Aust. Met. Mag. 57 (2008) 345-357

Occurrence frequencies and trajectories of mesoscale convective systems over southeast Brazil related to cold frontal and non-frontal incursions

Jose Ricardo Siqueira and Valdo da Silva Marques
Laboratorio de Meteorologia, Universidade Estadual do Norte Fluminense Darcy Ribeiro, Macae/RJ, Brazil

(Manuscript received December 2007; revised July 2008)

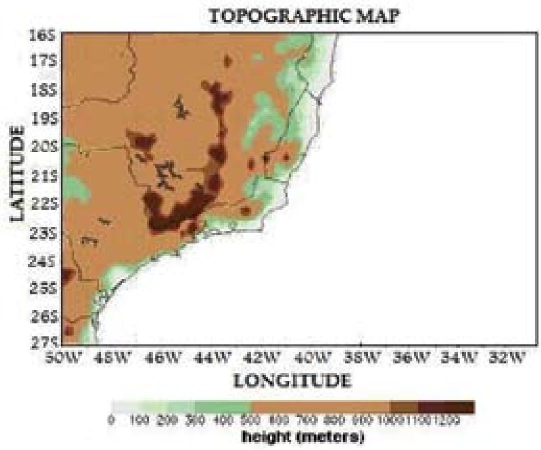
International Satellite Cloud Climatology Project (ISCCP DX) and National Centers for Environmental Prediction (NCEP) data are used to identify and study the occurrence frequencies and trajectories of mesoscale convective systems (MCSs) over southeast Brazil in a three-year period. A seasonal climatology for MCS events related to cold frontal and non-frontal incursions over the continental, coastal and oceanic areas is built by applying latitude-time diagrams and a cloud tracking method to DX data. Results show that the MCSs are frequent over continental, coastal and oceanic southeast Brazil during austral autumn, spring, and especially summer, suggesting an important modulation of deep convection by the frequent cold frontal incursions throughout the year and the diurnal forcing (thermal and/or orographic). Large seasonal and spatial variations (continent/ocean/coast) in the frequency of MCSs were found over southeast Brazil, and they were associated with the seasonal climatology of convection over South America and land-sea heating contrasts. The trajectories of the MCSs presented systems moving predominantly from continental towards oceanic areas of southeast Brazil, modulated by cold fronts and circulation forcing associated with temperature contrasts and atmospheric large-scale stratification. A smaller number of MCSs was found moving from oceanic towards continental areas of southeast Brazil, apparently modulated by thermodynamic influence (sea-breeze circulations) over the studied region. The spatial distribution of the MCSs over southeast Brazil revealed numerous MCSs over Rio de Janeiro, Minas Gerais, and central and eastern Sao Paulo State, but few MCSs over Espirito Santo State, southern Bahia State, and adjacent oceanic areas, probably inhibited by the weak moisture convergence and coastal topography of southeast Brazil.

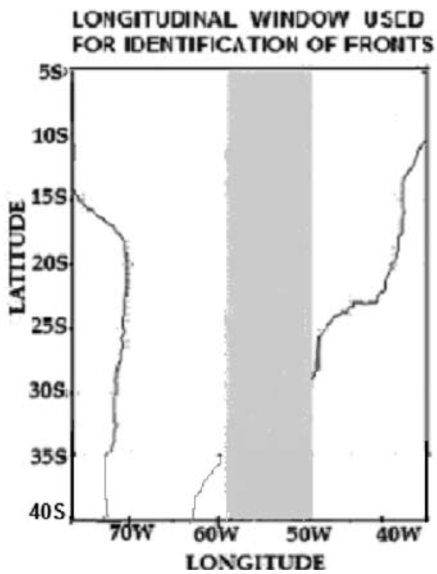
Introduction

Southeast Brazil is a region frequently influenced by meteorological systems that cause intense rainfall throughout the year and especially in austral summer, autumn and spring. The majority of these systems are known as 'mesoscale convective systems (MCSs)', and they are responsible for mostly tropical precipitation and are characterised by severe weather conditions (Zipser 1977; Maddox 1983; Houze 2004). The monitoring of MCSs over southeast Brazil is impor-

Corresponding author address: Jose Ricardo Siqueira, Laboratorio de Engenharia e Exploração do Petróleo, Universidade Estadual do Norte Fluminense Darcy Ribeiro, Rodovia Amaral Peixoto, km 163, Av. Brennand, S/N, Imboassica. Macaé/RJ, Brazil. Zip: 27925-310. Email: jricardo@lenep.uenf.br

Fig. 1 **Political and topographic maps of southeast Brazil together with the location of the oil production regions in Brazil, and the longitudinal window used for identification of frontal events over South America.**





tant not only for the improvement of weather forecast models in national centres of weather forecast and civil defence institutions, but also for oil production companies located in Bacia de Campos, Bacia de Santos, Bacia do Espirito Santo, and Bacia de Mucuri, as shown in Fig. 1. These companies need continuous information about severe weather conditions over the Atlantic Ocean for realisation of their different operational activities (oil production, sustentation of platforms, and maritime transports).

The extensive collection of weather satellite observations provided by the International Cloud Climatology Project (ISCCP) has been used to track MCSs and describe their cloud and radiative properties over the whole of the tropics (Machado and Rossow 1993; Machado et al. 1998). Machado and Rossow (1993) and Machado et al. (1998) identified and studied the time evolution of important physical properties of MCSs over tropical South America, such as effective radius, propagation velocity, propagation direction, convective fraction, and cloud-top temperature. The above authors also found a direct relationship between the MCS radius and time evolution (larger systems exhibited longer lifetimes), as well as similar lifecycle variations between their physical properties.

Since the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite in late 1997, important studies have also been done using the TRMM microwave precipitation radar (PR) to describe the three-dimensional structure of rain produced by MCSs over the tropics (Thurai and Iguch 2000; Nesbitt et al. 2000; Morales et al. 2002; Siqueira et al. 2005). Morales et al. (2002) described the vertical rainfall structural characteristics of MCSs over the Amazon Basin during the Large-scale Biosphere Atmosphere (LBA) experiment. From the combined TRMM PR precipitation profiles and Geostationary Operational Environmental Satellite (GOES) brightness temperatures, the above authors noted strong dependence of convective activity within MCSs on their lifetime and radius, such that longer and larger MCS began with a more intense initial development. Recently, Siqueira et al. (2005) combined ISCCP DX and TRMM data to estimate cloud and rainfall properties of MCSs stimulated by three types of mid-latitude front-tropical convection interaction over South America studied by Siqueira and Machado (2004). The above authors found strong modulation of convective cloudiness and rainfall regimes by cold fronts in austral summer, autumn and spring, as well as important relationships between the MCS cloud and rainfall properties. Types 1, 2 and 3 consist respectively of mid-latitude frontal incursions that penetrate over South America and move with convection into lower tropical latitudes, mid-latitude frontal incursions over South America that interact with Amazon convection and favor the South Atlantic convergence zone (SACZ) formation, and mid-latitude frontal incursions that remain quasi-stationary over the subtropics and exhibit weak interaction with tropical convection.

In Siqueira's and Machado's (2004) mean circulation composites obtained from National Centers for Environmental Prediction (NCEP), a low-level transient cyclone over southeast Brazil, that is maintained by the convergence of hot, wet air masses from the Amazon basin (produced from the equatorial air in the Atlantic Ocean modified by its travel over the South America continent and enriched in water vapour) and cold, dry air from the mid-latitudes (cold front) during the type 1 to 3 events, also evidenced the interaction between the fronts and the tropical convection over South America, especially for types 1 and 2. This cyclone moves northeastward and is accompanied by intense southerly winds in the tropics during the type 1 events, characterising the penetration of the cold front and cold air incursions into tropical South America for type 1, respectively. The cyclone remains quasi-stationary over southeast Brazil during the type 2 events, but it is also accompanied by southerly winds (cold air incursions) that support the SACZ formation for type 2. During the type 3 events, the cyclone remains quasi-stationary over southeast Brazil and the southerly winds are reduced (weak cold air incursions), consistent with the weak interaction of the cold fronts with tropical convection in South America for type 3.

The goal of this paper is to describe the occurrence frequencies and trajectories of MCSs over southeast Brazil related to cold frontal and non-frontal incursions. The cold frontal incursions consist of the passage of mid-latitude cold fronts and/or the synoptic formation of the SACZ over southeast Brazil. The non-frontal incursions consist of the convective processes indirectly related (or not related) to cold frontal incursions over southeast Brazil, such as diurnal forcing (thermal and/or orographic). In this paper, a seasonal climatology for MCS events over southeast Brazil is built by applying latitude-time diagrams and a cloud tracking method to ISCCP DX data. In the next section we describe the data-sets used in the analysis. The identification of cold frontal and non-frontal events over southeast Brazil and the methods employed for tracking the evolution of their corresponding MCSs are detailed in the following section. The distributions of occurrence frequencies of the MCSs are then described and the trajectories and spatial distributions of the MCSs during their life cycle are then presented. The circulation and thermodynamic features in southeast Brazil associated with one cold frontal and one non-frontal case are studied followed by our summaries and conclusions.

Data

ISCCP DX and NCEP data are used in this study. The DX data were acquired from Goddard Institute for Space Studies/National Aeronautics and Space Administration (GISS/NASA). The data were extracted for the region 5°S to 40°S and 30°W to 65°W, for January 1998 through to December 2000. The DX data consist of radiances that are measured by passive radiometers on board geoestationary satellites in visible (wavelength ~0.6 μm) and infrared (wavelength ~11 μm) bands together with the retrieved cloud properties (Rossow and Schiffer 1999). The horizontal resolution of the data is 7 km sampled to about 30 km for the times 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC. Approximately 8520 DX images were used in this study. The DX data are produced by the combination of satellite-measured radiances of the ISCCP B3 data (from GOES-East for South America) with the TIROS Operational Vertical Sounder (TOVS) atmospheric temperature-humidity correlative dataset. All DX results in the infrared are collected for high cold clouds, that is, clouds with cloud-top temperature lower than 245K (top heights above 8 km). The DX results used are infrared-retrieved cloud-top temperature and pressure. The infrared-retrieved high cold cloud variables are obtained by assuming that high cold clouds are opaque to the upward infrared radiation from the earth's surface. Daily analyses of horizontal wind, horizontal moisture divergence, and equivalent potential temperature at 850 and 300 hPa from NCEP were used to study circulation and thermodynamic features in southeast Brazil, with 2.5° latitude-longitude resolution (Kalnay et al. 1996).

Cold frontal incursions over southeast Brazil

Identification of events

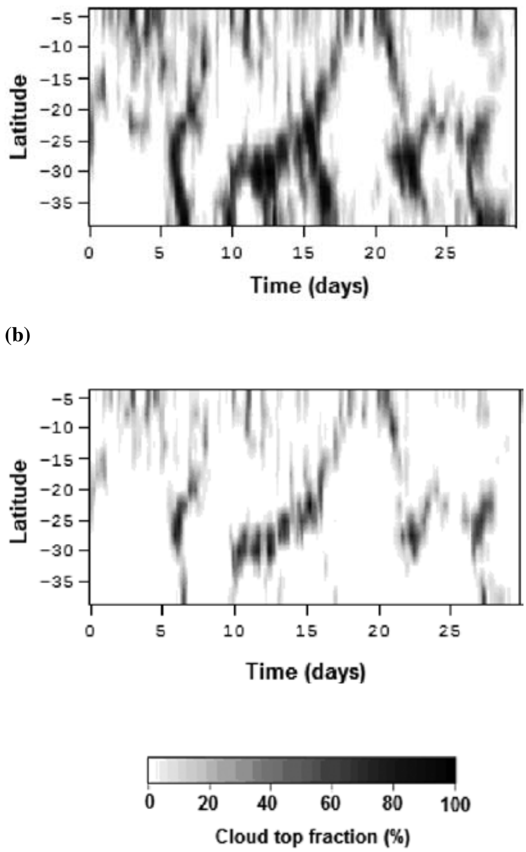
The identification of cold frontal incursions over southeast Brazil during the 1998-2000 period was based on the method developed and detailed by Siqueira and Machado (2004). This method identifies events representative of three types of mid-latitude front-tropical convection interaction over South America by producing latitude-time diagrams for high cold cloud fractions from the DX data for every three hours. The high cold cloud fraction is defined as the ratio between the number of DX cloudy pixels with Infrared cloud-top temperature lower than 245 K and the total number of DX pixels inside a 10° longitudinal region. The high cold clouds often cluster in meso-β (20-200 km) or in meso-α scales (200-2000 km) and are normally related to convective processes over the tropics, since the majority of the thin cirrus clouds are eliminated by this test because they are semitransparent to infrared radiances (Orlanski 1975; Houze 1993; Machado and Rossow 1993; Rossow and Schiffer 1999). A 10° longitudinal window between 48.75°W and 58.75°W is defined to compute zonal means of the high cold cloud fractions for the latitude-time diagrams covering the latitudinal band between 5°S and 40°S, as shown in Fig. 1. This longitudinal window has been defined for identification of all cold frontal incursions over South America during the 1998-2000 period.

Figure 2 shows the latitude-time diagram produced for high cold cloud fractions inside the area 48.75°W to 58.75°W and 5°S to 40°S for every 2.5°, for April 1998. The latitude-time diagram produced for a second definition of high cold cloud cover (very high cold cloud fraction), which will be employed in the following analysis steps, is also shown in Fig. 2. The very high cold cloud fraction represents the fraction of the total number of DX cloudy pixels with cloud-top temperatures lower than 220 K (cloud-top heights above 12 km) and is a measure of the MCS convective intensity. The very high cold clouds refer to individual convective cells in the atmosphere, which usually cluster in meso-γ scales (2-20 km) and produce a characteristic 'cumulonimbus' cloud, 'cumulus tower', or 'thunderstorm' (Orlanski 1975; Houze 1993; Machado and Rossow 1993). The influence of the three types of mid-latitude front-tropical convection interaction on the high cold clouds organisation over South America in April 1998 can be observed in Fig. 2 as follows: high cold clouds moving northward from the mid-latitudes to lower tropical latitudes between days 16 and 18 correspond to the occurrence of one type 1 event, while the southward development of high cold clouds from the tropics to the subtropics from day 20 to 22 characterises the occurrence of one type 2 event (Fig. 2(a)). The occurrence of one type 3 event is represented by a quasi-stationary feature of high cold clouds (with respect to the meridional direction) in the subtropics and mid-latitudes from day 10 to 12. These three types of mid-latitude front-tropical convection interaction are related to cold frontal incursions over South America.

Since the three types of mid-latitude front-tropical convection interaction discussed previously also establish a direct relationship with the meridional evolution of high cold clouds and very high cold clouds,

Fig. 2 Latitude-time diagrams produced for (a) high cold cloud fractions and (b) very high cold cloud fractions over the longitudinal window 48.75°W to 58.75°W for April 1998. Adapted from Siqueira et al. (2005).

(a)



the main idea of the above method consists of capturing the time of a local maximum value of high cold cloud fraction for a given latitude and finding the time of a similar maximum value at a neighboring latitude (Siqueira and Machado 2004). As a result, the meridional evolution of high cold clouds during the time is known and associated with the occurrence of type 1, 2 or 3 events. By applying this method to the DX data, we have identified 76 type 1, 15 type 2, and 33 type 3 events over South America, resulting in a total of 124 events of cold frontal incursions over southeast Brazil during the 1998-2000 period (32 events in austral summer, 28 in austral autumn, 28 in austral winter, and 36 in austral spring).

Tracking of convective systems

The infrared cloud tracking method developed by Machado et al. (1998) was applied to infrared-retrieved cloud-top temperatures from the DX data to track the MCSs associated with cold frontal incursions over South America during the 1998-2000 period. The infrared cloud tracking method is an objective calculation method that detects MCSs by applying two thresholds for infrared cloud-top temperatures: 245 K, equivalent to high cold clouds; and 220 K, equivalent to very high cold clouds. According to the methodology of Machado et al. (1998), each cluster of high cold clouds that exhibits similar cloud morphologic characteristics (location of the mass centre, size, and eccentricity) during the time in the DX data and contains a cluster of very high cold clouds (convective cells) at some time of its lifecycle is classified as an MCS. If an MCS splits, the infrared cloud tracking method will track the MCS that most closely resembles the original, usually the larger one; the other MCSs will be tracked as separate systems. If an MCS merges with a smaller system, the infrared cloud tracking method continues to track, but if it merges with a larger system, its lifecycle is terminated.

Only the MCSs that formed over southeast Brazil (16°S to 27°S and 30°W to 49°W, see Fig. 1) are studied. The MCSs that formed between day –2 and day +2 of the central day of the cold frontal incursions are classified as frontal MCSs. The selection of all MCSs identified between days –2 and +2 is based on the minimum period of convective variability associated with cold fronts estimated by Siqueira and Machado (2004), which is five days. This procedure allows the study of all MCSs over southeast Brazil that are related to cold frontal incursions. All MCSs that formed outside of these periods are classified as non-frontal MCSs, and these systems are indirectly related (or not related) to cold frontal incursions over southeast Brazil. To restrict analysis to mesoscales (200-2000 km), only the systems with effective radius (radius of a circle with same area as the MCSs) larger than 90 km are studied (including the stratiform component). The first (last) time at which an MCS is present in the DX data is defined as the initiation (decay) phase, while the time at which an MCS acquires its largest very high cold cloud fraction corresponds to the maturation phase. Since the infrared cloud tracking method identifies MCSs using DX data separated by three hours, the first detection may be at an advanced stage of convective development, so some MCSs exhibit coincident initiation and maturation phases. Despite that, no significant bias was introduced by this limitation of temporal sampling, as was also found by Siqueira et al. (2005).

The next analysis step consists of obtaining the occurrence frequencies and trajectories of the MCSs identified over southeast Brazil by applying statistical analyses. The frontal and non-frontal MCSs are also decomposed seasonally and with respect to the studied area (continental, oceanic, and coastal). All MCSs that initiated and decayed over continental (oceanic) areas are defined as continental (oceanic) MCSs, while all MCSs that initiated over continental (oceanic) areas and decayed over oceanic (continental) areas are defined as coastal MCSs.

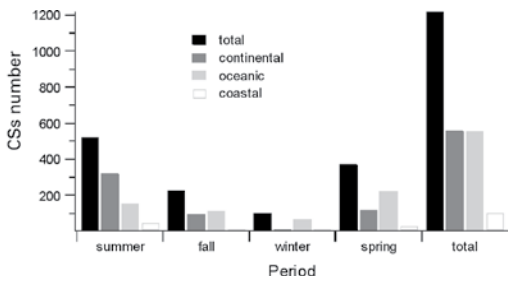
Occurrence frequencies of the mesoscale convective systems over southeast Brazil

Comparative occurrence frequencies of MCSs over southeast Brazil related to cold frontal and non-frontal incursions have been calculated for the total and seasonal periods of the 1998-2000 period for the following MCS groups: total, continental, oceanic, coastal, frontal, non-frontal, frontal over continental areas (LF), non-frontal over continental areas (LNF), frontal over oceanic areas (OF), non-frontal over oceanic areas (ONF), frontal over coastal areas (CF), and non-frontal over coastal areas (CNF).

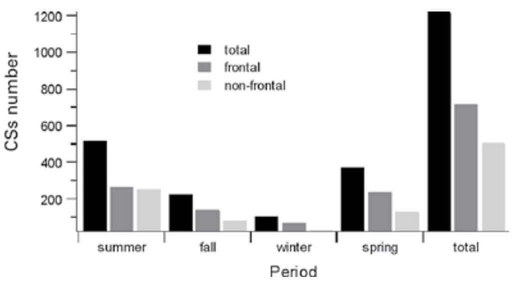
Figure 3 shows the total and seasonal distributions of the total, continental, oceanic, coastal, frontal, and non-frontal number of MCSs over southeast Brazil. The total number of continental MCSs is approximately equal to the total number of oceanic MCSs and is much larger than the total number of coastal MCSs. These three MCSs groups together result in a total of 1220 MCSs over southeast Brazil (Fig. 3(a)). Although the continental area of the study is around half the oceanic area, the stronger surface and atmospheric heating over continental areas (causing land-sea heating contrasts) favours more intense convection over those regions and consequently formation of the substantial number of continental MCSs identified. The coastal MCSs are much less numerous due to the small coastal area of the study, but the number of these systems over southeast Brazil is also significant. The seasonal distributions of the MCSs show a larger (smaller) total number of MCSs in austral summer (winter), consistent with the seasonal climatology of convection over South America (Satyamurty et al. 1998). The continental MCSs are much more numerous than the oceanic MCSs during austral summer, but these systems are less numerous during austral autumn, winter, and spring due to the reduced land-sea heating contrasts during those seasons and the larger oceanic area of the study. The total number of frontal MCSs is much larger than the total number of non-frontal MCSs, which is indicative of the importance of cold fronts in organizing convective cloudiness over southeast Brazil throughout the year (Fig. 3(b)). For the same reason, the frontal MCSs are much more numerous than the non-frontal MCSs during austral autumn, winter, and spring (especially in winter), while the number of non-frontal MCSs is comparable to the

Fig. 3 **Total and seasonal distributions of the number of total, continental, oceanic, coastal, frontal, and non-frontal MCSs over southeast Brazil during the 1998-2000 period.**

(a)



(b)

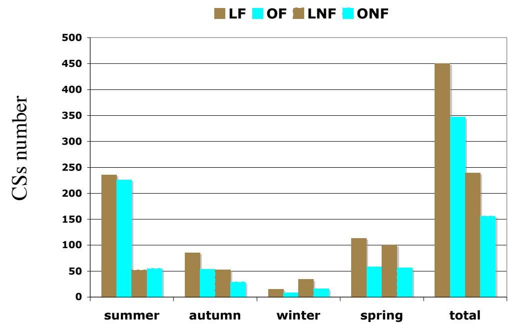


number of frontal MCSs in austral summer. The non-frontal MCSs are also most frequent in the hottest seasons of the year, suggesting the important role of diurnal forcing (thermal and/or orographic) in organizing MCSs over continental and oceanic areas of southeast Brazil. The modulation of convective cloudiness in mesoscales over continental and oceanic South America by diurnal forcing was also pointed out by Machado and Rossow (1993). The formation of the oceanic MCSs may also be related to gravity wave generation in a manner similar to that described by Mapes et al. (2003) for northwestern South America. That is due to both locations experiencing initiation of convection in association with elevated thermal heating and subsequent convection offshore.

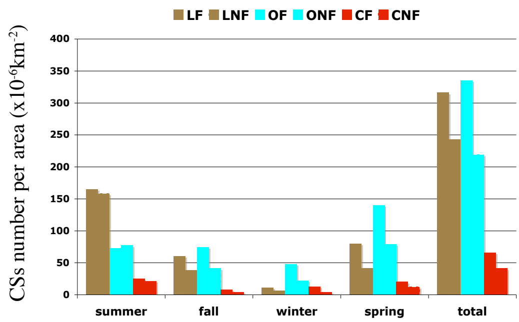
The total and seasonal distributions of the number of LF, LNF, OF, ONF, CF, and CNF MCSs over southeast Brazil (Fig. 4) are consistent with those presented in Fig. 3, and with the number of non-frontal MCSs over the continental, oceanic, and coastal areas of southeast Brazil. By evaluating the number of MCSs per unit area in southeast Brazil, we have observed that the total number of continental MCSs per unit area is larger than the total number of oceanic MCSs per unit area during austral summer, autumn, and spring for both frontal and non-frontal MCSs (Fig. 4(b)). This distribution confirms the larger seasonal frequencies of the MCSs over continental southeast Brazil, probably favored by the land-sea heating contrasts discussed previously.

Fig. 4 **Total and seasonal distributions of the (a) number of LF, LNF, OF, ONF, CF, and CNF MCSs and (b) number per unit area of LF, LNF, OF, and ONF MCSs over southeast Brazil during the 1998-2000 period. Abbreviations indicate continental (land) (L), coastal (C), oceanic (O), frontal (F) and non frontal (NF).**

(a)



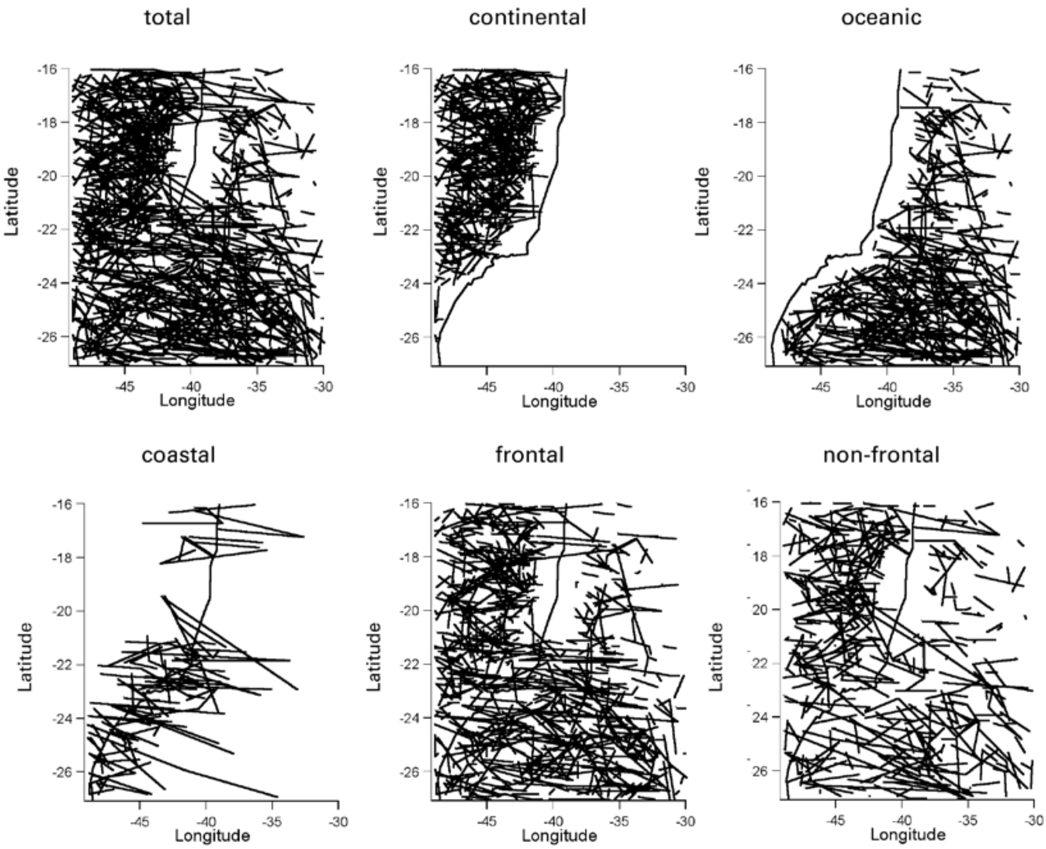
(b)



Trajectories and spatial distributions of MSCs over southeast Brazil

The trajectories of MCSs over southeast Brazil are presented for the total, continental, oceanic, coastal, frontal, and non-frontal MCS groups during the total, austral summer, and austral winter period of the 1998-2000 period. Figure 5 shows the trajectories of 1220 MCSs identified over southeast Brazil during the total period, represented by straight lines. More than 50% of the total number of MCSs were observed moving from continental towards oceanic southeast Brazil, with propagation directions between -30° and +30° (between 150° and 210°) with respect to the zonal direction (not shown). The main sources for the direction of these MCSs are the cold frontal incursions, the SACZ, and the circulation forcing associated with temperature contrasts and the atmospheric large-scale stratification, which exhibit similar propagation directions over southeast Brazil. Less than 30 per cent of the total number of MCSs were identified moving

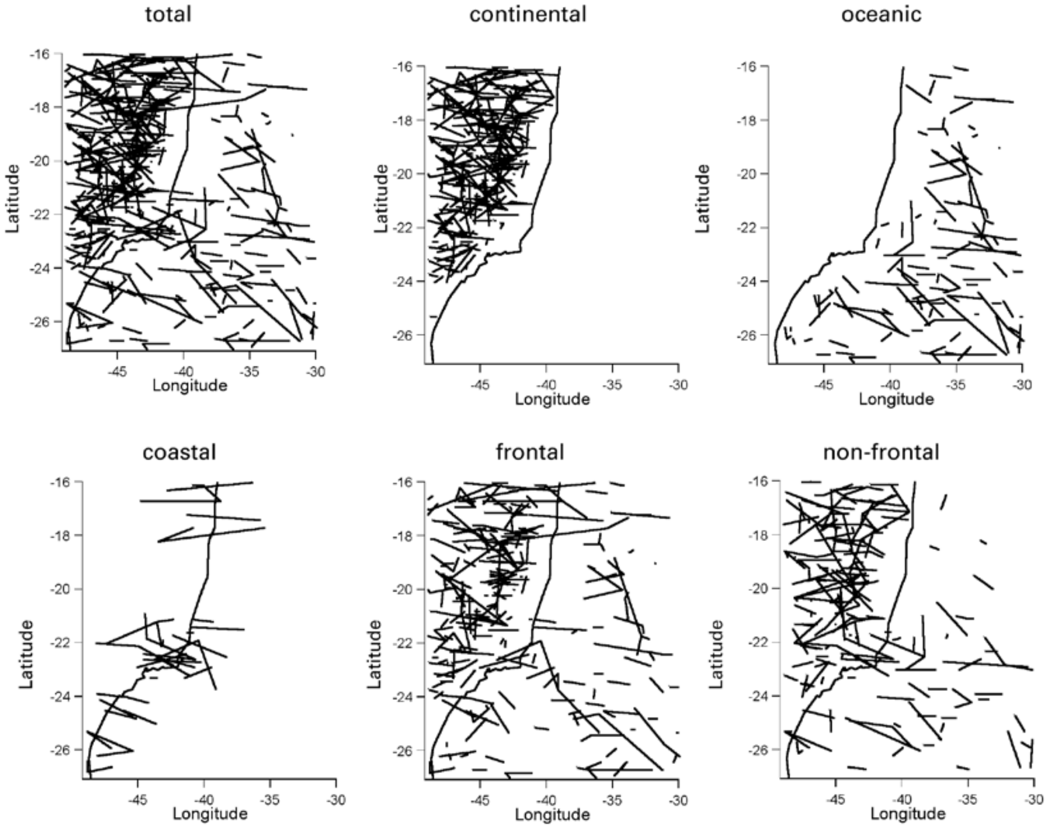
Fig. 5 **Trajectories of the total, continental, oceanic, coastal, frontal, and non-frontal MCSs identified over southeast Brazil during the 1998-2000 period.**



from oceanic towards continental southeast Brazil, with propagation directions between 150° and 210° with respect to the zonal direction (not shown). These MCSs were established by thermodynamic influences over southeast Brazil (sea-breeze circulations). The contribution of sea-breeze circulations to producing upward air motion, favouring convective development offshore and onshore, was also pointed out by Jorgensen and Weckwerth (2003). The larger number of MCSs moving from continental towards oceanic southeast Brazil and the smaller (but also significant) number of MCSs moving in the opposite direction were also found during the periods of cold frontal incursions (frontal MCSs group) and non-frontal incursions (non-frontal MCSs groups). The majority of the MCSs were observed moving with propagation speeds < 10 m/s, consistent with a more frequent organisation of deep convection in mesoscales by cold frontal incursions over southeast Brazil (not shown). Relatively similar propagation directions to the total period were found for the 519 MCSs identified over southeast Brazil during austral summer and the 104 MCSs identified during austral winter, whose trajectories are shown in Figs 6 and 7, respectively.

By examining the spatial distributions of MCSs over southeast Brazil during the total, austral summer, and winter periods, the continental MCSs are seen to be frequent over almost the whole of continental southeast Brazil, that is, central and eastern Sao Paulo (SP) State, Rio de Janeiro (RJ) State, and Minas Gerais (MG) State (Figs 1, 5, 6, and 7). However, the continental MCSs are rare inside the area 40°W to 42°W and 18°S to 22°S, that is, Espirito Santo (ES) and southern Bahia (BA) State. Despite that, we must not neglect a possible presence in this area of continental MCSs on smaller scales (effective radii smaller than 90 km), or even continental MCSs in mesoscales with weaker vertical development over southeast Brazil (the physical mechanisms responsible for the lack of MCSs inside this area will be discussed in the next section). The oceanic MCSs are also

Fig. 6 Trajectories of the total, continental, oceanic, coastal, frontal, and non-frontal MCSs identified over southeast Brazil during austral summer of the 1998-2000 period.



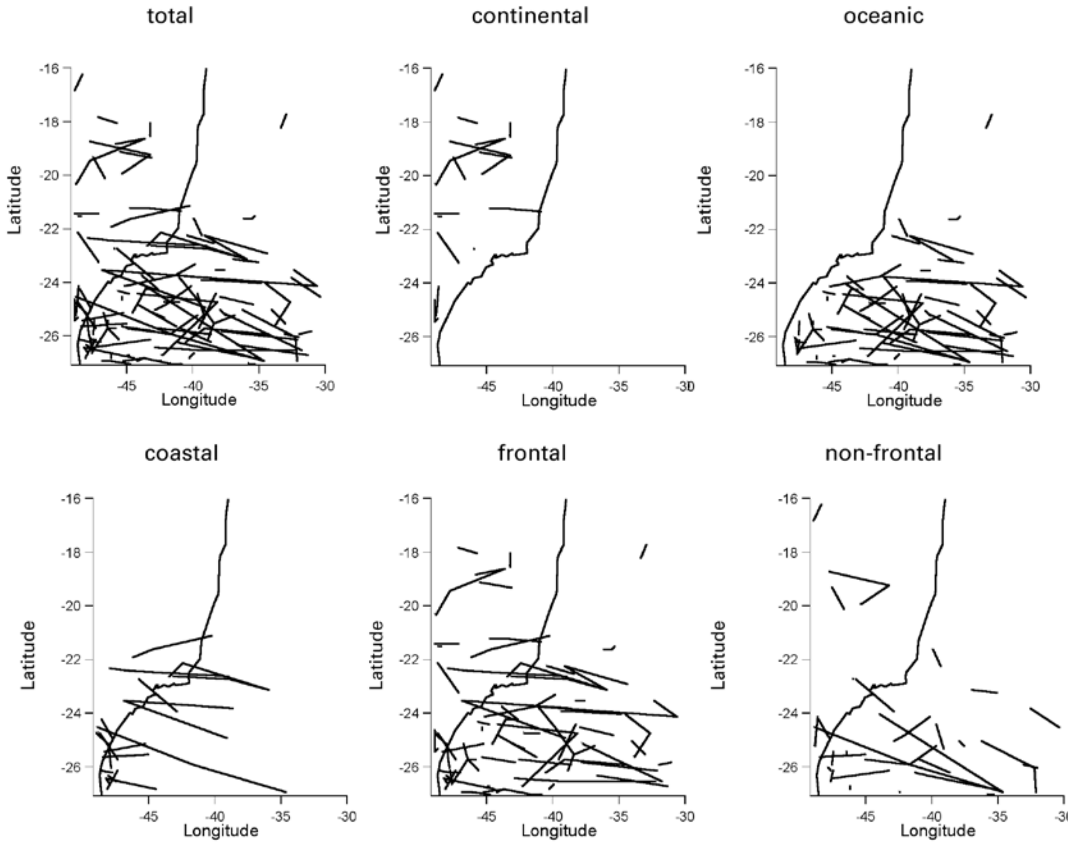
frequent over almost the whole of oceanic southeast Brazil, but they are rare inside the area 30°W to 40°W and 18°S to 22°S (oceanic region of ES State and southern oceanic region of BA State). Similarly, the coastal MCSs have a high frequency over almost the whole of coastal southeast Brazil, being rare only inside 18°S to 22°S (coastal region of ES State and southern coastal region of BA State). The frontal and non-frontal MCSs exhibit similar distributions to the total MCSs, except for having smaller numbers.

Main circulation features in southeast Brazil associated with cold frontal and non-frontal incursions

The most important circulation patterns in southeast Brazil associated with cold frontal and non-frontal incursions are investigated in this section by studying two individual cases that occurred in December 2000. The first case consists of a cold frontal incursion event that occurred between days 24 and 26, and the second case consists of a non-frontal incursion event that occurred between days 18 and 20. The horizontal wind and divergence of the horizontal moisture flux fields from NCEP were used to prepare a composite analysis describing the mean daily fields (24 h data) for day -1 to day +1 of occurrence of the cold frontal incursion case and the non-frontal incursion case. Figure 8 shows the trajectories of 8 frontal MCSs and 18 non-frontal MCSs identified during day –1 to day+1 of the occurrence of one cold frontal incursion and one non-frontal incursion case, respectively, in December 2000. Similarly to the total period, the number of MCSs moving from continental towards oceanic southeast Brazil is either larger (for frontal MCSs) or comparable (for non-frontal MCSs) to the number of MCSs moving from oceanic towards continental southeast Brazil, favored by the same mechanisms described in the previous section.

Figure 9 shows the mean daily fields of horizontal

Fig. 7 **Trajectories of the total, continental, oceanic, coastal, frontal, and non-frontal MCSs identified over southeast Brazil during austral winter of the 1998-2000 period.**



wind at 300 hPa for the two studied cases. The main circulation features found for the cold frontal incursion case consist of strong westerly and southwesterly winds moving towards northeast South America and tropical Atlantic Ocean, being representative of the penetration of a mid-latitude cold front over southeast Brazil that moves towards the tropics. For the non-frontal incursion case, the presence of strong westerly and northwesterly winds moving towards the tropical Atlantic Ocean are the main features found over southeast Brazil. Another important feature observed for both cases is the predominantly zonal circulation at 300 hPa, which favors the zonal movement (from continental towards oceanic areas) of the majority of MCSs, as verified in the previous section. This is because the dynamical influence is stronger than the thermodynamical influence over the studied region, such that the circulation is predominantly zonal above 500 hPa in southeast Brazil (Satyamurty et al. 1998). Nicolini et al. (2004) and Velasco and Fritsch (1987) discuss the relationship of the low level jet (LLJ) to the frequency and propagation of MCSs, while Marengo et al. (2004) suggested that intensification of the LLJ leads to a more intense SACZ, equatorward penetration of cold fronts and the development of an area of enhanced convection near the exit region of the LLJ. In future it would be very interesting to decompose our data-sets into periods of different LLJ intensities to assess these issues.

Figure 10 shows the mean daily fields of divergence of the horizontal moisture flux for the cold frontal incursion and non-frontal incursion cases studied. Positive or small negative values are observed on the majority of the days for both studied cases, and especially for the cold frontal case inside the area 30°W to 40°W and 18°S to 22°S. This suggests an important role of the moisture divergence (weak moisture convergence) in inhibiting deep convection in mesoscales (especially that organised by cold fronts) over this region, apparently justifying the lack of CSs observed previously. Another mechanism that apparently inhibits deep convection on mesoscales over this region is the topography of coastal southeast Brazil, which is high-

Fig. 8 **Trajectories of the MCSs identified during day –1 to day +1 of occurrence of one cold frontal and one non-frontal incursion case over southeast Brazil in December 2000. Circles represent systems at the decay phase of the MCS lifecycle.**

(a) **(b)**

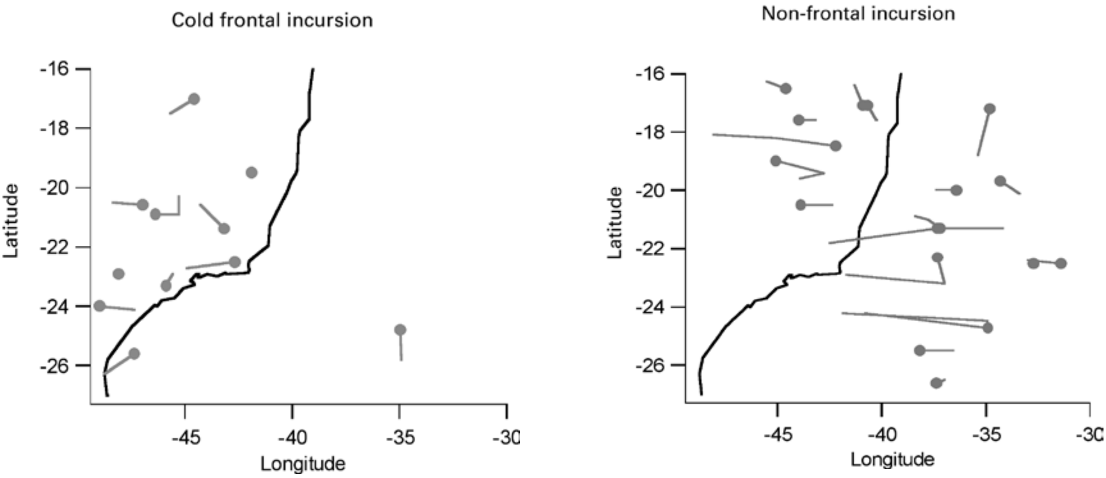


Fig. 9 **Mean daily 300 hPa component of the horizontal wind for day -1 to day +1 of occurrence of one cold frontal and one non-frontal incursion case over southeast Brazil in December 2000.**

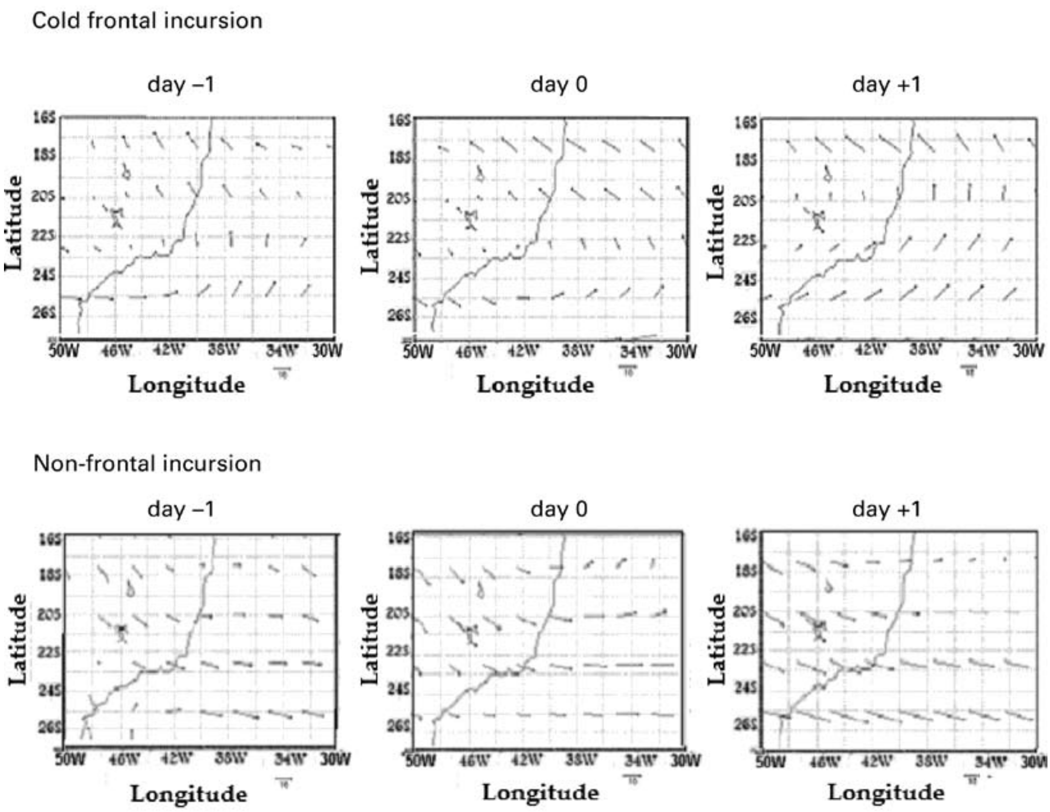
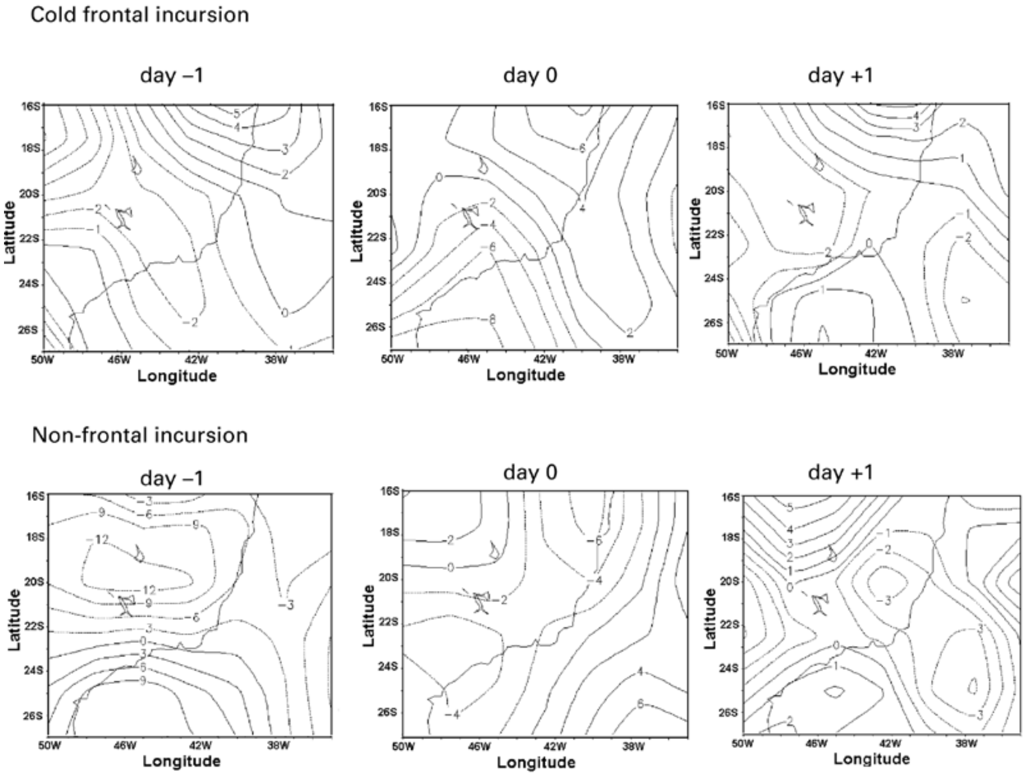


Fig. 10 Mean daily 850 hPa component of the horizontal divergence of the moisture flux for day -1 to day +1 of occurrence of one cold frontal and one non-frontal incursion case over southeast Brazil in December 2000.

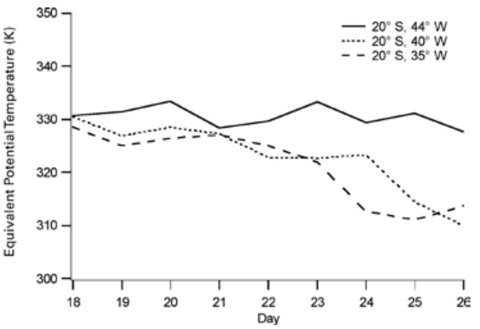


er between 18°S and 22°S than to the north and south (Fig. 1). The coastal topography tends to disorganise the convective activity of the frontal and non-frontal MCSs that move from continental areas towards oceanic areas of southeast Brazil, and hence its influence is most significant over continental and coastal areas, and oceanic areas closer to the coast. As the number of MCSs moving towards the oceanic areas was observed to be larger than the number of MCSs moving towards the continent, the coastal topography seems to be important for inhibiting deep convection related to cold frontal and non-frontal incursions over the above region relative to the rest of southeast Brazil.

The atmospheric instability conditions during the occurrence of the two cases described above have been investigated by computing the equivalent potential temperature and the instability index Total-Totals at one continental, one coastal, and one oceanic location in southeast Brazil, whose coordinates are: (20°S, 44°W), (20°S, 40°W), and (20°S, 35°W), respectively. The continental and oceanic locations were influenced by MCSs, but no MCS was present at the coastal location (Fig. 6). Figure 11 shows the mean daily 850 hPa component (24-hour data) of the equivalent potential temperature at these three locations during the days 18 to 26 of December 2000. The equivalent potential temperature was significantly higher at the continental location, followed by the coastal and oceanic locations, which exhibited relatively similar temperature values for the majority of the time. These distributions were very similar to the distributions of the index Total-Totals (not shown), and they indicate stronger convective instabilities at the continental location and smaller convective instabilities at the coastal location and the oceanic locations closer to the coast. As a result, deep convection was stimulated and consequently the MCSs were numerous over continental southeast Brazil, while deep convection was reduced and the MCSs were rare over coastal and oceanic southeast Brazil at latitudes around 20°S, as verified previously.

By examining the seasonal sea-surface temperature anomalies in December 2000 using the Climanalise monthly climate bulletin (Cavalcanti et al. 2000), we found positive anomalies of between 0.5 and 1°C over the South Atlantic. As a consequence, the sea-surface temperature anomalies apparently do not contribute significantly to the inhibition of deep convection inside the area 30°W to 40°W and 18°S to 22°S; neither do the South Atlantic subtropical high and the coastal resurgence phenomenon, which are

Fig. 11 Mean daily 850 hPa component of the equivalent potential temperature at three different locations in southeast Brazil during the days 18 to 26 December 2000.



located to the south of this region (23°S). The coastal resurgence, which is a process in which cold, often nutrient-rich waters from the ocean depths rise to the surface, may offer some minor contribution to reducing convection over the coastal areas of the above region, since it is usually characterised by high evaporation rates and small rainfall rates in the subtropics between September and March.

Summary and conclusions

Data from ISCCP DX and NCEP were used to study the occurrence frequencies and trajectories of MCSs over southeast Brazil over a three-year period. A seasonal climatology for MCS events related to cold frontal and non-frontal incursions over continental, coastal, and oceanic southeast Brazil was built by applying latitude-time diagrams and a cloud tracking method to the ISCCP DX data.

The occurrence frequencies of MCSs were large over continental, coastal, and oceanic southeast Brazil during austral autumn, spring, and especially summer, indicating an important modulation of deep convection by the frequent cold frontal incursions throughout the year and the diurnal forcing (thermal and/or orographic). Large seasonal and spatial variations (continent/ocean/coast) in the frequencies of MCSs were found over southeast Brazil, and they were associated with the seasonal climatology of convection over South America and land-sea heating contrasts.

The trajectories of the MCSs showed systems moving predominantly from continental towards oceanic southeast Brazil, modulated by cold fronts and circulation forcing associated with temperature contrasts and atmospheric large-scale stratification. A smaller but significant number of MCSs was found moving from oceanic towards continental southeast Brazil, apparently modulated by thermodynamic influences over the studied region (sea-breeze circulations). The spatial distribution of MCSs over southeast Brazil revealed numerous MCSs over Rio de Janeiro (RJ) State, Minas Gerais (MG) State, and central and eastern Sao Paulo (SP) State, and few MCSs over Espirito Santo (ES) State, southern Bahia (BA) State, and adjacent oceanic areas.

By describing the most important circulation patterns in southeast Brazil associated with one cold frontal incursion and one non-frontal incursion case, we have noted that the predominantly zonal circulation above 500 hPa favored the zonal movement of the majority of the MCSs discussed previously. This is because the dynamical influence is stronger than the thermodynamical influence over the studied region. An important role of the moisture divergence (weak moisture convergence), along with the coastal topography of southeast Brazil, in inhibiting deep convection in mesoscales over Espirito Santo (ES) State, southern Bahia (BA) State, and adjacent oceanic areas was observed, apparently reducing convective instabilities and explaining the lack of MCSs over these regions. The sea-surface temperature anomalies apparently do not contribute significantly to inhibiting deep convection inside this region, along with the South Atlantic subtropical high and costal resurgence phenomena, which are located south of the region (23°S). This topic deserves further study.

The use of ISCCP DX data allowed us to examine the time, trajectory, and spatial distributions of a wide variety of MCSs over southeast Brazil related to cold frontal and non-frontal incursions. In addition to knowing the different frequencies of the convective processes associated with these meteorological systems over southeast Brazil throughout the year, the knowledge about the structural characteristics of different events including types of clouds and rainfall rates is also extremely important for weather forecast centres, civil defence institutions, and oil companies at these important oil production regions in Brazil. We hope to address some of these topics in future work.

Acknowledgments

The authors gratefully acknowledge the support of Centro de Ciencia e Tecnologia of the Universidade Estadual do Norte Fluminense Darcy Ribeiro (CCT/UENF, Brazil). This study was also supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) Grant 473760/2006-1 and by Fundacao de Apoio a Pesquisa do Estado do Rio de Janeiro (Faperj) Grant E26/170875/2006. We also thank NASA Goddard Institute for Space Studies (GISS/NASA) for making the datasets available.

References

Cavalcanti, I.F.A., Melo, A.B.C. and Castro, C. 2000. Boletim de monitoramento e análise climática. *Climanalise, 15*, 46 pp.

Houze, R.A. 1993. *Cloud dynamics*. Academic Press, 573 pp.

Houze, R.A. 2004. Mesoscale convective systems. *Rev. Geophys., 42,* 1-43.

Jorgensen, D.P. and Weckwerth, T.M. 2003. Forcing and Organization of Convective Systems. *Met. Monogr., 30*, 75-103.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D. 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Met. Soc., 77,* 437-71.

Machado, L.A.T. and Rossow, W.B. 1993. Structural characteristics and radiative properties of tropical cloud clusters. *Mon. Weath. Rev., 121,* 3234-60.

Machado, L.A.T., Rossow, W.B., Guedes, R.L. and Walker, A.W. 1998. Life cycle variations of mesoscale convective systems over the Americas. *Mon. Weath. Rev., 126*, 1630-54.

Maddox, R.A. 1983. Large-scale meteorological conditions associated with midlatitude, mesoscale convective complexes. *Mon. Weath. Rev., 111,* 1475-93.

Mapes, B.E., Warner, T.T. and Xu, M.U. 2003. Diurnal patterns of rainfall in northwestern South America. Part III: Diurnal gravity waves and nocturnal convection offshore. *Mon. Weath. Rev., 131,* 830-44.

Marengo, J.A., Soares, W.R., Saulo, C. and Nicolini, M. 2004. Climatology of the low-level jet east of the Andes as derived from the NCEP-NCAR reanalyses: characteristics and temporal variability. *Jnl climate, 17,* 2261–80.

Morales, C., Machado, L.A.T. and Laurent, H. 2002. Preliminary results of 3D rainfall structure characteristics of the MCS observed in the Amazon during the LBA field campaign. Preprints, *Twelfth Congresso Brasileiro de Meteorologia,* Foz do Iguaçu, Brazil, Soc. Bras. de Meteor., 3287-305.

Nesbitt, S.W., Zipser, E.J. and Cecil, D.J. 2000. A census of precipitation features in the tropics using TRMM: Radar, ice scattering, and lightning observations. *Jnl climate, 13,* 4087-106.

Nicolini, M., Salio, P., Torres, J.C. and Zipser, E. J. 2004. The relationship between South American low level jet events with the formation and maintenance of mesoscale convective systems. *14th Int. Conf. on Clouds and Precipitation,* Bologna, Italy, IAMAS/ International Commission on Clouds and Precipitation, 13–6.

Orlanski, I. 1975. A rational subdivision of scales for atmospheric processes. *Bull. Am. Met. Soc., 56*, 527-30.

Rossow, W.B. and Schiffer, R.A. 1999. Advances in understanding clouds from ISCCP. *Bull. Am. Met. Soc., 80*, 2261-88.

Satyamurty, P., Nobre, C.A. and Silva Dias, P.L. 1998. South America. *Met. Monogr., 27*, 119-39.

Siqueira, J.R., and Machado, L.A.T. 2004. Influence of the frontal systems on the day-to-day convection variability over South America. *Jnl Climate, 17,* 1754-66.

Siqueira, J.R., Rossow, W.B., Machado, L.A.T. and Pearl, C. 2005. Structural characteristics of convective systems over South America related to cold frontal incursions. *Mon. Weath. Rev., 133,* 1045-64.

Thurai, M. and Iguchi, T. 2000. Rain height information from TRMM precipitation radar. *Electronic Lett., 36,* 1059-61.

Velasco, I. and Fritsch, J.M. 1987. Mesoscale convective complexes in the Americas. *J. Geophys. Res., 92,* 9591-613.

Zipser, E. J. 1977. Mesoscale and convective-scale downdrafts as distinct components of squall-line circulation. *Mon. Weath. Rev., 105*, 1568-89.