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On Frontal Zone Analysis in the Tropical Region of the Northeast Brazil

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Abstract—A frontal structure in the tropical region is different than in the extratropical region and traditional methods of frontal identification are not accurate. The use of a horizontal distribution of the equivalent potential temperature and its advection is the new aspect in frontal identification and will support forecasters in their daily operational practice. Six fronts over 3 years were identified by the method used in operational practice. Twenty fronts were registered by cloud bands together with the equivalent potential temperature and its advection maps. A cold front separated from the cyclone's center and affected weather on the Northeast Brazil.

Key words: Frontal zone, tropical region, northeast Brazil.

1. *Introduction*

Frontal zones (FZs) are very important synoptic-scale systems over South America. Cold, warm, occlusion and stationary fronts were observed more frequently to the south of 30°S (Taljaard 1972; Satyamurti and Mattos 1989; Cavalcanti and Kousky 2009; Reboita *et al.* 2010). The influence of the warm front on the weather in southern Brazil was discussed in Carvalho and Fedorova (2011).

Frontal zones are observed more frequently in the southern latitudinal belt between 35° and 40°S (about nine per month) and less frequently in the northern belt, north of 20°S (about two per month) (Satyamurti *et al.* 1998). Baroclinic waves of the extra tropical latitudes are modified after passing over the Andes. Troughs that pass through the Andes combine with troughs at the east side of the Andes, being deflected to the north while crossing the mountain range and, as a consequence, the frontal zones move in the northeast direction (Satyamurti *et al.* 1998; Seluchi *et al.* 1998; Seluchi and Marengo 2000). The displacement of midlatitude air toward tropical latitudes on the eastern side is linked to cold fronts whose trajectory and movement are also favored by the presence of the Andes. During wintertime, the cold fronts are more intense and faster, and sometimes even reach tropical and equatorial latitudes. In contrast, the incursions of cold air are notably weaker and less frequent in summer, and during these events the active cold fronts move northwards, merging with the South Atlantic convergence zone, which becomes more intense. Results of Gan and Rao (1994) show that when the wave approaches the Andes Cordillera, it exhibits an orographic effect; such as anticyclonic turning of the trajectory at the low levels, a zonal trajectory at the upper levels, a decrease in the vertical tilt on the windward side and an increase in the tilt on the lee side.

Frontal zones pass regularly over the South of Brazil and Sao Paulo State, about 80–130 times per year (Cavalcanti and Kousky 2009; Fig. 1). Information about FZs in the Santa Catarina region (26°–29°S and 48°–54°W) presents a smaller number; from 1990 to 1999, the number of events per year was an average of 43 and a few inter-seasonal variations were identified (12 events per spring and 9–10 events in the other seasons) (Rodrigues *et al.* 2004). A similar result was obtained using ERA-Interim's data (Simmonds *et al.* 2012). Morais's (2010) research presents an analysis of the climatology of cold fronts over the Metropolitan Region of Sao Paulo (MRSP) over a period of 21 years from 1987 to 2007. The results showed that three fronts, on average, reached the MRSP monthly, and their frequency is higher from March to May and from August to December. An observational study of the frontal zones (cold, warm,

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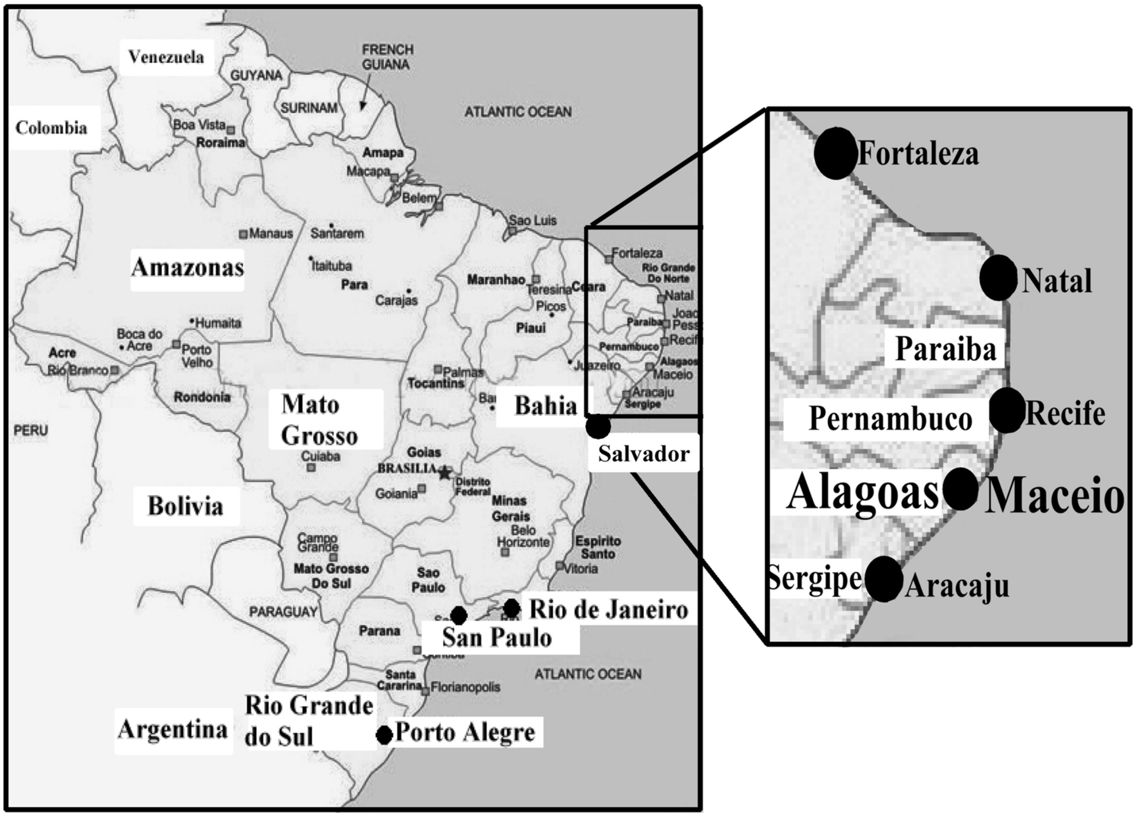


Figure 1
Map of Brazil with the names of the states mentioned in the text

occluded and secondary fronts) during El Niño, La Niña and Neutral events (in the active phase of the phenomenon) was elaborated for the latitudinal range between 20° and 40°S and also 40° and 60°S (Fedorova and Carvalho 2000). The cold fronts were observed with a greater frequency in the south of South America in both La Niña and El Niño events, but in the El Niño events these fronts had a great frequency in the Rio Grande do Sul region and Uruguay. Warm fronts were more frequent in the winter than in other seasons. The occluded fronts were observed very rarely in the La Niña events and somewhat more often in El Niño and Neutral events. The secondary cold fronts were observed very rarely in La Niña and Neutral events and a little more often in El Niño events.

Identification of the frontal zones depends on many parameters, such as frontal structure, the velocity of a frontal zone's displacement and the method of frontal identification. For example, the same frontal zone has different characteristics near the cyclone center and on the periphery; frontal characteristics on the periphery, in general, are not clearly seen. The identification of a frontal zone, using a variation of pressure at sea level, temperature and wind (direction and speed) at the 925 hPa level (Cavalcanti and Kousky 2009), can present some difficulties on the frontal periphery. Cold front displacement was identified by Rodrigues *et al.* (2004), taking into account a decreasing of air temperature, wind shifts to a southern direction, and a persistence of this wind for, at least, one day. At the same time, temperature variation can be masked in days without clouds or with clouds at high levels due to incoming radiation. Also, frontal zones with slow dislocation are difficult for identification, using parameter variation (for example, temperature variation during 24 h). Also, parameter variation can occur step by step. For example, MORAIS's (2010) research presents a discussion about two wind shifts during one frontal zone pass.

Spatial correlations of the daily surface pressure fluctuations observed in Brazil and their relation with the synoptic systems and tropical convective activity of the Southern Hemisphere are discussed by KOUSKY and FERREIRA (1981). Also, the authors conclude about the considerable enhancement of tropical cloudiness and convective activity associated with midlatitude systems that penetrate to low latitudes over Brazil and, in particular, into the Amazon Basin. This correlation analysis shows that a large area of southern and western Brazil has high values of the correlation coefficient, while the correlation is near zero along the east coast (near 15°S) and near 0.2 in the northern part of the Northeast Brazil (NEB).

Frontal frequency decreases quickly to the north of 30°S (LEMOS and CALBETE 2011). The mean monthly frequency of a frontal passage between 20°S and 05°S was 1–4 events (OLIVEIRA's (1986) research, which has been quoted by SATYAMURTI *et al.* 1998). This result is based on 10 years of study, from 1975 to 1984. The frontal zone regularly affected the weather in the southern region of the NEB (15°–0°S, 35°–47°W) (south of Bahia, KOUSKY 1979); the number of the fronts was equal to 15 per year at 18°S. Also, winter and spring (summer) have the maximum (minimum) number of fronts of 4.5 (1.8), respectively. KOUSKY (1979) has recommended the using of the equivalent potential temperature or wet-bulb temperature for frontal identification in this region. Also, in this paper, Kousky shows a connection between precipitation and frontal passage. Some events of the cold front passage over the equator were documented (for example, PARMENTER 1976).

TALJAARD (1972) defines a front in the tropical region as "a narrow hyperbaroclinic zone, separating relatively barotropic air masses". Also, "many other lesser discontinuities, such as shallow fronts between subtropical anticyclones, can be very important for local forecasting". This front is located between two anticyclones corresponding to the Bjerknes' *Passatfront*, or the "trade wind front" or "intercell front" (quoted by TALJAARD 1972).

LI and FU (2006) show that rapid southeastward expansion of the rainy area from the western Amazon to southeastern Brazil is a result of midlatitude cold air intrusions. Each time the cold fronts pass by, they tend to increase the atmospheric humidity and the buoyancy of the lower troposphere, which destabilizes the atmosphere.

Differences between troughs and real fronts over the United States and adjacent portions of Canada were studied by SANDERS (2005). A high temperature gradient on the cold side of the wind shift was observed at a real front. For a baroclinic trough, there is a temperature gradient along the wind shift line, which tends to be accompanied by a local maximum of temperature. The wind shift is more gradual, in the cyclonic sense. There is (1) a cyclonic wind shift and a local pressure minimum; (2) warm advection ahead of the shift and cold advection to its rear; (3) a change of dew point or wet-bulb temperature and (4) a substantial temperature change over a 24-h period, which may occur gradually and without any abrupt change in a short period.

SCHULTZ's (2005) research reviewed a number of different mechanisms for prefrontal troughs and wind shifts, illustrating the variety of physical processes acting in cold fronts. Ten different mechanisms were identified and have been discussed in the literature. These mechanisms include those external and internal to the front. The external mechanisms are the following: synoptic-scale forcing, interaction with lee troughs/dry lines, interaction with fronts in the mid- and upper troposphere, and frontogenesis associated with in homogeneities in the prefrontal air. Internal mechanisms include the following: surface friction, frontogenesis acting on along front temperature gradients, moist processes, descent of air, ascent of air at the front, and generation of prefrontal bores/gravity waves.

Another important role of a frontal zone is its interaction with the tropical convection over South America. Fronts can initiate severe convection in the tropics. Some studies about it are cited below. Convective activity associated with the frontal passages over South America between 40°–35°S, 35°–25°S, 25°–20°S and 20°–05°S was described by Satyamurti *et al.* (Oliveira's (1986) research, which has been quoted by SATYAMURTI *et al.* 1998), using information over 10 years (1975–1984). Convective activities are observed when a frontal system approaches the southern and southeastern parts of Brazil (Satyamurti *et al*. 1998). The processes between the extremity of a cold front in southern Brazil and a barotropic cyclone in the center of South America (North of Argentina and Paraguay) were studied in 1997 by Signorini (2001). The region between the systems was characterized by (1) high instability, (2) low values of cyclonic vorticity, (3) low values of convergence at the low levels and divergence at the high levels and (4) an association with the jet current from the north at the low levels (between 1000 and 700 hPa). On the other hand, fronts reaching tropical regions tend to suppress the convection in the ITCZ (Reeder and Smith 1998). Siqueira and Machado (2004) separated three frequent types of interaction of the frontal systems with the tropical convection over 11 years. This analysis included 3-hourly data for the period from July 1983 to December 1993. Type 1 is frequent throughout the year, especially in austral summer, and is characterized by the penetration of a cold front in subtropical South America that interacts with the tropical convection and moves with it into the lower tropical latitudes. Type 2 is also more frequent in austral summer, and is characterized by Amazon convection and a quasi-stationary band of the convection extending from the Amazon basin to the southeast along the cold front. Contrary to Type 1, Type 3 does not have any significant interaction with tropical convection, is more frequent in austral winter and is represented by a quasi-stationary cold front in the subtropical SA and midlatitudes.

Frontal identification in the tropical and extratropical regions is different and this problem of identification is discussed in some papers for different geographical regions (see below). A quasi-stationary frontal zone in East Asia (The Baiu Frontal Zone—BFZ) has several characteristics different from that of the Intertropical Convergence Zone (ITCZ) and polar front, which was classified, as a subtropical frontal zone (Kodama 1992). The BFZ, South Pacific Convergence Zone (SPCZ) and South Atlantic Convergence Zone (SACZ) were referred to as SPZs (Subtropical Precipitation Zones). Since the SPCZ and the SACZ have several unique characteristics different from that of the ITCZ and polar frontal zones, but still similar to the BFZ, it has been concluded that all of the SPZs can be classified as subtropical frontal zones. All SPZs are characterized by: (1) convergence zones with a thick, moist interior layer, (2) baroclinic zones, (3) upper subtropical jet and, also, (4) as poleward boundaries of the moist tropical or monsoon air mass, associated with a low-level, large gradient of a moisture mixing ratio. An additional study (Kodama 1993) shows that these zones are characterized with strong moisture convergence, frontogenesis in equivalent potential temperature fields and the generation of convective instability. These zones appeared where two conditions were quasi-stationarily satisfied: (1) subtropical jets flow in the 30°–35° latitudes and (2) low-level poleward flows prevail along the western peripheries of the subtropical highs. Another investigation was elaborated in China (Fu and Qian 2011) with the aim of studying the Mei-Yu precipitation front, which extends northward from Southern China to the Yangtze River, Huaihe River and Yellow River. This front was identified by a gradient of the equivalent temperature. A front usually formed due to the convergence of the subtropical oceanic warm, moist air mass and the extra tropical continental dry, cold air mass.

Summarizing the above results, it is possible to make the following conclusions regarding frontal analysis in South America. Frontal frequency to the south of 30°S has been studied in detail. This frequency decreases quickly to the north of 30°S, to 15 per year at 18°S and one event when a cold front passing over the equator was documented. The shortage of frontal zone studies in the tropical regions (especially to the north of 15°S) is evident. An interaction of a frontal zone with tropical convection was observed frequently over the entire continent of South America, from southern Brazil to the tropical latitudes Oliveira's (1986) research, which has been quoted by Satyamurti *et al.* (1998). The passage of the cold fronts tends to increase the atmospheric humidity and the buoyancy of the lower troposphere and, therefore, formation and displacement of the precipitation area. For a baroclinic trough, a high temperature gradient on the cold side of the wind shift, thermal advection and the local maximum of temperature were observed at well-defined fronts in the extratropical regions. These characters are diffused in the tropical region, which creates problems for frontal identification. The external and internal mechanisms of the physical processes in prefrontal troughs have not been documented up to now in the tropical regions. In the authors' opinion, it is very important to study in the tropical region the interaction of the troughs of different origins with fronts in the mid- and upper troposphere.

Frontal zones in Brazil are analyzed regularly in the operational work at the Center of Weather Forecasting and Climate Studies (Centro de Previsão de tempo e Estudos Climáticos—CPTEC) and these results have been published by the journal *Revista Climanalise* (translation: Climanalise journal) http://climanalise.cptec.inpe.br/~rclimanl/boletim (Accessed May 2015). The *Revista Climanalise* in that form stopped being published in 2006. This webpage has information for each month about all synoptic processes in Brazil by verbal description. The section about frontal zones presents a verbal description of the days and geographical locations of the frontal zones using names of cities. Moreover, this section has figures with the location of the frontal zones: "number of days" (axis X) and names of cities (axis Y). The "number of days" shows a frontal zone, which passed through the station between 9 a.m. local time the previous day and 9 a.m. local time of the day shown. Definition of the frontal zones by Climanalise was elaborated daily, using maps of the wind and temperature at 1000 hPa, the pressure at sea level, the convergence of humidity and relative humidity at the 925 hPa level at 12 UTC and, also, satellite imagery.

The necessity of frontal zone identification is associated with the occurrence of precipitation at this frontal zone. Processes of precipitation formation in the NEB were summarized by Molion and Bernardo (2002), where the authors present evidence of intensive precipitation occurrence in the frontal zones. An association of the synoptic and mesoscale systems with intensive precipitation was studied by Pontes da Silva *et al.* (2011). Frontal zones were detected between more important systems, which produced precipitation. That said, frontal identification in the tropical region is difficult in operational practice. A frontal structure in this region is different than in the extratropical region and, therefore, a traditional method of frontal identification is not accurate. For this reason, the principal study goal is the description of frontal zone identification and the analysis of its passing in the tropical region in the NEB. The use of a horizontal distribution of the equivalent potential temperature and its advection in the present study is the new aspect in frontal identification in the tropical region. This information can support forecasters in daily operational practice.

2. *Data sources and methodology*

2.1. *Data sources*

FZs were analyzed using reanalysis I data (00, 06, 12 and 18 UTC) from the *National Center for Environmental Prediction—National Center for Atmospheric Research* (NCEP–NCAR) during 2004, 2004 and 2006. This information was obtained from www.cdc.noaa.gov and was available in grid points with 2.5° × 2.5° of latitudinal and longitudinal resolution (Kalnay *et al.* 1996). The surface pressure, zonal and meridional wind components, temperature, humidity and vertical motion at the standard isobaric levels (1000, 850, 700 and 500 hPa) were used. The package "Grid Analysis and Display System", supplied by the Center for Ocean–Land–Atmosphere, was used for data visualization and manipulation. Satellite imagery from GOES-10 and 12 and METEOSAT in the infrared channel with a spatial resolution of about 5 km were obtained four times per day from the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais) http://satelite.cptec.inpe.br/.

The frontal zones, which cross South America and arrive in the NEB region, and then FZ cloudiness, which influenced the Alagoas State (9°–11°S), were selected. This region was selected for FZ analysis due to a previous study by Kousky (1979), which presented detailed results regarding the appearance of FZs up to the north of the Bahia State (11°S). The number of FZs decreased quickly to the north of the Bahia State and there is an influence of FZs on the weather in the Alagoas State, which was not studied before. Selected FZs were analyzed from their first appearance over South America until their last appearance in the region between 0°–90°W and 0°–60°S. The results of Pontes da Silva *et al.* (2011) show that the principal synoptic-scale systems which have influenced the formation of precipitation and adverse phenomenon in the NEB are located in this region. Therefore, this region was selected for study.

2.2. Frontal identification

2.2.1 Frontal identification by operational analysis

Frontal zone location was identified by the method used in synoptic operational practices. This zone is determined as the following: (1) an "elongated" zone in a trough of a baroclinic cyclone (by pressure maps at the surface level) and cyclonic vorticity (at the 1000 hPa level), (2) a zone of high gradient of 1000/500 hPa thickness and a "strong" temperature gradient (at the 1000 hPa level), (3) a zone of a confluence of streamlines at the low levels (925 and 850 hPa), (4) localized between regions with cold and warm air advection (925 and 850 hPa levels) Petterssen (1956), Bluestein (1993), Smith *et al.* (1995), Djuric (1994), Fedorova (1999), Fedorova and Carvalho (2000). By "strong" temperature gradient is "usually mean an order of magnitude or more greater than the typical synoptic-scale strength of 10 K per 1000 km^{-1} (or 10 g kg^{-1} water vapor mixing ratio per 1000 km)" (Bluestein 1993). On frontal zone "the temperature changes sharply in the horizontal direction by an average of at least 3 °C in subtropical regions and 4–5 °C in middle latitudes and polar regions" by Taljaard (1972) definition.

2.2.2 Frontal identification using equivalent potential temperature

The study of the structure of a front passing through South America from the south to the northeast of Brazil (Gemiacki 2005) shows that a temperature variation in the FZ was not observed in the NEB. At the same time, a variation in the equivalent potential temperature (θ_e) was significant in this region. Therefore, a horizontal distribution of θ_e and θ_e advection (Advθ_e) was used for frontal identification. These parameters were calculated by the following equations (Bolton 1980):

$$\theta_e = T_K \left(\frac{1000}{p}\right)^{0.2854(1-0.28\times 10^{-3} r)} \exp\left[\frac{3.376}{T_{\mathrm{lcl}}} - 0.00254 r\left(1+0.81\times 10^{-3} r\right)\right], \tag{1}$$

where T_K is the absolute temperature (K), p pressure, r the mixing ratio at the initial level (g kg^{-1}), T_{lcl} the absolute temperature at the lifting condensation level (K), calculated by the equation:

$$T_{lcl} = \frac{1}{\frac{1}{T_d-56} + \frac{\ln(T_K-T_d)}{800}} + 56, \tag{2}$$

where T_d is the dew point temperature and

$$\mathrm{Adv}\theta_e \equiv -\boldsymbol{V}_H.\nabla_H \theta_e = -\left(u\frac{\partial\theta_e}{\partial x} + v\frac{\partial\theta_e}{\partial y}\right), \tag{3}$$

where x and y are the wind's components (m/s).

A heat wave in the maps of θ_e (K) ahead of the FZ and a cold wave of θ_e (K) with a high gradient behind it have been used as the criteria for FZ identification. Also, FZs were observed between the positive Advθ_e values in front of the FZ and negative Advθ_e values behind it.

Classical frontal zones have not been observed in the tropical regions and only weak frontal characteristics were observed in some events; for example, the periphery of a weak trough of a baroclinic cyclone; a weak gradient of 1000/500 hPa thickness; a zone of a confluence of the stream lines at the low levels.

2.2.3 Types of frontal zones

All frontal zones were divided into two types, using the following characteristics:

- Type I, if one or more maps used in synoptic operational practice and described in Sect. 2.2.1 show a frontal zone with weak frontal characteristics;
- Type II, if maps do not show even weak frontal characteristics, but maps of θ_e and Advθ_e confirm the presence of a FZ.

It is important to note that satellite images show cloud bands for both types.

A frontal zone was classified (Type I or Type II) in a northern study position, in the center of the NEB, in Alagoas State (Maceio). The frontal zone in the NEB was identified as Type I when the frontal characteristics described above were observed along the entire frontal zone. The frontal zone in the NEB was identified as Type II when a part of the frontal band on the satellite imagery could be identified as a frontal zone only when using the characteristics of Type II.

3. Results

3.1. Frontal zone frequency in the coastal region of Brazil from 2004 to 2006 based on operational analysis

The number of FZs in the different stations during 2004–2006 was obtained by the method used in the synoptic operational practices and described in Sect. 2.2.1. They are presented in Table 1. The number of FZs in the south of Brazil (Rio Grande-RS; 32.5°S) was 82 over 3 years. This number increases to 133 events at the 24.6°S latitude (Iguape-SP) and decreases to 78 events at the 20.3°S latitude (Vitoria-ES). These numbers of fronts are associated with the typical trajectories of cyclones and with the location of cyclogenesis regions. The number of frontal zones increases in Iguape-SP region due to the cyclogenesis process. The surface cyclogenesis over South America shows two regions with the highest frequency; the first being that over Argentina, with the center near 45°S; and the second being over southern Brazil, adjacent to the ocean at around the latitude of 30^{o}S (Gan and Rao 1991; Sinclair 1995). More recent information (Reboita *et al*. 2010) shows the existence of three cyclogenesis regions in the western sector of the Southern Atlantic Ocean (SAO) near South America's east coast. This investigation was based on ten years of study from 1990 to 1999 over the SAO. The cyclones were identified with an automatic scheme that searches for cyclonic relative vorticity (ζ_{10}) obtained from a 10-m height wind field. All systems with $\zeta_{10} \leq -1.5 \times 10^{-5}$ s^{-1} and a lifetime equal or larger than 24 h were considered in the climatology. A third area of cyclogenesis is located near Uruguay and the Northeast of Argentina (Buenos Aires). Baroclinic cyclones with frontal zones cross South America on typical trajectories from west to east, or northeast along the central regions of Argentina, and their cold fronts frequently reach latitude of 20°S. A second typical trajectory

Table 1

Number of frontal zones in coastal region of Brazil by the method used in synoptic operational practices in 2004–2006

	Lat	Lon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Maceio-AL	**9.6**	**35.6**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**2**
Aracaju-SE	**10.9**	**37.0**	**0**	**0**	**0**	**0**	**2**	**1**	**0**	**0**	**0**	**1**	**0**	**1**	**5**
Salvador-BA	**12.9**	**38.5**	**1**	**1**	**0**	**2**	**3**	**2**	**3**	**1**	**1**	**2**	**1**	**1**	**18**
Ilheus-BA	**14.8**	**39.0**	**2**	**2**	**1**	**4**	**7**	**3**	**4**	**3**	**3**	**5**	**3**	**2**	**39**
Caravelas-BA	**17.6**	**39.3**	**4**	**3**	**3**	**7**	**7**	**5**	**5**	**4**	**5**	**6**	**5**	**2**	**56**
Vitória-ES	20.3	40.3	5	5	8	7	8	7	6	5	6	6	8	7	78
Campos-RJ	21.8	41.3	5	7	9	10	8	6	8	8	9	7	8	8	93
Cabo Frio-RJ	22.9	42.0	6	9	9	10	11	6	7	8	11	11	9	8	105
Rio de Janeiro-RJ	22.9	43.1	5	10	9	12	12	7	8	11	13	12	11	10	120
Ubatuba-SP	23.4	45.0	5	11	9	11	14	7	10	11	13	14	10	11	126
Santos-SP	23.9	46.3	7	12	10	11	11	9	10	13	12	12	11	11	129
Iguape-SP	24.6	47.5	9	12	9	11	12	12	11	11	13	13	10	10	133
Paranagua-PR	25.5	48.5	9	10	11	9	10	11	10	12	10	13	10	10	125
Florianopolis-SC	27.5	48.5	8	9	9	10	12	10	11	10	12	13	10	12	126
Torres-RS	29.3	49.6	7	8	8	8	11	11	11	10	11	11	9	11	116
Porto Alegre-RS	30.0	51.1	7	8	7	5	8	12	11	8	11	10	7	10	104
Rio Grande-RS	32.0	52.0	8	4	5	3	7	11	7	4	10	7	7	9	82
$\sum$			13	13	14	18	20	20	16	19	18	20	15	14	200

The data for the NEB region is presented in bold

Lat latitude (^{o}), *Lon* longitude (^{o})

begins from the cyclogenesis region in the south and southeast of Brazil (near Rio Grande do Sul and San Paulo regions) and then has a direction to the southeast of the Atlantic Ocean.

The number of FZs in the south of the NEB (17.6°S, south of Bahia-BA) was equal to 56 events (Table 1). This number decreases quickly as FZs go northward or northeast and down to 18 events in the north of Bahia. Only 5 and 2 FZs were registered over 3 years in the Sergipe State (Aracaju) and the Alagoas State (Maceio), respectively.

The number of FZs in the south of the NEB (Caravelas-BA) shows a maximum value (7–6 per month) in autumn, in spring (7 in April and May, and 6 in October) and a minimum (2) in December. An analysis of FZs in the center of Bahia (Salvador) presents a low variation in the number of FZs, between 0 and 3 per month. Month to month variation was similar to that in the southern part of Bahia, but the maximum number was observed also in winter: the maximum number of FZs was in autumn (2 and 3 in April and May), in winter (2 and 3 in June and July), in spring (2 in October). FZs were not observed in March in Salvador. Only two FZs were observed in Maceio, in May and December.

The results presented in Table 1 are similar to the frontal analysis using Climanalise data in the regions to the south of 20°S. Frontal frequency by Climanalise data (Lemos and Calbete 2011) was made in three bands: (1) 35°–25°S (band D); (2) 20°–25°S (band C); and 3) to the north of 20°S (band B). The result of Lemos and Calbete's study shows that frontal frequencies during 9 years from 1987 to 1995 presented two maximums. The first maximum appeared in winter (June) in all bands. The second maximum was in autumn (October in bands D and B and November in band C). These values varied between 0.4 and 2.8 (June, October, respectively) in band D. The same were between 1.2 and 3.3 (first maximum, June) and 4.0 (second maximum, November) in band C. The values were between 3.2 and 4.6 (first maximum, June) and 4.8 (second maximum, October) in band B. Also, the results presented in Table 1 show the increase of frontal frequencies in the Sao Paulo region. This has to do with the cyclogenesis process in this region, which was discussed above (3.1, first paragraph). Climanalise data show that the frontal frequency in November is equal to 4.0 for bands B and C.

Also, for comparison, information of the frontal frequency at Caravelas (17°44′S; 39°15′W; south of Bahia) over 10 years (1961–1970) is presented (Kousky 1979). Frontal identification by Kousky was based on: (1) a significant and sustained wind shift to a southerly direction, (2) a drop in the mean daily wet-bulb temperature of 2 °C, and (3) continuity with stations further south. Using this classification, frontal passages at Caravelas were analyzed. Cold fronts or their remains may be expected in this region throughout the entire year. During the summer season (January–February), there are fewer frontal passages (0.2 and 0.4 per month). The greatest frequencies occurred during the months of March to December. The maximum frequency was observed in May, 2.4 frontal zone per month. Variability in the annual number of cold frontal passages was also evident. Similar results were obtained and are presented in Table 1, with the maximum frontal frequency equal to 2.3 frontal zones per month in April and May, and a minimum of 0.7 and 1.3 frontal zones per month in December and January, respectively.

3.2. *Frontal zone frequency in the NEB using equivalent potential temperature*

Frontal zone frequency in the NEB was calculated with the use of the maps for θ_e and Advθ_e and the types of frontal zones were identified. Twenty-six FZs were selected in the NEB over 3 years using the method previously mentioned of Type I and II frontal identification (Table 2). One FZ per month was usually registered; three FZs were found in the NEB just in March of 2006. FZs were observed in the NEB during all seasons without any preferences.

Each FZ was analyzed from its first appearance over South America in the southern part of the continent until its last appearance on satellite imagery in the NEB. The time period from the beginning of a front formation over the south of South America, then its dislocation along the continent until it reached the NEB, was analyzed. The duration of this time period is presented in Table 2. FZs pass over the continent

Table 2

Information about two types of frontal zones, which reached Maceio in the NEB from 2004 to 2006

Year	month	NM	Days	Duration	Type	NY
2004	JAN	1	07–18	12	1	7
	FEB	1	24–29	6	2	
	MAR	0				
	APR	0				
	MAY	0				
	JUN	1	31 May–06 Jun	7	2	
	JUL	1	12–24	13	1	
	AUG	1	04–10	7	2	
	SEP	0				
	OCT	1	29 Sep–09 Oct	11	2	
	NOV	1	12–21	10	2	
	DEC	0				
2005	JAN	1	07–14	8	2	7
	FEB	1	05–15	11	2	
	MAR	0				
	APR	0				
	MAY	1	26 Apr–02 May	7	1	
	JUN	0				
	JUL	1	03–09	7	2	
	AUG	0				
	SEP	1	14–20	7	2	
	OCT	0				
	NOV	1	21–28	8	2	
	DEC	1	26 Nov–05 Dec	7	1	
2006	JAN	0				12
	FEB	0				
	MAR	3	06–12	7	2	
			23–28	6	2	
			26 Mar–01 Apr	7	2	
	APR	2	06–11	6	2	
			10–22	13	2	
	MAY		08–17	10	1	
			19–27	9	2	
	JUN	1	28 May–04 Jun	8	2	
	JUL	0				
	AUG	1	24–31	8	2	
	SEP	0				
	OCT	2	13–21	9	1	
			21–29	9	2	
	NOV	0				
	DEC	1	29 Nov–10 Dec	12	2	
∑	21 months		26 events	228 days; 8.8 days on average	Type I: 6 Type II: 20	

Type I: one or more classical maps show frontal zones

Type II: no classical maps showing even weak frontal characteristics, but maps of θ_e and Advθ_e confirm the presence of a FZ

NM number of events in the month, *NY* number of events in the year

during 9 days, on average, and the duration varies between 6 and 13 days. Three cases were observed in 2006 (in March, April and October) when two FZs were observed during one day: the first FZ was located over the NEB and the second was detected in the southern part of the continent. Therefore, two FZs were observed in the same day: one of them was in the final position and other in the initial position.

Table 3

Numbers of FZs in the NEB during the seasons

	Type I	Type II	$\sum$
DEC, JAN, FEB	2	4	6
MAR, APR, MAY	2	6	8
JUN, JUL, AUG	1	5	6
SEP, OUT, NOV	1	5	6
$\sum$	6	20	26

Only 6 FZs were confirmed by classical maps over three years (2 FZs per year) (Tables 2, 3). Twenty FZs were detected by θ_e and Advθ_e maps. All FZs were associated with cloud bands on infrared satellite images. FZs of both types were observed during studied years without any seasonal preference.

A comparison of numbers of frontal zones in Tables 1 and 2 shows that only two FZs over 3 years in the Alagoas State (Maceio) were registered by the method used in operational practice. At the same time, using the existence of cloud bands on satellite images and one or more classical maps of a frontal zone with weak frontal characteristics (Type I), six frontal zones were observed in this period. This number reached 20 events, if frontal zones were identified using maps of θ_e and Advθ_e and also cloud bands (Type II).

3.3. *Example of a frontal zone in the NEB*

One example shows a cold front over the NEB on 01 May 2005, 18 UTC (Fig. 2). One baroclinic low was observed over the Southern Atlantic with the center position at 30°S and 30°W, approximately. The trough had a position from this center to the NEB direction. Isobars with cyclonic curvature on the pressure map, streamline confluence at 850 hPa and a FZ of Type I were observed over the ocean (Fig. 2a,b, dark gray line). A FZ band of cloudiness stretched out toward the continental region of the NEB (Fig. 2, gray line). A wave of cold air is presented on the θ_e map at the backside of this frontal cloudy band (Fig. 2c). The highest θ_e temperatures were registered over the continental region in the Bahia State (with maximum values in the regions with isoline θ_e of 345 K). Therefore, a cold front of Type II was identified over the continental region (Fig. 2, gray line). The region with negative values of Advθ_e was observed in the wave of cold air of the θ_e at the backside of this front and also in the eastern part of the continental region of the NEB (Fig. 2c). The location of a Type II cold front over the continental region was confirmed by this map.

Figures for the next day on 02 May 2005, 18 UTC show the cloudy band of the cold front divided, with the continental part of the front beginning to separate from the cyclone center (Fig. 3). This separation was observed on the satellite imagery (Fig. 3a). The pressure map shows the entrance of a high-pressure ridge into the continental region with frontal cloudiness. A streamline map presents the confluence over the ocean and diffluent air current over the Bahia (Fig. 3b). All this information shows that a typical frontal zone was located only over the ocean. At the same time, the θ_e map presents a similar temperature distribution over the ocean and the continental region (isolines of θ_e 325 and 335 K) (Fig. 3c). Also, similar negative values of Advθ_e were observed in the continental and oceanic regions. Positive values of Advθ_e were observed between the baroclinic low center and the cold front band (Fig. 3d). This incursion of Advθ_e shows the frontal band separation from the cyclone.

3.4. *Diagram of frontal zone passing in the tropical region of the NEB*

The relationship of frontal zones in the NEB with cyclonic activity is presented in Fig. 4. It shows the process of the formation and development of a baroclinic cyclone between 20° and 30°S over the Atlantic Ocean. The process of the cyclone's

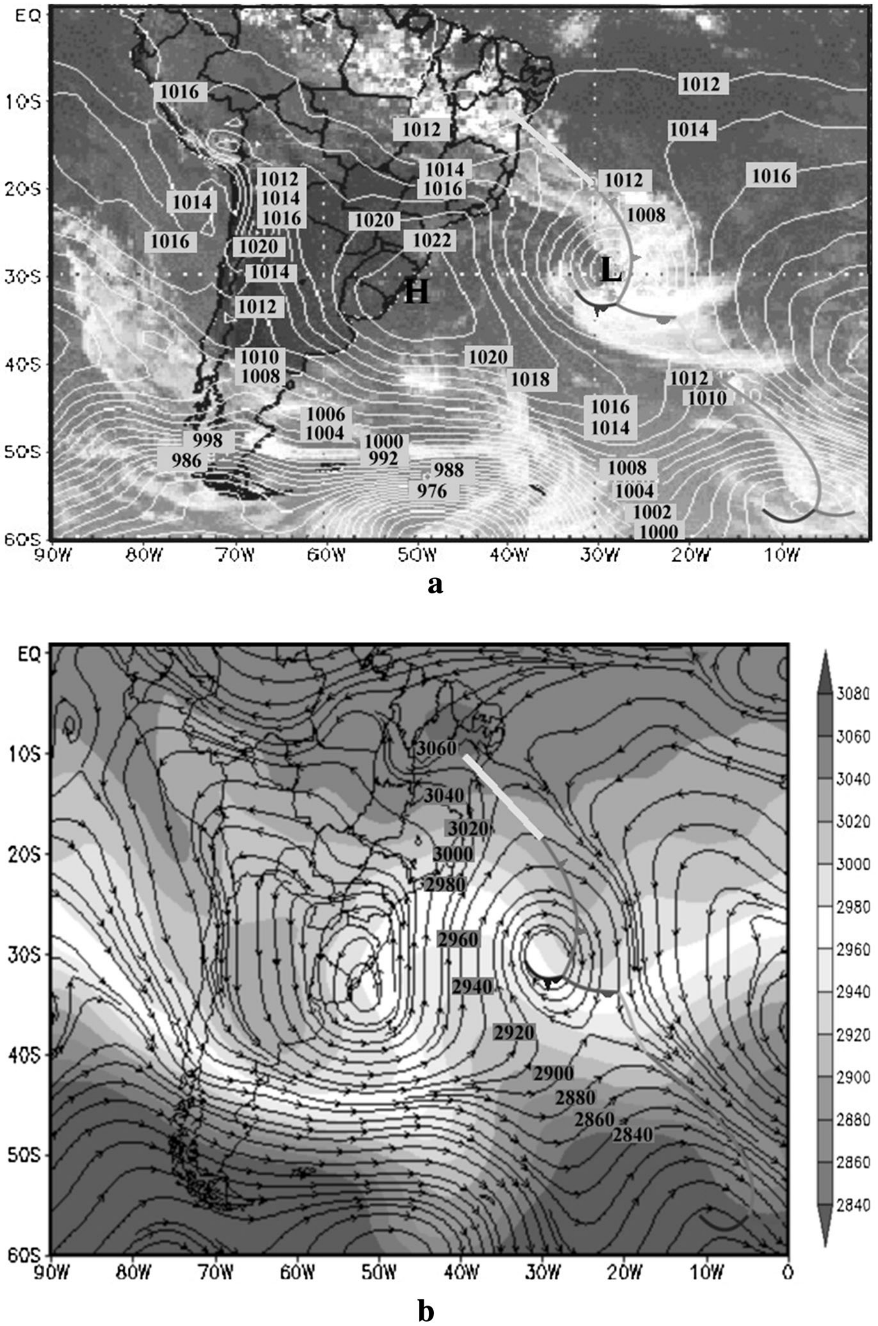


Figure 2

Frontal zone position at 1000 hPa together with different maps on 01 May 2005, 18 UTC: **a** infrared satellite imagery together with the pressure map; **b** stream lines at 850 hPa together with 1000/700 hPa thickness (*gray colors*); **c** infrared satellite imagery together with θ_e map (K) at 850 hPa; **d** infrared satellite imagery together with Advθ_e map (Ks^{-1}) at 850 hPa. Type I cold front line represented by a *thick dark gray line*. Type II cold front represented by a *thick gray line*

development was typical according to the Shapiro–Keyser model (as described in detail below). The cloudy band of the frontal zone can be seen on the satellite images over the Atlantic Ocean and reached the continental region of the NEB (Fig. 4). In Sect. 3.3 it is shown that this entire cloudy band of the

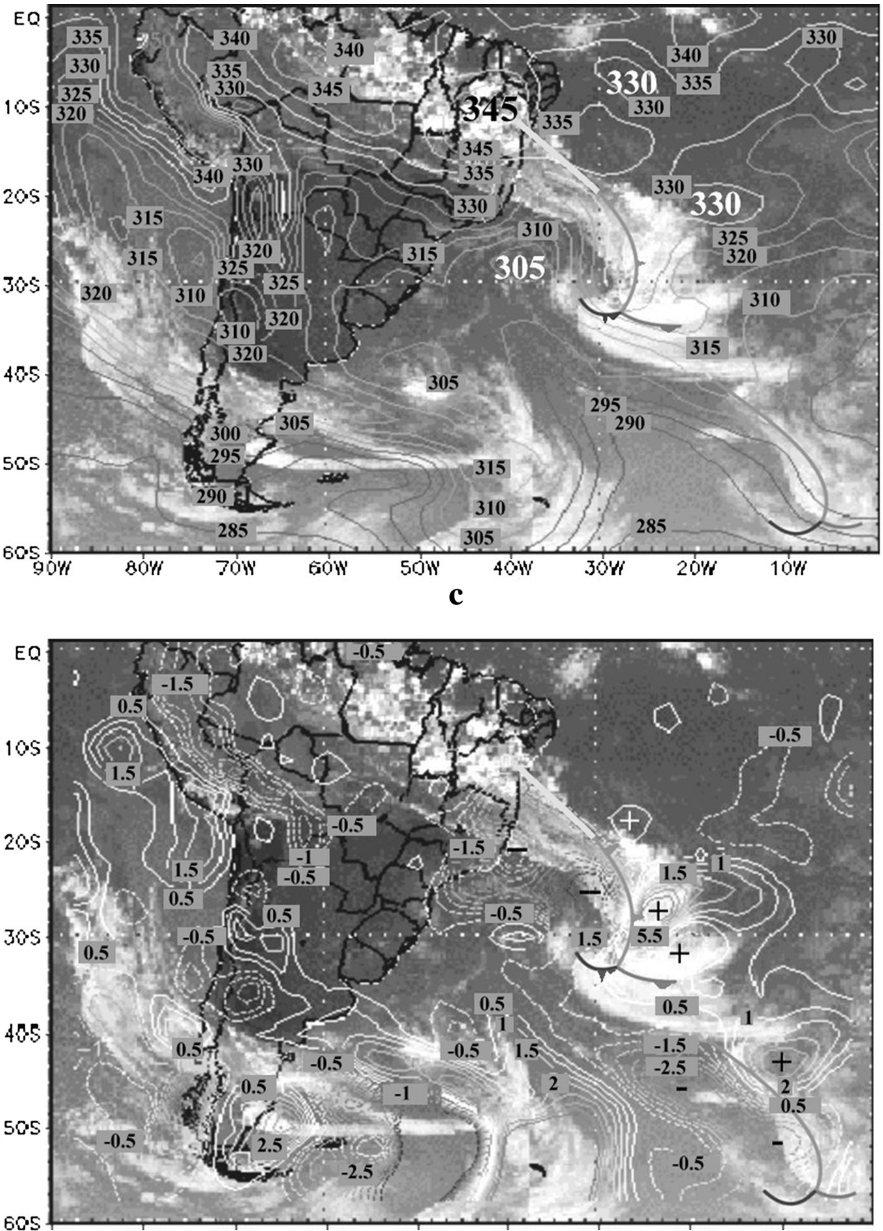


Figure 2
continued

frontal zone was not identified as a frontal zone, using the operational method of frontal identification. Horizontal distributions of the equivalent potential temperature and its advection helped in frontal identification in the entire band of cloudiness. That said, the same satellite images show that the formation of this band of cloudiness was observed together with the cyclone development, and was also connected with the cyclone.

The Norwegian cyclone-frontal model was formulated analyzing cyclones developing within diffluent, high-amplitude background flows, favoring

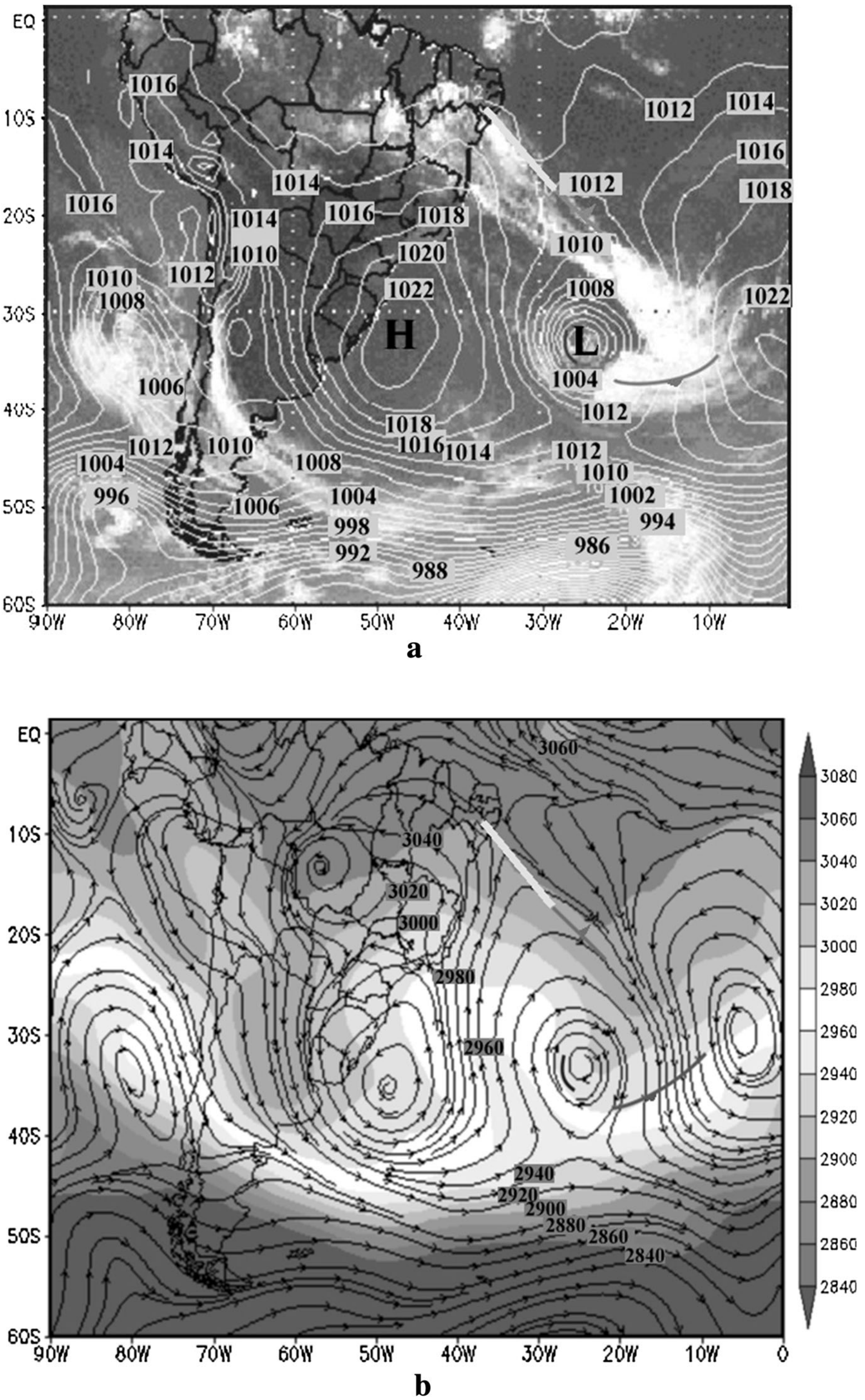


Figure 3
The same as in Fig. 2 on 02 May 2005, 18 UTC

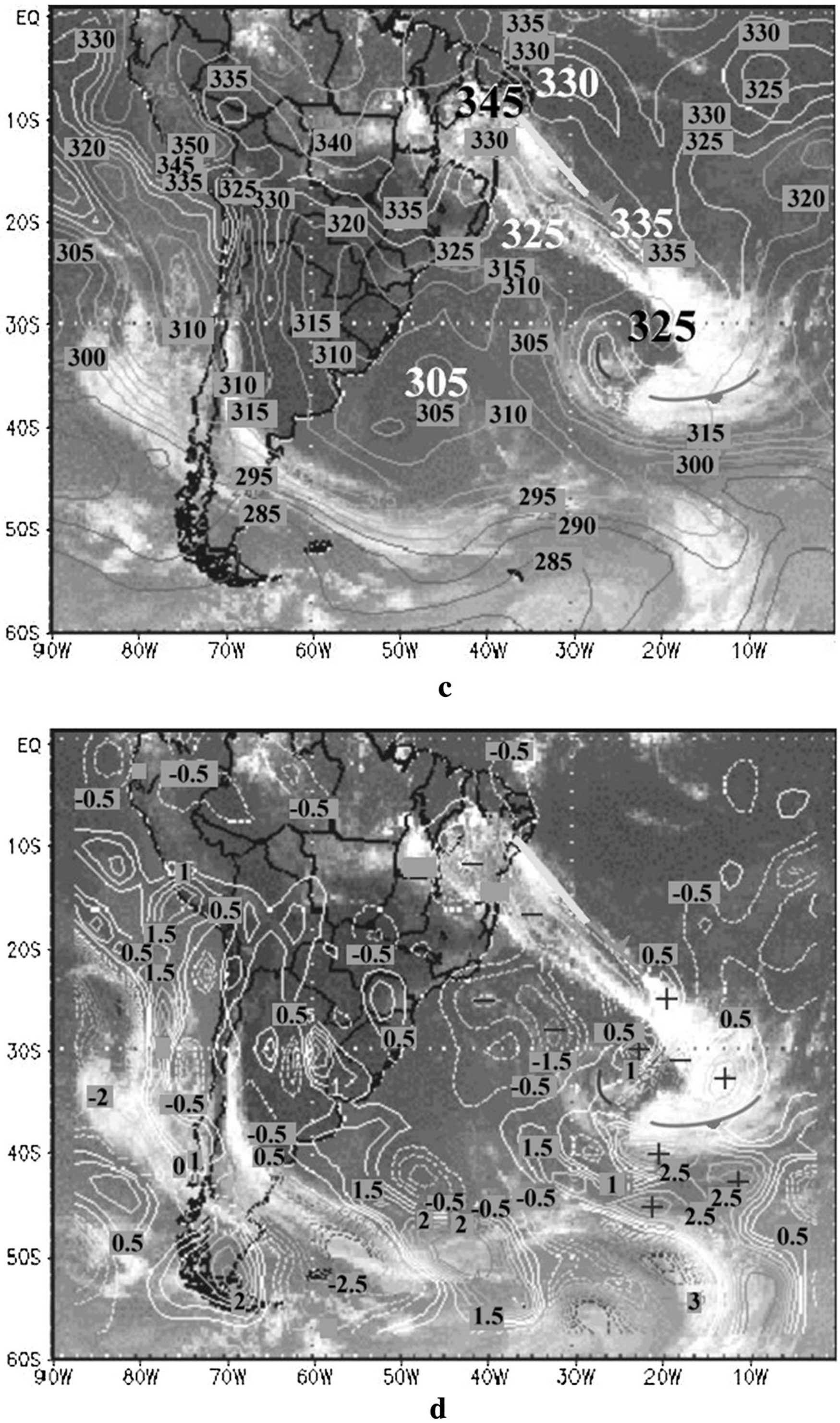
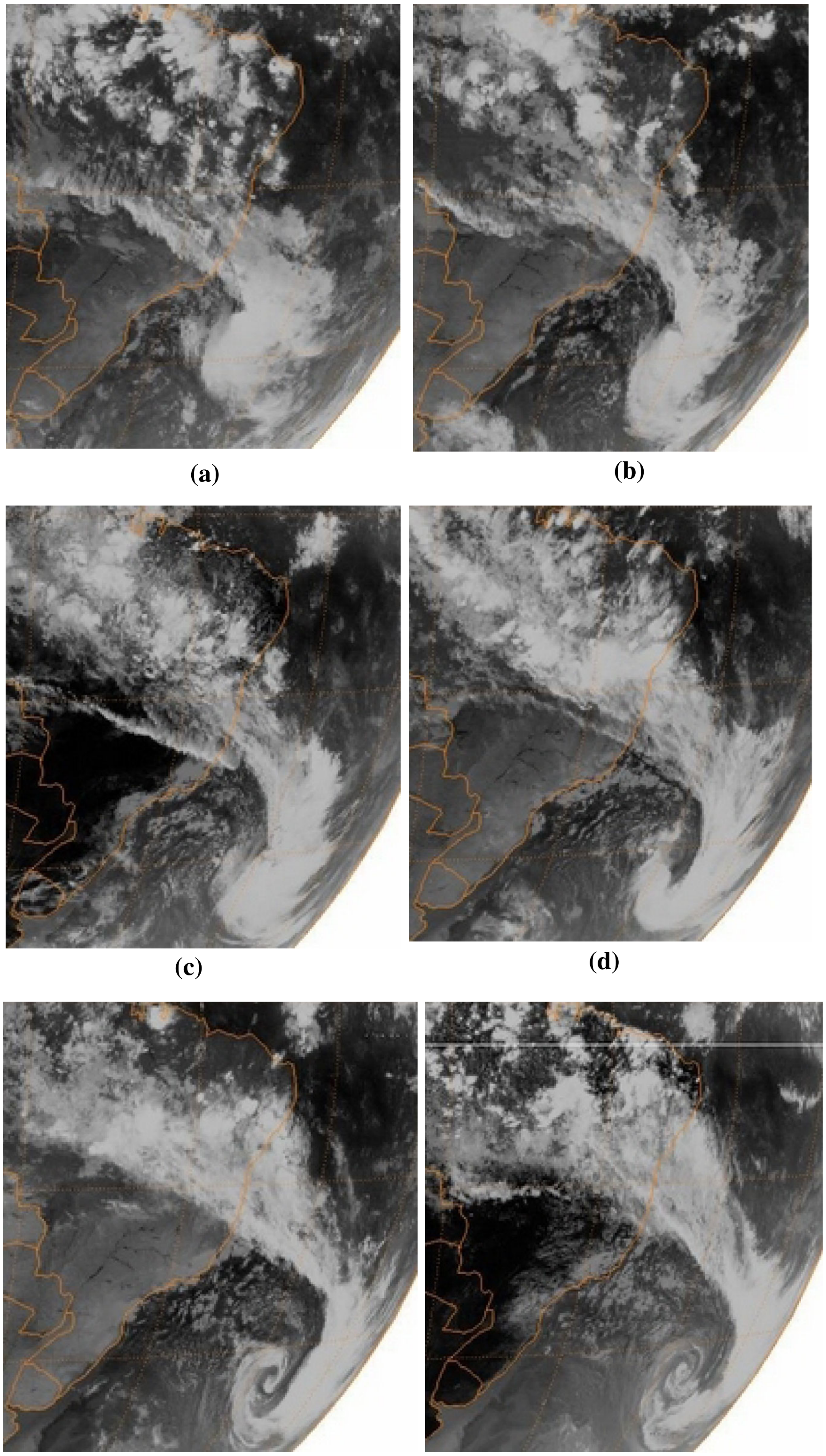


Figure 3
continued



(a) (b)

(c) (d)

(e) (f)

◀ Figure 4

Connection of the frontal zone in the NEB with the cyclone over the Atlantic Ocean, using Goes-12 satellite imagery on: **a** 30 April 2005, 21UTC; **b** 1 May 2005, 06UTC; **c** 1 May 2005, 15UTC; **d** 2 May 2005, 00UTC; **e** 2 May 2005, 09UTC; **f** 2 May 2005, 18UTC

the meridional elongation of the cyclone and its fronts in the North Atlantic region. Shultz *et al.* (1998) suggested that cyclone model is "insufficient to describe the frontal structure and evolution of the majority of midlatitude cyclones for the purpose of operational surface analysis".

The Norwegian model presents a dominant cold front and narrowing warm sector. Alternatively, the Shapiro–Keyser model (Shultz *et al.* 1998) shows that the cyclone is placed in the confluent background flow with warm front domination and a wide warm sector. Also, this model shows how "cold air wraps around cool postfrontal air and frontal fracture". The Shapiro–Keyser model was synthesized during a field experiment that examined cyclones generally originating in the low-amplitude trough of the North Atlantic.

Considering the differences in the large-scale flow and continent distribution, it is perhaps not surprising that diagram of the cyclone/frontal structure and evolution will be different in the tropical region of the Atlantic Ocean in the Southern Hemisphere.

A diagram of the frontal zone appearance in the tropical region of the NEB was created on the basis of frontal analyses of all the events mentioned in Sect. 3.2, in the tropical region of the Atlantic Ocean. This diagram is shown in Fig. 5.

A description of the Norwegian model was based on the analysis of pressure maps. Shapiro–Keyser shows new cyclone models not only by pressure maps but also by potential temperature distribution. As these maps were not sufficient for frontal identification in the tropical region, maps of θ_e and Advθ_e were used for the description of the whole process from the frontal formation up to frontal appearance in the tropical region.

A cyclogenetic process occurred in a weak baroclinic and slightly deformed zone (Fig. 5I), as in the Norwegian and Shapiro–Keyser cyclone models. Maps of θ_e and Advθ_e show a wave disturbance before cyclonic formation (before the first closed isobar formation). Similarities between the Norwegian and Shapiro–Keyser cyclone models are observed in the following stages too: while the cyclone deepens (Fig. 5II, III), the warm front

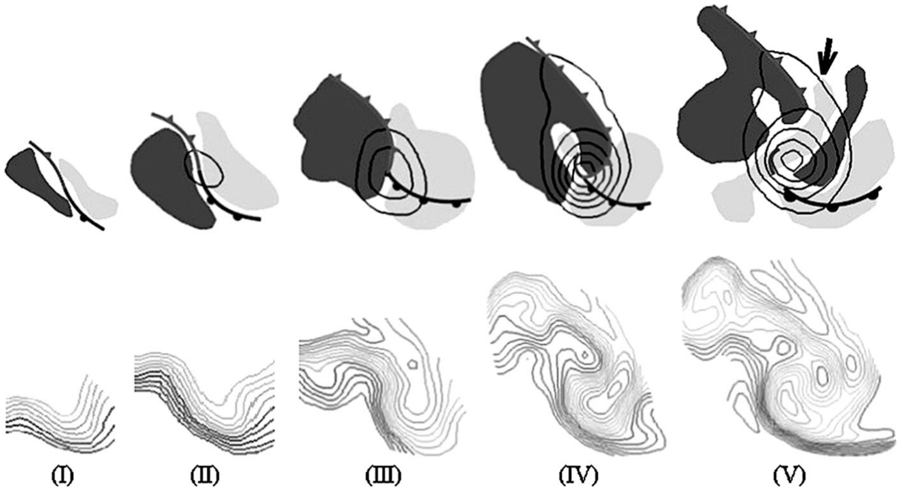


Figure 5

Diagram of the evolution of the baroclinic low in tropical–subtropical regions in the Atlantic Ocean of the Southern Hemisphere and frontal zone appearance in the BNE. The figures above show isobars (*black line*), Advθ_e maps (positive *gray*; negative *gray dark*) and frontal zones. The figures below show θ_e maps. *I* before low formation, *II* incipient low with one closed isobar, *III* young low, *IV* maximum development stage, *V* dissipation stage with frontal fracture. The *arrow* on this figure shows the position of separation between the cyclonic center and the FZ intensifies and lengthens. The gradient of the θ_e and Advθ_e was intensifying on the FZ and was weakening behind the FZ during its development and intensification of the baroclinic wave (Fig. 5II, III).

The difference between the frontal diagram in the tropical region and the Norwegian and Shapiro–Keyser models (Shultz *et al*. 1998) appeared in the dissipation stage. By the Norwegian model, "The warm sector narrows as the cold front rotates toward the warm front, forming a thermal ridge characteristic of the Norwegian occluded front (III, IV). As the occlusion process continues, the baroclinicity along the warm front may become so diffuse that the cyclone may not appear to possess a well-defined warm front (IV)." "At its maximum intensity (IV), the Shapiro–Keyser cyclone develops a warm seclusion as cold air wraps around cool postfrontal air."

In the tropical region of the NEB, a separation of the cold front from the cyclonic center was accompanied by the appearance of positive values of Advθ_e near the cyclonic center, between this center and the cold front (Fig. 5IV, V). The arrow on this figure shows the position of separation between the cyclonic center and the FZ. A cold front, separated from the cyclone center, influences the precipitation and adverse phenomenon formation in the NEB.

The separation was observed in all study events. The frontal zones began to show an influence on the NEB before it was separated from the cyclone only in some events. But after, in all events, a separation had occurred, and the separated part of the cloud band had an influence on the weather of the NEB. The difference between these events was in the type of clouds, which was in the separated cloud band over the NEB. Clouds at the low levels (stratus e stratocumulus) were predominant in 43 % of the events and intense convection with cumulonimbus developed in 58 % of the events.

Summarizing the results presented, it is possible to describe the process of the frontal origin in the tropical region. Frontal zones are formed from the baroclinic cyclone. The difference between the Norwegian and Shapiro and Keyser conceptual models is observed only in the dissipation stage, when a frontal zone is separated from the cyclone.

4. *Conclusions*

Frontal zones over the Northeast Brazil were observed more frequently in the Bahia State. There were 18 FZs in the north of the state and 56 events in the south over 3 years. The number of FZs decreases quickly to the north and only two of them were observed in Maceio from 2004 to 2006 according to the method of operational analysis.

At the same time, cloud bands on infrared satellite imagery, associated with the baroclinic subtropical low, were observed more frequently. These cloud bands, in zones which one or more maps show FZ (Type I), were registered in 6 events over 3 years. Twenty FZs were identified by cloud bands together with high gradients of θ_e and Advθ_e maps (Type II). High gradients of θ_e and high (low) values of θ_e in front of (behind) FZs were used as a criterion for its identification. Also, positive (negative) values of Advθ_e in front of (behind) FZs were observed. Seasonal preferences were not observed for both FZ Types. Therefore, we can conclude that 2–5 frontal zones per year pass over Alagoas and affect the weather of the State.

A wave disturbance was registered using θ_e and Advθ_e maps before the first closed isobar formation on the pressure maps. The appearance of positive values of Advθ_e between the cyclonic center and the cold front precedes the cold front separation from the cyclone center. Cloud bands of this cold front affect the NEB weather.

Frontal zones in the tropical region are formed from the baroclinic cyclone. The difference between the Norwegian and Shapiro and Keyser conceptual models is observed only in the dissipation stage, when a frontal zone is separated from the cyclone.

The study presents 3 years of analysis and shows that between 7 and 12 frontal zones cross the NEB during a given year. The number of the frontal zones can vary over the years. Frontal zones have a very important role in the formation of adverse phenomenon and rain. Therefore, frontal zones must be identified more exactly. The use of θe and Advθe maps make it possible to identify more frontal zones and will help to more precisely forecast precipitation and adverse phenomenon.

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