Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 1935-1944.

NUMERICAL STUDY OF FOG EVENTS ALONG RIO DE JANEIRO COAST, USING THE MM5 MODEL COUPLED WITH THE UNIDIMENSIONAL MODEL COBEL

Flávia R. Pinheiro, Rachel G. Peterson, William C. M. De Farias*
Navy Hydrographic Center (CHM), Niterói, RJ/ Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, RJ

1. INTRODUCTION

Fog events cause visibility degradation, which are harmful for maritime, terrestrial and aerial navigation. Despite all of development on weather prediction through years, fog forecasting still is a challenge to meteorologists around the world.

Seeking for a numerical model which could improve fog forecasting, simulations of some fog event periods were made, using two different models. Firstly, it was made an analysis of some meteorological parameters derived from MM5 mesoscale model simulations. Then, several variables derived from MM5 output results were used to initialize simulations of COBEL, a high-resolution French model, specially designated to study the boundary layer and simulate its vertical evolution, in a local scale.

This paper aimed to specify meteorological conditions which are favorable to fog formation at Rio de Janeiro coast, in order to find a useful tool to provide good prognostics of fog events and give support to meteorological centers.

2. FOG CHARACTERISTICS

2.1. Definition

We can define fog as a stratiform cloud layer on the surface or next to it.

Stratiform clouds occur in the lower atmosphere, whenever it forms a well developed thermal inversion or in a nearest isothermal layer. A surface thermal inversion usually occurs because of air cooling at low levels, a characteristic of air masses that are originally hotter than the surface below it.

2.2 Formation and dissipation processes

To fog formation, it is necessary that surface air be saturated. Other factors are also desired such as absence of cloud cover at night, relatively weak winds and high dew point temperatures, capable of reaching local air temperature, generating saturation.

Liquid water vertical distribution, radiative cooling and condensation rate have an important role in fog development.

Fogs are usually considered passive phenomena, since their formation process depends entirely on parameters such as temperature, humidity, cloud cover and surface conditions. However, after their formation, fogs become extremely dynamic events (Stull, 1994). Dissipation process depends on each type of fog, but it generally occurs by local heating, increasing speed winds, air masses changes or precipitation occurrence. Dissipation process generally begins by the edges of the fog. Solar radiation penetrates it and heats the surface. It also increases air temperature, generating fog droplets evaporation, which allows more solar radiation to reach the surface, accelerating even more evaporation process and generating an effect of a “raising” fog, until it definitely disappears. If fog layer is sufficiently thick, complete dissipation may not occur, forming a stratiform cloud layer covering the region.

2.3 Classification

Fogs are classified according to their formation process. Physically, they may be formed by decreasing air temperature until it reaches dew point temperature, or by water vapor addition, until dew point temperature reaches air temperature. Classification considerates two principal types:

(A) Fogs formed by decreasing of an air mass temperature: advection, radiation, advection-radiation and mountain fogs;

(B) Frontal fogs: formed due to precipitation. Frequently, the most important factor is dew point temperature increase.

2.4 Fog Microstructure

Even if it is expected that relative humidity inside a fog must be near 100%, it is known that observed values of this parameter are extremely variable. Observations show that fogs, differently from most of the clouds, are characterized by relatively low values of liquid water and small drops (Pinheiro, and Torres Jr, 2004).

During formation stage, increase of number of drops with time is a result of increasing liquid water content, while drops size keep constant or increase just a little. During mature stage, number of drops and liquid water content remains reasonably constant. Dissipation stage is the period when there is a decrease of these concentrations.

There is not a good understanding of fog microstructure yet, due to difficulties of measuring parameters like relative humidity variations inside fogs, although they are extremely important so as to obtain a good fog forecast.

*Corresponding author addresses: Flávia R. Pinheiro, Rachel G. Peterson and William C. M. De Farias, CHM, Div. of Environmental and Numerical Forecast, Niterói, RJ, +5521-26138270; and UFRJ, Dept of Meteorology, Rio de Janeiro, RJ, +5521-25989471; e-mails: flavia@smm.mil.br, kelgiglio@yahoo.com.br and willcossich@yahoo.com.br.

3. THE STABLE BOUNDARY LAYER

Boundary layer can be stably stratified, when the air near the surface gets colder than the air immediately above it. Balance between mechanical generation of turbulence and decaying due to stability depends on each case, what makes stable boundary layer be well mixed in some situations and almost not turbulent in others. Consequently, there are many difficulties to model this layer.

Air humidity is, in special, a parameter that is quite hard to describe, because in some cases surface evaporation process continues all night long, while in other moments it occurs condensation, resulting in dew deposition. Complicated balance between turbulence and stability gets more apparent when it occurs a "conflict" between fog formation and dew deposition. It is known that dew deposition may delay, or even avoid fog formation, so it is an extremely important parameter to formation process of fog events (Bergot and Guédalia, 1994).

4. STATISTIC VERIFICATION

4.1 Methodology

It was made an analysis of some meteorological information derived from METAR data from Galeão and Santos Dumont airport stations (both located in Rio de Janeiro, Brazil), during the period between December 2002 until May 2005. The major goal is to understand behavior of parameters such as local wind direction and intensity and also visibility.

According to Guanabara bay´s geographical localization, wind directions were classified with the following methodology:

- 061º to 119º - east component
- 120º to 240º - maritime component
- 241º to 299º - west component
- 300º to 060º- continental component

Wind intensities were classified as followed:

- calm: < than 1KT (knot)
- weak: 2 to 10 KTS
- moderate: 11 to 16 KTS
- strong: > than 16 KTS

Fogs were classified as *dense* whenever horizontal visibility was less than 200 meters.

4.2 Synoptic analyses during fog events

A synoptic analysis made during foggy days at Rio de Janeiro coast, pointed out that predominant synoptic situation was characterized by a high center pressure above the area of interest and in some few cases, the periphery of these highs influenced the region, as it can be exemplified in Figure 1.

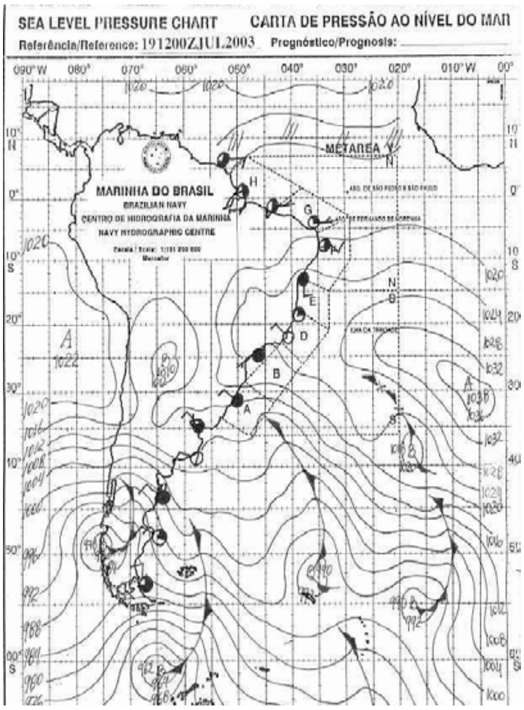

Figure 1: Sea Level Pressure Synoptic Chart (from Brazilian Navy Hydrographic Centre), at 07/19/2003 – 12 GMT, a foggy day in Rio de Janeiro.

4.3 Statistics

Observations showed that predominant winds were characterized as *continental weak* winds (as it can be seen in Figures 2 and 3), even so there were some rare cases of moderate and strong winds. According to the methodology used and figure 4, during around 45% of the studied days, it occurred fogs which could be considered as *dense* ones.

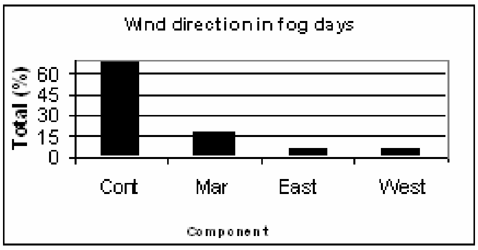

Figure 2: Wind direction during fog events, represented in components of wind.

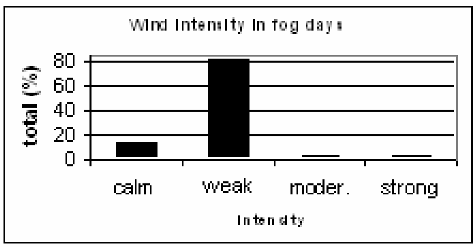

Figure 3: Wind intensity during fog events.

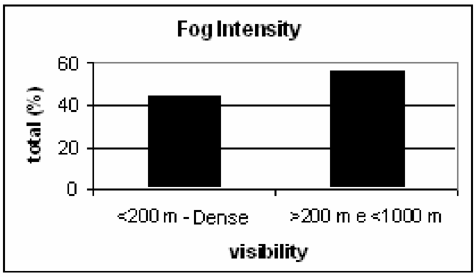

Figure 4: Fog intensity.

5. MODEL SIMULATIONS

5.1 Methodology

They were simulated all cases of fog events observed during the period of study (December/2002 to May/2005), however results of two different cases will be focused in this paper. The first case analyzed is referent to period from 18 to 25, July, 2003, in which occurred fog events in the following days: 19, 23 and 24. This case was a typically winter period, which is quite favorable to fog formation.

Second studied case, however, occurred during summer, a relatively atypical period to fog formation at Rio de Janeiro coast. Also, fog was formed in a post-frontal synoptic situation, making this foggy period even less common. This case goes from 12 to 14, January, 2005, in which fog formation was on day 13, January.

Were used two different models to simulate fog events during these periods: a mesoscale (MM5) and a local scale model (COBEL). As it is known, fogs are local scale phenomena. This makes them quite difficult to be represented by mesoscale models. Consequently, the aim of this study is not to prove inefficiency of mesoscale models to fog prognostics. Major goal of this paper is to search for the ideal mesoscale model microphysics, in order to obtain output results as good as possible to provide initialization data for COBEL model. As this high-resolution model is specially designated to forecast local events such as fogs, tests can be made to verify how precise and useful this tool can be to fog prognosis.

6. MM5 MESOSCALE MODEL

The Fifth-Generation Mesoscale Model (MM5) is a limited-area, nonhydrostatic or hydrostatic (Version 2 only), terrain-following sigma-coordinate model designed to simulate mesoscale phenomena and regional-scale atmospheric circulation. It has some special characteristics, such as: (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale, (iii) a four-dimensional data-assimilation capability, and (iv) many physics options.

6.1 Methodology

MM5 mesoscale model was initialized with data derived from Reanalysis project (NCEP/NCAR), in order to analyze model´s ability to simulate, in such an appropriate way, those meteorological conditions which are inherent to fog phenomena.

To perform this analysis, they were used Galeão airport´s coordinates (Latitude = -22,47S; Longitude = -043,14W) inside a 10 km grid with 33 sigma vertical levels. In addition, it was used an appropriate microphysics for cloud and boundary layer representations. Detailed information on microphysical properties is not in the scope of this text, however some parameterizations used must emphasized:

- Cumulus parameterization: Kain-Fritsh 2. It uses a sophisticated scheme of cloud mixture, including shallow convection;
- Planetary Boundary Layer (PBL) scheme and Diffusion: MRF PBL, suitable for high resolution in PBL;
- Explicit Moisture scheme: Reisner Graupel (Reisner 2), which is an updated scheme suitable for cloud-resolving models;
- Radiation scheme: RRTM (Rapid Radiative Transfer Model) longwave scheme that uses a correlated-k model to represent effects of the detailed absorption spectrum taking into account water vapor, carbon dioxide and ozone. It is combined with cloud-radiation shortwave scheme.
- Surface scheme: Noah Land-Surface Model (LSM), capable of predicting soil moisture and temperature in four layers (10, 30, 60 and 100 cm thick). It also outputs surface and underground run-off accumulations. This scheme uses a diagnostic equation to obtain a skin temperature. Detailed description can be found online: MM5 Community Model - http://www.mmm.ucar.edu/mm5/overviewPhysics.html.

After analyzing MM5 results, output variables derived from this model such as air temperature, liquid water mixing ratio and zonal and meridional wind components were used to initialize COBEL model run.

6.2 MM5 Model Results

Simulation results related to winter period are presented in graphs referred to days 18 to 20, July, 2003 and others referred from day 22 to 25, July, 2003, for a better visualization of the graphs. Y axis in these graphs represents sigma levels. As it was already mentioned in this text, a mesoscale model is not designated to represent accurately boundary layer evolution in such a local scale in which fog develops. Also, it was used a 10 km grid to simulations, which may not be the ideal one for this subject. Consequently, MM5 simulation results couldn't represent meteorological parameters related to fog, in such a way it could be forecasted these events for those periods. MM5 difficulties to simulate fog properties can be seen in the following graphs.

According to figures 5 and 6, graphs indicate an increase of mixing ratio during early mornings before foggy days. However, figures 7 and 8 show how far from fog formation these results may be, indicating relative humidity values of less than 80% near the surface, which doesn't represent real local conditions as well.

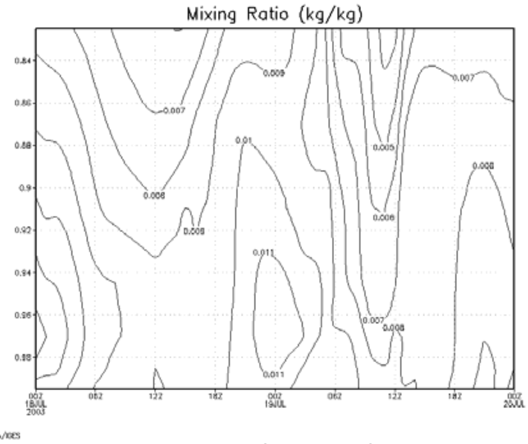

Figure 5: Mixing Ratio for period from 18 to 20/JUL/2003. (MM5)

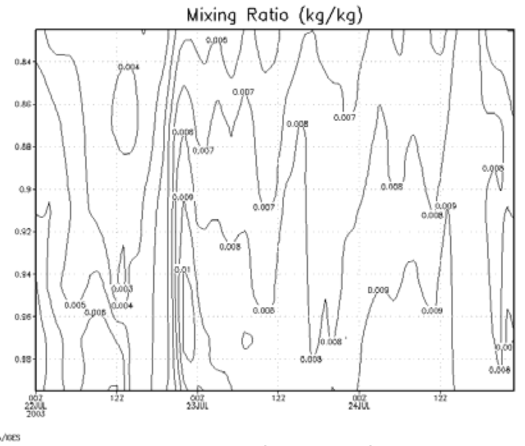

Figure 6: Mixing Ratio for period from 22 to 25/JUL/2003. (MM5)

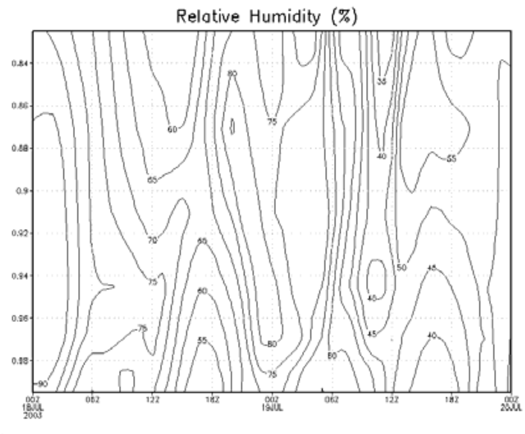

Figure 7: Relative Humidity for period from 18 to 20/JUL/2003. (MM5)

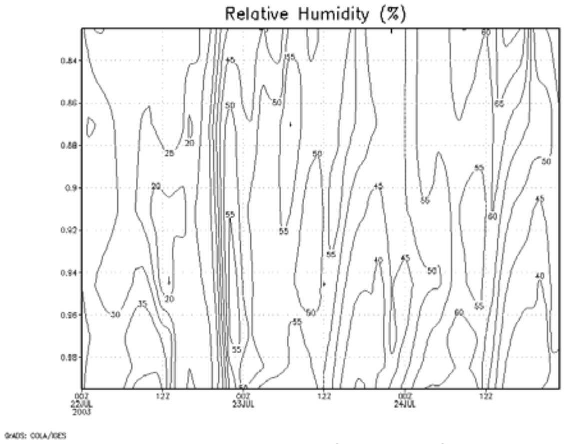

Figure 8: Relative Humidity for period from 22 to 25/JUL/2003. (MM5)

Consequently, cloud water near the surface couldn't be represented, as it can be seen in figure 9 (results related to period between 22 and 25, July, 2003, exhibited some undefined values, so it is not shown in this text).

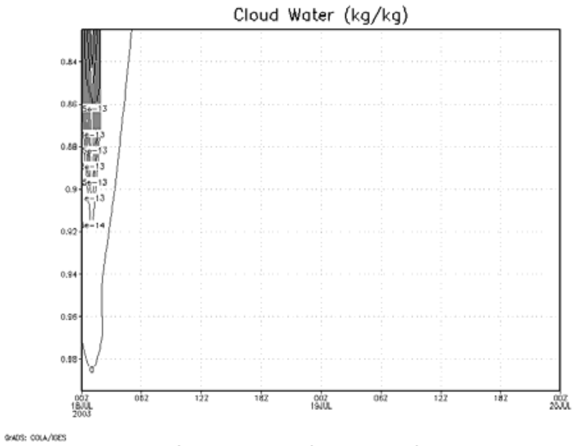

Figure 9: Cloud Water for period from 18 to 20/JUL/2003. (MM5)

During second case, occurred in summer period, MM5 represented meteorological variables related to fog formation much better, probably because it was characterized as a post-frontal fog. That means, the day before fog occurrence was an extremely moisty day, due to frontal conditions, and high humidity values were maintained the day after, during fog formation.

Model indicated increases in mixing ratio and relative humidity values near the surface, at the exact fog formation time (see figures 10 and 11). However, model was not able to represent cloud water near the surface during fog day (January, 13), which could be desirable in such conditions (figure 12).

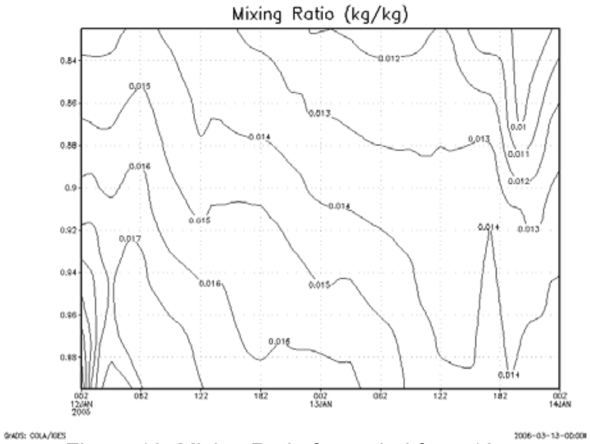

Figure 10: Mixing Ratio for period from 12 to 14/JAN/2005. (MM5)

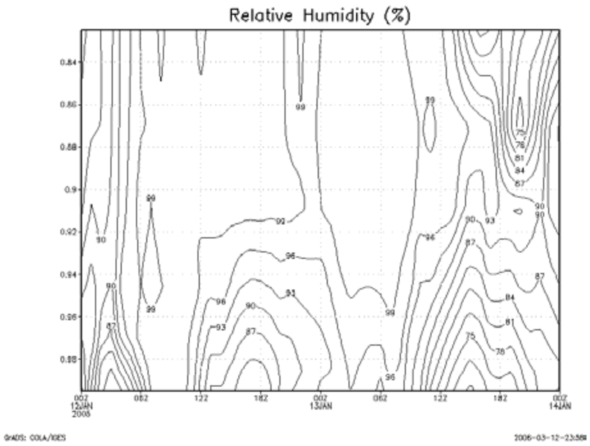

Figure 11: Relative Humidity for period from 12 to 14/JAN/2005. (MM5)

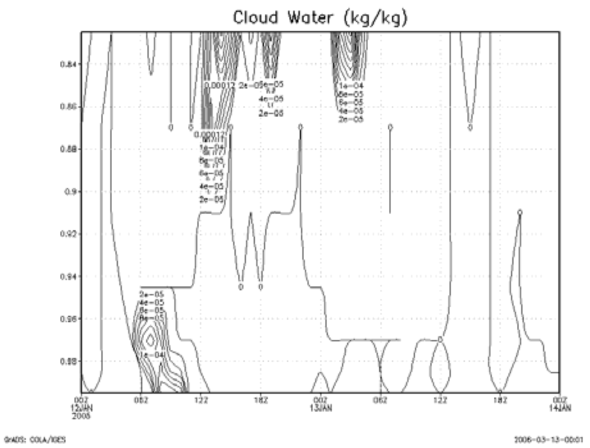

Figure 12: Cloud Water for period from 12 to 14/JAN/2005. (MM5)

7. COBEL MODEL

Numerical model COBEL (**CO**UCHE **B**ROUILLARD **E**AU **L**IQUIDE) used in this study is a boundary layer model, developed in Toulouse, France. It is designated to study the nocturnal boundary layer (Estournel and Guedália, 1987) and simulate its vertical structure evolution, in a local scale, focusing on physical processes involved in formation, evolution and dissipation of fog and stratiform clouds.

COBEL model is coupled to a mesoscale model, so as to be considered external parameter effects, such as: geostrophic wind, temperature and humidity advection, vertical movements and pressure local tendencies. These external parameters were not considered in the present study, however basic input variables to initialize COBEL were derived from MM5 model.

Also, COBEL has sophisticated parameterizations for radiative transfer and turbulent mixing. A coupling scheme between mesoscale model and high-resolution COBEL model is presented in figure 13.

For more details see: Bergot (1993), Bergot and Guédalia (1994) and online: (http://www.rap.ucar.edu/staff/tardif/COBEL).

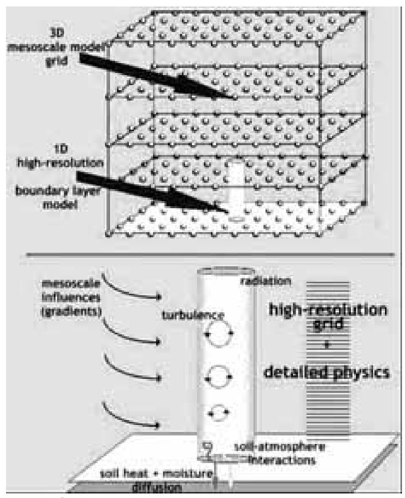

Figure 13: Scheme representing coupling between mesoscale model and COBEL

COBEL uses:

- Mixing turbulent parameterizations based on Turbulent Kinetic Energy (TKE) and mixture length;
- Implicit parameterization for microphysics;
- Sedimentation parameterization of fog droplets;
- Soil model based on diffusion equation for soil temperature;
- Fouquart and Bonnel (1980) scheme for solar radiation; and
- IR radiation scheme with high spectral resolution (232 channels) (Vehil et al, 1989).

7.1 Basic Equations

Basic dynamic and thermodynamic equations are derived from *Boussinesq* system of equations:

$$\frac{\partial v}{\partial t} = -f\left(u - u_g\right) - \frac{\partial}{\partial z}\left(\overline{w'v'}\right) - w\frac{\partial v}{\partial z} \qquad (1)$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'\theta'}\right) + \frac{\theta}{T}\left[-\frac{1}{\rho C_p}\frac{\partial F_I}{\partial z} + \frac{L}{C_p}C\right] - w\frac{\partial \theta}{\partial z} - \vec{V}\cdot\vec{\nabla}\theta \qquad (2)$$

$$\frac{\partial q}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q'}\right) - C - w\frac{\partial q}{\partial z} - \vec{V}\cdot\vec{\nabla}q + E_r \qquad (3)$$

$$\frac{\partial q_1}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{w'q_1'}\right) + C + \frac{\partial G_c}{\partial z} - w\frac{\partial q_1}{\partial z} - P \qquad (4)$$

where *f* is Coriolis Parameter, *u* and *v* are orthogonal components of horizontal wind, θ is potential temperature, *T* is the air temperature and *q*, mixing ratio. $w'\alpha'$ represent turbulent fluxes (α being principal variables), F_r indicates total radiation flux, *C* is condensation rate, c_p is the air specific heat at constant pressure, *L* is evaporation latent heat and ρ is specific mass of air. Geostrophic wind components (u_g e v_g) and horizontal advection of temperature and moisture, are external parameters, calculated from output results of coupled mesoscale model.

In order to obtain visibility estimates (in meters), it is used an equation proposed by Kunkel (1982), which relates horizontal visibility and liquid water content:

$$\mathrm{VIS(m)} = \frac{3.9}{144.7\left(\rho q_1\right)^{0.88}} \qquad (5)$$

7.2 Model Numerics

Equations are solved through finite difference method, in a vertical grid with 30 levels distributed in a log-linear way, between soil and 1400 m. In addition, it has other 5 levels in the soil, between surface and 1 m depth. Grid increment is minimum near the surface, so as to better follow surface cooling and fog development. First atmospheric level is at 0.5 m height and second one is at 1.65 m. First level in the ground is at 0.05 m depth. Time step used is of 60 seconds for dynamics and 30 seconds for microphysics.

7.3 Methodology

The major goal of this study is to follow behavior of some physical parameters related, principally, to moisture and mixing ratio, in a simplified simulation of COBEL model to forecast fog. In this study, they were not considered external parameter effects, such as horizontal advection, geostrophic wind, vertical movements and pressure tendencies.

The following MM5 model output variables were used as COBEL input data: air temperature (*t)*, liquid water mixing ratio (*q*), meridional and zonal wind components (*u* and *v)*. Seven first levels derived from MM5 outputs were used. COBEL integrates its own vertical interpolation during simulation. Moreover, they were used six additional levels in air temperature and liquid water mixing ratio input data, for radiative calculations. Simulation period was of 21 hours, starting at 15 GMT of the previous day of fog event, and finishing at 12 GMT of fog day.

7.4 COBEL Model Results

Same periods of MM5 simulations were used for COBEL tests. For better visualization, in some graphs it will be shown only those time intervals in which occurred fogs, instead of showing all 21 hours of COBEL simulation.

Although it is known that COBEL initialization with data derived from MM5 outputs was not as precise as desirable, high-resolution COBEL model demonstrated some ability to simulate fog phenomena, as it will be seen in following results.

Between 18 and 19, July, 2003, COBEL represented efficiently local conditions, as it can be visualized in relative humidity graph (figure 14). As it is known, increase of this meteorological parameter is an important feature to fog formation.

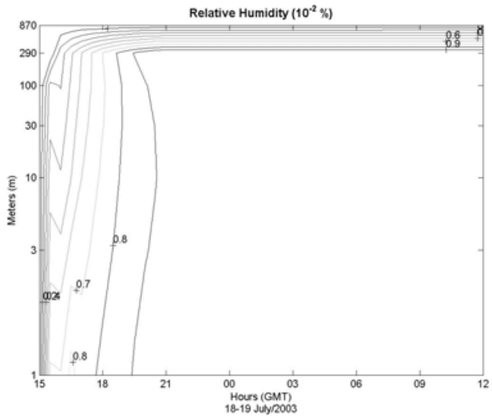

Figure 14: Relative Humidity between 18 and 19/JUL/2003. (COBEL)

Model indicates a dryer atmosphere at beginning of simulation, on the previous day of fog occurrence. During afternoon, relative humidity naturally decreases, as temperature increases, as these two parameters are inversely proportional (Stull,1994). According to simulations, at night, relative humidity increased significantly up to almost 300 meters, which configures an important support to fog formation. Sounding data referent to the previous night of fog occurrence (figure 15) can be compared to simulation results, illustrating how properly COBEL represented increase of moisture during the period of interest.

83746 SBGL Galeao Observations at 12Z 19 Jul 2003

PRESSURE hPa	HEIGHT m	TEMP C	DEWPT C	RELHUM %	MIXRATIO g/kg
1023.0	42	18.2	18.2	100	13.02
1000.0	201	17.4	16.8	96	12.18
993.0	261	17.0	15.9	93	11.57
978.0	392	18.9	13.4	70	9.95
963.0	525	20.8	10.8	53	8.51
925.0	872	18.6	7.6	49	7.13

Figure 15: Sounding data provided by University of Wyoming – Department of Atmospheric Science (http://weather.uwyo.edu/upperair/sounding.html).

According to results, liquid water mixing ratio also increased at night before fog formed, as it is represented in graph (figure 16).

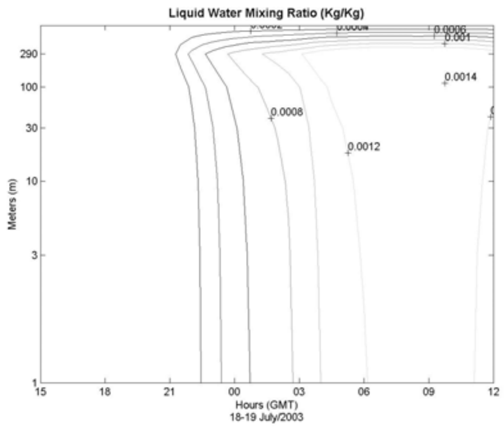

Figure 16: Liquid Water Mixing Ratio between 18 and 19/JUL/2003. (COBEL)

Finally, COBEL was capable of promoting condensation, indicating, as desirable, some visibility reduction (figure 17). However, model anticipated event occurrence, representing fog at night, although it really occurred at morning. This problem may have different sources: COBEL configuration (number of vertical levels used, time steps performed by the model, soil parameters etc) or poor quality of MM5 input data, which is the most crucial problem.

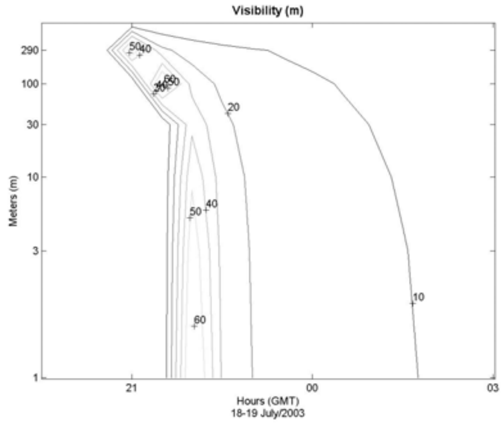

Figure 17: Visibility reduction between 18 and 19/JUL/2003. (COBEL)

Performing tests for 22-23 and 23-24, July, 2003, COBEL represented similarly well relative humidity and liquid water mixing ratio increases (figures 18 to 21).

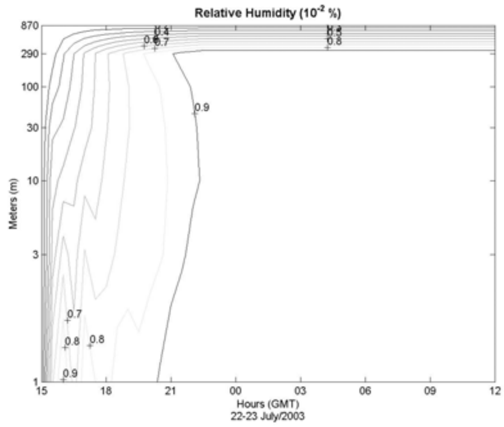

Figure 18: Relative Humidity between 22 and 23/JUL/2003. (COBEL)

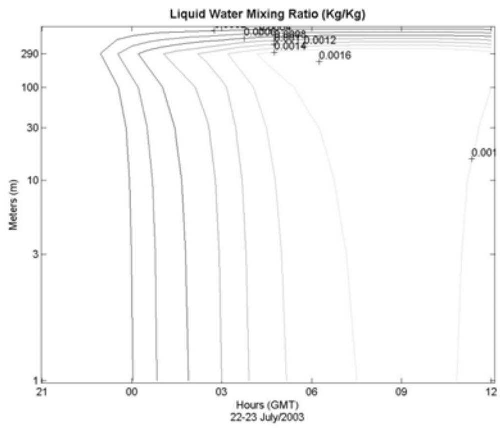

Figure 19: Liquid Water Mixing Ratio between 22 and 23/JUL/2003. (COBEL)

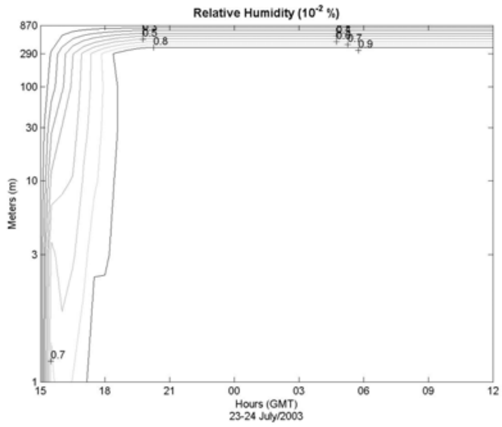

Figure 20: Relative Humidity between 23 and 24/JUL/2003. (COBEL)

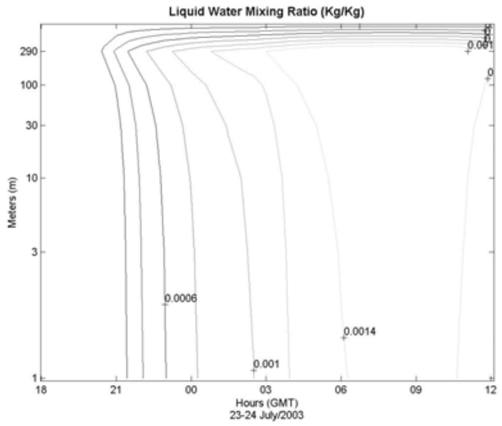

Figure 21: Liquid Water Mixing Ratio between 23 and 24/JUL/2003. (COBEL)

Although moisture content variables such as relative humidity and mixing ratio were well simulated by COBEL, fogs occurred in 23 and 24, July, 2003 were not represented as a visibility reduction near the surface (figures 22 and 23).

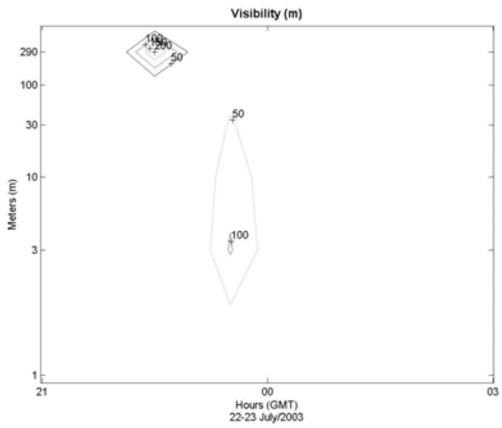

Figure 22: Visibility reduction between 22 and 23/JUL/2003. (COBEL)

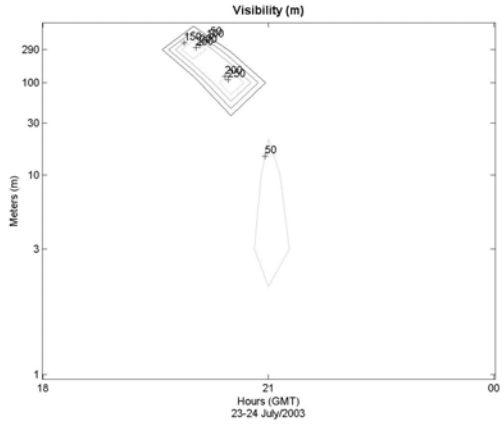

Figure 23: Visibility reduction between 23 and 24/JUL/2003. (COBEL)

As these results were not able to represent correctly visibility reduction, new model runs were performed, in which time steps were changed, in order to investigate which influences this new configuration could have on visibility results. New time steps used were 20 s for dynamic processes and 10 s for microphysics processes.

Simulation performed with these changes presented better results, indicating visibility reduction near the surface as it occurred, although it still presented time problems, not being able to represent the phenomena in the morning, as it really happened (figures 24 and 25).

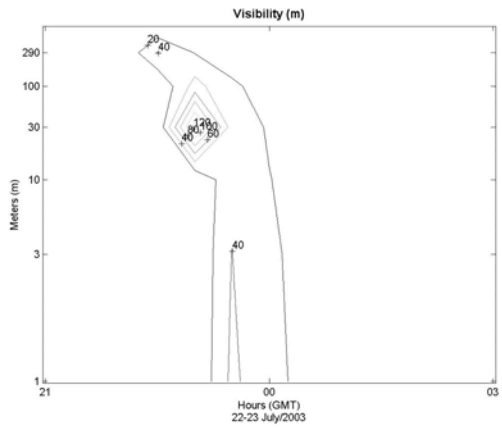

Figure 24: Visibility reduction between 22 and 23/JUL/2003 using time steps of 20s (dynamics) and 10s (microphysics). (COBEL)

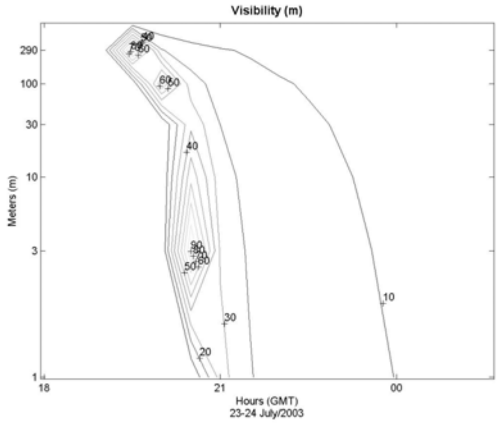

Figure 25: Visibility reduction between 23 and 24/JUL/2003 using time steps of 20s (dynamics) and 10s (microphysics). (COBEL)

By the other hand, for second case, which is summer period, COBEL simulations were much more realistic. Relative humidity and liquid water mixing ratio increasing and also visibility decreasing near the surface were well represented on figures 26, 27 and 28, although it still indicated some hours of anticipation on fog occurrence.

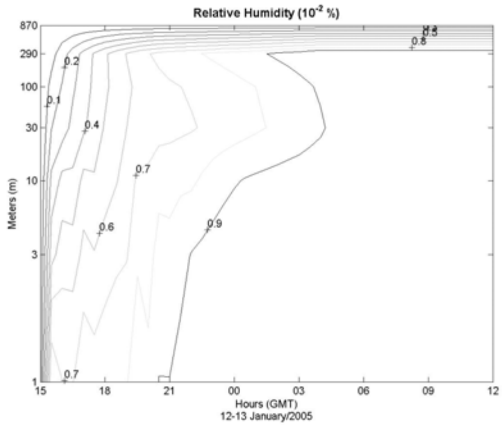

Figure 26: Relative Humidity between 12 and 14/JAN/2005. (COBEL)

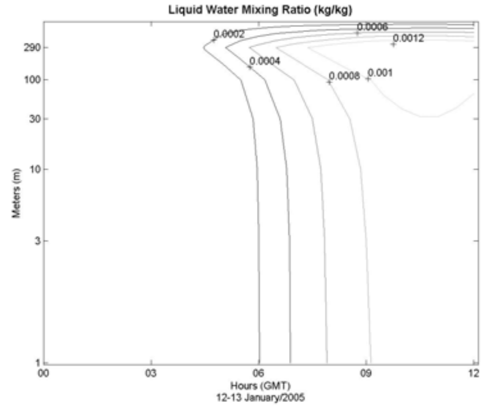

Figure 27: Liquid Water Mixing Ratio between 12 and 14/JAN/2005 (COBEL).

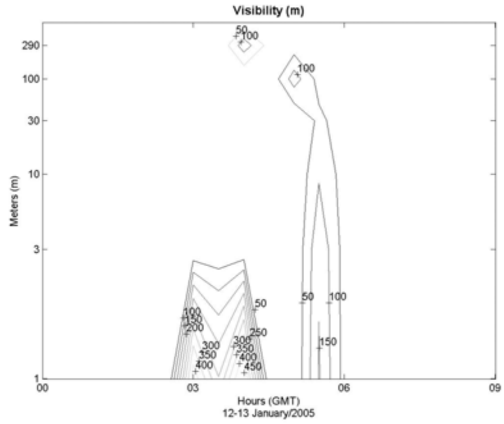

Figure 28: Visibility between 12 and14/JAN/2005. (COBEL)

For these summer simulations initial time steps were used: 60 seconds for dynamics and 30 seconds for microphysics processes.

8. CONCLUSIONS

Simulations of fog events were made, using two different models: MM5 mesoscale model and COBEL high-resolution model. The main purpose is to specify favorable meteorological conditions to fog formation at Rio de Janeiro coast, seeking for a useful tool to provide good prognostics of fog events.

Comparisons between simulation results of both models have shown that, although a mesoscale model may not be an ideal tool to efficiently forecast fogs, it can be able to provide useful data for initialization of a high-resolution model, in order to obtain a more precise fog prognosis.

Results have shown COBEL skills to forecast boundary layer evolution, principally revealing moisture vertical evolution in a coherent way.

Tests showed clearly that fog prognosis is extremely sensible to initial conditions, requiring more accurate input data to COBEL initialization.

Consequently, it is relevant to mention that COBEL presented some deficiencies to accurately forecast beginning time of fog events. In fact, poor quality initialization data derived from MM5 outputs were preponderant factors, restricting COBEL results in this short-term weather forecast. Ideal COBEL input data would be those ones derived from high resolution observation profiles, which could certainly improve forecast skill. Tests are being made with observations from an experiment occurred in 2001, in Santarém (Pará state), in order to analyze how helpful high resolution measurements can be. Unfortunately, costs of a high resolution observational site are high, which contributes to weak predictability of fogs in meteorological centers.

Other cases will be studied, in order to better evaluate models behavior and find a useful tool to detect, more precisely, fog events at Rio de Janeiro coast. Mesoscale model parameters will be analyzed, seeking for the best adjustment of its microphysics, to improve initial conditions provided to COBEL high resolution model.

Major topics for future work:

- make an improvement in MM5 properties, also testing an increase in grid resolution;
- calibrate COBEL configuration, adjusting number of vertical levels, soil parameters and testing which time step is more advisable in such cases, as well as different initialization times;
- make tests with some observational data derived from an experiment in Santarém;
- complement statistics with METAR data from Santa Cruz and Afonsos aerodromes, in order to follow fog development inside continent, and its interaction with local orography; and
- analyze meteorological parameters during preceding days of fog occurrence, to evaluate atmospheric behavior during these periods.

Acknowledgments. We are particularly grateful to Navy Hydrographic Center and Department of Meteorology from UFRJ (Federal University of Rio de Janeiro). Authors address special thanks to Thierry Bergot (MÉTÉO FRANCE) and David Garrana (UFRJ), for their great support with model information, and also Commanders Antonio Claudio Magalhães Vieira, Rodrigo de Souza Obino and Carlos Augusto Chaves Leal Silva, for contributing with authors participation in this conference.

REFERENCES

Arya, S. P., 1988: Introduction to Micrometeorology. *Academic Press*, 303 pp.

Bergot, T., 1993: Modélisation du Brouillard à l'Aide d'un Modèle 1D Forcé par des Champs Mésoéchelle: Application à la Prévision. Ph.D. thesis, Université Paul Sabatier, Toulouse, France, 1546, 191pp.

Bergot, T., and D. Guédalia, 1994: Numerical forecasting of radiation fog. Part I: Numerical model and sensitivity tests. *Mon. Wea. Rev.*, **122**, pp.1218-1230

Estournel, C., and D. Guédalia, 1987: A new parameterization of eddy diffusivities for nocturnal boundary layer modeling. *Bound. Layer Meteor.*, **39**, 191-203.

Fouquart, Y., and B. Bonnel, 1980: Computations of solar heating of the Earth's atmosphere: a new parameterization. *Beitr. Phys. Atmos.,* **53**, 35-62.

Guédalia, D., and T. Bergot, 1994: Numerical forecasting of radiation fog. Part II: A comparison of model simulations with several observed fog events. *Mon. Wea. Rev.*, **122**, 1231-1246.

Guédalia, D., and T. Bergot, 1992: Premiers résultats de la campagne "Lille 88" d'étude du brouillard. *La Météorologie*, **42**, 11-20.

Kunkel, B., 1984: Parameterization of droplet terminal velocity and extinction coefficient in fog model. *J. Appl. Meteor.*, **23**, pp.34-41.

Pinheiro, F.R., and A.R. Torres Jr, 2004: Avaliação de alguns parâmetros físicos na simulação de um modelo unidimensional para previsão de nevoeiros. *12th Brazilian Congress of Meteorology*, CD-ROM.

Stull, R.B., 1994: An Introduction to Boundary Layer Meteorology. *Kluwer Academic*, **666** pp.

Vehil, R., J. Monneris, D. Guédalia, and P. Sarthou, 1989: Study of the radiative effects (longwave and shortwave) within a fog layer. *Atmos. Res.*, **23**, 179-194.