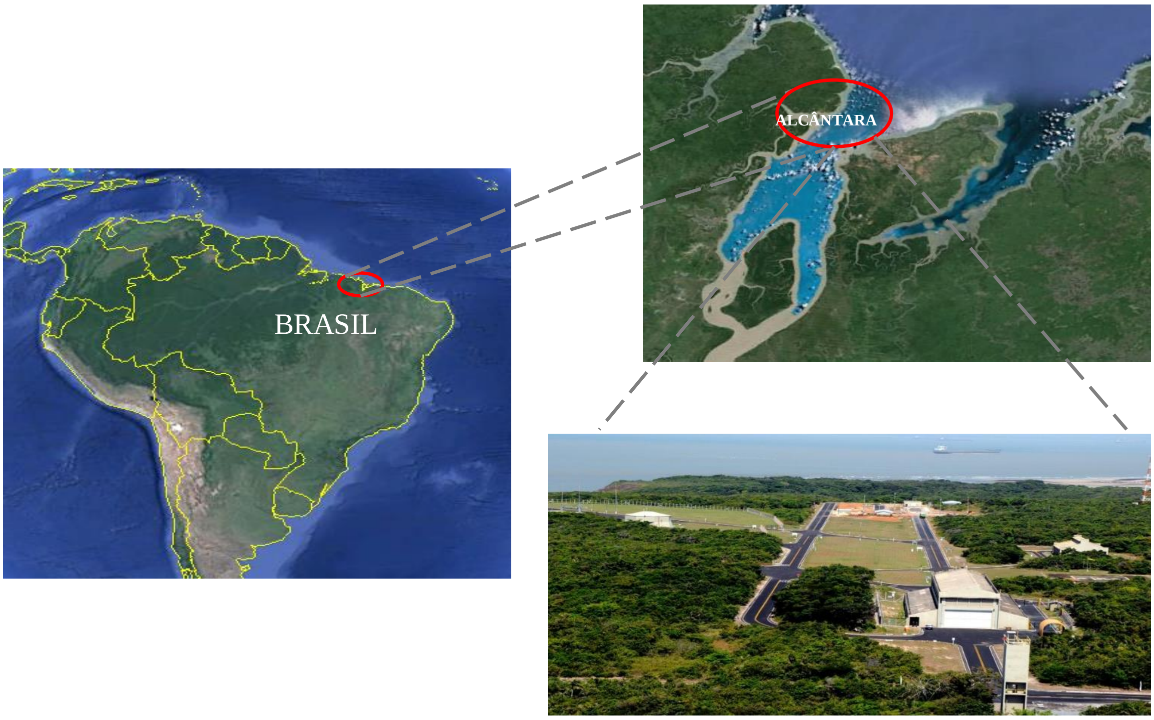

Figure 1: Location of Rocket Launch Center in Alcântara - MA (Images from Google Earth).

This region presents an abrupt roughness: a smooth surface followed by a rough surface. In addition, in this discontinuity occurs a relative topographic variation (sea cliffs), with around 50 m high. Next to this abrupt transition region (coast), is located the launch pad for rockets, which suffers the influence of these two factors. This ramp is located approximately 50 m from the coast, at an altitude of 42 m. In this case, the rockets placed on ramp suffer the influence of strong turbulence, due to the influence of the wind profile. The wind, initially in equilibrium with its oceanic surface, interacts with the shrubby vegetation (average height of the trees of 3 m), modifying itself. Increasing the complexity of this situation, there is the vertical offset from the surface, due to the cliffs (Fisch, 1999).

Climatologically, there is a very distinctive rainfall characteristic in the region of the ALC: a wet season from January up to June, with highest rainfall in March and April (monthly rainfall about 300 mm/mo) and a dry season from July up to December (rainfall almost null or very low – less than 30 mm/mo). The winds follow this climatic behavior presenting high wind speed during the dry season (winds around 7-8 m/s at 70 m height) and a moderate winds (winds around 5-6 m/s) during the wet season. To represent this behavior, it was released a radiosonde in the ALC on March 18 until 20, 2013. The radiosonde uses a Vaisala Oy system (sonde RSV92G), which is the state-of-art in terms of upper air measurements.

3 THE WEATHER RESEARCH AND FORESCATING MODEL - WRF

The Weather Research and Forecasting (WRF) model was developed by a joint effort of several American organizations, among them the National Oceanic and Atmospheric Administration's (NOAA) and the National Center for Atmospheric Research (NCAR), which is operated by the University Corporation for Atmospheric Research (UCAR). It was created for the purpose for both research and operational applications in numerical weather prediction.

The numerical simulations are performed in four dimensions (x, y, z, t), because each step of time horizontal mesh repeats in all vertical levels. Vertical levels are provided to the model in sigma coordinates that follow the contour of the terrain, according to Eq. 1.

$$\eta = \frac{p_h - p_{top}}{p_s - p_{top}} \tag{1}$$

Where, p_h is the pressure at each level, p_{top} is the pressure at the top of the atmosphere (constant) and p_s is the surface pressure. The variable η ranges from 0 to 1, with 0 at the top of the atmosphere and 1 at the surface.

The model structure consists of a preprocessing performed by a package of separate programs called WPS (WRF preprocessing system), whose output is passed to the primary processing core (ARW Solver), first by "real" program, and then to the WRF itself. Finally, the final output of the WRF may be post-processed to a friendly format for graphical programs such as GrADS, for example. An even more detailed description of the WRF model can be found in its manual, available in (Skamarock et al., 2008).

The data used to initialize the model were the fields generated by the global GFS model prediction of the National Centers for Environmental Prediction (NCEP), with spatial resolution of 0.5° x 0.5º (approximately 55 x 55 km to the local latitude) and 6 hours of temporal resolution. And the terrain data were provided by the United States Geological Survey (USGS). The WRF model provides a ready-to-use terrain dataset to use at different levels of resolution, where the finest is the 30’’ (thirty arc seconds), which is equivalent of 925m (or approximately 1 km). This terrain resolution is suitable for most high resolution mesoscale applications. However, as explained before, the strong turbulence that the rockets are subjected, due to the specific conditions that generate that wind profile, occurs in a lower scale than 1 km. Therefore, this work performed an effort to incorporate a higher terrain resolution that should fit this requirement. A 3’’ (three arc second) terrain database, which is equivalent of 92.5m, was acquired from the USGS dataset download site in raw Geotiff format, and then was prepared for being used in the WPS, by its transformation to the binary format required for WPS. This task was essential to this work, leading it to model a grid with 100 m of resolution, allowing the modeling of large eddies caused by the strong turbulence experienced in the ALC region, using the large eddy simulation (LES) capability of the WRF model for real cases.

The domains were configured and modeled using the version 3.6 of the WRF model in order to generate meteorological fields. The horizontal resolutions of the nested grids were 8.1 km, 2.7 km, 900 m, 300 m and 100 m, and the horizontal dimensions in grid cells were 40 x 40, 64 x 64, 76 x 76, 76 x 76 and 112 x 112, for domain 1 to 5, respectively. Recently, (Silva and Fisch, 2014) did a detailed analysis about the use of WRF for the ALC using radiosonde data collected during dry (2008) and wet season (2010) as a comparison. They found that the WRF, using the default parameterizations, can represent the wind speed at the site reasonably well (difference between the model and the observed is less than 2.0 m/s).

4 MODELO SIMULADOR DA DISPERSÃO DE EFLUENTES DE FOGUETES - MSDEF

The space shuttle flight system will be powered by chemical solid rocket motors and liquid rocket engines. The main environmental effect at launch arises from combustion of the space shuttle SRM's (Solid Rocket Motors). Combustion products are released into various 1ayers of the atmosphere as the vehicle gains altitude during launch. The bulk of the shuttle combustion products is released into the troposphere. In the middle and upper troposphere, the exhaust products are deposited in a thin column because of the relatively high velocity of the vehicle there. This column quickly mixes and dissipates. At lower altitudes (near the surface), a cloud of exhaust products is generated. This “ground-cloud” disperses slowly and has been the subject of extensive analysis. In a normal launch, the ground-cloud is formed at the base of the launch platform; it includes hot exhaust products from the SRM's, the main liquid propulsion engines, steam from launch platform cooling and acoustic damping water injection, and some sand and dust drawn into the cloud from the platform area. Because of the high temperature of the gas cloud, buoyancy effects cause it to rise to an altitude of 0.7 to 3 km, where it stabilizes because of the cooling of the gases. Figure 2 shows the launching of Titan IV, in Cape Canaveral, USA, and the formation of the so called ground-cloud and contrail-cloud.

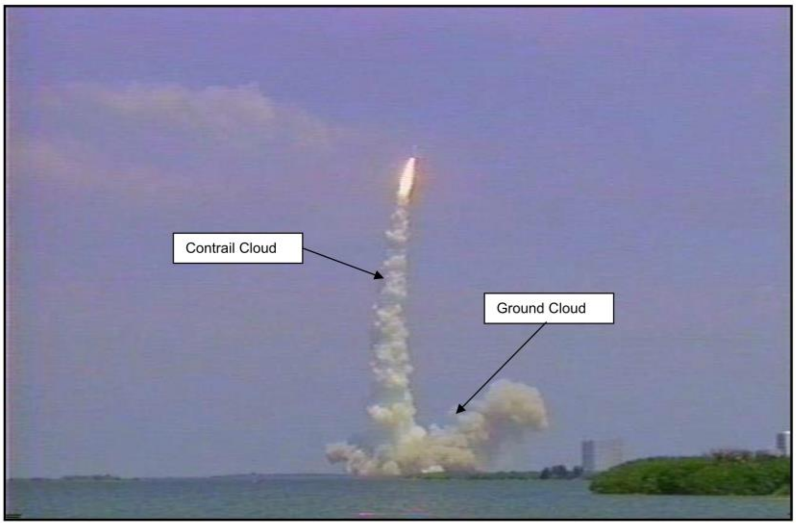

Figure 2: Illustration of the formation of the ground and contrail clouds during a rocket launch (Nyman, 2009).

For analysis of atmospheric dispersion of emissions of flares that can affect receivers on the ground, has been standard practice in the USA ("Cape Canaveral" and "Vandenberg Air Force Base") simulate a launch vehicle emissions from the ground up to about 3000 m. The tool used is the model REEDM version 7.13 (Rocket Exhaust Effluent Diffusion Model), easily found in (Bjorklund et al., 1982), (Bjorklund et al., 1990), and (Bjorklund et al., 1998). Therefore, this program was used as reference in physics and mathematics modeling of the problem concerned in the preparation of program code MSDEF.

It is relevant to mention some assumptions used by the REEDM model, which will be taken into consideration by the MSDEF model. One of the hypotheses that the REEDM model does, about the nature and behavior of the cloud released by the rocket is that it can be initially set as a single cloud that grows and moves but stays as a cloud during the formation of the ascending phase of the same. This concept can be noticed that the REEDM model is designed to obtain concentrations downwind from the preferred position in the cloud.

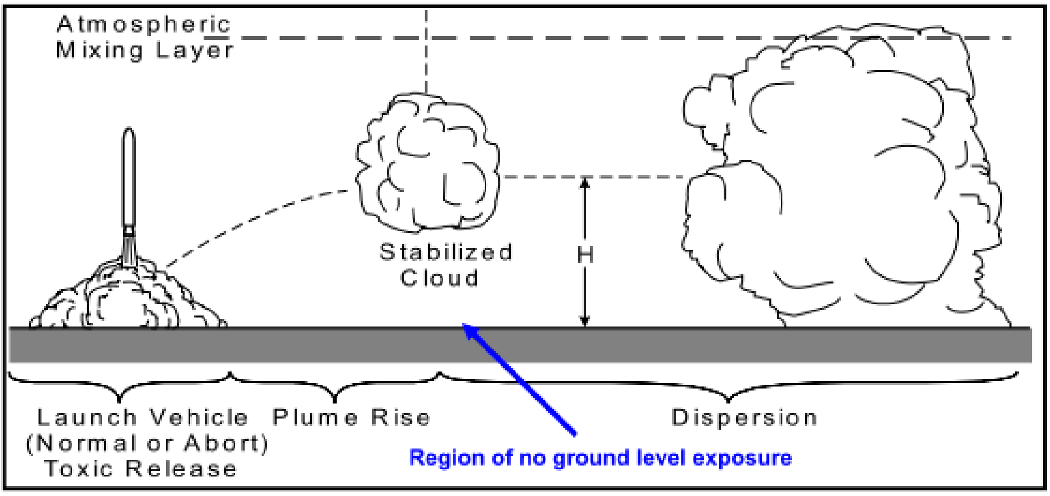

Figure 3: Conceptual illustration of cloud formation (source), "cloud-rise" and atmospheric dispersion of the cloud (Nyman, 2009).

The second hypothesis is related to the multilayer system. The multilayer aspect of the REEDM model currently is still used and relates to the partitioning of the stabilized cloud in "discs" of the cloud material represented by different meteorological levels at different altitudes. The model relates the initial formation of the cloud in the spherical shape to normal and releases on cylindrical shape for aborted releases/tests/explosions. Once the cloud is set and has achieved the condition of thermal stability with the atmosphere, the cloud is partitioned into "discs". The placement of each disc with respect to the origin (launch pad) is determined based on the time of the rise of the cloud through a sequence of weather layers that are defined using levels of measurement obtained through upper air. Each weather layer can have a single wind speed and direction that moves the disc of the cloud in the direction of the same.

The hypothesis of transport in a straight line during the transport of clouds and phase dispersion ignores the possibility of wind fields that can arise in complex mountainous terrain or may evolve during the passage of a sea breeze front or greater scale. Thus, it is recommended that the assumption of uniform wind is limited to the transport of the plume at distances not exceeding 25 km. In this sense, the model does forecast concentration ranging from 5 to 10 km from the launch pad. The REEDM model also assumes that all chemical reactions are completed before the combustion process of the rise of the cloud. A mass fraction is assigned to each constituent and the total mass of the source (cloud) is multiplied by this fraction to determine the total mass of each chemical component in the cloud. The molecular weight of each species is used to convert the concentration of mass per unit volume (mg/m^3) to part per million (ppm).

The MSDEF model uses the same physical aspects used in the REEDM model, but with differences in the meteorological layers, with the condition of continuity of flow and concentration (vertical profiles more real), different parameterizations of turbulence (diffusion coefficients and dispersion parameters), considering the current understanding of the physics of the ALC. It is important to stress that the fundamental scale parameters, such as the height of the atmospheric boundary layer (h), the convective speed (w_*), friction speed (u_*), vertical wind profiles ($u(z)$), length of Monin-Obukhov (L) and other important parameters in the determination of these scales of length and speed, are all obtained from upper air data. However, in this work these parameters are derived from the WRF mesoscale model.

4.1 The MSDEF Formulation

Physically, the MSDEF model is based on the K theory of turbulent dispersion. The K theory is widely used in many atmospheric conditions because it describes the diffusive transport of Eulerian form where almost all measurements are Eulerians, producing results that agree with experimental data as well as any more complex model, and requires no extra computational power as much as higher-order models require.

A typical problem with the turbulent diffusion equation is the search of solutions corresponding to instant and continuous sources of pollution. This item is presented a general method for solving the equation of turbulent diffusion using the Laplace transform considering the ALC as a multi-tier system. This method enables you to use continuous values of diffusion coefficients and wind more physically real.

For convenience, the concentration equations are written in a rectangular coordinate system with the origin at the point of stabilization of the cloud. The x axial is directed in the direction along the average wind direction u, and the y axial is directed in the direction perpendicular to the wind. In the program, the origin of the coordinate system is placed on the launch pad.

The advection-diffusion equation can be written in this way:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=-\frac{\partial\overline{u'c'}}{\partial x}-\frac{\partial\overline{v'c'}}{\partial y}-\frac{\partial\overline{w'c'}}{\partial z}+S \tag{2}$$

Where, C represents the mean concentration, K_x, K_y, K_z e u, v, w are the Cartesian components of the diffusion coefficient of wind speed, respectively, and S is the source term. The terms $\overline{u'c'}$, $\overline{v'c'}$ and $\overline{w'c'}$ represent turbulent flows of pollutants in the longitudinal, lateral and vertical direction, respectively.

The most used mathematical model is concerned with solving the problem of closing the Eq. 2 based on hypothesis of gradient transport that, in analogy with the molecular diffusion, assumes that the turbulence is proportional to the magnitude of average concentration gradient:

$$\overline{u'c'}=-K_x\frac{\partial C}{\partial x}\;\;;\;\;\overline{v'c'}=-K_y\frac{\partial C}{\partial y}\;\;;\;\;\overline{w'c'}=-K_z\frac{\partial C}{\partial z} \tag{3}$$

Thus, considering a Cartesian coordinate system where the x direction matches the wind, the advection diffusion equation can be written as (Blackadar, 1997):

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)+S \tag{4}$$

Lateral integration (*y* direction) from Eq. 4 leads to the following equation:

$$\frac{\partial \overline{C}}{\partial t}+u\frac{\partial \overline{C}}{\partial x}+w\frac{\partial \overline{C}}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial \overline{C}}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial \overline{C}}{\partial z}\right)+S \tag{5}$$

Where,

$$\overline{C}=\int_{L_y} C(x,y,z,t)\,dy \tag{6}$$

It is the laterally integrated concentration. This is acceptable, because the lateral dispersion can be taken which will result in the Gaussian equation:

$$C(x,y,z,t)=\overline{C}(x,z,t)\frac{e^{\left(-y^2/2\sigma_y^2\right)}}{\sqrt{2\pi}\sigma_y} \tag{7}$$

The model for simulating the dispersion of rockets should take into account the following: wet and dry deposition and chemical reactions of the first order. For this, the resulting equation to be solved is:

$$\frac{\partial \overline{C}}{\partial t}+u\frac{\partial \overline{C}}{\partial x}-v_g\frac{\partial \overline{C}}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial \overline{C}}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial \overline{C}}{\partial z}\right)-\lambda\overline{C}-\Lambda\overline{C} \tag{8}$$

Where, v_g is the particle fall speed due to gravity, λ represents first-order chemical reactions and Λ represents the coefficient of removal due to precipitation.

For the solution of Eq. 8 should bear in mind the initial conditions and outline. It is assumed that the dispersion is not polluted:

$$\overline{C}(x,z,0)=0 \qquad \text{at} \quad t=0 \tag{9}$$

And at the point $(0,H_s,t)$ there is a continual source with constant emission rate Q:

$$\overline{C}(0,z,t)=\frac{Q}{u}\left[\eta(\mathrm{t})-\eta(\mathrm{t}-\mathrm{t_r})\right]\delta(z-H_s) \qquad \text{at} \quad x=0 \tag{10}$$

Where $\delta(z-H_s)$ is the Dirac delta function, H_s is the height of the font, η is the Heaviside step function and t_r is the release time (Bianconi e Tamponi, 1993).

Take boundary conditions of null flux of pollutants at the top of the ALC:

$$K_z\frac{\partial \overline{C}}{\partial z}=0 \qquad \text{at} \quad z=h \tag{11}$$

And a non-null condition on the surface:

$$K_z \frac{\partial \overline{C}}{\partial z} = V_d \overline{C} \quad \text{at} \quad z = 0 \tag{11}$$

Where, h is the ALC height and V_d (m/s) is the dry deposition rate.

The Laplace transform is a technique well known to solve linear differential equations and a vast literature is found on this subject. This methodology is applied to solve the Eq. 8 in order to build analytical solutions to the equation of diffusion-advection and that will allow you to perform numerical simulations of the dispersion of pollutants released by rockets in the ALC. To achieve this goal, the Eq. 8 is transformed into a set of ordinary differential equations by applying the Laplace transform. After solving these equations with standard procedure, the concentration of pollutants becomes the reversal of the concentration transformed by Gaussian quadrature numerical scheme. There is vast literature on this method of solution (Moreira, 1999, 2004a, 2006).

5 RESULTS AND DISCUSSIONS

The wind speed and direction parameters, obtained from the output data of the WRF-LES, are displayed in the Figure 4. These values are corresponding to the height of 10 m. It is possible to note that, as the wind flows from the ocean to the continent, its speed decreases from 4 - 6 m/s to 2 - 4 m/s. It is due to the sudden change in the surface roughness: while it is lower near the ocean surface, it increases abruptly when it reaches the continent due to the sea cliffs – as mentioned previously in the site description section – leading to low down the wind speed near the continental surface. The wind direction prevails in the East and Northeast directions, which, according to (Fisch, 1999), is a common behavior in the coastline of the State of Maranhão, Brazil, due to the presence of the trade winds during the rainy season that goes from January to July, being more representative in the months of March and April.

Figure 5 presents the scenario for the temperature parameter at 2 m. As one can note, the temperature variation of the 300 presented 303 degrees Kelvin, being higher in the Earth's surface than the ocean, which can be attributed to the greater specific heat of soil. Show that the temperature has remained low and did not suffer abrupt changes over the days to the period of the month of March, which is also a feature of the region, as discussed in detail in (Fisch, 1997).

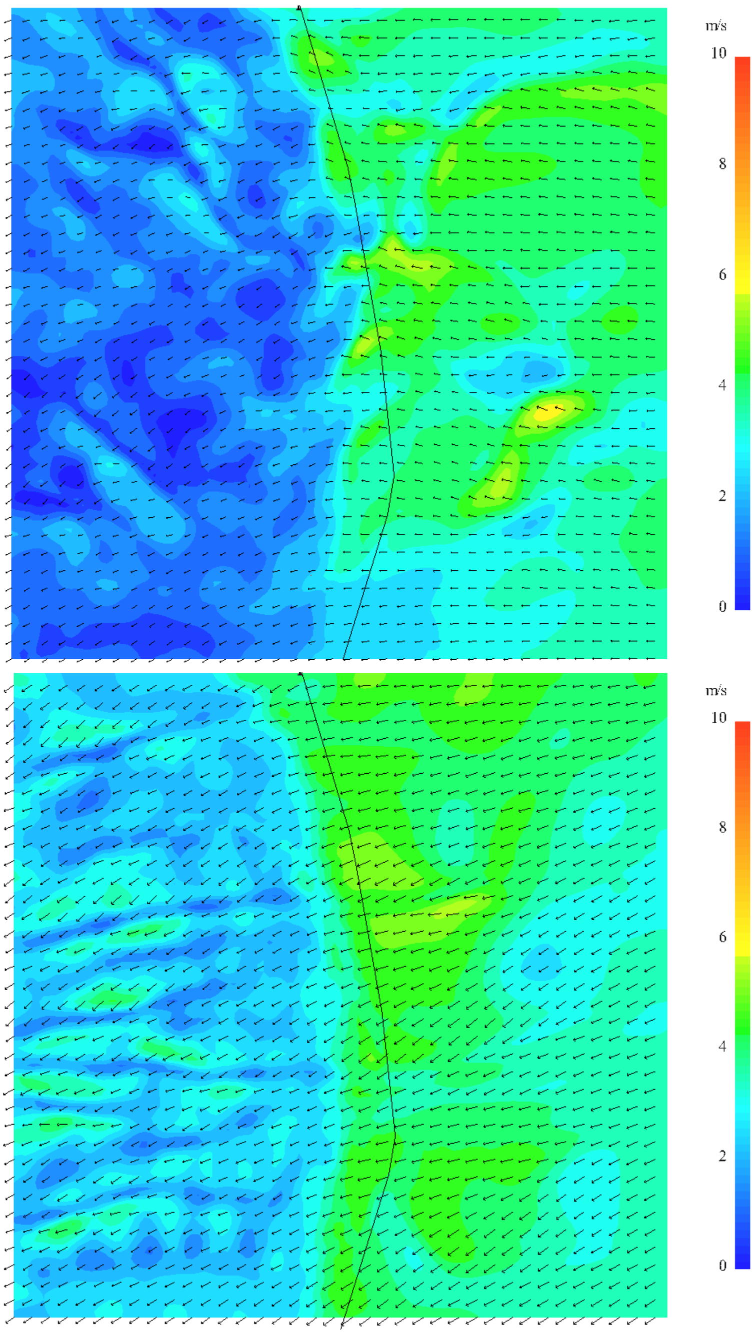

Figure 4: Wind speed and direction for the ALC region, for the days 20 and 21, respectively.

Comparative analyses were carried out between the model output and sounding data measured in the launch site with the Apparatus equipment. Figure 6 shows this comparison for wind speed parameter for the 4 days of simulation. In general, it can be noted that the model showed the same behavior as the upper air observed data, however this last presenting some abrupt variations with respect to time for the days of 18 and 19, which may be referred to the higher sensitivity of the equipment to upper air wind gusts. For the days 20 and 21 it showed minor variations for the same variable, in addition to greater parity between the modeled and measured values, where the average wind speed was 7 m/s.

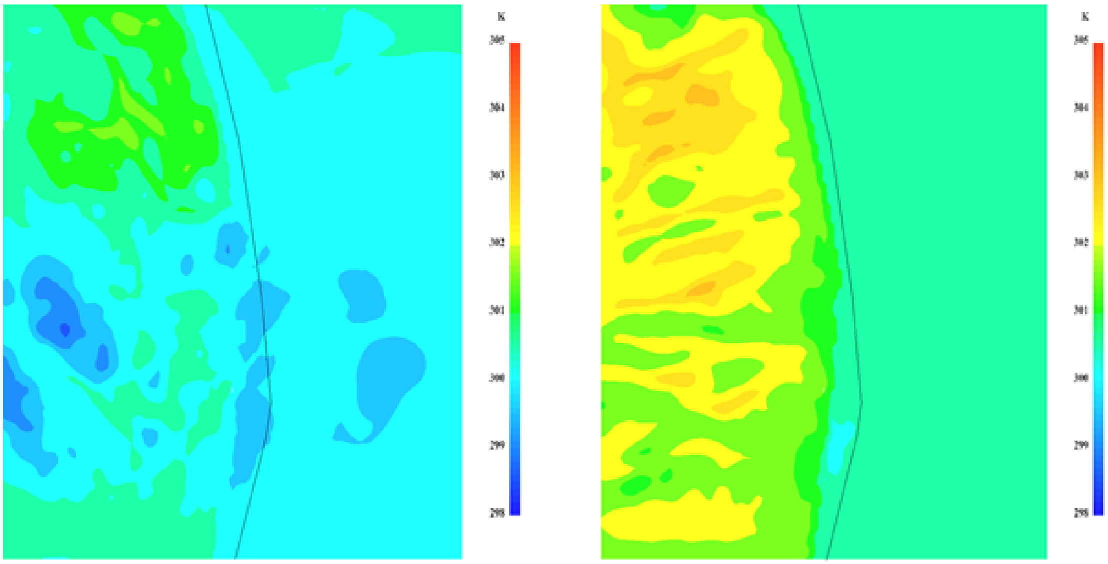

Figure 5: Temperature for the ALC by WRF-LES.

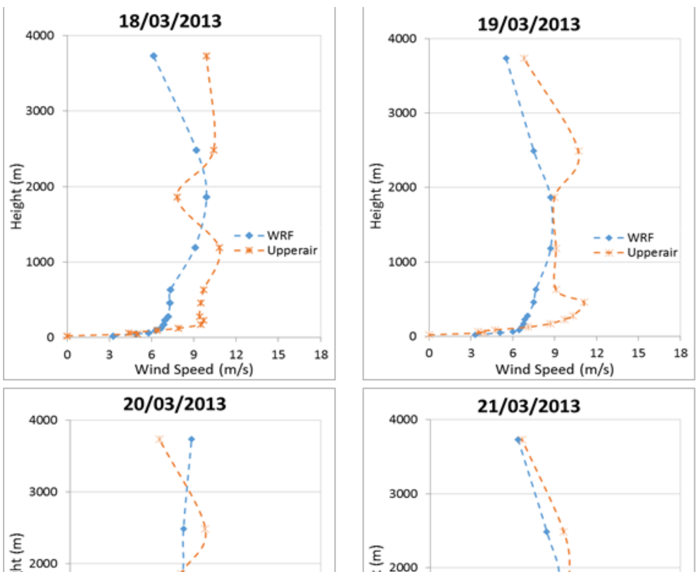

Figure 6: Comparing upper air data and WRF-LES for wind speed parameter.

The wind direction parameter, shown by Figure 7, presented winds mostly blowing from East and Northeast. The values found in model output were very close to those measured for the 4 days, being possible to observe very similar values for the days 19 and 20.

Figure 8 shows the temperature comparison plot as a function of height. It is also worth mentioning the proximity of the behavior of both data sets, which, in all 4 days, showed parity in temperature values in relation to height, following the trend of the curve in which the temperature decreases with height.

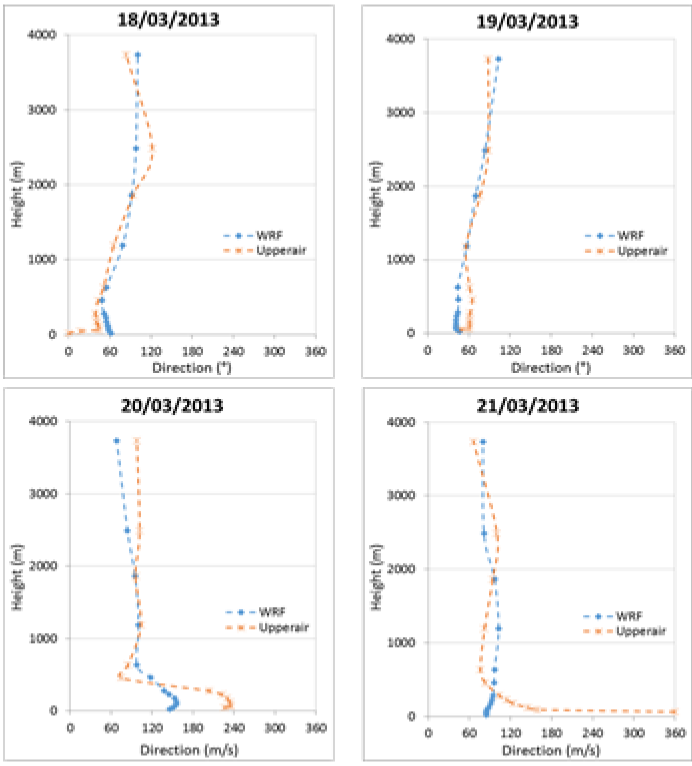

Figure 7: Comparing upper air data and WRF-LES for wind direction parameter.

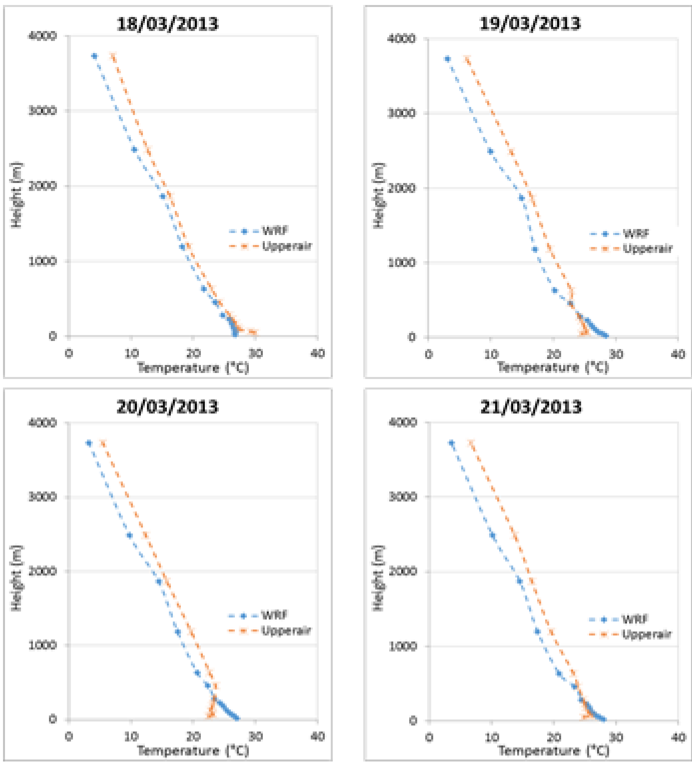

Figura 8: Comparing upper air data and WRF-LES for temperature parameter.

In order to statistically validate the simulation produced by WRF-LES modeling system, it was applied the methodology developed by Emery et al. (2001), which uses benchmarks values to evaluate the quality of the modeled data. According USEPA (2007), benchmark values should not be used to determine whether the simulation failed or succeeded, but to assess how the data are behaving and if further analysis on the simulation and parameterization are needed.

Table 1 shows the results for temperature, wind speed and direction and their respective benchmarks for each day of the simulation case.

Table 1: Evaluation of the meteorology parameters output by WRF model

Model Evaluation						
Variable	Statistic	Benchmark	03/18/2013	03/19/2013	03/20/2013	03/21/2013
Temperature	MB (K)	≤ ± 0.50	-3.29	-2.48	-2.11	-2.54
	MAGE (K)	≤ 2.00	3.29	3.56	3.65	3.11
	IOA	≥ 0.80	1.00	1.00	3.65	3.11
Wind speed	MB ($m.s^{-1}$)	≤ ± 0.50	-1.39	-1.23	0.62	0.68
	RMSE (m.s-1)	≤ 2.00	2.74	2.86	2.34	2.41
Wind direction	MB (°)	≤ ± 10.00	2.98	1.89	-24.44	6.57
	MAGE (°)	≤ 30.00	23.59	31.87	44.04	47.11

It is notable that for the days 18 and 19, only the wind direction variable remained within the limits proposed by Emery et al. (2001), considering that in day 19 occurred a subtle extrapolation of MAGE. Regarding the other parameters, they are not so far from the recommended values.

Based on the results presented, considering the use of the meteorological model WRF-LES model of large scales, it can be said that its performance was good and promising, since it is improved the accuracy of the results, making the values simulated got too close, and for some times to equal the values measured in the field.

Figure 9 presents a plot of the application of the MSDEF coupled with the WRF-LES model to generate concentration fields (in ppm), showing the vector wind speed and dispersion of the plume in the downwind direction. TMI represents the Integration Mobile Tower and VLS is the Satellite Launch Vehicle. Since there is no observed concentration data from rocket launch events in ALC available yet for comparison with the model results, it has been done a qualitative analysis, which consisted in setting up a hypothetical rocket launch event in ALC. It is important to note that, in this case, the plume would not reach the capital city of São Luis, however the Alcântara city would be impacted by the plume. It demonstrates why is so imperative to assess in advance what would be the impact of a rocket launch in a specific moment, showing the degree of importance of pre-launch forecasts of the environmental effects of launch operations and post-launch environmental analysis, through coupling these modeling tools.

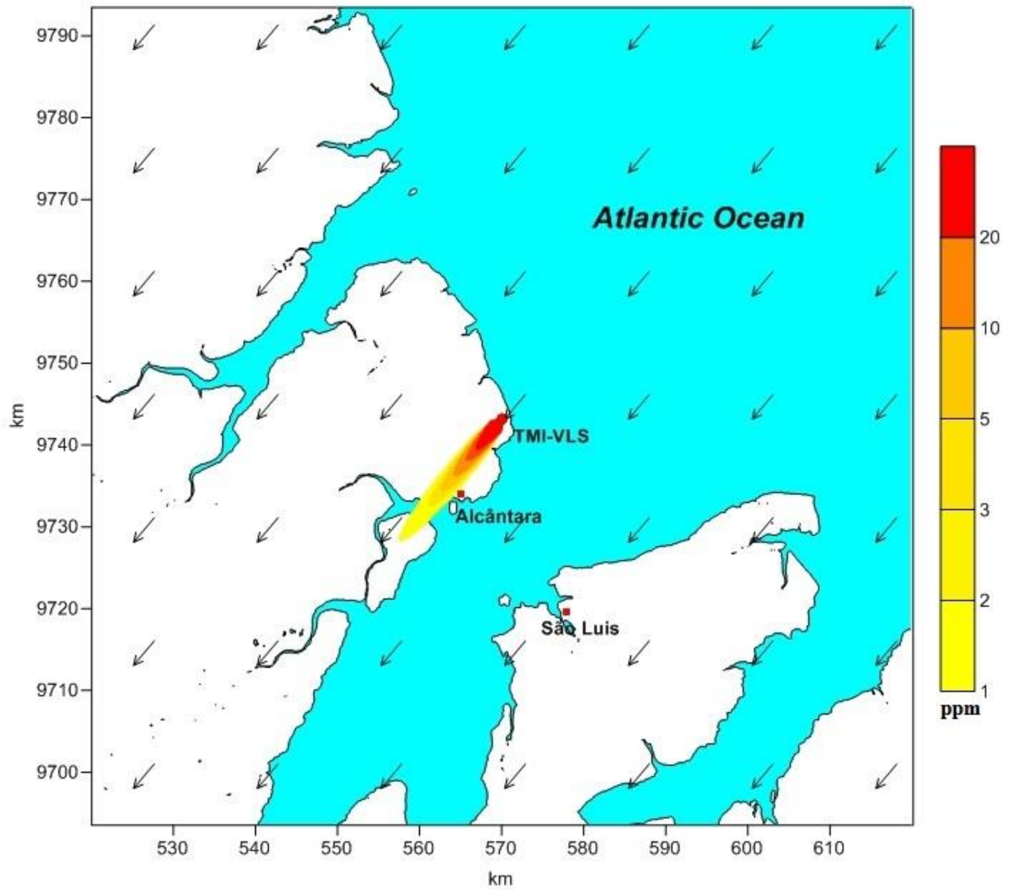

Figure 9: Plume generated by the MSDEF model, showing the second-hour average scenario

6 SUMMARY AND PERSPECTIVES

This work presented an important and up-to-date research theme in air quality modeling. Although such events are not usual, when rocket exhaust clouds are emitted, they release a huge amount of hazardous pollutants in the atmosphere, like HCl and CO. The previous evaluation and environmental assessment are needed, which is done by meteorological and air quality modeling, in conjunction with other techniques. This air quality problem is unique due to its uncommon nature – an instantaneous source releasing a huge amount of effluents to the atmosphere in a controlled system – which is not the target of common air quality models (like AERMOD and CALPUFF), but needs to be addressed as well as any other air quality problem. Thus, for this purpose we presented the development of the MSDEF model, which was built to deal with this specific air quality issue, incorporating some advances in comparison with other air quality models, due to its innovative design and approach. This work presented an effort to use the meteorological output from WRF in LES mode for real cases, to be input into the MSDEF model. The meteorological modelled results were compared to sounding data collected in the launch pad site, and showed good accordance with the observed data. The MSDEF model was successfully coupled with the WRF-LES model, and a hypothetical rocket launch event was set up in order to conduct a qualitative analysis, which showed what would be the impact of a rocket launch in the region of ALC in these circumstances.

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