Mesoscale and Synoptic Environment in Three Orographically Enhanced Rain Events on the Coast of Santa Catarina (Brazil)

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(Manuscript received 6 January 2015, in final form 10 February 2016)

ABSTRACT

In this study three cases of extreme rainfall events are analyzed in Florianópolis, Santa Catarina (SC), on Brazil's coast, lying between the mountains and the South Atlantic Ocean in southeastern South America. The largest rainfall totals, 200–300 mm in 12–24 h, resulted in flash floods. ECMWF 6-hourly 1.5° × 1.5° data were used to determine the synoptic fields and quasigeostrophic forcing, along with observational data from local networks, for subsynoptic analyses. In case C1, during May 2010, there was a frontal passage. In C2 and C3 (January 2008 and February 1979, respectively) the coastline separated a ridge over the continent from a trough over the sea at the surface, with an atmosphere of low baroclinicity predominating at 500 hPa. All three events were characterized by postfrontal conditions; the presence of an anticyclone over the sea, centered at 35°–40°S; and slow-moving or quasi-stationary midlevel cyclones over the continent, at 27°S. The circulation generated in the cyclone resulted in strong (10 m s−1) and persistent low-level east-northeast winds along the coast of SC, favoring the influx of heat and humidity on days with heavy rain. The upward motion at 850 hPa was concentrated over the affected areas and stronger than that at 500 hPa. Even so, the moist air that reached the mountain in a conditionally unstable environment rose only to middle levels. The features presented were similar to those observed for orographic rain events in Europe and the United States.

1. Introduction

Cases of floods and landslides related to heavy rainfall are enhanced on the coast of Santa Catarina (SC), in southern Brazil (Fig. 1), as a result of the relief, hydrology, soil, and vegetation characteristics (Herrmann 2007). Some of these events are associated with severe impacts and loss of life (e.g., Herrmann 2007; Lima et al. 2009), as in March 1974, December 1995 (Haas 2002), and November 2008 (Silva Dias 2009), which resulted in the largest flood in the state. These few works suggest orographically enhanced rain was a factor. A brief account found in Lima et al. (2009) is presented below.

From 21 to 26 March 1974 in Tubarão, along the southern coast of SC, the total rainfall was 290.2 mm. The river that runs through the city reached a level of 10.22 m above normal, causing 46 deaths and left 85% of the population homeless. In the episode of 23–25 December 1995 about 50 cities were affected, with 24000 left homeless and 30 deaths. In Florianópolis, on the central coast of SC, 372.4 mm of rain were recorded during 48 h. The landslides over large areas, during 22–24 November 2008, affected several cities in the northern state, with large numbers of victims: 126 deaths and 78 000 homeless. Rain totals of 495.2 mm were registered in 48 h around Blumenau city.

Events like these have been well studied throughout areas in Europe, Asia, and the United States (Doswell et al. 1998; Ramis et al. 1998; Pontrelli et al. 1999; Bousquet and Smull 2003; Lin et al. 2001). But no detailed studies highlighting the importance of topography in episodes of heavy rain were found in the literature for the coast of South America. The present work fills this gap.

Within this framework, the objective of this study was to identify the synoptic–dynamic environment where these events developed along with the subsynoptic aspects that result in more intense rain across the SC coast. In the middle latitudes, the ingredients for high rainfall rates are favored at the synoptic scale, which provides the development and maintenance of environmental
instability, and also at the mesoscale, which provides the conditions for the rapid lifting of moist air (Maddox et al. 1979; Doswell et al. 1996).

The coastal plain of the state of SC is located between the latitudes of approximately 26° and 29°S, along the 561.4-km-long coast, with elevations of less than 300 m, lying close to large areas of mountains. The Serra do Mar, with altitudes between 600 and 800 m, is to the north of the plain, while in the south of the state there are the slopes of the Serra Geral with altitudes of around 1000 m. In the metropolitan region of Florianópolis (MRF), located on the central coast of SC (Fig. 1), Herrmann (2007) separated 204 flood cases that happened between 1980 and 2004 into gradual (132) or abrupt (72) occurrences. Herrmann also found that in the mountain areas, landslides associated with intense rain were highly frequent.

Seluchi and Chou (2009) produced a synoptic climatology of heavy rainfall episodes that can cause landslides in southeastern coastal Brazil, in the area around 24°S. These rainfall episodes were mostly related to cold front passages and the South Atlantic convergence zone (SACZ). However, despite frequent frontal passages that occur along the coast of SC at an average interval of 8 days (Rodrigues et al. 2004), and the predominance of extratropical cyclones in the south of Brazil (Gan and Rao 1991; Reboita et al. 2009), these are not necessarily the main weather systems associated with heavy rains in the region. In cases of heavy rainfall in MRF (Fig. 1), Rodrigues et al. (2011) found a persistent low-level circulation pattern directed approximately perpendicular to the coast of SC. The easterly wind is associated with an anticyclone in the South Atlantic, moving slowly behind a front, or staying near the coast over a prolonged period of more than 3 days. In these events, more frequent in the summer months, the high daily totals of precipitation, exceeding 100 mm, generally occurred within 1 or 2 days, with the presence of closed cyclones in short-wave disturbances in the upper atmosphere. Haas (2002) used numerical modeling to study an orographically enhanced rain event in MRF and along the south coast of SC in December 1995, in which the easterly wind helped by transporting moisture from the sea to the mainland.

As a common factor present in cases of heavy orographic precipitation in different mountainous regions of the United States (Maddox et al. 1978; Pontrelli et al. 1999), Europe (Doswell et al. 1998), and Asia, Lin et al. (2001) mention a low-level wind flow of more than 10 m s⁻¹ [low-level jet (LLJ)] impinging perpendicular to the mountains. According to the authors, this flow transports moist air to the affected area, which, in the presence of the mountain, is forced to ascend to its level of free convection, triggering the conditional instability.

In this work, three episodes of rainfall along the SC coast are analyzed: February 1979, January 2008, and May 2010. In all cases, the more intense daily rainfall was 200–250 mm in the MRF, where the greatest impacts were recorded. During May 2010, the 1-day total of 253.0 mm was the second highest on record for the time series data between 1969 and 2010. Across the central coast of SC, the peak seasonal rainfall occurs in the austral summer, with monthly totals of around 250 mm (Grimm et al. 1998). In January 2008 and May 2010, there were floods in MRF, and many houses were
inundated by the water. Landslides also occurred in May 2010 and the major highways were closed. No information is available on the damages associated with the case of February 1979. It is hoped that this work may provide guidance to forecasters about the identification of an atmospheric pattern of these events and to future research efforts performed with numerical modeling. Various studies of flash floods, performed for the mountainous regions of the United States (e.g., Maddox et al. 1978; Maddox et al. 1979; Pontrelli et al. 1999) and Europe (Doswell et al. 1998; Ramis et al. 1998; Romero et al. 2000; Bousquet and Smull 2003), considered the importance of a detailed investigation of the synoptic–dynamic fields and observational data from the local network (subsynoptic scale), to supplement the research with the use of modeling techniques.

2. Data and methodology

The mesoscale analysis was performed with observational data consisting of daily and hourly values of precipitation, wind, and temperature from surface stations belonging to the Agricultural Research Corporation of Santa Catarina [Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI)], the National Institute of Meteorology [Instituto Nacional de Meteorología (INMET)], the Brazilian National Water Agency [Agência Nacional de Águas (ANA)], and the Meteorological Network of the Aeronautical Command [Rede de Meteorologia do Comando da Aeronáutica (REDEMET); www.redemet.aer.mil.br]. The north coast of SC, extending from MRF (Fig. 1) toward the north, was regarded as LN (from the Portuguese litoral norte), and the south coast of SC, extending from MRF toward opposite direction, as the LS (litoral sul).

The upper-air data were obtained from radiosonde stations located at airports (Florianópolis and Curitiba) operated by REDEMET and made available by the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). The satellite images from GOES-10 and GOES-12 [National Oceanic and Atmospheric Administration (NOAA)] were obtained from the National Institute for Space Research [Instituto Nacional de Pesquisas Espaciais (INPE); satelite.cptec.inpe.br]. For case C3, from 1979, hourly data and radiosonde and satellite images are not available.

For the synoptic-scale diagnostics, atmospheric fields were obtained from the European Centre for Medium-Range Weather Forecasts’ (ECMWF) ERA-Interim reanalysis, on a 1.5° × 1.5° horizontal grid at 0000, 0600, 1200, and 1800 UTC. The fields of geopotential height, temperature, and wind, from low to high levels, and sea level pressure (SLP) were analyzed from the beginning of the period of the activity of high pressure off the coast of SC until 12 h after the recording of heavy rain. The other fields were analyzed every 6 h, starting 24 h before the beginning of the heavy rain.

The vertical motion was analyzed by use of ω at 850 and 500 hPa, obtained directly from the reanalyses (Dee et al. 2011). The ECMWF atmospheric model uses a hydrostatic dynamical core, and omega is estimated using the continuity equation.

Also determined from the reanalysis were the fields of convergence of specific humidity at 850 and 700 hPa, temperature advection at 850 hPa, and advection of relative vorticity at 500 hPa. The moisture divergence on the 850-hPa surface was obtained from the continuity equation for the water vapor, where q is the specific humidity and v is the horizontal wind, calculated as ∇ · (qv).

The vertical forcings from quasigeostrophic theory (Holton 2004) have been used in studies of orographically intensified rain (Doswell et al. 1998; Ramis et al. 1998) as good indicators in the middle latitudes for determining large-scale areas favorable to the development of precipitation. The low-level moisture convergence is considered important in the identification of subsynoptic areas of rapid ascent of moist air, which are favorable to heavy rain (Doswell et al. 1996, 1998). Teixeira and Satyamurty (2007) analyzed such parameters, with good results, in a study that identifies the synoptic–dynamic patterns in cases of heavy rainfall in southern Brazil.

Using reanalysis fields and/or radiosonde data from MRF, we also analyzed information on specific humidity q; relative humidity (RH); vertical stability, due to variations in potential temperature θ; equivalent potential temperature θ_e; and values of convective available potential energy (CAPE).

3. Mesoscale synoptic–dynamic environment

a. Case C1: May 2010

Of the 1-day precipitation total of 253.0 mm in MRF at 1200 UTC 19 May 2010 (Table 1; C1), 189.6 mm of rain was recorded during the 12 h between 0000 and 1200 UTC 19 May 2010 (Fig. 2), with a rate of nearly 50 mm h⁻¹ between 0300 and 0400 UTC.

The fields in Fig. 3 are presented for two different times: at the start of the heavy rain and 12 h earlier. In the geopotential height and temperature fields at 500 hPa at 1200 UTC 18 May 2010 (Fig. 3a) and at 0000 UTC 19 May 2010 (Fig. 3b), there was a cold-core cutoff low over the mainland at 27°F. The trough into which the cyclone became absorbed lost its northwest–southeast tilt, undergoing a slow zonal displacement, with decreased values of relative vorticity advection at 500 hPa. The upper low favored the development of a cyclone in the...
low levels, around 25°S, 58°W (Figs. 3c,d), that moved south-southeastward over southern Brazil, accompanied by a cold front, while an anticyclone moved out to sea along a zonal trajectory (35°–40°S). The entry of warm air at 850 hPa is observed over the SC coastal area and the temperature reached 12°–14°C at 0000 UTC 19 May (Fig. 3d). In the satellite image of 1200 UTC 18 May (Fig. 3e), cloudiness is associated with the cold front. An area of cloudiness is seen to the east-southeast of the cyclone and the subsidence at its center, south of Paraguay. At 0000 UTC 19 May (Fig. 3f), the cloudiness decreased over the interior of SC, and it was concentrated to the south of SC.

At 1200 UTC 18 May, just offshore of SC, the winds at 10 m were easterly with speeds between 8 and 10 m s\(^{-1}\) (Fig. 4a). At 0000 UTC 19 May, at the start of the heavy rain and the frontal passage along the coast, this flow became predominantly northeasterly with greater speed (12 m s\(^{-1}\)) (Fig. 4b), as a result of the intensification of the pressure gradient over the region. At 850 hPa a northeasterly flow prevailed just off the coast that was much stronger at 0000 UTC 19 May (10–12 m s\(^{-1}\)), as seen in the wind fields of Figs. 4c and 4d.

In the fields of specific humidity (Figs. 4c,d) and thermal advection (Figs. 5a,b) at 850 hPa, the entry of more warm, moist air over the coastal area and the nearby sea can be seen, starting at 1200 UTC 18 May and more prominently at 0000 UTC 19 May, when the specific humidity reached about 10 g kg\(^{-1}\). Concentrated values of upward motion at 850 hPa were also observed over the LN at 1200 UTC 18 May (Fig. 5e). The diagnostical fields in Fig. 5 gave a good indication of the motion and behavior of the atmospheric systems in SC. The presence of the cold front and cyclone in western SC was indicated by the extensive area of moisture.

### Table 1. The 24-h (1200–1200 UTC) precipitation totals (mm) from municipalities along LN and LS of SC. MRF (larger total, bold), I1, and I2 are along the central coast. The rightmost column is a straight-line distance from MRF to the municipality specified.

<table>
<thead>
<tr>
<th>Municipalities</th>
<th>19 May 2010 (C1)</th>
<th>31 Jan and 1 Feb 2008 (C2)</th>
<th>24 Feb 1979 (C3)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN Itapevi</td>
<td>0.0</td>
<td>55.2</td>
<td>110.2</td>
<td>165</td>
</tr>
<tr>
<td>LN Joinville</td>
<td>22.5</td>
<td>57.2</td>
<td>50.6</td>
<td>145</td>
</tr>
<tr>
<td>LN Araraquari</td>
<td>0.0</td>
<td>0.8</td>
<td>20.5</td>
<td>135</td>
</tr>
<tr>
<td>LN Piçarras</td>
<td>—</td>
<td>18.7</td>
<td>137.3</td>
<td>95</td>
</tr>
<tr>
<td>LN Itajaí</td>
<td>55.5</td>
<td>60.0</td>
<td>68.9</td>
<td>75</td>
</tr>
<tr>
<td>LN C. Ramos</td>
<td>83.9</td>
<td>110.9</td>
<td>140.8</td>
<td>30</td>
</tr>
<tr>
<td><strong>MRF</strong></td>
<td><strong>253.0</strong></td>
<td><strong>136.9</strong></td>
<td><strong>216.4</strong></td>
<td>—</td>
</tr>
<tr>
<td>I1</td>
<td>136.2</td>
<td>112.2</td>
<td>179.8</td>
<td>—</td>
</tr>
<tr>
<td>I2</td>
<td>88.5</td>
<td>115.6</td>
<td>212.8</td>
<td>—</td>
</tr>
<tr>
<td>LS P. Lopes</td>
<td>284.5</td>
<td>17.54</td>
<td>176.4</td>
<td>40</td>
</tr>
<tr>
<td>LS Imbituba</td>
<td>101.3</td>
<td>20.6</td>
<td>167.5</td>
<td>70</td>
</tr>
<tr>
<td>LS Jaguaruna</td>
<td>32.6</td>
<td>25.2</td>
<td>33.4</td>
<td>122</td>
</tr>
<tr>
<td>LS Urussanga</td>
<td>21.1</td>
<td>11.9</td>
<td>69.9</td>
<td>125</td>
</tr>
<tr>
<td>LS S. Bento</td>
<td>32.8</td>
<td>7.6</td>
<td>43.2</td>
<td>170</td>
</tr>
<tr>
<td>LS Timbê</td>
<td>22.4</td>
<td>36.1</td>
<td>66.0</td>
<td>185</td>
</tr>
</tbody>
</table>

**Fig. 2.** Hourly precipitation (mm) from 1200 UTC 18 May to 1200 UTC 19 May 2010, in MRF, on the coast of SC (Source: observational data INMet).
FIG. 3. Fields from ECMWF at (a),(b) 500 and (c),(d) 850 hPa, and (e),(f) satellite images (with yellow indicating temperatures between $-40^\circ$ and $-50^\circ$C) from GOES-12 at 1200 UTC 18 May and 0000 UTC 19 May 2010. Shown are the geopotential height (solid lines; contour interval is 30 gpm) and temperature (dotted lines; contour interval is $3^\circ$C) in (a)–(d) and advection of negative relative vorticity ($\times 10^{-9} \text{s}^{-1}$; shaded with contour interval of 1, starting at $-1$) in (a) and (b).
convergence at 850 hPa (Fig. 5c) and ascending motion between the low (Fig. 5e) and middle levels (figure not shown). Twelve hours later, warm advection (Fig. 5b), moisture convergence (Fig. 5d), and $\omega$ of $-1.2 \text{ Pa s}^{-1}$ (Fig. 5f) were recorded at 850 hPa, in a concentrated area between MRF and the LS. The highest values of CAPE in the reanalysis fields (300–600 J kg$^{-1}$; figures not shown), also moved from the interior of the state to the coast.

Table 1 shows that rainfall occurred in various municipalities throughout coastal SC, with higher amounts (>100 mm day$^{-1}$) between MRF and 100 km to the south (Imbituba). In other municipalities, the daily totals were between 20 and 50 mm.

b. Case C2: January 2008

Rainfall totaling 353.3 mm in MRF (136.9 + 216.4 mm; C2 in Table 1) was measured in 24 h (0000 UTC 31 January–0000 UTC 1 February) (Fig. 6). Heavy rain began around 1200 UTC 31 January and persisted until 2200 UTC, with hourly totals of 10–20 mm and two extreme peaks (>30 mm h$^{-1}$) at 1200 and 2100 UTC.

At 1200 UTC 30 January, 24 h before the start of the heavy rain, a cutoff low at 500 hPa (Fig. 7a) positioned itself over southern Brazil. While extending northeast–southwest along the coast of Brazil, the upper low moved toward SC at 1200 UTC 31 January (Fig. 7b), remaining a dipole with the postfrontal anticyclone positioned along the coast of Argentina between 35° and 40°S. The temperature remained around $-9^\circ$C on the coast of SC, at 1200 UTC on 30 and 31 January (Figs. 7a,b), when an atmosphere of low baroclinicity predominated throughout southern Brazil. The relative vorticity advection field at 500 hPa, with values close to zero, indicated the weak motion of the cyclone, which extended only up to 700 hPa (figure not shown). In the east-southeast...
FIG. 5. Fields from ECMWF at 850 hPa at 1200 UTC 18 May and 0000 UTC 19 May 2010: (a),(b) temperature advection ($\times 10^{-4}$ K s$^{-1}$; interval of 0.2 starting at 0.2), (c),(d) moisture divergence ($\times 10^{-7}$ s$^{-1}$; interval of 1, starting at 1), and (e),(f) geopotential height (interval is 20 gpm) and negative $\omega$ (interval of 0.2 Pa s$^{-1}$, starting at $-0.2$).
portion of the region, low cloudiness predominated (Figs. 7e,f), with a core of deeper cloudiness over coastal SC. On 30 and 31 January, an extensive low pressure area at 850 hPa prevailed in south-central Brazil (Figs. 7c,d), with a pronounced trough over the continent, toward the interior of SC (56°W), and another trough over the sea, at 24°S, 42°W. The low-level circulation favored the transport of warm air toward the LN and MRF at 1200 UTC 31 January (Fig. 7d). These conditions were not observed at 1200 UTC 30 January (Figs. 7c), when the input of warm air was directed mainly toward the trough over the sea, at 24°S. In the SLP fields in Figs. 8a and 8b, the coast of SC lay between the high over the continent and the trough over the sea. The wind at 10 m and at 850 hPa remained easterly offshore of SC, and its speed increased from 6–8 m s\(^{-1}\) on 30 January (Figs. 8a,c) to 8–10 m s\(^{-1}\) on 31 January (Figs. 8b,d), as a result of the intensification of the southward-moving cyclone over the sea. The low-level circulation also favored the transport of humid air toward the LN and MRF at 1200 UTC 31 January (Fig. 8d). Warm advection was observed along the coast of SC at 0600 UTC (figure not shown) and 1200 UTC (Fig. 9a) on 31 January, close to the time of onset of heavy rain. On this day, there was concentrated upward motion at 850 hPa in MRF and the LN, where the rainfall was higher with daily totals over 100 mm (Table 1). Between 0000 and 0600 UTC (figures not shown), the values of \(\omega\) began to increase, reaching \(-0.6\) Pa s\(^{-1}\) at the times of peak rainfall [1200 (Fig. 9c) and 1800 UTC (Figs. 9c, Table 1)]. Between 0000 and 0600 UTC (figures not shown), the values of \(\omega\) began to increase, reaching \(-0.6\) Pa s\(^{-1}\) at the times of peak rainfall [1200 (Fig. 9c) and 1800 UTC (Figs. 9c, Table 1)]. Both values, however, were twice as high across the LS, east of the low pressure areas, where the total precipitation was less than 100 mm day\(^{-1}\) (Table 1). The core of highest CAPE from the reanalysis, 600 J kg\(^{-1}\), appeared over the LN (figure not shown).

In case C2, the persistence of easterly winds at low levels occurred following the intensification of a cyclone over the sea (24°S), as part of a dipole with an anticyclone to the south. This environment showed similarities to the cases of subtropical cyclones that developed in this same area over the coast of Brazil, as studied by Gozzo et al. (2014). They found that the South Atlantic subtropical high (SASH) winds transport humidity to the south and southeast Brazilian coastlines. According to this study, after the occurrence of rain in SC, in this case C2, the cyclone over the Brazil coast, near 24°S, developed subtropical characteristics. It is possible that some of the conditions conducive to the occurrence of heavy rainfall along the SC coast could also be favorable for the formation of the hybrid systems.

c. Case C3: February 1979

In case C3 190.3 mm of rain was recorded for the 24-h period ending at 1200 UTC 24 February 1979 (Table 1). Of this total, 81 mm fell in 6 h (1800 UTC 23 February–0000 UTC 24 February) and 98.9 mm over in the following 12 h (0000–1200 UTC 24 February). The heavy rain, therefore, began after 1800 UTC 23 February. The cold core of the 500-hPa cutoff at 27°S on 22 and 23 February can be observed in the fields of geopotential height and temperature in Figs. 10a and 10b. The trough axis became positioned almost meridionally during these days, with the center of the cyclone shifting slightly to the southeast on 23 February. Advection of cyclonic relative vorticity at middle levels, of \(-2 \times 10^{-10}\) s\(^{-2}\), can be seen to the southeast of the cyclone on 22 February (Fig. 10a). At 850 mb, on 22 and 23 February (Figs. 10c,d), the zonally moving center of high pressure intensified over the sea. Casarin and Kousky (1986) identified a case of blocking in the austral summer of 1979, when southern Brazil was affected by a long dry period.
Beginning 1800 UTC 23 February, the approximate time of the onset of the heavy rain, the temperature at low levels (14°C–16°C) increased relative to those of 22 February (Figs. 10c,d) over the coast of SC and the nearby sea. At 500 hPa, the temperature remained around −6°C in this area during the two days (Figs. 10a,b). The LN of SC separated a ridge over the continent from a trough over the sea (as in case C2) between 22
and 23 February, and the winds in the region between the surface and low levels turned from east to northeast during these days, while strengthening (Fig. 11). At 0000 UTC 24 February, in the area offshore of MRF, the wind at 10 m from the northeast, remained steady at around 8 ms\(^{-1}\) (Fig. 11b) and, at 850 hPa, reached 10 ms\(^{-1}\) (Fig. 11d), contributing to the transport of moist and warmer air along the SC coast. Also starting at 1800 UTC 23 February (figure not shown), the values of specific humidity increased, reaching 12–14 g kg\(^{-1}\) over all of coastal SC, as can be seen in Fig. 11d (0000 UTC 24 February).

At 1200 UTC 23 February, warm advection at 850 hPa (Fig. 12a) was observed over the coast of SC and an extensive adjacent area offshore, with higher values over MRF and the LN, where the vertical motion showed concentrated ascent at this level (Fig. 12b). In spite of the smaller amount of observational data for C3 (Table 1), it can be discerned that rainfall totals above 50 mm occurred across the LN and in MRF, reaching above 100 mm in municipalities 100 km from MRF, toward the LN as well as the LS, where the CAPE from the reanalysis showed a value of 300 J kg\(^{-1}\) (figure not shown). While at 850 hPa the moisture divergence predominated along the coast of SC (Fig. 12c), convergence was identified at 700 hPa (Fig. 12d). The midlevel upward motion was not observed over the SC (Fig. 13a), far from the activity of the cyclone at this level.

A persistent northerly flow had been directed toward the coast of SC at 500 hPa (Fig. 13a), and at 700 hPa too (Fig. 12d), favoring the warming throughout the layer. This flow reached its maximum at 500 hPa (10 ms\(^{-1}\)) at 0000 UTC 24 February (Fig. 13a). At this time, from the radiosonde at the Curitiba airport in Paraná State (Fig. 13b), located around 200 km to the north of MRF (Fig. 1), a strong flow from the north can be seen between the 700- and 300-hPa levels, with a speed of 11 ms\(^{-1}\) (20 kt) at 500 hPa.

FIG. 8. As in Fig. 4, but at 1200 UTC 30 Jan and 31 Jan 2008. The specific humidity starts at 12 g kg\(^{-1}\); isotachs are shown with contour intervals of 2 m s\(^{-1}\).
d. Similarities and differences among the events

Among the synoptic characteristics common to the three events were 1) postfrontal conditions in southern Brazil; 2) stronger and more persistent winds predominantly from the east-northeast on the SC coast near the surface and at low levels, favored by the presence of a anticyclone over the South Atlantic with a center at 35°–40°S; and 3) closed cyclones in the middle levels over the continent with centers at 27°S, embedded in semistationary or slow-moving short-wave troughs.

The case of C1 in the austral autumn was differentiated from the rest by the cold front and cyclogenesis at the surface. The enhanced values in the diagnostic fields of warm advection and moisture convergence at 850 hPa, as well as the ascending motion of air between the low and middle troposphere, were good indications of the movement of the rain-producing atmospheric systems.

The presence of a ridge in eastern SC and a trough on the coast was observed in the austral summer cases of C2 and C3. In a study of orographic rain in the western Mediterranean, Ramis et al. (1998) identified a mesoscale front at the surface separating a mesohigh over the continent and a mesolow over the sea, with heating over the whole column from the surface to the upper levels.

The parameter that best indicated a synoptic environment favorable for the development of precipitation on the SC coast, in both cases C2 and C3, was the vertical motion of the air at 850hPa in association with the temperature advection. The large values of $\omega$ at this level became concentrated between the LN and MRF, the region with precipitation that was most enhanced in comparison with the LS, with the largest input of heat and moisture at times closest to the heavy rain. Another characteristic that distinguished the two cases was the
environment of low baroclinicity and the irregularity of the values of the moisture divergence at 850 hPa.

In the three events, the flow in the lower troposphere contributed to the transport of moisture and heat to the coast on the day of heavy rain. According to Teixeira and Satyamurty (2007), the convergence of the low-level moisture flux, directed toward southern Brazil during heavy rain events, shifts from the continental area to the coastal area of SC in the summer months.

In 2008 (C2), the low-level easterly flow came from the vicinity of a cyclone that intensified over the South Atlantic Ocean near the Brazilian coast at 24°S, in a zone identified by Reboita et al. (2009) as being of less intense cyclone development. In C1 and C3, the flow from the northeast originated over a warmer and moister area in the lower latitudes. The SASH extending from low to high levels predominated close to the coast of Brazil, with its northeast edge penetrating into the continent to latitudes below 22°S. In C3, the flow at 500 hPa played an important role in favoring the heating at this level over the SC coast on the day of the heavy rain. The study by Gozzo et al. (2014) showed the important role of SASH transporting moisture to the south and southeast Brazilian coastal areas.

The values of temperature and specific humidity obtained from the radiosondes at MRF stayed very close to the values found in the reanalyses. In general in the three events, the characteristics observed in the fields of wind, temperature, and moisture, as well as in the principal diagnostic fields, at the times of heavy rain can be summarized as follows:

- The wind near the surface, approximately from the east on the SC coast and adjacent ocean, increased with velocities between 8 and 10 m s\(^{-1}\). At 850 hPa, the wind along the coast, between the east (C2) and

![Image](500px-geop_T_advR_18Z22FEB1979.png)

![Image](500px-geop_T_advR_18Z23FEB1979.png)

![Image](850px-geop_T_18Z22FEB1979.png)

![Image](850px-geop_T_18Z23FEB1979.png)

**FIG. 10.** As in Figs. 3a–d, but for 1800 UTC 22 Feb and 1800 UTC 23 Feb 1979.
northeast (C1 and C3), was around 10 m s$^{-1}$ or greater. The flow at both levels had persisted since 12–24 h prior to the onset of the heavy rain.

- At 850 hPa, the arrival of heat and moisture from lower latitudes favored temperatures of around 14$^\circ$–16$^\circ$C over the coastal area and the nearby sea, as well as specific humidities of 10–12 g kg$^{-1}$.
- At 850 hPa, the maxima of warm advection (0.4–0.6 $\times$ 10$^{-4}$ K s$^{-1}$) and of upward motion (−0.3 Pa s$^{-1}$), over MRF, the LN and adjacent sea started between 6 and 12 h earlier.
- The value of $v$ at 500 hPa on the coast of SC was always smaller than that found at 850 hPa.

At 1200 UTC on 19 May 2010, 1 February 2008, and 24 February 1979 (figures not shown), when the end of the heavy rain was observed in the three cases analyzed, the centers of the midlevel cyclones remained positioned over the continent, where they had been for the previous 3 days. The flow directed toward the coast of SC between low and middle levels, nevertheless, differed from the pattern observed previously, when there was heavy rain, and it favored a decrease in the temperatures and a diminution in the values of the specific humidity.

4. Radiosondes and mesoscale analysis

From the MRF radiosondes at both times in case C1 (Fig. 14) and case C2 (Fig. 15), the value of precipitable water (PW) was around 45 mm. Humid air (RH > 80%) to approximately 400 hPa was observed, in an environment that remained statically stable ($\partial \theta / \partial z > 0$) throughout the layer, and conditionally or potentially unstable at low levels. This condition is associated with forced orographic ascent (Llasat et al. 1996).

Potential or convective instability ($\partial \theta / \partial z < 0$) was observed at low levels (1000–850 hPa) at 1200 UTC 18 May (C1 in Fig. 14a) and at both times in Fig. 15 (C2). At the time of heavy rain, 0000 UTC 19 May (C1 in Fig. 14b) and 1200 UTC 31 January (figure not shown for...
C2), potential or convective instability ($\frac{\delta \theta_e}{\delta z} < 0$) was observed in the layer between 850 and 500 hPa. During this time period, the radiosonde information indicates increased instability in MRF. For the case of C1 (Fig. 14), the CAPE increased from 1.05 to 42.6 J kg$^{-1}$, and the lifted index (LI) went from 4.5 to −0.64. The LI that remained around −0.3 for the case of C2 (Fig. 15) was more unstable (−2.44) at 1200 UTC 31 January (figure not shown), when the PW had increased to 53.8 mm. The CAPE is not available at this time, but increased from 41.5 to 114.5 J kg$^{-1}$ in the time prior to the soundings (Fig. 15).

At 1200 UTC 18 May (1200 UTC 30 January) the lifted condensation level (LCL) was observable at 974.5 hPa (922.8 hPa) and the level of free convection (LFC) was at 928.1 hPa (896.4 hPa), with a difference of only 46.4 hPa (26.4 hPa). Twelve hours later, at 0000 UTC 19 May (0000 UTC 31 Jan), the LCL rose to 958.65 hPa (fell to 963.5 hPa), the LFC is at 943.25 hPa (920.73 hPa), and the difference changed to 15.4 hPa (42.8 hPa). The LFCs of 943.25 and 920.73 hPa correspond to altitudes lower than 600 and 800 m, respectively, which are approximately the height of the mountains that surround MRF (Fig. 1). These conditions indicate a forced lifting due to the interaction of the mountains with the flux of water vapor transported to the affected area. The humid eastern/northeastern low-level winds reach this free convection favorable environment.

Low clouds during the heavy rainfall were verified in satellite images for both cases (C1 and C2) (Figs. 3f and 7f). The approach of the midlevel cyclone toward the coast in C1 (Fig. 3b) favored the occurrence of thunderstorms in MRF, which were recorded between 0000 and 0700 UTC 19 May (source: REDEMET), during the same period as the heavy rain (Fig. 2). In C2, the rain with thunder occurred across the municipalities of LN, between 1200 and 2000 UTC 31 January (source: REDEMET).
This was also the period of heavy rain at MRF (Fig. 6), but with no thunderstorms reported.

On 18 May (C1) at the Florianopolis airport, the surface temperature was about 17°–19°C \((T - T_d = 2°–3°C)\) and increased to 20°–22°C \((T - T_d \text{ decreased to } 1°–2°C)\) between 1900 UTC 18 May and 0700 UTC 19 May. At this same time the northeast local wind at the surface intensified, reaching 8.5–11 m s\(^{-1}\) near the airport between 2000 UTC 18 May and 0200 UTC 19 May, and 5–7 m s\(^{-1}\) in the MRF during the time of the heavy rain (0100–0600 UTC 19 May in Fig. 2). In C2, during the whole day (31 January), the temperature at the Florianopolis airport was 21°–22°C \((T - T_d = 0°C)\). At the same time as the heavy rain in MRF (1100–2100 UTC in Fig. 6), the southeast local wind at the surface intensified to 4.5–8.5 m s\(^{-1}\) at the airport (there was no wind speed information available at the MRF station).

In both cases (C1 and C2), municipalities at LN near the coast recorded temperatures similar to those at Florianopolis's airport. However, more continental and LS, temperatures were between 18° and 20°C, which indicates the presence of a warmer air mass between MRF and the LN coastal zone. The local winds also intensified at LN, but between 6 and 8.5 m s\(^{-1}\).
In the case of C2, the northwestern/southwestern local winds at the surface remained steady throughout the night until 0700 LST (1000 UTC) at the airport and the MRF station, possibly in association with the land breeze, which is quite characteristic of the region during the summer months (Franco et al. 2006). This condition may have contributed to promoting convergence of a local nature. Between 1100 and 2000 UTC the local wind shifted to the east/southeast at the airport, but remained westerly/south westerly around the MRF at 1100–1400 UTC (heavy rain).

Radiosonde results shown in Figs. 14 and 15 make it possible to observe stronger winds between 925 and 850 hPa at the time of the heavy rain and 12 h earlier. In the case of C1, the wind speed at 925 hPa at the time of the heavy rain (53 kt; 1 kt = 0.51 m s\(^{-1}\)) was greater than at 500 hPa (48 kt) (Fig. 14b). In the case of C2, between 12 and 24 h prior to the heavy rain, the wind speed at 850 hPa (approximately 20 kt) is the largest across the entire layer below 300 hPa (Fig. 15). The westerly wind in the upper (500–300 hPa) layer did not exceed 8 m s\(^{-1}\) in this case. The Richardson number (\(Ri\)) reached an elevated value of 78.4 at 0000 UTC 31 January. This is a consequence of the very weak vertical shear.

5. Final considerations

This work therefore has contributed toward filling the knowledge gap that has existed concerning orographically enhanced rain in South America. The results show that the mainland coast between the Atlantic Ocean and the mountain areas is as favorable for these events as has been seen in other parts of the world. Events of heavy rain along the SC coast were analyzed in the years 2010 (C1), 2008 (C2), and 1979 (C3).

For these three cases, the characteristics identified in rain intensified by orography that are common to localities in the United States, Asia, and Europe (Lin et al. 2001) were found to be 1) the presence of steep mountains, which contributes to the ascent of moist air; 2) the slow movement or stationarity of synoptic systems, contributing to the maintenance of precipitation over a prolonged period, causing excessive local rainfall; 3) intense flow at low levels (LLJ) transporting moist air to the affected area; and 4) potentially unstable air colliding with the mountains. Other characteristics of the cases along the SC coast were also encountered during events in the United States and across the Alps in Europe (Maddox et al. 1978; Pontrelli et al. 1999; Lin et al. 2001), as well as the western Mediterranean (Ramos et al. 1995; Doswell et al. 1998), in which values of CAPE varied from 200 to 2000 J kg\(^{-1}\). These characteristics include 1) weak flow between 500 and 300 hPa, favoring slow movement of the systems, and 2) heavy rain located between an upper-troposphere ridge (which is the quasi-stationary atmospheric system mentioned) and a short-wave trough that can be closer or farther away from the area affected.

The absence of surface frontal systems and of evident ascending motion at 500 hPa, as well as the presence of a midlevel closed low, in an equivalent barotropic atmosphere, with weak influence on the development of precipitation on the coast, makes case C3 similar to some events in the western Mediterranean (Ramos et al.
Both regions, MRF and some areas in eastern Spain, are situated between the sea and areas of 800-m mountains.

The more intense precipitation was registered in MRF and in municipalities at least 50 km away (Table 1) with 1-day totals of 200–250 mm. The major portion of the precipitation was concentrated within a period of 6–12 h, during which hourly totals reached more than 20 mm, hitting one or two peaks of between 40 and 60 mm (Figs. 2 and 7). Evaluating cases of flash floods in the United States, Doswell et al. (1996) considered precipitation rates above 25 mm h\(^{-1}\) as being moderately high and durations longer than an hour as moderately long. The suddenness of the rain and the high totals concentrated in localized areas imply flash floods influenced by mesoscale forcing (Maddox et al. 1979).

In C1, the 1-day total of over 200 mm in MRF was much higher than amounts measured at the other localities, where values were generally less than 100 mm (Table 1). The orography probably contributed to the intensification in the MRF area of a lifting process already established by the passage of atmospheric systems. In cases C2 and C3, the totals above 100 mm between Imbituba and the LN (Table 1), on the part of the coast perpendicular to the zonal wind (Fig. 1), show a less localized character. In both, there was a contrast among air masses over the coast and a mesoscale circulation involving an air mass predominating over the sea that was warmer and moister than that over the continent. In C2, whose rainfall totals were the highest and occurred over a more prolonged period, the east winds and conditionally unstable environment in MRF had predominated since 24 h before the onset of the heavy rain, in addition to being the event that showed the highest values of LI (−2.44) and CAPE (114.49 J kg\(^{-1}\)), in the radiosondes.

Research based on modeling techniques will be addressed in a future work, to investigate the role of coastal orography and water vapor flux from the Atlantic Ocean in the distribution of the rainfall.

Acknowledgments. The authors acknowledge the ECMWF for providing ERA-Interim reanalyses data, as well as ANA, EPAGRI, INMET, and REDEMET for station data, and the anonymous reviewers for all suggestions. Satellite pictures were provided by NOAA and INPE, and radiosondes by the University of Wyoming. MLGR acknowledges Dr. Shigetoshi Sugahara (UNESP/Brazil), and Dr. Clement Ramis (UIB/Spain) for discussions on various aspects of this work, and Elaine Canônica, for assistance. MLGR also received the support of CNPq, CAPES/PROEX, and FAPESC (Brazilian Research Agencies).

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