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Artigo

Fog Analysis and Forecast by PAFOG Model in Brazilian Northeast

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Abstract

There are few studies on fog in the Brazilian Northeast (BNE) and they show that the formation processes are different in each location. Data from various sources were used for 9 years (2008-2016): a) surface data obtained by REDEMET; b) radiosonde by the University of Wyoming; c) satellites images from the GOES and METEOSAT available on CPTEC; d) reanalysis products of the ECMWF, NOAA and NCAR. Meteorological fields and simulated vertical profiles were plotted for synoptic and thermodynamic analysis. In Maceio (M) 20 cases were reported, formed by surface trough, only one event was identified from satellite product. In Campina Grande (CG) 105 cases were recorded, most of which were caused by a surface ridge; only four events were identified by satellite products. All cases in all cities had a shorter duration than observed by METAR and satisfactory results by PAFOG were obtained. Fog forecast by PAFOG was satisfactory with 6 and 12 h antecedence in M and CG. Fog formation in the BNE is atypical, especially in Maceio, where it is rarely identified by satellite data. However, the prediction by the PAFOG model presents satisfactory results up to 12 h antecedence.

Keywords: fog, tropical region, satellite products, PAFOG model.

Análise e Previsão de Nevoeiro pelo Modelo PAFOG no Nordeste Brasileiro

Resumo

Existem poucos estudos sobre nevoeiro no Nordeste Brasileiro (BNE) e eles mostram que os processos de formação são diferentes em cada localidade. Foram utilizados dados de diversas fontes durante 9 anos (2008-2016): a) dados de superfície obtidos pela REDEMET; b) radiossondagem pela Universidade de Wyoming; c) imagens de satélite do GOES e METEOSAT disponíveis no CPTEC; d) produtos de reanálise do ECMWF, NOAA e NCAR. Foram plotados campos meteorológicos e perfis verticais simulados para análises sinóticas e termodinâmicas. Em Maceió (M) foram notificados 20 casos, formados por crista de superfície, apenas um evento foi identificado a partir de produto de satélite. Em Campina Grande (CG) foram registrados 105 casos, sendo a maioria causada por cavado na superfície; apenas quatro eventos foram identificados por produtos de satélite. Todos os casos em todas as cidades tiveram uma duração menor do que o observado pelo METAR e resultados satisfatórios pelo PAFOG foram obtidos. A previsão de nevoeiro pelo PAFOG foi satisfatória com 6 e 12 horas de antecedência em M e CG. A formação de nevoeiro no NEB é atípica, principalmente em Maceió, onde raramente é identificada por dados de satélite. Entretanto, a predição pelo modelo PAFOG apresenta resultados satisfatórios até 12 horas de antecedência.

Palavras-chave: nevoeiro, região tropical, produtos satélites, modelo PAFOG.

1. Introduction

Fog is an important meteorological phenomenon for aviation, due to reduced horizontal visibility (Gultepe *et al*., 2007). As a result, there are delays or cancellations of flights, and even fatal accidents.

An unpredicted fog event in 2007 caused a fatal accident involving a twin engine near Maceio airport in 2007 (Fedorova *et al*., 2012). This accident reinforces the need to develop more in-depth studies on fog formation in the tropical region of Brazil. More accurate methods of

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fog forecasting are crucial to minimize socio economic losses, which include human lives.

Fog consists of water droplets suspended close to the surface, reducing horizontal visibility to less than 1 km (Varejao *et al*., 2006). It can be classified according to its intensity as weak, moderate or intense, when the visibility varies, respectively, from 1000 m-500 m, 500 m-100 m and below 100 m.

The three most common types of fog are: radiation, advection and frontal (Willet, 1928). Evaporation from a wet surface is of great importance in the development of fog (Byers *et al*., 1959). For its prediction, equations based on existing theories of evaporation, cooling and mixing are used (Petterssen, 1956).

Radiation fogs have the following characteristics: 1) temperature inversion; 2) wet layer at low levels and a dry layer in the rest of the atmosphere; and 3) weak wind speed at the Earth's surface (Piva *et al*., 1999).

Fog development and dissipation depend on the following conditions: 1) temperature; 2) humidity; 3) available condensation cores from an air mass; 4) radiative cooling; 5) change in the total amount of water due to precipitation; 6) mixing of air masses (Gultepe *et al*., 2007; 2019).

Still in relation to fog dissipation, the most important factors are: 1) the sudden increase in air temperature in the early morning (Cotton and Anthes, 1989); and 2) The turbulence generated by the evaporation of dew in the type of vegetation at the site (evapotranspiration).

Urban development significantly increases the temperature of fog (Franca *et al*., 2019). It also reduces its average duration and the probability of occurrence.

1.1. Global fog forecast and climatology

Baltaci *et al*. (2022) conducted a study on the climatology of fog in Turkey using data from 1996 to 2016. The study found that fog events in Turkey occurred predominantly in the fall and winter months, with the highest frequency of fog observed in the eastern Black Sea coast region. The study also highlighted the role of synoptic-scale atmospheric conditions, such as the presence of a low-pressure system, in the formation of fog events. These findings have important implications for forecasting fog in Turkey, as meteorologists can use this knowledge to anticipate fog events in certain regions during specific times of the year.

In Japan, Akimoto and Kusaka (2015) conducted a climatological study of fog and concluded that the events occurred predominantly in the winter months, with the highest frequency observed in the western coastal regions. The study also highlighted the relationship between fog events and local topography, with fog more likely to occur in low-lying areas near mountains. This knowledge can aid in forecasting fog events in Japan, as meteorologists can take into account local topography when predicting the occurrence of fog.

Andersen *et al*. (2020) conducted a study on the synoptic-scale controls of fog and low-cloud variability in the Namib Desert. The study found that fog events in the Namib Desert were strongly influenced by synoptic-scale atmospheric conditions, such as the presence of an off-shore high-pressure system. Also, fog events were observed to occur primarily during the nighttime hours.

These findings can be used to develop more accurate and effective fog forecasting systems, ultimately improving safety and minimizing disruptions caused by low visibility.

1.2. Northeast Brazil (BNE)

The relief in Northeast Brazil (BNE) is quite diverse and rugged, ranging from coastal plains to plateaus, factors that contribute to the climatological heterogeneity of the region.

Tropical and semi-arid climates predominate, the first being characterized by two well-defined seasons, one in summer and one in winter; the latter being a transitional climate marked by scarce rainfall and poor distribution throughout the year (Molion and Bernardo, 2002).

According to Ratisbona (1976), the periphery of various synoptic-scale systems exerts a significant influence on the region. Among these systems, troughs in the trade winds are most commonly associated with fog (Molion and Bernardo, 2002; Rodrigues, 2010; Fedorova *et al*., 2008; 2015). When low-level moisture convergence resulting from troughs interacts with the downward motions typically associated with the jet stream, the formation of fog can be observed.

In addition, there are other physical mechanisms that contribute to the addition of more moisture to fog formation on the north coast of the BNE: a) confluence at low levels; b) changes in wind direction; c) precipitation before the event; d) hot evaporation of seawater; e) positive latent heat flux in the coastal region; f) negative sensible heat flow (air cooling generates condensation) (Fedorova *et al*., 2015; 2016).

1.3. Research on fog in Maceio - AL

Fog and stratus clouds are very rare on the northern coast of Brazil (Fedorova *et al*., 2008). Two events with Stratus clouds during three and four consecutive days were recorded in Maceió (Zumbi dos Palmares international airport) on the northeast coast of Brazil (Gomes *et al*., 2011). The process of these fog formations was typical for this location. Weak upward movements were reported at low levels and at the same time an anticyclonic curvature formed downward movements at high levels. Therefore, fog and stratus clouds are associated with wave disturbances in the trade winds (WDTW).

According to Fedorova *et al*. (2012), several conditions are necessary for the formation of intense fog in Maceio, including: 1) light winds; 2) nocturnal radiative cooling prior to sunrise; 3) the presence of a near-surface thermal inversion; 4) atmospheric instability above 925 hPa; and 5) weak upward motion in the lower levels of the atmosphere and downward motion at mid-levels. These conditions are typically associated with radiation-type fog, with additional influence from ocean moisture.

There has been significant progress worldwide in improving fog and low visibility forecasting techniques with several days in advance (Bott *et al*., 2002; Bergot *et al*., 2005; Gultepe *et al*., 2007; Kneringer *et al*., 2007; Kneringer *et al*., 2019). However, a specific model for predicting low visibility in BNE has not yet been developed.

The one-dimensional forecasting model developed by Bott and Trautmann (2002) for Germany, the PArameterized FOG (PAFOG), was used in Northeast Brazil. The PAFOG model is capable of predicting fog 24 h in advance. The use of this model presents satisfactory results for the Maceio International Airport (Fedorova *et al*., 2015). Fast-growing sugarcane vegetation does not affect the low visibility predicted by the PAFOG model.

The objective of the work is to analyze all the fog events during nine years in two airports in the tropical region of the Brazilian Northeast and, for comparison, during two years in an airport in the extratropical region. All processes from fog formation to dissipation have the following description: 1) in situ observations, 2) synoptic conditions, 3) thermodynamic processes and 4) use of the PAFOG 1D model for fog forecasting.

2. Experiments

Fog formation has been analyzed in the tropical region of Northeastern Brazil (NEB) and in the southern region of Brazil. Some information about low visibility in the NEB has been published (Fedorova *et al*., 2015; 2016).

Information from two airports in the NEB: Maceio (SBMO) ("Zumbi dos Palmares International Airport") and Campina Grande (SBKG) ("Presidente Joao Suassuna Airport") has been used (Fig. 1).

Fog in Porto Alegre (SBPA) - "Salgado Filho Airport" in southern Brazil (Fig. 1) was studied in some works (Afonso *et al*., 2019b). The PAFOG model was used in southern Brazil to predict low visibility (Afonso *et al*., 2019a). The map in Fig. 1 shows the location of the mentioned cities.

2.1. Surface data and method

A database of fog events at the airports of Maceio and Campina Grande was created to categorize them according to intensity and study the meteorological variables at the time of reduced visibility. The defined study period was 9 years (2008 and 2016).

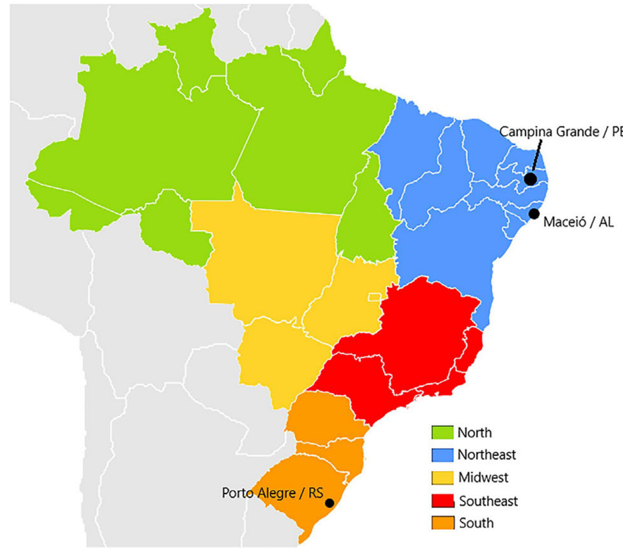

Figure 1 - Map of Brazil with location of the cities of study. Source: QGIS.

Visibility and adverse phenomena data were collected by the REDEMET API (Rede Meteorológica do Comando da Aeronáutica), and are available at REDEMET. According to the methodology of the Instituto de Controle do Espaço Aéreo - ICEA, the fog must be continuous. If the fog clears, the next event will be considered a new one.

The forecasting of the TAF code reported by REDEMET indicates the possibility of adverse weather phenomena; the code did not indicate the occurrence of "FG" (fog) during the study period in Maceió, which experienced 20 such events. Similarly, the code identified fog only 19 times in Campina Grande, which had 105 fog events during the study period.

Due to the immense number of fog events in Porto Alegre, the period of analysis was abbreviated to 2 years (2008 and 2009), with 23 records of "FG" being found in the METAR code for Porto Alegre (PA). In total, 148 fog events were recorded in the three cities.

Data with pressure (hPa), wind speed (knots), relative humidity (%), visibility (m), air temperature and dew point (°C) were collected using METAR and SPECI codes from surface stations in Maceio (SBMO), Campina Grande Airports (SBKG) and Porto Alegre (SBPA).

2.2. Satellite images

The GOES and METEOSAT satellite images were collected from the CPTEC website to identify the synoptic scale systems associated with fog formation.

Furthermore, this information allows the identification of atmospheric conditions conducive to the formation of radiation fog to assess the applicability of the PAFOG model. Additionally, fog identification products provided by CPTEC were used. No base calculation or fog identification principle used in the model was made available on this site.

2.3. Synoptic analysis

Data files were extracted from the Reanalysis models listed below for making synoptic fields (streamlines) and thermodynamic diagrams (Skew-T) using the Grid Analysis and Display System (GrADS) graphic tool software.

All standard pressure levels (1000, 950, 900, 850, 800, 700, 600, 500, 400 and 300 hPa) were used for the elaboration of the Streamlines (SL) maps, for all days and times. It aims to investigate the structure of the troposphere and the main synoptic systems responsible for the formation of low horizontal visibility at airports. The meridional and zonal wind components were extracted from the following models: NOAA, NCEP - Reanalysis I and II (2.5° × 2.5°); NCAR - CFSR (0.5° × 0.5°); ECMWF - ERA-Interim (0.125° × 0.125°).

2.4. Thermodynamic analysis

Radiosonde data, made available by the Department of Atmospheric Sciences at the University of Wyoming, were used for Porto Alegre International Airport.

Citing the lack of similar wind data for similar cities and Campina Grande, the following similar models of similar winds in the same synoptics were used: components above the relative wind in the same similarities (u - zone v - meridional of the same models), humidity (in %) and air temperature (in K converted to °C), available at NOAA's Earth System Research Laboratories website.

2.5. Forecast by PAFOG model

The one-dimensional PAFOG model (Bott and Trautmann, 2002) was also used to study fog events at three airports. The model is composed of a microphysics section where data such as: planetary boundary layer (PBL) height and vertical wind speed are entered; and 4 more modules:

1. Dynamic module: geographic data (latitude, longitude and altitude of the weather station); soil (soil type); vegetation (coverage and height); geostrophic wind speed below the CLP; meteorological data (air and dew point temperatures, relative humidity at 2 m, visibility and pressure).
2. Cloudiness module: cloud types in low, medium and high levels.
3. Radiation calculation: radiosonde data (pressure, air temperature and dew point, geostrophic wind speed and pressure levels.
4. Module for local vegetation: Soil temperature and relative humidity at different depths.

The PAFOG parameterization scheme is a set of prediction equations in the dynamic module (Nickerson *et al*., 1986 and Chaumerliac *et al*., 1987). The equation finds the concentration for the total number of cloud droplets (N_c) and for the total water content in the cloud (σ_c).

$$dN_c = \frac{N_c}{\sqrt{2\pi}\sigma_c D}\exp\left[-\frac{1}{2\sigma_c^2}ln^2\left(\frac{D}{D_0}\right)\right]dD \qquad (1)$$

here D is the droplet diameter; D_0 is the mean value of D; and σ_c is the dispersion parameter of the given droplet distribution.

Hourly meteorological data from the synoptic station at Maceio, Campina Grande and Porto Alegre airports are used as input in Modules 1, 2 and 4 of the model (Fig. 2).

No significant influence of the vegetation parameters to the low visibility forecast was detected in Fedorova *et al*., 2015. Therefore, standard data (Bott and Trautmann, 2002; Siebert *et al*., 1992) were used in Module 4.

The PAFOG model was used to forecast fog formation 24, 18, 12 and 6 h in advance.

3. Results and Discussion

3.1. Analysis of fog events in the city of Maceio - AL

Twenty fog events were identified over 9 years (2008 to 2016) (Table S1). Ten events (50%) weak, nine events (45%) moderate and one intense event.

May, June and July had the highest frequency of fog, corresponding to autumn and winter in the Southern Hemisphere. The events lasted from 10 min to 3 h and took place during the night and at dawn (between 21:00

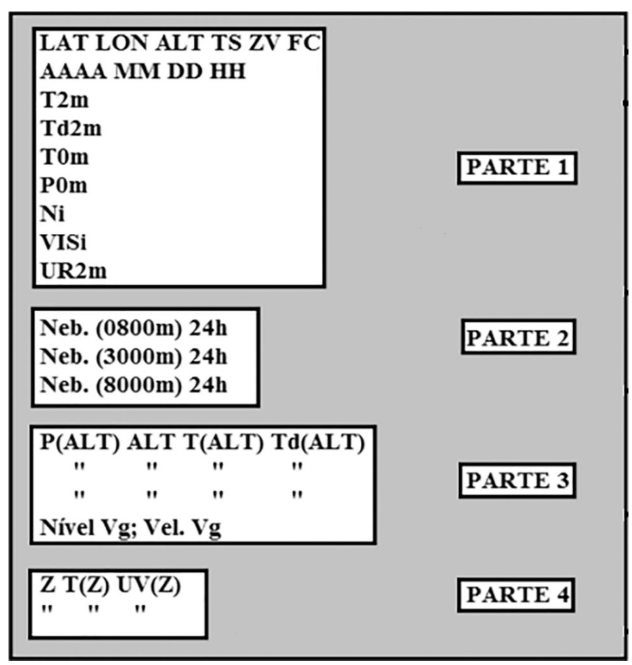

Figure 2 - PAFOG Parameterization Scheme. Source: Bott, 2002.

and 8:00 UTC). For Maceio it was not possible to identify fog through the satellite product.

3.1.1. Fog event in Maceio - AL, june 11, 2010

This was the most intense (< 50 m horizontal visibility) and longest (3 h duration) event in this data series (2008 to 2016).

Synoptic analysis with streamlines and satellite images: In this case, the horizontal visibility was reduced to less than 1000 m from 4:00 to 7:00 UTC, resulting in fog. The METAR code data did not indicate another adverse event before, during or after the event (Table 1).

There is a predominance of clouds with no convection in the airport region evidenced by the infrared channel (Fig. 3a), observing a smoother and more uniform texture. Streamlines indicate troughs at low levels (1000 hPa), responsible for lifting air at low levels over the study region (Fig. 3b). This uplift around the airport was observed at 1000 hPa before and during the fog event.

Thermodynamic analysis with skew-T/Log-P diagram: For Maceió there was no radiosonde available. Therefore, three Skew-T diagrams were plotted with data from different models: (Fig. 4) A) NCEP - Reanalysis II; B) NCAR - CFSR and C) ECMWF - ERA-Interim.

The models show that the relative humidity in the surface layer at 900 hPa was greater than 75% in profile (Fig. 4) A and greater than 90% in profiles (Fig. 4) b and c. The atmosphere at the middle levels was stable and dry. The ERA-Interim model (Fig. 4c) showed a high *CAPE* value: 596 J/kg; different from the others that were below 100 J/kg. The existence of weak convection in fog events has been found before (Fedorova *et al.*, 2015; 2016).

Table 1 - Fog events identified by satellite, intense cases and with another simultaneous adverse phenomenon (rain) in Campina Grande - PB. Source: METAR code - SBKG station.

Event	Date	Surface data				Satellite data	
		1st Obs. (UTC)[1]	Dur. (h)[2]	Min. vis. (m)[3]	Season	ID. (UTC)[4]	Dur. (h)[2]
1	07/08/2011	04:00	01:05	500	Winter	4:00	5:00

[1]First Observation (UTC).
[2]Duration (h).
[3]Minimum Visibility (m).
[4]Identification (UTC).

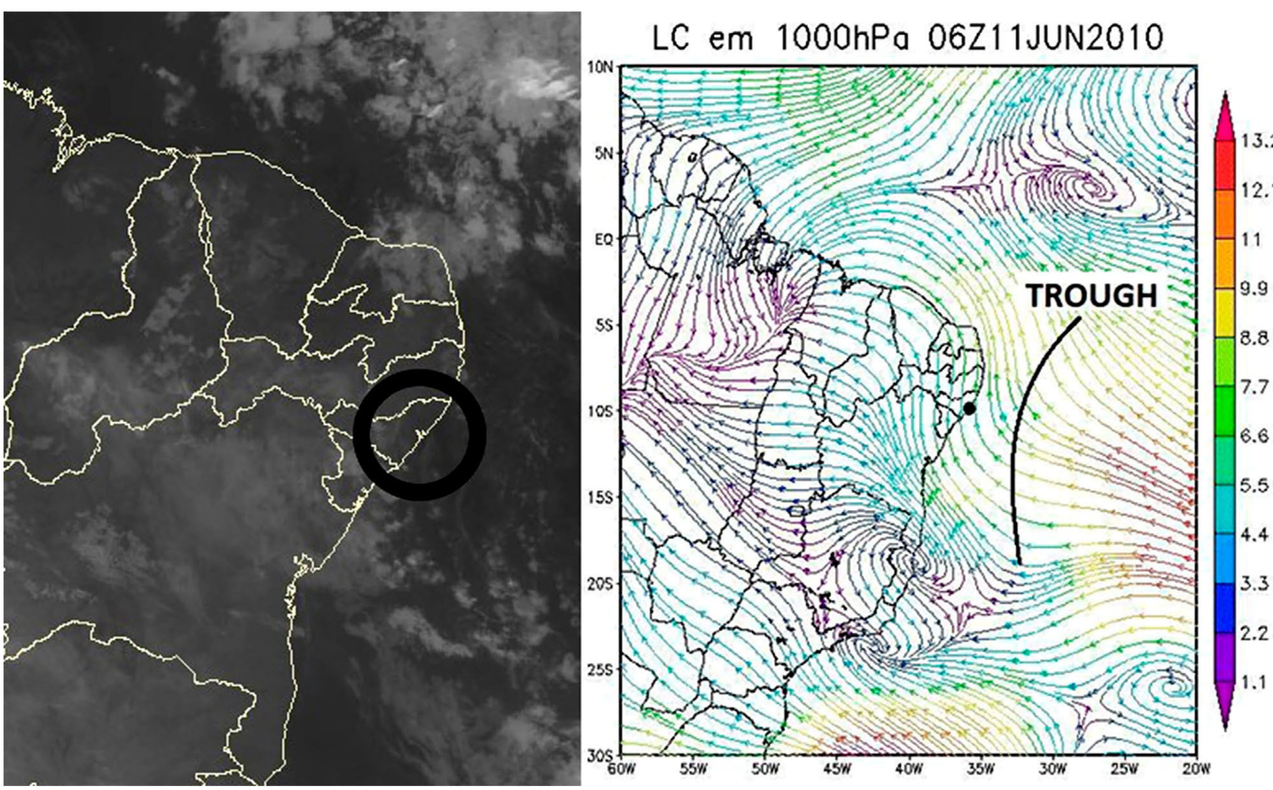

Figure 3 - Synoptic situation in Maceió, June 11, 2010. (a) Image of GOES-12 Channel IR. (b) Streamlines at 1000 hPa. Circle indicates the city of Maceio. Source: INPE - CPTEC and ECMWF - ERA-Interim.

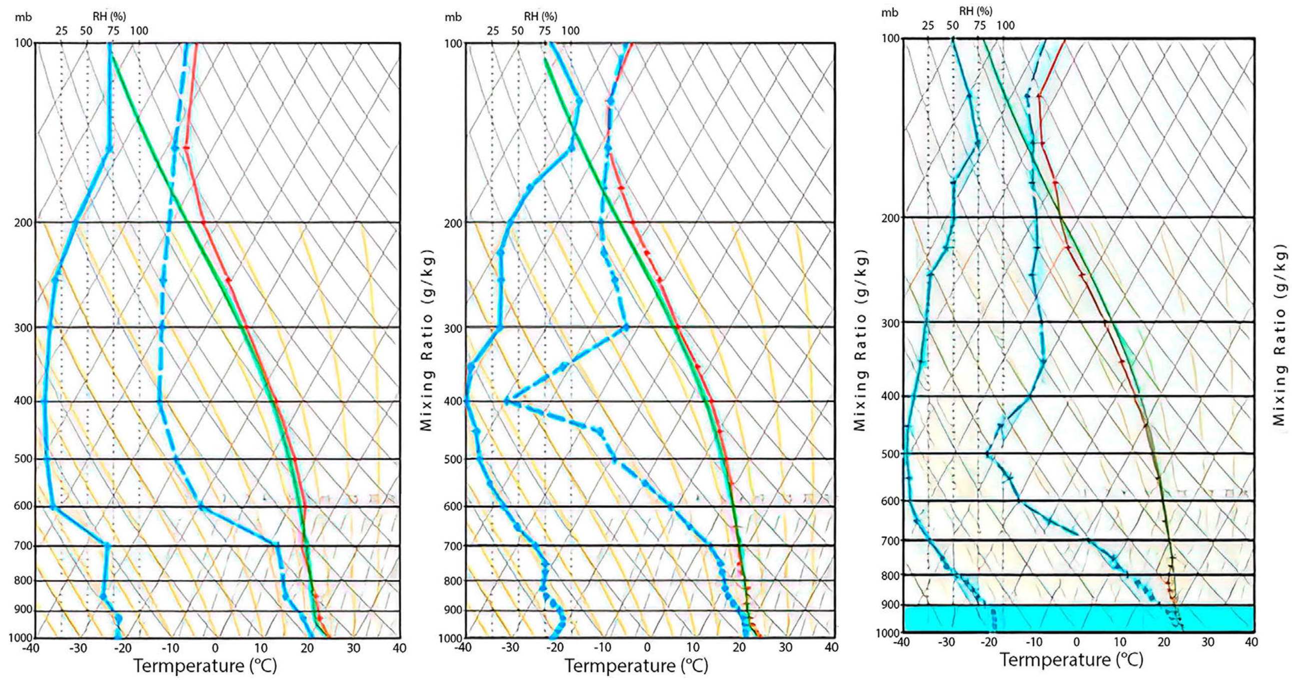

Figure 4 - Vertical profiles for Maceio - AL, June 11, 2010, by the three models. Blue layer shows fog. Thermodynamic Diagrams: Green Line: Lifting air parcel; Red line: Air temperature (T, °C); Dashed blue line: Dew point temperature (T_d, °C); Blue dotted line: Relative Humidity (RH, %). Source: (a) NCEP - Reanalysis II, (b) NCAR - CFSR and (c) ECMWF - ERA-Interim.

3.2. Analysis of Fog Events in the City of Campina Grande - PB

One hundred and five fog events were recorded during the 9 years (2008 to 2016) (Table S2). Of all events, 35% occurred in autumn, 33% in winter, 18% in summer and 14% in spring. The months of May, June and July had the highest frequency of fog. Due to the large volume of data, 34 moderate to strong events were studied in detail.

The fog lasted from 15 minutes to 8 hours. Twenty-two (65%) severe and moderate events occurred during the night and another 12 mild cases (35%) occurred in the morning.

Fog identification by satellite products: Only four fog events were identified by satellite over the study period. The records took place at a different time from that observed by the METAR (Table 2). The fog duration by the satellite product was equal to or longer than the METAR data.

3.2.1. Fog event in Campina Grande - PB, may 3, 2014

This event was chosen because it is the only one with another adverse phenomenon (rain) occurring simultaneously with the fog event.

Synoptic analysis with satellite images: Cumuliform clouds were observed in the infrared channel over the airport (Fig. 5a). Low-level clouds over the airport and convection development around it was previously described in Fedorova *et al.*, 2013. It is observed that the periphery of an upper-tropospheric cyclonic vortex is positioned over the study city about 300 hPa (Fig. 5b).

Table 2 - Fog events identified by satellite, intense cases and with another simultaneous adverse phenomenon (rain) in Campina Grande - PB. Source: METAR code - SBKG station.

Event	Date	Surface data				Satellite data	
		1st Obs. (UTC)[1]	Dur. (h)[2]	Min. vis. (m)[3]	Season	ID. (UTC)[4]	Dur. (h)[2]
1	06/17/2011	00:35	00:30	50	Winter	21:00	00:30
2	07/14/2012	04:00	02:00	50	Winter	23:30	02:00
3	07/12/2013	05:10	00:50	100	Winter	21:30	02:00
4	07/26/2013	03:25	04:35	50	Winter	03:15	05:45

[1]First Observation (UTC).
[2]Duration (h).
[3]Minimum Visibility (m).
[4]Identification (UTC).

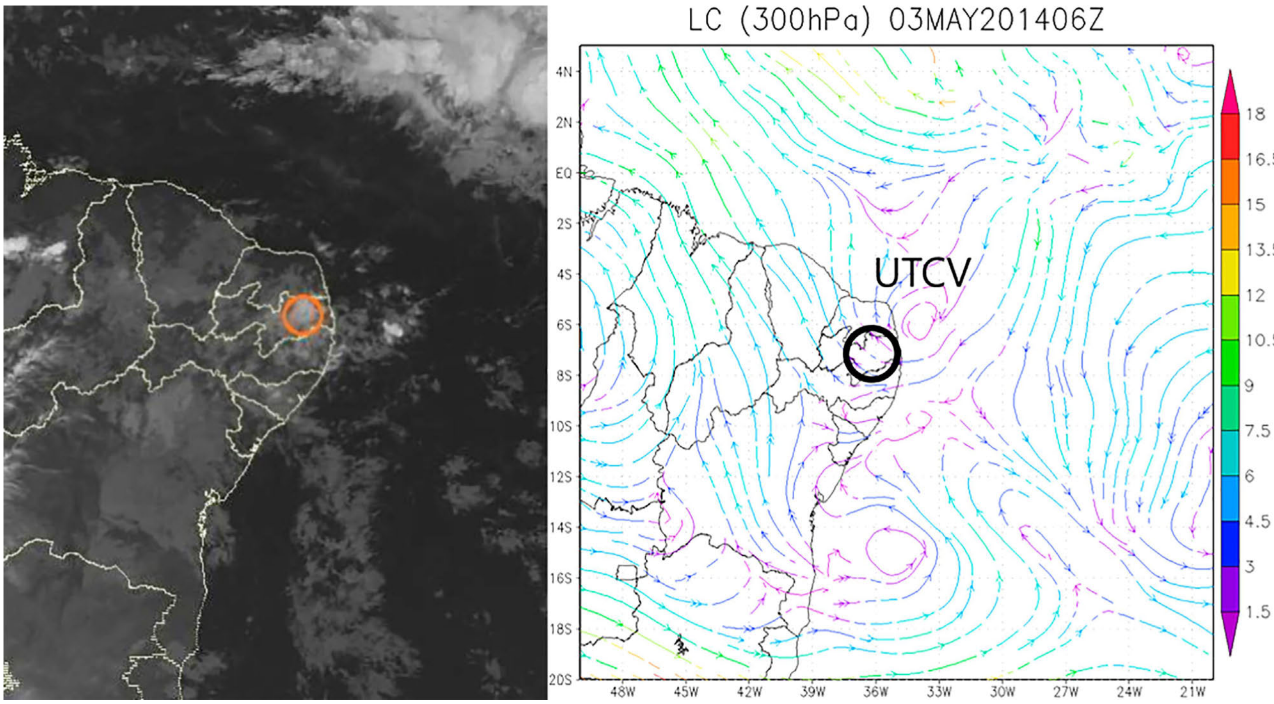

Figure 5 - Fog event in Campina Grande - PB, May 3, 2014. (A) IR Satellite Images; (B) Streamlines; and (C) Thermodynamic Diagrams: Green Line: Lifting air parcel; Red line: Air temperature (*T*, °C); Dashed blue line: Dew point temperature (T_d, °C); Blue dotted line: Relative Humidity (*RH*, %). Source: A) CPTEC; B) ECMWF; and C) NOAA Reanalysis II.

Thermodynamic analysis with skew-T/Log-P diagram: Thermodynamic diagram shows humidity around 90% between 1000 and 925 hPa, and a dry atmosphere above this layer (Fig. 5c). The *CAPE* value was 1144 J/kg, which confirms cumulus clouds near the airport at the time of the event.

3.2.2. Fog event in Campina Grande - PB, march 21, 2015

It was one of 13 intense events with less than 50 m of horizontal visibility. The METAR code did not indicate other adverse phenomena before, during or after the fog event.

Synoptic analysis with streamlines and satellite images: There are few stratiform clouds around the airport (Fig. 5a). The influence of the ridge in the airport region was observed at 1000 hPa during the event (Fig. 5b). This configuration is atypical for fog formation in the BNE region (Fedorova, 2008; 2012).

Thermodynamic analysis with skew-T/Log-P diagram: Conditional instability was observed between 1000 and 900 hPa (Fig. 6c). The atmosphere remained stable at medium and high levels with humidity between 30% and 50%. *CAPE* was equivalent to 1902 J/kg, a typical value for the development of deep convection. Fog formation in these conditions was atypical compared to the coastal region of the NEB, according to previous studies (Fedorova *et al*., 2012).

3.3. Analysis of fog cases in the city of Porto Alegre - RS

Eighty-two fog events were identified in Porto Alegre from 2008 to 2009, where 52% occurred in autumn, 32% in winter, 9% in spring and 7% in summer (Table 2) (Table S3). This result is in agreement with the results of previous studies (Piva, 1999). Only 1 fog event also recorded light rain at the same time, 8/20/2008.

3.3.1. Fog identification by satellite products

Fifteen haze events were identified in Porto Alegre by satellite data during the years 2008 and 2009 (Table 2). All fog events identified by satellite, with the exception of one case, had a shorter duration than that recorded by METAR (Table 3 and Fig. 7).

3.3.2. Fog event in Porto Alegre - RS, july 5th, 2008

This event was chosen because it was the most intense and the longest of the study period for Porto Alegre (2008 and 2009).

Synoptic analysis with streamlines and satellite images: Porto Alegre was under the influence of a ridge at 1000 hPa (Fig. 8a). There was an influence of Low-Level Jet Streams (LLJS) with speed above 20 m/s on the surface. This synoptic situation allows the use of the PAFOG model.

Thermodynamic analysis with skew-T/Log-P diagram: The radiosonde (Fig. 8b) and the simulated vertical profile (Fig. 8c) show high humidity only near the surface

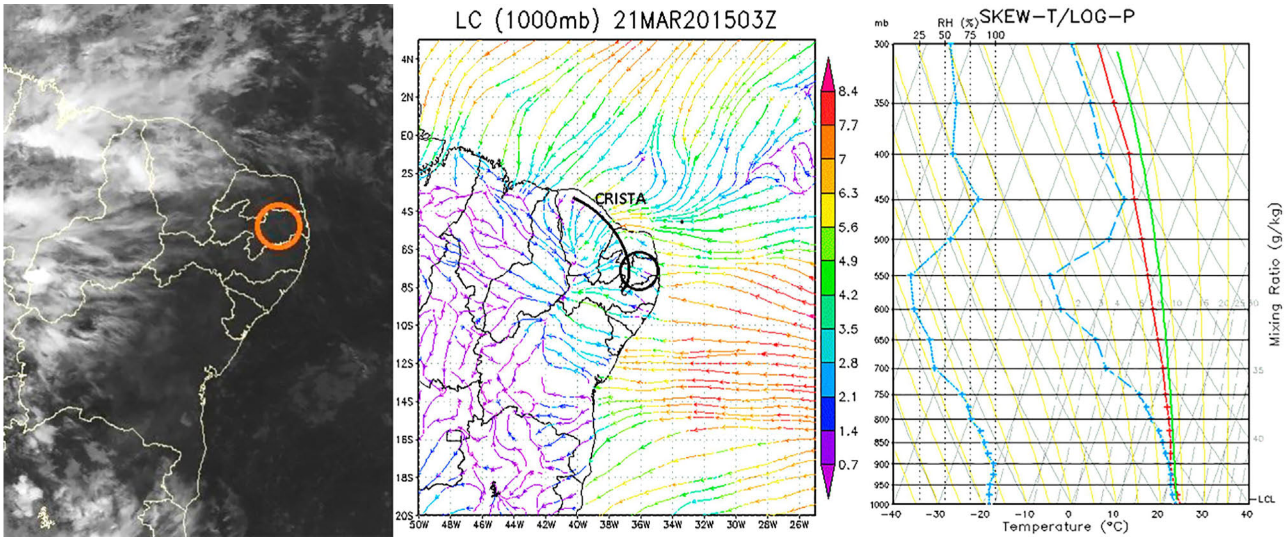

Figure 6 - Fog event in Campina Grande - PB, March 21, 2015: (A) Satellite image GOES-13 Infrared channel. (B) Streamlines at 1000 hPa. and (C) Thermodynamic Diagrams: Green Line: Lifting air parcel; Red line: Air temperature (T, °C); Dashed blue line: Dew point temperature (T_d, °C); Blue dotted line: Relative Humidity (RH, %). Circle indicates Campina Grande. Source: CPTEC - INPE and Reanalysis II.

Table 3 - Fog events in Porto Alegre identified by satellite. Source: METAR code - SBPA.

Event	Date	Surface data				Satellite data	
		1st Obs. (UTC)[1]	Dur. (h)[2]	Intensity (m)	Season	ID. (UTC)[3]	Dur. (h)[2]
1	04/20/2008	08:00	04:45	Moderated - 200	Autumn	7:00	2:27
2	06/02/2008	10:15	02:45	Moderated - 300	Autumn	1:45	1:09
3	06/25/2008	07:00	05:40	Moderated - 300	Winter	09:15	01:00
4	06/29/2008	09:11	02:49	Intense - 50	Winter	09:15	01:00
5	07/02/2008	07:20	05:25	Moderated - 400	Winter	02:45	00:09
6	07/04/2008	06:10	04:10	Moderated - 400	Winter	00:00	02:10
7	07/05/2008	03:00	10:25	Intense - 50	Winter	02:45	04:30
8	08/20/2008	02:00	08:00	Moderated - 400	Winter	00:30	02:30
9	03/03/2009	07:00	05:15	Moderated - 150	Summer	07:30	01:45
10	04/26/2009	09:12	02:58	Moderated - 300	Autumn	09:30	00:10
11	05/03/2009	06:25	06:25	Moderated - 300	Autumn	05:15	04:30
12	05/10/2009	08:00	04:40	Moderated - 300	Autumn	07:45	02:00
13	05/13/2009	03:10	09:10	Moderated - 400	Autumn	21:30	0:20
14	06/20/2009	05:00	07:00	Moderated - 200	Winter	1:30	4:30
15	07/05/2009	10:08	01:55	Moderated - 400	Winter	0:30	3:18

[1]First record (UTC).
[2]Duration (h).
[3]Identification (UTC).

(1000 hPa), with a dry layer above (up to 300 hPa). However, only the radiosonde showed subsidence inversion (up to 940 hPa). This is a typical temperature and humidity distribution for radiation fog events.

3.4. Forecast by the PAFOG model

Four forecasts with 24, 18, 12 and 6 h in advance were made by the PAFOG model. The following analyzes demonstrate its efficiency in relation to the type of fog in certain weather-climatic conditions of each location.

Maceio - AL, June 11, 2010: Fog was predicted 12h in advance (Fig. 9) and lasted 1h, shorter than the METAR data (3h duration). Still, it presents similar results to the one observed, a moderate fog.

Campina Grande - PB, May 3, 2014: PAFOG failed to predict fog 18 and 24 h in advance (Fig. 10). However,

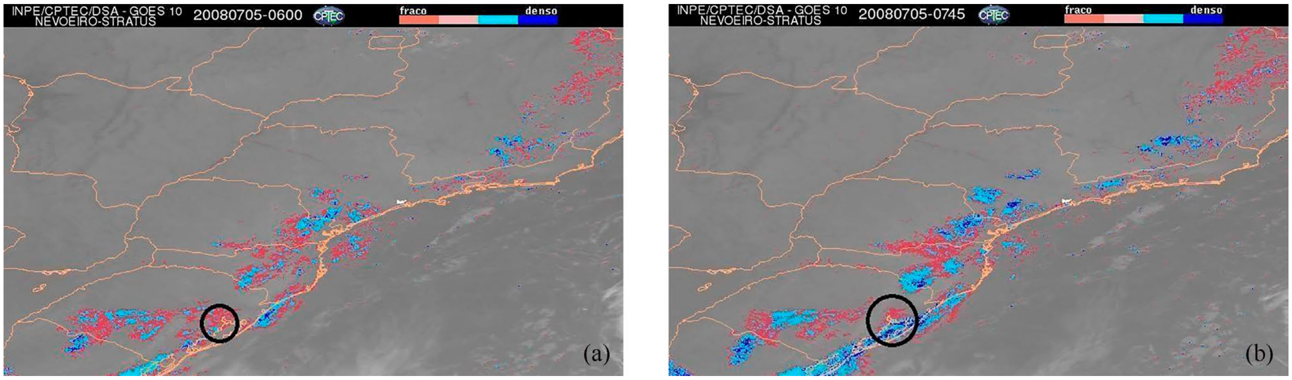

Figure 7 - Satellite fog identification product, on July 5, 2008 at 6:00 UTC (a) and 7:45 UTC (b). Circle indicates the city of Porto Alegre. Source: CPTEC/INPE.

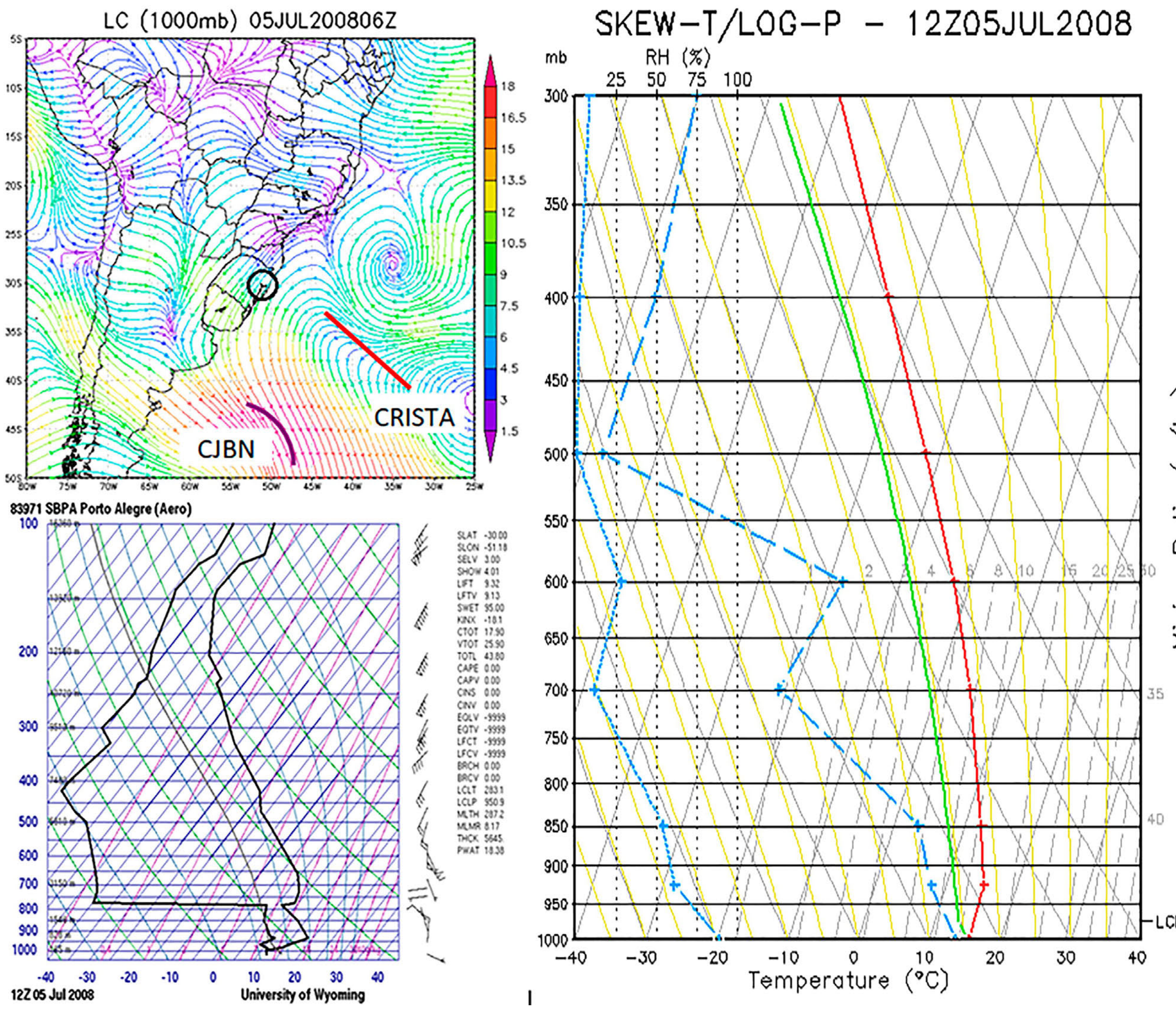

Figure 8 - Fog event in Porto Alegre - RS, July 5, 2008. (a) Streamlines at 1000 hPa. (b) Radiosonde. (c) Thermodynamic Diagrams: Green Line: Lifting air parcel; Red line: Air temperature (*T*, °C); Dashed blue line: Dew point temperature (T_d, °C); Blue dotted line: Relative Humidity (*RH*, %). Circle indicates Porto Alegre. Source: NCEP - Reanalysis II, University of Wyoming and CFSR II.

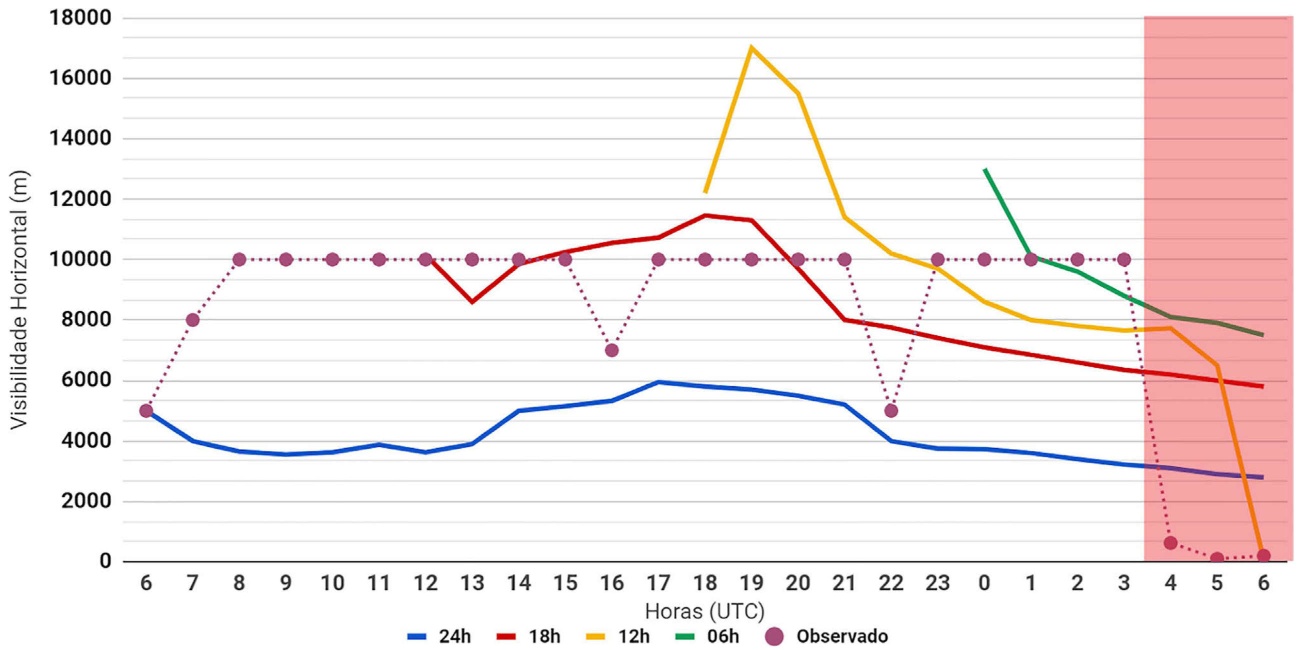

Figure 9 - Forecast of horizontal visibility for Maceio - AL, June 11, 2010. Source: METAR and PAFOG.

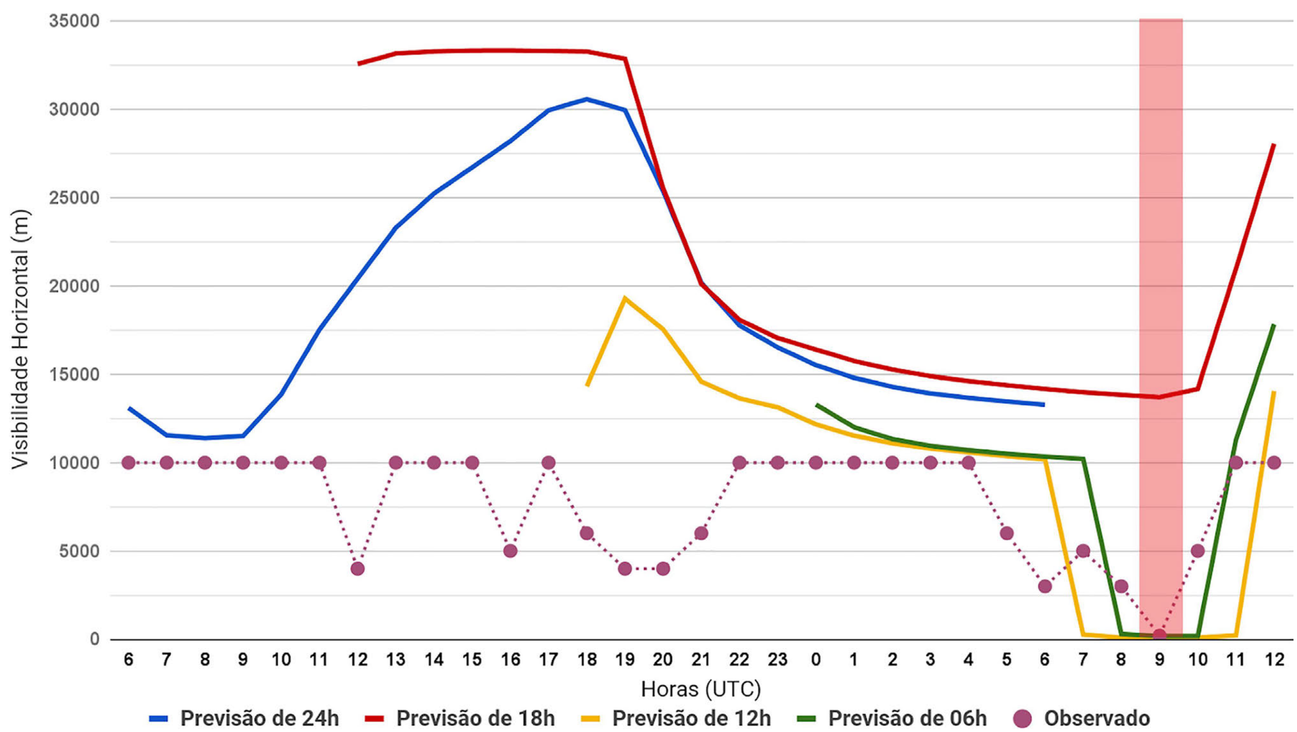

Figure 10 - Forecast of horizontal visibility for Campina Grande - PB, May 3, 2014. Source: METAR and PAFOG.

it was predicted 12 and 6 h in advance. It was observed that the PAFOG predicts fog despite the action of other adverse phenomena (in CG).

Campina Grande - PB, March 21, 2015: The PAFOG model predicted fog 6 h in advance (Fig. 11) at the exact moment of the registration. At the same time, the predicted and observed visibility values show similarity in the pattern.

Porto Alegre - RS, July 5, 2008: The forecast identified fog 18, 12 and 6 h in advance (Fig. 12) despite the start time and duration being different from what was observed. PAFOG underestimates radiation fog in southern Brazil.

4. Conclusions

In Maceio (M) there were 20 cases of fog between 2008 and 2016, 16 of them with intense cloudiness. Only one case was identified by satellite data. A trough at 1000 hPa generally affected the Maceió region. There were no cases with another adverse phenomenon acting at the same time (in M).

In Campina Grande (CG) 105 cases of fog were recorded between 2008 and 2016, characterized by intense fog and convective clouds. Of these, only four events were identified by satellite data. Often, a ridge at 1000 hPa influenced the Campina Grande region. Only in a fog event in Campina Grande it rained, but not exactly over the airport.

Differences between M and CG: The fog formation processes at two airports in the Northeast of Brazil (Maceió - M and Campina Grande - CG) were different.

— The fog formation process in Maceio was slow and lasted a short time. The longest fog lasted 3 hours and 40 minutes, averaging 1 hour and 18 minutes.

— Fog events formed faster in Campina Grande. The longest fog lasted 8 hours, and the average was 3 hours and 10 minutes.

— In CG the fog forms with a ridge at the low-level and in M with trough at the surface.

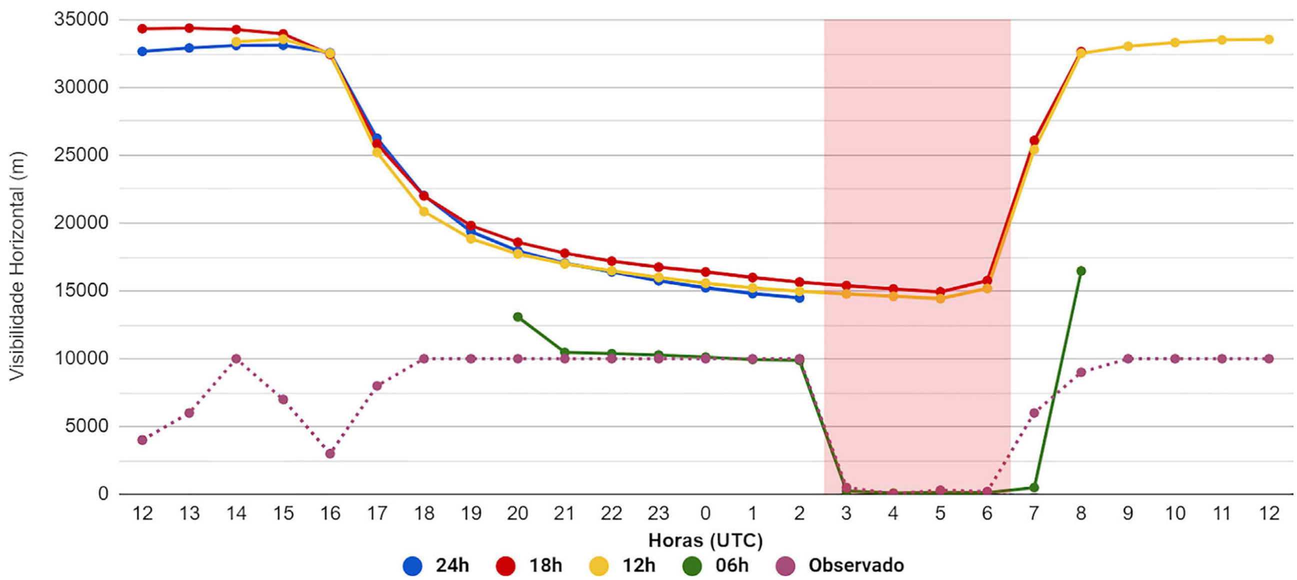

Figure 11 - Forecast of horizontal visibility for Campina Grande - PB, March 21, 2015. Source: METAR and PAFOG.

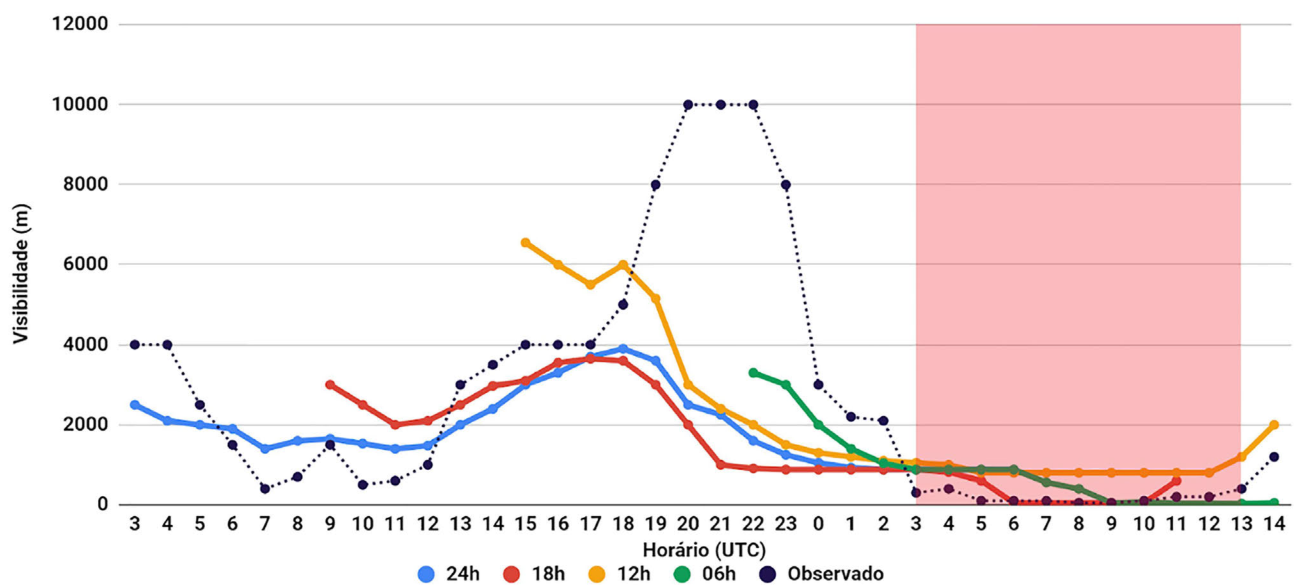

Figure 12 - Forecast of horizontal visibility for Porto Alegre - RS, July 5, 2008. Source: METAR and PAFOG.

Similarities between M and CG: Some similar conditions were detected at these two airports.

— All heavy fog events occurred early in the morning with clear skies.

— air and dew point temperatures were close to 20 °C; c) M and CG have a higher frequency of fog in the months of May, June and July.

It is seen that the air mass comes from the ocean as a function of the trough. Furthermore, the temperature of the mainland and the SST were around 20 °C when the fog occurred.

Comparisons of Porto Alegre with BNE: In Porto Alegre (PA), in the period 2008 and 2009, most cases of fog were identified by the satellite product (65% of cases), unlike NEB, where less than 13% (of the total) were identified. All fog events identified by the satellite data in PA had different durations from those reported by the METAR code, as well as in the NEB as well.

Forecast by the PAFOG model: The fog events identified by satellite data present satisfactory results also by the prediction of the PAFOG model. The fog forecast was satisfactory up to 12 h in advance in M and CG. PAFOG presented flaws in forecasts with 18 and 24 h in advance in the BNE. The PAFOG was used in PA and predicted heavy fog (100 m) with 6 h in advance, as recorded by METAR (50 m).

Final considerations: The physical process of fog formation in Maceio was previously described in detail (Fedorova *et al*., 2015, 2016), but fog in Campina Grande was studied in this work for the first time.

Therefore, the difference between the fogs of the two regions (Brazil South and Northeast) lies in the system that causes the formation process. Mostly frontal in PA, trough in M and ridge in CG (both at 1000 hPa).

Fog formation in Northeast Brazil is atypical, especially in Maceio, where it is rarely identified by satellite data. However, the prediction by the PAFOG model presents satisfactory results up to 12 h in advance.

The article addresses how physical processes in the tropics are different from processes in other areas. All these data show the need to continue the study of the physical processes of fog formation in the tropical region.

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Internet Resources

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ICEA, http://clima.icea.gov.br/clima/metodologia.php.
NOAA - ESRL, http://www.esrl.noaa.gov.
OpenGrADS, http://opengrads.org/.
Redemet, https://www.redemet.aer.mil.br/.

Supplementary Material

Table 1 - Table with all cases in Maceió from 2008 to 2016.
Table 2 - Table with moderate and intense cases in Campina Grande from 2008 to 2016.
Table 3 - Table with moderate and intense cases in Porto Alegre from 2008 to 2009.