A HYBRID SYSTEM TO SIMULATE THE ATMOSPHERIC DISPERSION OF ROCKET EXHAUST CLOUDS

ERICK GIOVANI SPERANDIO NASCIMENTO[1,3], DAVIDSON MARTINS MOREIRA[2]

[1]Department of Environmental Eng., Universidade Federal do Espírito Santo, Vitória, ES, Brazil. E-mail: erick@lcad.inf.ufes.br
[2]Center for Integrated Manufacturing and Technology, SENAI/CIMATEC, Salvador, BA, Brazil. E-mail: davidson.moreira@fieb.org.br
[3]Vitória Software Ltda, Vitória, ES, Brazil. E-mail: erick@vitoriasoftware.com.br

RESUMO

Nuvens de exaustão de foguetes são compostas por poluentes perigosos, como alumina, monóxido e dióxido de carbono, e cloreto de hidrogênio, os quais são gerados durante a queima dos motores de foguetes. No caso do lançamento de veículos, nuvens enormes e quentes são geradas próximo ao solo e são compostas por produtos de exaustão, que irão se ascender, expandir, estabilizar, arrastar o ar ambiente, e começarão a ser dispersadas de acordo com as condições atmosféricas. Esse processo leva alguns minutos para acontecer, e geralmente áreas povoadas localizadas próximas ao centro de lançamento (CL) poderão ser expostas a altos níveis de concentração em um intervalo que varia de alguns poucos a algumas dezenas de minutos, até uma hora. Também, esses poluentes podem ser levados para mais longe devido à dispersão atmosférica, e interagir quimicamente com outros compostos, formando novos poluentes, impactando áreas povoadas mais distantes. Os CL ao redor do mundo precisam operacionalmente avaliar tais impactos, tanto de curto quanto de longo alcance antes dos lançamentos através da modelagem meteorológica e da qualidade do ar. Em geral, contudo, modelos de qualidade do ar não lidam com o cálculo de pico e média de concentração em uma escala de tempo mais curto, isto é, entre alguns minutos até uma hora. Além disso, há o fato de que a modelagem de nuvens de exaustão de foguetes é um problema de qualidade do ar único. Para este fim, escolheu-se utilizar um modelo moderno que visa resolver este problema, denominado MSDEF. Para a avaliação de longo alcance, foi escolhido o sistema de modelagem CMAQ, uma vez que ele representa o estado da arte na modelagem regional e do transporte químico, e devido à sua capacidade de lidar com gases clorados. A fim de acoplar ambos os modelos, o código do MSDEF foi reescrito utilizando a biblioteca I/O API, tornando-o capaz de gerar as condições iniciais de entrada no CMAQ. Desse modo, está formada a base para um sistema híbrido, moderno e multidisciplinar que, em conjunto com o WRF, poderá ser operacionalmente utilizado em diferentes missões de lançamento para uma completa avaliação do impacto ambiental.

Palavras-chaves: nuvem de exaustão de foguete; dispersão atmosférica; modelagem matemática; MSDEF; CMAQ.

ABSTRACT

Rocket exhaust clouds are composed by hazardous pollutants, e.g. alumina, carbon monoxide and dioxide, and hydrogen chloride, which are generated during the burning of rocket engines. In the case of vehicle launching, huge and hot clouds are generated near the ground level and are composed by the buoyant exhaust products, which will rise, expand, stabilize, entrain the ambient air, and they will start to be dispersed according to the atmospheric conditions. This process takes a couple of minutes to occur, and generally human receptors located in populated areas nearby the launching center may be exposed to high levels of concentrations within a few to tens of minutes, up to less than one hour. Also, these pollutants may be carried farther due atmospheric dispersion, and chemically interact with other atmospheric compounds, forming new pollutants, impacting other populated areas located in farther distances. The launch centers around the globe, like spaceports, need to operationally assess the impact of rocket launchings events in the environment, requiring to evaluate both short and long range impacts prior to launchings through meteorological and air quality modeling. In general, however, air quality models do not account for calculating peak and average concentration for a short time scale, i.e. ranging from minutes to one hour. In addition, there is the fact that modeling rocket exhaust clouds formed due rocket/vehicle launching is quite a unique air quality problem. For this purpose, this work chose to use a modern air quality model which targets this problem, named MSDEF. For long range assessment, it has been chosen the CMAQ modeling system, since it represents the state-of-the-art in regional and chemical transport air quality modeling, and due to its capability to deal with chlorine gases – which is a considerable part of rocket exhaust clouds. In order to couple both models, the MSDEF code has been rewritten using the I/O API library, making it possible for MSDEF to generate the initial conditions as input to CMAQ model. Thus, it forms the basis for a hybrid, modern and multidisciplinary system which, in conjunction with the WRF model, can be operationally used in different launching missions for a complete environmental assessment.

Keywords: rocket exhaust cloud; atmospheric dispersion; mathematical modelling; MSDEF; CMAQ.

INTRODUCTION

An important and singular air pollution problem is related with rocket launches. The burning of rocket engines during the first few seconds immediately before and after vehicle launch operations forms a large cloud of hot and buoyant exhaust contaminants near the ground, which ascends and entrains ambient air until the temperature of the cloud reach an equilibrium with ambient conditions.

Some of the space launching centers are located close to populated areas and they 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 [0]. This model assumes a constant wind profile and Gaussian plume turbulence to assess the movement of the clouds derived from the exhausted gases. Derived from this model, a modern approach has been developed by [0] called *Modelo Simulador da Dispersão de Efluentes de Foguetes* (MSDEF), in Portuguese, which stands for "Simulation Model of Rocket Effluent Dispersion", incorporating some advances that will be further explained.

Although the assumption regarding the formation of the ground and contrail cloud (see Figure 1) is a major concern in rocket exhaust cloud modeling, it is also important to predict weather and air quality conditions in short and long range terms in order to operationally assess the impact in the environment of normal and aborted launching operations. Recently, the REEDM model has been used in a hybrid system, in conjunction with other modeling tools to simulate the weather and the dispersion of toxic gases in launch operations. The French Space Agency (CNES) conducts simulations of the impact of rocket exhaust pollutants using a model called SARRIM (Stratified Atmosphere Rocket Release Impact Model), during normal or aborted launching operations in the European Spaceport in Kourou, French Guyana [0]. However, more recent works present the idea of using a more complete, multi-disciplinary and hybrid approach in order to achieve the goal of assessing the impact of effluents released from launching operations for the European Space Agency (ESA). The work presented in [0] presents a first-step effort for the Indian Space Agency to evaluate a hybrid approach in the assessment of the impact of rocket exhaust pollutants during launching operations.

Unfortunately, there is no model fully operational to meet these demands in Alcântara Launch Center (ALC), the Brazilian Spaceport. Therefore, it is very important to develop a modeling system 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, is truly needed. To this end, this paper aims to provide the basis for the construction of a more complete, multi-disciplinary, modern hybrid system that will allow the development of a model fully adapted to the Brazilian site characteristics. This system will be composed by a meteorological model, a dispersion model and a chemical transport model for short and long range assessment, respectively, all representing the state-of-the-art in their respective research field.

METHODOLOGY

Meteorological Modeling Approach

The system needs to be provided with surface and sounding wind speed and direction, in addition to other meteorological variables like temperature, radiation and terrain height. Commonly, it can be achieved by conducting measurement campaigns for certain periods that can be representative for the target region. However, this approach is often expensive and mostly do not cover the entire region or period being considered. In this case, we choose to use the Weather Research and Forecasting Model (WRF), which is the state-of-the-art in atmospheric modeling for weather applications.

Thus, we ran the WRF model to generate the meteorological fields. We used the Global Forecast System (GFS) with a resolution of 1 arc degree. Fisch and Silva [0] 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. For this work, we chose to apply a large-eddy simulation in WRF to better represent the turbulence in the ALC region, activating the LES option available in WRF for real-world applications. The reference [0] showed that the application of WRF-LES is quite interesting, since it provides very high resolution information about the atmospheric turbulence and terrain elevation for the air quality modeling, which is an important issue regarding the short range dispersion modeling.

One of the major challenges needed to accomplish this task of running WRF in LES mode for real cases, was to get and configure a new and complete terrain dataset information for the ALC region in a very high resolution (~ 100m), since the highest resolution of the default WRF terrain dataset is 1 km, which is not suitable to run large-eddy simulations. Thus, we downloaded from USGS site a GeoTIFF dataset of the terrain elevation for the surrounding area of the ALC site. Then, we processed this dataset, generating a new one in the geogrid format, enabling WRF to model this case using very high resolution terrain information of 100m.

This case was configured as a four-day simulation, from March 18, 2013 at 00:00h GMT to March 22, 2013 at 00:00h GMT. The horizontal resolution of the grid and its nests were 8.1 km, 2.7 km, 900m, 300m and 100m, and the horizontal dimensions, in grid cells, were 40x40, 64x64, 76x76, 76x76 and 112x112, for domain 1 to 5, respectively, with 20 vertical levels.

The Short-Range Dispersion Model

The initial problem, whose solution is particularly important for predicting the atmospheric dispersion of gases from static test firing 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 (see Figure 1). 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.

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 layers of the atmosphere as the vehicle gains altitude during launch. The bulk of the shuttle combustion products are 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 0. 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.

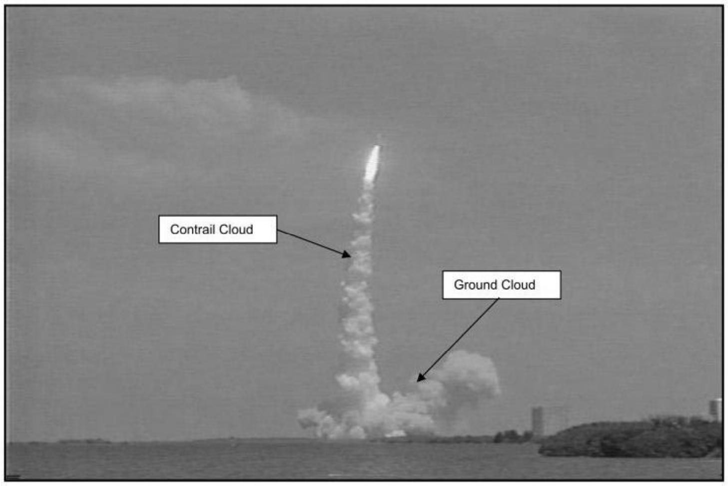

Figure 1. Illustration of the formation of the ground and contrail clouds during a rocket launch. Source:[0].

In order to simulate the impact of rocket exhaust clouds, the MSDEF model was developed using the REEDM model as reference for modeling physics and mathematics, but featuring some improvements. It applies a stepwise approximation of the eddy diffusivity and wind speed, the Laplace transform to the diffusion-advection equation, a semi-analytical solution of the linear ordinary equation set resulting in the Laplace transform application, the construction of the pollutant concentration by the Laplace transform inversion through the application of the Gaussian quadrature scheme, the computation of first-order chemical reactions, and the discretization and the parameterization of the ABL. Such as in the REEDM model, the MSDEF model assumes that the cloud released by the rocket can be initially defined as a single cloud that grows and moves, but remains as a single cloud during the formation of the ascending phase of it. This concept is illustrated in Figure 2, and can be noticed that the model is designed for concentrations from the vertical position of the stabilized cloud. Thus, the discretization of the ABL is applied through the partitioning of the stabilized cloud in "disks" representing the different meteorological vertical levels at different altitudes, each one having a single meteorological speed and wind direction that moves the disk into the same cloud. 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.

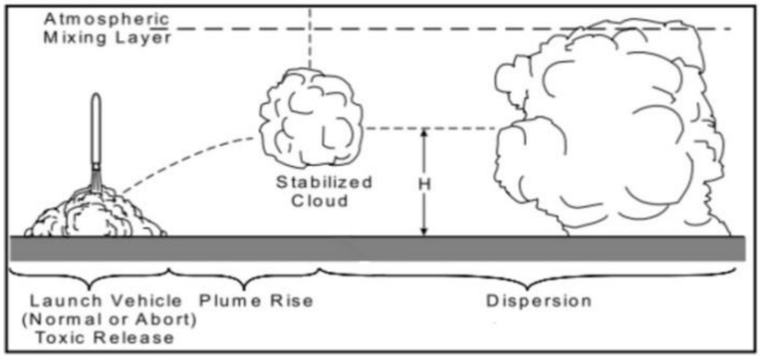

Figure 2. Conceptual illustration of cloud formation (source), "cloud-rise" and atmospheric dispersion of the cloud. Source: [0].

The model makes predictions of instantaneous and average concentration in time (typically 10 min and hourly average). In many situations it is made an average of 1 hour to compute the average concentrations. A shorter average time is appropriate for exposure to the cloud of the rocket, because the source (cloud) typically goes on a receiver with a time scale of tens of minutes before the hour.

The Long-Range Chemical Transport Model

Once the short range assessment model has been applied, for a time scale ranging from minutes to a couple of hours, it is important to assess how the rocket exhaust pollutants will impact in the region of the surrounding area of the launch site for the next hours after the launch event. Commonly, the launching centers are close to big and populated region/cities that may be affected by the gases released during the launchings. In the case of ALC, the capital city of Maranhão State, São Luís, with more than 1 million inhabitants, is located southwards far 30 km. Recently, [0] presented a work where the Community Multi-scale Air Quality (CMAQ) modeling system is applied for regional scale modeling of the chemical transport of rocket exhaust pollutants in the region of ALC, which showed interesting and promising results. Therefore, since CMAQ represents the state-of-the-art in regional and chemical transport air quality modeling, and due to its capability to deal with chlorine gases –

which plays an important role in rocket exhaust clouds – we chose this model to be applied in this hybrid system for assessing the impact of rocket exhaust clouds in air quality for long range assessment.

RESULTS AND DISCUSSION

Figure 3 presents two scenarios of the surface wind field simulated by the WRF model at the time of March 19, 2013 at 16:00h GMT, and March 20, 2013 at 11:00h GMT, for domain 5. Figure 4 shows how domain 5 fits in the considered region. From Figure 3, it is possible to note that the wind is predominantly blowing from the northeastern direction at the first scenario, flowing to the continent in the direction of an inhabited area, and a hypothetical launch at this time would not impact in populated areas, like the large city of São Luís. Some hours later the scenario changes: the wind direction starts to change, and, at March 20, 2013 at 11:00h GMT, 19 hours later, the wind field entirely changes and blows from the southeastern direction, showing that in few hours the meteorological scenario can considerably change. The figures 3 and 4 were produced using the program VAPOR [0].

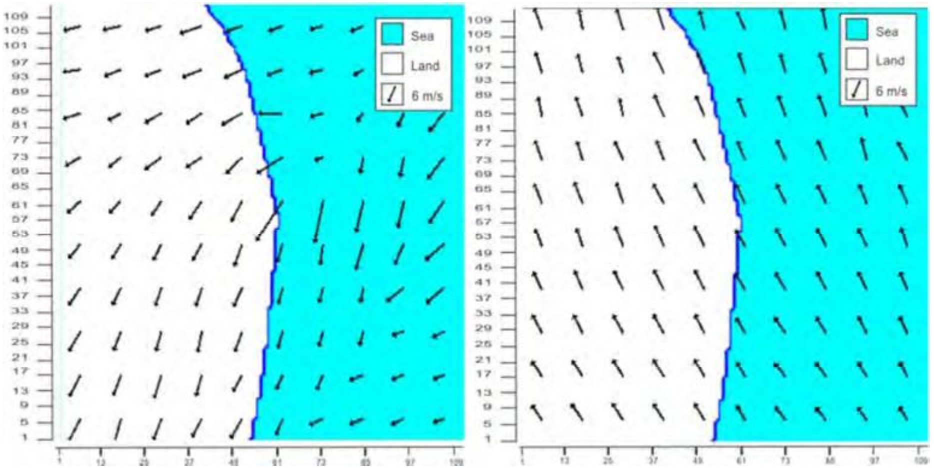

Figure 3. Simulated wind field for March, 19 2013 at 16:00h GMT, and March, 20 2013 at 11:00h GMT, for domain 5.

Figure 4. Simulated wind field for March, 19 2013 at 16:00h GMT, for domain 5, using a background map (taken from Google Earth application)

Figure 5 presents a plot of the application of the MSDEF coupled with the WRF model to generate concentration fields (in ppm) for short range assessment, showing the vector wind speed and dispersion of the plume in the downwind direction. Figure 6 shows a sequential tile plot for HCl concentrations simulated using the CMAQ model. Both cases were applied to the ALC region.

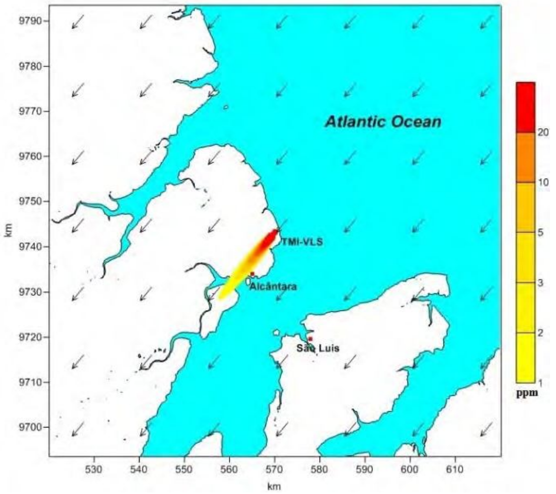

Figure 5. Plume generated by the MSDEF model, showing the second-hour average scenario. TMI represent the Tower Mobile Integration and VLS is the Satellite Launch Vehicle.

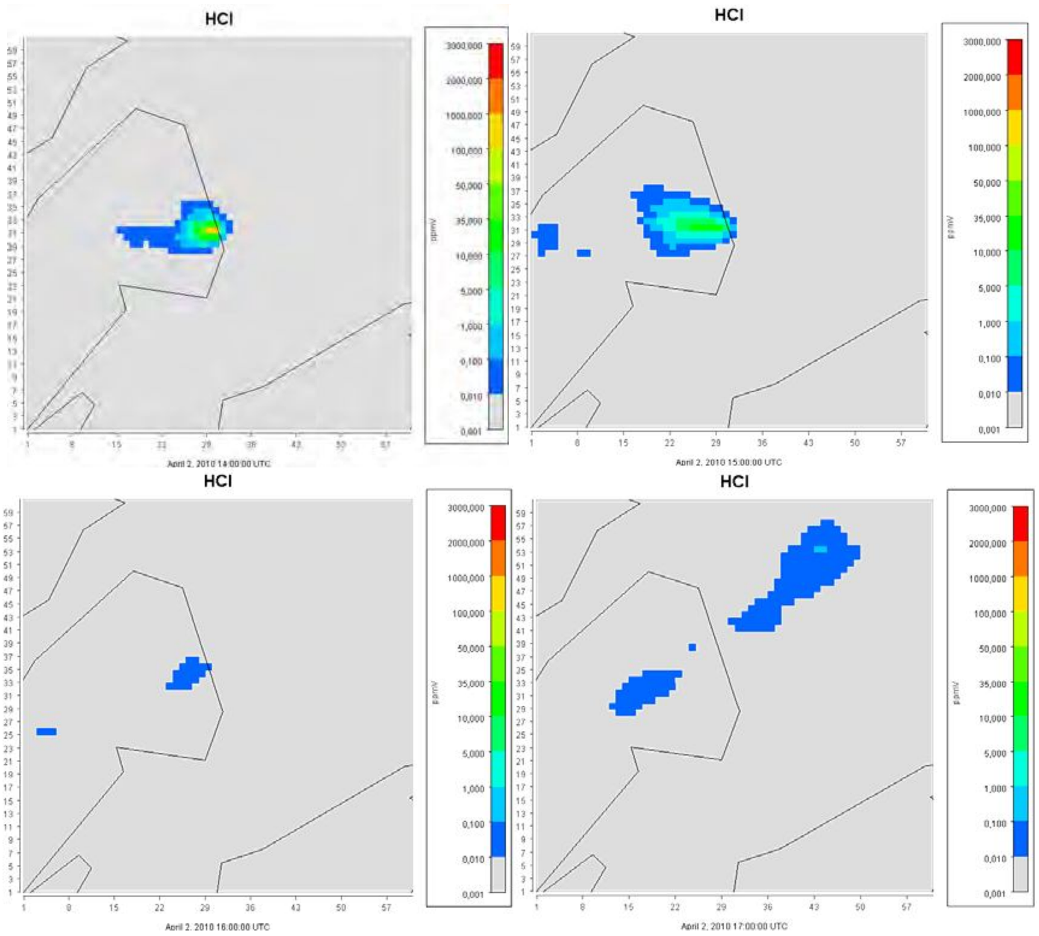

Figure 6. Hourly concentration scenario for HCl generated by the CMAQ model for the surface layer.

CONCLUSIONS

This work aims to present the development of a more complete, hybrid, multi-disciplinary system, based on the state-of-the-art, to simulate the weather, dispersion and chemical transport for short and long range assessment of rocket exhaust clouds in launching centers. Despite our intention is to develop and apply this system to the ALC, it will be built on general atmospheric science concepts that will let this system to be applied in any site in the world. This system can be operationally used in different missions, as planning activities and environmental assessments, pre-and post-launching forecasts of the environmental effects of rocket operations.

REFERENCES

Bjorklund, J.R.; Dumbauld J.K.; Cheney, C.S.; Geary, H.V. User's manual for the REEDM (Rocket Exhaust Effluent Diffusion Model) compute program, *NASA contractor report 3646*. NASA George C. Marshall Space Flight Center, Huntsville, AL, **1982**.

Moreira, D. M.; Trindade, L. B.; Fisch, G.; Moraes, M. R.; Dorado, R. M.; Guedes, R. L. A multilayer model to simulate rocket exhaust clouds. *Journal of Aerospace Technology and Management, v. 3, pp. 41-52*, **2011**.

Cencetti, M.; Veilleur, V.; Albergel, A.; Olry, C. SARRIM: A tool to follow the rocket releases used by the CNES Environment and Safety Division on the European Spaceport of Kourou (French Guyana), *International Journal of Environment and Pollution, vol. 44, pp. 87-95*, **2011**, doi: 10.1504/IJEP.2011.038406.

Rajasekhar, M.; Kumar, M. D.; Subbananthan, T.; Srivastava, V.; Apparao, B.; Rao, V. S.; Prasad, M. Exhaust dispersion analysis from large solid propellant rocket motor firing using HYSPLIT model over Satish Dhawan Space Centre (SDSC SHAR), *Indo-US Conference-cum-Workshop on "Air Quality and Climate Research", ASCI Hyderabad,* **2011**. doi: 10.13140/2.1.4008.1284.

Silva, A. F. G.; Fisch. G. WRF Model Assessment for the Wind Profile Forecast at the Alcantara Launching Center, *Brazilian Journal of Meteorology, vol. 29, n. 2, pp. 259-270*, **2014**.

Nascimento, E. G. S.; Moreira, D. M.; Albuquerque, T. T. A.; Reis, N. C. Jr; Santos, J. M.; Goulart, E. V.; Fisch, G. Atmospheric dispersion modeling to simulate rocket exhaust clouds. *Proceedings of the 17th International Conference on Computational Methods and Experimental Measurements, WIT Transactions on Modelling and Simulation, vol. 59, pp. 481-492*, **2015**. ISSN: 1743-355X.

Nyman, R.L. Evaluation of Taurus II Static Test Firing and Normal Launch Rocket Plume Emissions, *NASA Report*, **2009**.

Nascimento, E. G. S.; Moreira, D. M.; Albuquerque, T. T. A.; Fisch, G. Simulation of Rocket Exhaust Clouds at the Centro de Lançamento de Alcântara Using the WRF-CMAQ Modeling System, *Journal of Aerospace Technology and Management, v. 6, n. 2, pp. 119-128*, **2014**. doi: 10.5028/jatm.v6i2.277.

Clyne, J.; Mininni, P.; Norton, A.; Rast, M.; Interactive desktop analysis of high resolution simulations: application to turbulent plume dynamics and current sheet formation. *New Journal of Physics 9, 301*, **2007**.