Revista Brasileira de Meteorologia, **v.24**, **n.3**, 276-291, 2009

MESOSCALE CONVECTIVE COMPLEXES IN RIO GRANDE DO SUL BETWEEN OCTOBER AND DECEMBER OF 2003 AND ASSOCIATED PRECIPITATION

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Received December 2007 - Accepted May 2009

ABSTRACT

This study investigates the occurrences of Mesoscale Convective Complexes (MCC) and the associated precipitation in the southernmost Brazilian state, Rio Grande do Sul (RS), from October to December of 2003. The identification of MCC events was done using ForTraCC. The MCC precipitation was based on the daily data of 31 local weather stations. Twenty-two MCC events were identified over RS during the three month study period, and this total, seven events occurred in October, seven in November and eight in December. Results point to an MCC associated precipitation average of 119 mm in October, 90 mm in November and 152 mm in December. The percentages for MCC precipitation averages, for the period, were 64% in October, 65% in November and 61% in December. The average accumulated volume of MCC precipitation for the three months was 361 mm (63%). This confirms that MCC events contributed significantly to the precipitation totals in RS, and were responsible for almost two thirds of the precipitation in RS, for the period.
Keywords: Mesoscale Convective Complexes, precipitation anomalies, Rio Grande do Sul

RESUMO: COMPLEXOS CONVECTIVOS DE MESOESCALA NO RIO GRANDE DO SUL ENTRE OUTUBRO E DEZEMBRO DE 2003 E QUANTIFICAÇÃO DA PRECIPITAÇÃO ASSOCIADA
Este estudo investiga a ocorrência de Complexos Convectivos de Mesoescala (CCM) e a precipitação associada aos eventos no Estado do Rio Grande do Sul (RS), entre outubro e dezembro de 2003. A identificação dos CCM foi feita através do aplicativo ForTraCC e, para quantificação dos totais de precipitação oriundos de CCM, foram utilizados dados diários de 31 estações meteorológicas. Durante o período de estudo, foram identificados 22 eventos de CCM sobre o RS. Deste total, sete ocorreram em outubro, sete em novembro e oito em dezembro. Os dados analisados apontam para um volume médio de precipitação de CCM no RS de 119 mm em outubro, 90 mm em novembro e 152 mm em dezembro. Do total de precipitação registrado para o período, o percentual oriundo de CCM ficou em 64% no mês de outubro, 65% em novembro e 61% em dezembro. O volume médio de precipitação de CCM acumulado no trimestre ficou em 361 mm, uma participação percentual de 63%, confirmando que os CCM contribuíram significativamente para a precipitação no Estado e foram responsáveis por quase dois terços da chuva observada no RS no período.
Palavras-chave: Complexos Convectivos de Mesoescala, Anomalias de Precipitação, Rio Grande do Sul

1. INTRODUCTION

October, November and December of 2003 registered precipitation above the historic average across nearly the entire southern region of Brazil (Climanálise 2003a, 2003b, 2003c). For October, slightly positive deviations were identified for the northeastern sector of Rio Grande do Sul (RS), western Santa Catarina (SC) and Paraná (PR), with anomalies exceeding 50 mm, and, in November, above average precipitation occurred across nearly the entire region. The most significant accumulation (>100 mm) occurred in the southern and northeastern sectors of RS, in the north central and western sectors of SC, and in the south and west of PR. December had the highest precipitation totals during the three-month period for the region, with positive precipitation deviations above 200 mm in the north and northwest sectors of RS, mid-west of SC and south of PR.

Bulletins of Climanálise (2003a, 2003b, 2003c) indicate that the occurrence of frontal systems and Mesoscale Convective Complexes (MCC) were responsible for the excessive volume of precipitation observed for the region during this period. In October, according to Climanálise (2003a), seven frontal systems were associated with cyclogenesis in the region and were responsible for the precipitation. In November, besides the cyclogenesis, the intensification of the Low Level Jet (LLJ) and the increase of convective activity in southern Brazil, Uruguay, northeastern Argentina and Paraguay promoted MCC development, and were responsible for the intense rains and strong winds in many localities (Climanálise, 2003b). Nine frontal systems associated with MCC events were observed in December, resulting in above average precipitation in the southern region. These MCC events were observed on December 8, 13, 19 and 20 (Climanálise, 2003c).

1.1 A brief review of MCC events occurring in South America

Satyamurty et al. (1998) described the main air masses and atmospheric systems, at lower levels (850 hPa) as well as upper levels (200 hPa), active over South America (SA) in the summer. These authors also indicate that besides the influence of extratropical anticyclones, southern Brazil is also significantly influenced by MCC events. They also observe that the northwest sector of RS is prone to summer MCC occurrences. Severo and Gan (2004) show higher precipitation values in spring, summer and fall for the north and northwestern sectors of RS. According to Velasco and Fritsch (1987), this precipitation distribution suggests that MCC events are one of the mechanisms responsible for the high rainfall for the southern region.

MCCs are characterized as clusters of individual cells, covered by an extensive cirrus (Ci) layer, originating from the tops of mature cumulonimbus (Cb) clouds, with a quasi-circular form and rapid development, lasting at least 6 h. (Maddox, 1980; Maddox, 1983; Silva Dias, 1987; Velasco and Fritsch, 1987). In SA, MCC events are observed leeward of the Andes Mountains, between 25ºS and 40ºS, which includes the northern portion of Argentina, Bolivia, southern Paraguay and frequently reaching the southern and southeastern regions of Brazil (Scolar and Silva Dias, 1982; Guedes and Silva Dias, 1984; Velasco and Fritsch, 1987). These systems occur predominately in the warm seasons of the year (summer, spring and fall) and produce a great variety of significant convective phenomena, such as tornados, hail storms, strong wind gusts, floods and intense electric storms (Maddox, 1980; Maddox, 1983).

The first storm cells, preceding MCCs formation, develop during the early evening and then make the transition to a larger, well organized system, after late evening. Most MCCs reach their maximum size after midnight, persisting until the next morning (Maddox, 1980; Velasco and Fritsch, 1987). For SA, MCCs show a "double peak" in build up time of the first storms, suggesting two different mechanisms possibly initiating the convection: the first is related to the diurnal heating cycle and the second is linked to the night-time convergence of the Paraná River Valley, enhanced by the katabatic winds from the Andes Mountains and LLJ, both reaching the maximum velocity after midnight (Velasco and Fritsch, 1987).

The mean duration for MCCs varies from 10 h to 20 h (Silva Dias, 1987). Machado et al. (1994) found that convective systems over SA, across the mid-latitudes and in summer, have a mean radius of 240 km and an average duration of 15 h. According to Silva Dias (1996), some systems initially classified as MCCs can turn into vortices, such as described by Bonatti and Rao (1987), where the system presents itself as an MCC during the first six hours and then assumes the form of an inverted comma cloud, characteristic of a cyclonic vortex, persisting 48 h more.

The paths of most MCCs are from east to southeast, frequently reaching the southern Brazilian states, but some take a northeastern track into the mid-western and south-eastern regions of Brazil. Figueiredo and Scolar (1996) analyzed 25 MCCs and concluded that 70% of the systems moved to the east and southeast, reaching RS and SC. The remaining 30% progressed to the northeast and north, reaching the southeast of Brazil, as also observed by Guedes (1985). Velasco and Fritsch (1987) show greater MCC event variability, with a more zonal trend (from west to east) in spring and the beginning of fall, and more meridional (from south to north) in summer. Guedes et. al (1994) evaluated the paths of > 6 hour duration convective systems over SA, between July 19, 1987 and June 19, 1988. This latter study found that these systems move from the southeast to the northeast, over the southern and south-eastern regions of

Brazil. Machado et al. (1998) state that the paths of SA mid-latitude convective systems, in summer and fall, are similar to those observed by Velasco and Fristch (1987), that demonstrated a more zonal trend for MCC paths, in spring and early autumn, and more meridional in summer.

The LLJ is responsible for the low latitude heat and humidity transport from the tropics, representing a main factor for MCC formation and development. Marengo et al. (2004) propose that the LLJ is a primary characteristic of atmospheric circulation over SA during summer, responsible for the meridional transport of humidity at low levels from the tropics. Although LLJs can occur at any time of year, bringing a warm humid stream of air from the Amazon to southern Brazil and northern Argentina, they are most frequent in summer when the most intense phase is after midnight. Paegle (1987) and Torres and Nicollini (2002) analyzed the relationship between the LLJ and convective systems over SA; they showed that the jets, east of the Andes Mountains, produced a favorable environment to organize deep convection. Nogués-Peagle and Berbery (2000) observed an extensive area of convective development during spring and summer, predominantly at night. This convective phenomenon is capable of systematically altering the basic precipitation pattern of the South American continent.

Corrêa et al. (2007) found that the LLJ is a transport mechanism for water vapor directly from the Atlantic Ocean to SA, which is responsible for conserving a great deal of MCC convection. These authors suggest that LLJs, when considered independently of other factors, have the capacity of generating baroclinic instabilities, building convective systems such as MCC events, which particularly present a trend of night-cycle events for RS.

Seluchi and Marengo (2000) investigated the importance of air mass transport for both precipitation and temperature. During summer, the Chaco Low intensifies, due to the positive balance of solar radiation, favoring the transport of tropical air to the south. This produces convective activity fueled with humidity from the region. After comparing days with and days without MCCs, Tuker and Zentmire (1999) asserted that the relative humidity at 500 hPa was significantly higher during MCC days. Mean temperatures of the MCC and non-MCC cases differ by < 1°C at 500 hPa. The associated differences in relative humidity fields are mainly caused by the atmospheric moisture content at this level. Conversely, at 700 hPa, the relative humidity was lower on MCC days, with temperatures more than 1°C warmer for the MCC than non-MCC cases.

Corfidi et al. (1996) established that MCC propagation is directly proportional and correlated to the velocity and direction of the LLJ, obtaining correlation coefficients of 0.78 and 0.80, respectively. Of the 133 systems studied, 99 were MCC events, showing a significant tendency for MCC propagation in the same direction as the LLJ. Duquia and Silva Dias (1994) confirmed that the generation area for MCCs is to the northeast of the Maximum Velocity Center (MVC), at high levels. Case studies, such as Scolar and Figueiredo (1990) also confirm this large-scale conditioning, and concluded that such events were formed to the east of low pressure centers and in areas dominated by low-level moisture convergence. The generation area for these systems is best described at 850 hPa: closed advection cells, strong humidity convergence and the LLJ in the northerly flow, with a velocity of approximately 15 m s^{-2}. These storms initially develop in areas of low-level warm air advection and moisture convergence.

Rocha (1992) performed model sensitivity studies showing that MCC evolution is symbiotically linked to latent heat release of convective processes, concluding that the system rapidly falls apart without this energy source. In both simulation studies (Rocha, 1992) and observational studies (Cotton et al., 1989), the gradual formation of cyclonic vorticity centers were observed at low and mid levels. These are probably responsible for the quasi-circular shape of MCCs. Similarly, there is a diverging anticyclonic vorticity center, directly above the MCCs.

Various studies were produced after Maddox (1980; 1983) regarding the precipitation produced by MCCs. Studying 74 MCCs from 1982 and 1983, Fritsch et al. (1986) observed that these events contributed from 20 to 50% of the annual precipitation totals for the Great Plains of the USA, showing that during June and August, the precipitation was dominated by MCCs. McAnelly and Cotton (1989) analyzed seven years of June to August MCC events, between 1977 and 1983, and concluded that in 122 cases analyzed, MCCs contributed 45% to the total June to August precipitation. Ashley et al. (2003) showed that during the warm season, significant portions of the Great Plains receive, on average, between 8% and 18% of their total precipitation from MCC rainfall. However, there is large yearly and even monthly variability in the location and frequency of MCC events that lead to highly variable precipitation contributions. The study encompasses 527 events over 15 years, an average of 35 MCCs per year.

Several investigations have been done in other regions to identify the occurrence of MCC events. Laing et al. (1999) analyzed June to September of 1987 and found that MCCs accounted for 22% of the average precipitation in the Sahel. Laing and Fritsch (1993), employing the MCC classification proposed by Maddox (1980), asserted that the systems observed in the Indian monsoon region share characteristics with MCCs over the Americas (e.g. night-time systems, developing over the continent, with an average life cycle of 9 h). The high precipitation frequency indicates that MCCs are fundamental components of the Indian monsoon hydrological cycle. MCCs have also been documented in other regions, such as the western Pacific (Miller and Fritsch, 1991), showing similar characteristics to those of North American MCC events.

Scaglioni and Gomes (2005) found that one MCC, on February 3, 2003, was responsible for impressive precipitation values in RS. According to the authors, this MCC reached the southwestern sector of RS and resulted in high daily accumulated precipitation at three local municipalities: Santana do Livramento (149.9 mm), Bagé (67.2 mm) and Santa Vitória do Palmar (24.5 mm).

Based on the previous research, regarding MCCs over SA, it is apparent that RS is frequently in the path of MCCs. Abdoulaev et al. (1996) showed that convective systems cause a minimum of 13 natural hazards every year just in RS, and some of these disasters were directly related to MCCs. The research presented in this article focuses on identifying MCCs that occurred during October to December of 2003, in RS, to quantify the associated MCC precipitation and the percentage of MCC rainfall, for the period.

2. DATA

2.1 Satellite imagery

GOES-12 and Meteosat (infrared channel) imagery, enhanced according to Cloud Top Temperature (CTT), was employed to visualize and locate MCC events and their area of influence. Along with the diagnostic files, the DSA-INPE team offered this imagery in JPEG, comprising the whole study period (October to December of 2003), with a time interval of one-half hour. In all, around 9,700 images of the southern region of Brazil and SA allowed for visual identification and the observation of MCC event evolution, over RS.

2.2 Precipitation data

To evaluate precipitation in RS, data were examined from 31 weather stations. These weather stations are maintained by Fundação Estadual de Pesquisa Agropecuária do Rio Grande do Sul (FEPAGRO) and from the 8º Distrito de Meteorologia-8º DISME, a regional division of Instituto Nacional de Meteorologia (INMET). Figure 1 illustrates the spatial distribution of the weather stations and Table 1 presents geographic references for each site.

Monthly precipitation climate normals (1971-2000) were calculated from monthly accumulated values for each weather station. The climate normal (normal) corresponds to a standard 30-year observation period, recommended by the World Meteorological Organization (WMO). The data were distributed by INMET and FEPAGRO. The regional pondering method, proposed by Tubelis and Nascimento (1980), was used to fill in any data gaps, shown as:

$$y = \frac{1}{3} \times \left[\frac{x1}{xm1} + \frac{x2}{xm2} + \frac{x3}{xm3} \right] \times ym \tag{1}$$

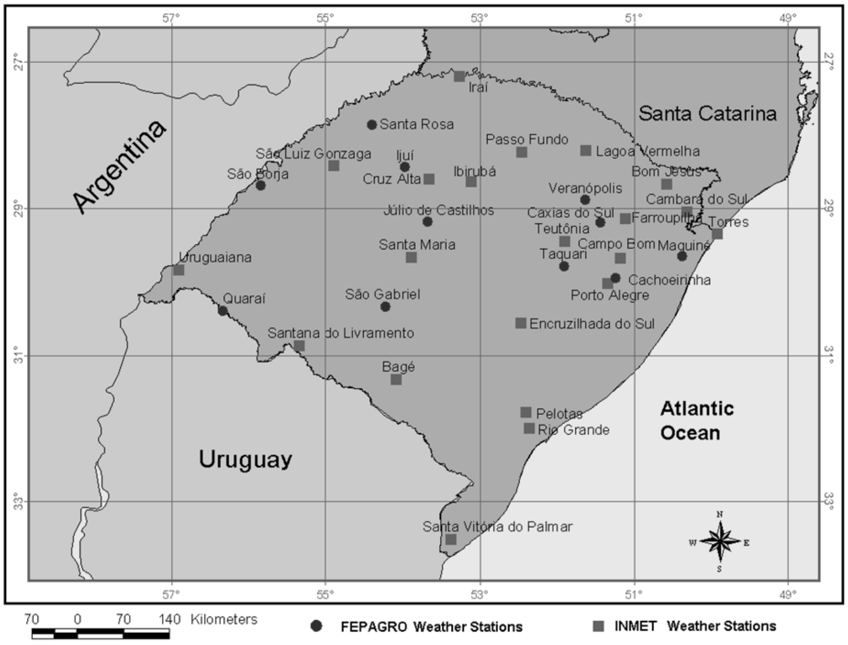


Figure 1 - Geographic distribution of the employed weather stations in RS.

where *y* is the precipitation of each weather station to be estimated; *x1, x2 e x3* are the corresponding precipitations for each month, observed at three different neighboring stations; *ym* is the average precipitation of *y*; and *xm1, xm2* and *xm3* are the average precipitations of three neighboring weather stations. The neighboring weather station criterion seeks to establish, not only the shortest distance among the weather stations, but also the topographic similarities with the focused weather station. The climate averages are shown in Table 2.

3. METHODOLOGY

3.1 MCC IDENTIFICATION CRITERIA

The Forecast and Tracking of Active Convective Cells (ForTraCC) software permitted the identification of MCCs that occurred from October to December of 2003. This software was developed by Divisão de Satélites Ambientais (DSA) of Instituto Nacional de Pesquisas Espaciais (INPE). This program employs thermal infrared (IR) images from GOES-12 satellite, with a spatial resolution of 4 km (16 km^2), based on the similarities between morphologic characteristics (pattern recognition) and the superposition of convective systems, from successive imagery (Machado et al., 1998).

ForTraCC employs CTT thresholds of 235 K (–38°C) to define the convective cell centers and also 250 K (–23°C) for early detection of the systems. It should be noted that for this research, the DSA-INPE team was asked to reprocess the ForTraCC application for the study period, altering the temperature thresholds, being changed from 235 K (–38°C) to 241 K (–32°C) (warm limit) and from 210 K (–63°C) to 221 K (–52°C) (cold limit). Based on these changes, it was possible to detect the convective systems with MCC characteristics, strictly following the MCC criteria given by Maddox (1980). Initially, these cloud top temperature parameters (–32°C and –52°C) were proposed by Scofield and Oliver (1977), and came from satellite image estimated precipitation data, where the –32°C threshold corresponds to medium height cloudiness (approximately 6.000 m). Although, this limit marks the beginning of the precipitation accumulation, it does not guarantee the determination of active precipitation areas. Conversely, the –52°C limit assures that the system is active, and that there is precipitation on the surface. Also, according to Scofield and Oliver (1977), the precipitation data gathered at the

Table 1 - Location and altitude of the employed weather stations.

N°	Municipality	Institution	Latitude (decimal)	Longitude (decimal)	Altitude (m)
1	Bagé	INMET	-31.33	-54.11	216
2	Bom Jesus	INMET	-28.67	-50.42	1047
3	Cachoeirinha	FEPAGRO	-29.95	-51.12	5
4	Cambará do Sul	INMET	-29.05	-50.14	1031
5	Campo Bom	INMET	-29.68	-51.05	26
6	Caxias do Sul	INMET	-29.14	-50.99	760
7	Cruz Alta	INMET	-28.60	-53.67	473
8	Encruzilhada do Sul	INMET	-30.55	-52.41	427
9	Farroupilha	FEPAGRO	-29.20	-51.33	680
10	Ibirubá	INMET	-28.63	-53.09	395
11	Ijuí	FEPAGRO	-28.44	-54.00	448
12	Iraí	INMET	-27.19	-53.25	227
13	Júlio de Castilhos	FEPAGRO	-29.18	-53.69	514
14	Lagoa Vermelha	INMET	-28.21	-51.53	807
15	Maquiné	FEPAGRO	-29.66	-50.21	32
16	Passo Fundo	INMET	-28.23	-52.40	709
17	Pelotas	INMET	-31.77	-52.34	7
18	Porto Alegre	INMET	-30.03	-51.23	10
19	Quaraí	FEPAGRO	-30.39	-56.48	100
20	Rio Grande	INMET	-32.00	-52.30	2
21	Santa Maria	INMET	-29.67	-53.91	138
22	Santa Rosa	FEPAGRO	-27.86	-54.44	273
23	Santa Vitória do Palmar	INMET	-33.52	-53.37	5
24	Santana do Livramento	INMET	-30.87	-55.43	210
25	São Borja	FEPAGRO	-28.69	-55.96	99
26	São Gabriel	FEPAGRO	-30.34	-54.26	109
27	São Luiz Gonzaga	INMET	-28.41	-54.96	251
28	Taquari	FEPAGRO	-29.79	-51.83	76
29	Torres	INMET	-29.34	-49.73	43
30	Uruguaiana	INMET	-29.84	-57.08	74
31	Veranópolis	FEPAGRO	-28.89	-51.54	705

pertaining weather stations (where the cloud top threshold was –52°C) almost always agreed with these criteria. It is important to state that precipitation related to higher thresholds (warmer cloud tops) may also occur.

According to Macedo et al. (2004), the identification method of a system in time (t and t+Δt) is obtained by employing the maximum system area superposition criteria of successive images. Convective system persistence must have a minimum number of pixels to be considered the same event (150 pixels, corresponding to approximately 2,400 km^2) for Δt = 30 minute. If the superposed image shows a smaller area than this, then the system is not considered the same as that shown in the preceding time.

ForTraCC (Macedo et al., 2004) was employed to identify MCC events, after being adapted to convective systems with cloud top temperature thresholds (–32° and –52°C), defined by Maddox (1980). The DSA provided the meteorological system diagnostics text file for the period. This work only used the ForTraCC fields (data) pertaining to MCC event related parameters. These fields and their respective descriptions are offered on Table 3.

According to Macedo et al. (2004), the respective eccentricity is based on ratio between the axes of convective systems, and calculated by Equations 2.1 or 2.2:

$$e = \left| \frac{xx(\max) - xx(\min)}{yy(\max) - yy(\min)} \right| \tag{2.1}$$

or

$$e = \left| \frac{yy(\max) - yy(\min)}{xx(\max) - xx(\min)} \right| \tag{2.2}$$

where *xx* and *yy* represent the longitudinal and latitudinal axes, minimum and maximum of the convective system (minor and major axes of the ellipse). The values for the eccentricity

Table 2 - Precipitation averages (mm) for RS (1971-2000).

N	Weather station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	year
1	Bagé	131	142	100	143	129	112	136	95	107	113	112	95	1415
2	Bom Jesus	167	156	115	114	109	126	150	155	141	148	119	144	1645
3	Cachoeirinha	120	121	87	108	96	152	138	126	123	117	112	105	1404
4	Cambará do Sul	165	197	119	118	118	138	155	150	154	163	138	160	1774
5	Campo Bom	139	124	111	138	114	164	164	147	145	162	130	121	1658
6	Caxias do Sul	143	152	112	136	117	162	164	161	160	160	130	146	1743
7	Cruz Alta	149	143	121	146	133	154	144	136	164	155	140	124	1708
8	Encruzilhada do Sul	119	120	115	117	121	156	142	127	134	115	111	102	1477
9	Farroupilha	140	130	112	125	109	155	162	149	159	161	135	133	1668
10	Ibirubá	157	155	121	157	140	155	158	144	161	189	170	142	1849
11	Ijuí	143	146	116	144	141	159	134	136	162	173	145	130	1730
12	Iraí	170	190	136	152	170	164	148	159	165	214	156	153	1977
13	Júlio de Castilhos	130	137	123	124	124	150	149	134	144	158	132	114	1619
14	Lagoa Vermelha	169	166	123	114	139	126	150	166	170	181	124	148	1774
15	Maquiné	182	198	163	103	102	124	119	136	137	133	120	162	1680
16	Passo Fundo	162	152	123	128	146	144	166	157	176	190	157	153	1853
17	Pelotas	114	165	96	107	98	108	144	101	126	99	103	103	1365
18	Porto Alegre	108	111	102	110	106	145	146	134	130	115	110	109	1426
19	Quaraí	160	162	142	166	134	97	100	71	101	137	123	122	1514
20	Rio Grande	121	119	93	91	90	97	147	126	129	95	92	77	1277
21	Santa Maria	144	125	142	147	116	139	149	121	138	144	127	106	1597
22	Santa Rosa	151	149	125	160	153	166	121	127	155	197	143	131	1778
23	Santa Vitória do Palmar	108	140	94	97	99	105	139	102	104	88	94	87	1256
24	Santana do Livramento	144	149	115	144	128	108	134	96	130	136	118	108	1511
25	São Borja	151	135	158	189	135	121	94	90	124	156	142	127	1623
26	São Gabriel	119	127	114	139	118	128	134	90	128	120	111	88	1416
27	São Luiz Gonzaga	165	159	167	200	163	175	151	140	162	193	158	154	1987
28	Taquari	138	127	110	131	106	162	152	136	148	136	129	107	1583
29	Torres	150	160	146	108	102	108	109	147	130	133	117	121	1529
30	Uruguaiana	148	158	141	168	129	90	78	69	117	128	108	98	1432
31	Veranópolis	148	140	99	120	120	133	149	144	163	152	140	139	1647
	Average	144	147	121	134	123	136	139	128	142	147	127	123	1610

should always be positive, varying between 0 (linear system) and 1 (circular system). In this way, if the results of Equation 2.1 are negative then Equation 2.2 should be employed, and vice-versa.

TAM_A and TAM_B fields were calculated from the GOES-12 pixel size, corresponding to an area of 4x4 km (16 km^2). The areas of the system were calculated in km^2, employing Equations 3 and 4:

$$\text{TAM\_A} = (\text{SIZE} \times 16) \tag{3}$$

$$\text{TAM\_B} = (\text{CBNUM} \times \text{CBMED} \times 16) \tag{4}$$

were SIZE defines convective system size, in pixels (cloud tops, temperature threshold of $\leq -32°C$); CBNUM indicates cold cloud tops (Cb) totals that are present in the system and CBMED estimates the average Cb size. TAM_B (Equation 4) corresponds to an estimation of cold nucleus system size. This method estimates the size (km^2) of cold nucleus convective systems, temperature lower than –52°C (Macedo et al., 2004).

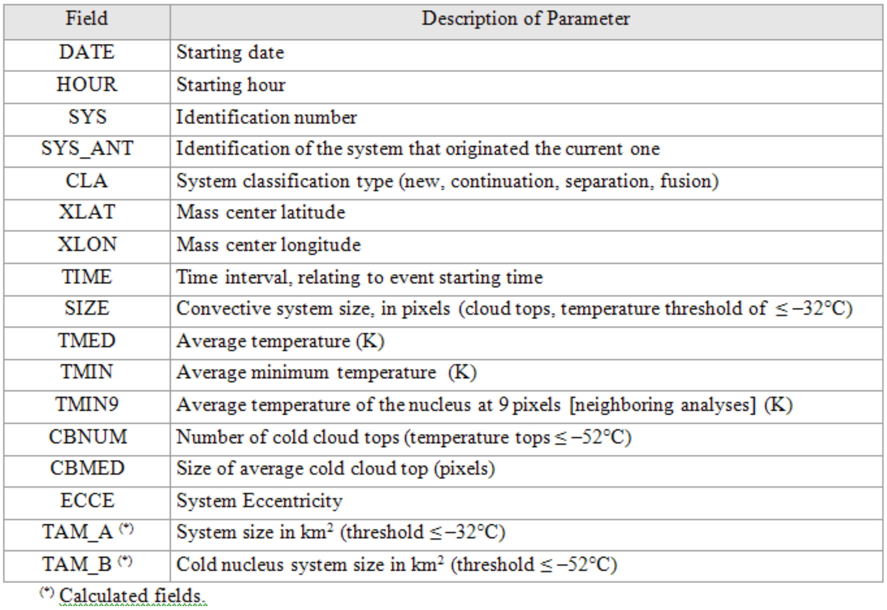
GOES-12 (enhanced and IR) and Meteosat (IR) satellite imagery was used to visualize the events and localize MCC ranges for SA, Brazil (Meteosat) and southern Brazil. At this point, only the events that, at some stage of their cycle, had cloud cover area observed over RS were selected.

3.2 Identification of MCC event associated precipitation

Daily data were employed to identify the associated precipitation, from the 31 weather stations (Figure 1 and Table 1). The data was adjusted to a standard date/time-of-collection. Under INMET standards, the total daily precipitation from each weather station corresponds to the sum of the observations, from 18:00 UTC of the day before the observation until 12:00 UTC of the attributed day. For the FEPAGRO weather stations, the observations are read daily at 12:00 UTC and are attributed to the day before the observations were taken. To establish a standard between the different date/time-of-collection methods, the INMET dataset was adjusted to the date/time-of-collection of the day before, thus in agreement with the FEPAGRO method of collection.

After establishing the presence of cloud cover over RS, the associated precipitation was calculated using the full state data set. The date/time standard was set to the day on which rainfall was observed. Due to the time of observation, if the MCC began before 9:00 local time (LT), the precipitation was then added to the beginning of the event, the day before. The precipitation observed in the days immediately following this event was only considered if the MCC ended after 9:00 LT on any subsequent day. The spatial distribution was done using the Kriging interpolation method.

Table 3 - Selected ForTraCC fields for MCC classification



Field	Description of Parameter
DATE	Starting date
HOUR	Starting hour
SYS	Identification number
SYS_ANT	Identification of the system that originated the current one
CLA	System classification type (new, continuation, separation, fusion)
XLAT	Mass center latitude
XLON	Mass center longitude
TIME	Time interval, relating to event starting time
SIZE	Convective system size, in pixels (cloud tops, temperature threshold of $\leq -32°C$)
TMED	Average temperature (K)
TMIN	Average minimum temperature (K)
TMIN9	Average temperature of the nucleus at 9 pixels [neighboring analyses] (K)
CBNUM	Number of cold cloud tops (temperature tops $\leq -52°C$)
CBMED	Size of average cold cloud top (pixels)
ECCE	System Eccentricity
TAM_A (*)	System size in km^2 (threshold $\leq -32°C$)
TAM_B (*)	Cold nucleus system size in km^2 (threshold $\leq -52°C$)

(*) Calculated fields.

Due to Daylight Savings Time (DST), beginning on October 19, 2003, it was necessary to adjust MCC event occurrence times from UTC to LT. This adjustment was necessary because ForTraCC data output corresponds to the UTC standard. Accordingly, up to October 19, three hours were subtracted from the UTC standard (Brasília UTC-3), after which, only two hours were subtracted.

4. RESULTS AND DISCUSSION

4.1 MCC Identification

ForTraCC permitted the identification of MCC events that occurred between October and December of 2003 and that, at some instance of each MCC life cycle, was active over RS. In the three month period, 22 MCC events were active over RS, contributing to the state´s precipitation totals. Of these, seven occurred in October, seven in November and eight in December. Figure 2 shows the location of the geometric center of each identified MCC event, at the time of its maximum extent. Table 4 describes their main characteristics.

The average size of the MCCs, at their maximum extent was 1,066 x 103 km^2 (Size A: threshold of –32°C) and 319 x 103 km^2 (Size B: threshold of –52°C). Size A class was approximately twice the size found by Velasco and Fritsch (1987), which was 500 x 103 km^2. This distinction may be associated with the differences in cloud top temperature thresholds, employed by Velasco and Fritsch (1987), –42°C and –62°C for Size A and B, respectively. When compared to MCC size B events obtained by Durkee and Mote (2008), this work obtained slightly larger values. Both these studies employed Maddox´s criteria, although Durkee and Mote (2008) considered more events, over a much larger area.

Figures 3a, 3b and 3c show three MCC events that occurred on October 26, November 15 and December 15, respectively. In Figure 3a, the event marked “F” extended over all of RS, SC and Uruguay, covering an area of 2,209,456 km^2. Figure 3b shows event “J” in the northwest of RS and west of SC. Figure 3c shows two events, one positioned over RS, event “R”, and the other over northern of Argentina.

The average duration of the 22 MCC events was 18.6 h. The monthly averages were 13 h for October, 14.4 h for November and 27.2 h for December of 2003. MCC duration varied significantly from one event to another, October and November had averages of 10 to 20 h, agreeing with the results obtained by Silva Dias (1987), while December had an average greater than 20 h.

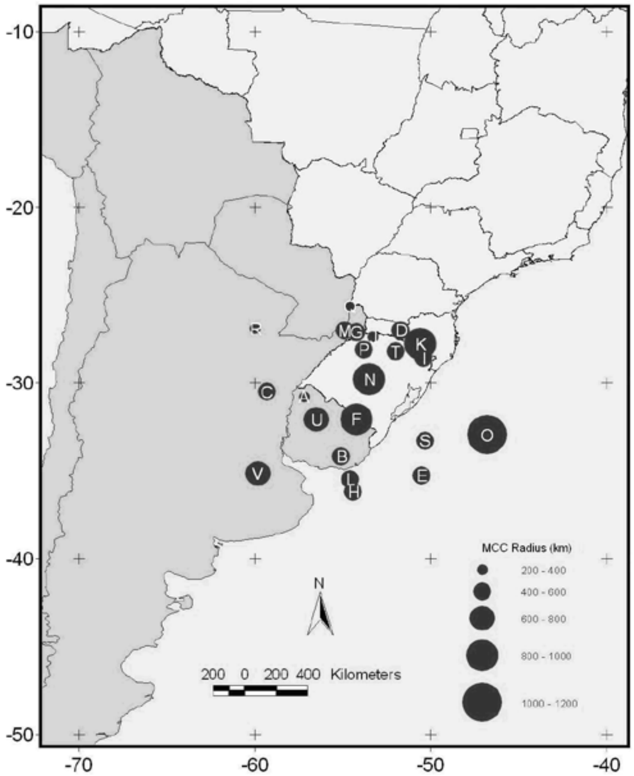


Figure 2 - Location of geometric centers of MCCs that affected RS, from October to December of 2003. The letters correspond to events listed under “MCC Code” in Table 4.

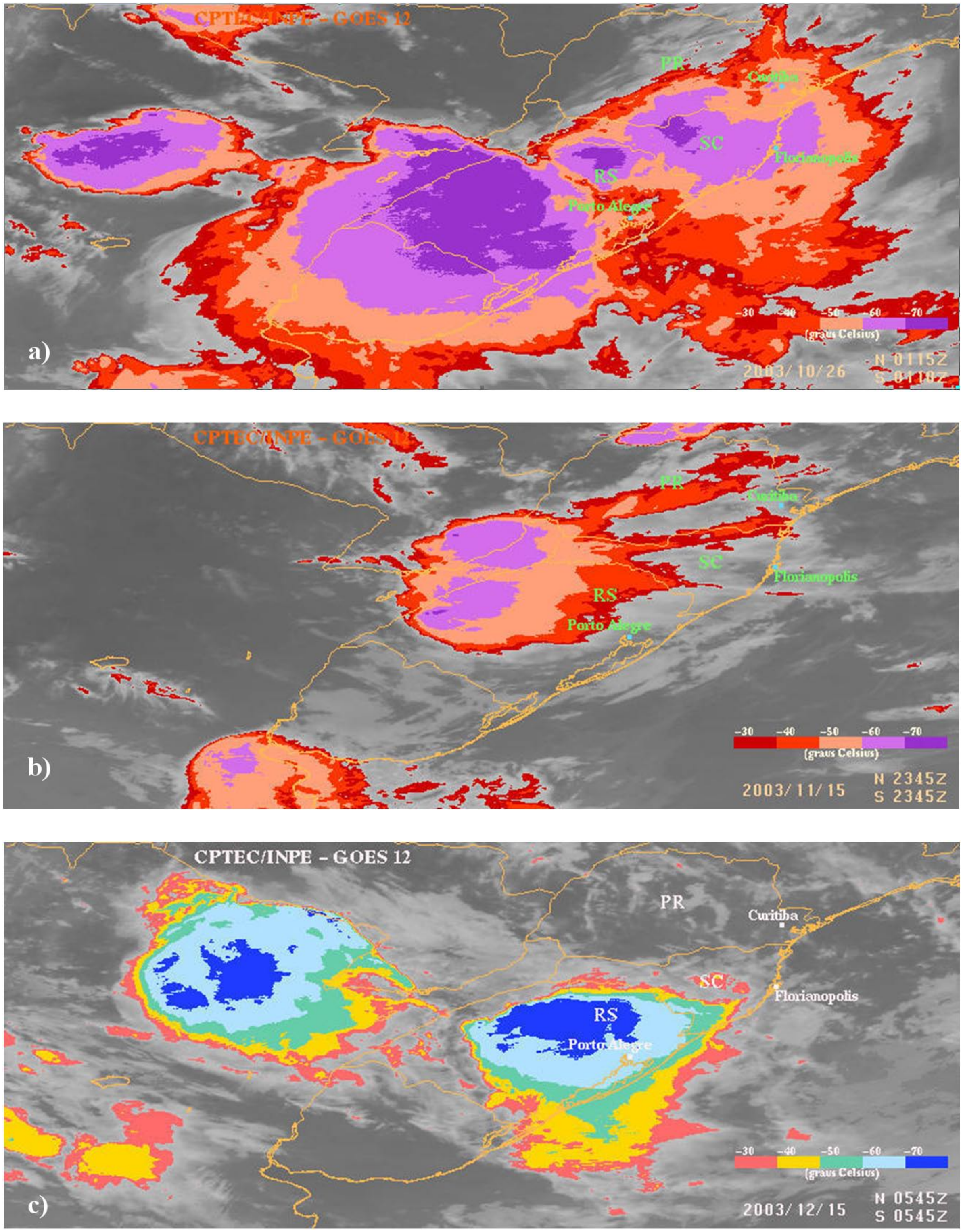


Figure 3 - GOES-12 images showing cloud top temperature enhancements of MCC events over RS on October 26 (a), November 15 (b) and December 15 (c).

In relation to MCC event starting time, “double peak” events composed 50% of the events that began between 15:00 and 21:00 LT, and 27% between 03:00 and 09:00 LT. These results agree with Velasco and Fritsch (1987) who found the same double peak events, revealing two different starting mechanisms for the convection: one set off by daytime heating (from 15:00 to 21:00 LT), and the other conditioned to the maximum flow of LLJ intensity, between 03:00 and 09:00 LT (Velasco and Fritsch, 1987). MCC ending time had its greatest concentration between 6:00 and 18:00 LT (64% of the events). These results agree partially with Velasco and Fritsch (1987) and Silva Dias (1987). These studies pointed out that the ending time was between 09:00 and 12:00 LT. For this study, MCC event ending time was considered the time of dissipation or when the event split or merged with another.

An analysis of the hours when MCC maximum extent occurred revealed that 59% of MCCs reached maximum size between 18:00 and 06:00 LT, agreeing with results from Maddox (1980), Cavalcanti (1982), Maddox (1983), Velasco and Fritsch (1987). These results support the importance of the LLJ in MCC event development, due to their maximum development occurring at night when the LLJ is strongest (Virji, 1981; Cavalcanti, 1982; Guedes, 1985; Paegle, 1987; Corrêa et al., 2007).

4.2 MCC associated precipitation

The daily precipitation values for periods with MCCs (Table 4) compose the data set used to evaluate the MCC associated precipitation. These daily accumulations made it possible to also determine MCC event precipitation contribution (percentage) relating to monthly and three month precipitation totals (Table 5).

In the month of October 2003, the average MCC associated precipitation was 119 mm, local values varying from 28 mm (Santa Vitória do Palmar) to 200 mm (Uruguaiana). In more than two thirds of these stations (68%), MCC related rainfall was more than 100 mm. MCC related precipitation, alone, was above the normals in 11 localities (35% of the weather stations). In relation to the total precipitation for the period, the MCC contribution was 64% of the state’s total precipitation. This contribution varied from 26% in Ijuí to 81% in Uruguaiana.

November showed the smallest MCC related precipitation value (90 mm). The associated precipitation varied from 11 mm (Torres) to 176 mm (Santa Vitória do Palmar). At five weather stations, MCC precipitation surpassed the expected normal. Despite having the smallest average precipitation, November registered the largest contribution by MCCs (65%). The contribution of MCCs to the total precipitation varied from 21% (Torres) to 96% (Santa Vitória do Palmar).

December had the highest average precipitation from MCCs (152 mm) for the state as a whole, while individual stations had between 9 mm (Rio Grande) and 324 mm (Júlio de Castilhos). December had the greatest range in MCC precipitation. In 20 municipalities (65% of the weather stations) MCC related precipitation exceeded the expected normal. Conversely, the MCC contribution to total precipitation was the smallest among the three months (61%). MCC contribution also had significant variations among weather stations from 14% (Pelotas) to 89% (Júlio de Castilhos).

Total accumulated precipitation for the three months was 361 mm, averaged across all 31 weather stations. The range was from 88 mm in Pelotas to 585 mm in Santa Maria. In average, 40% of the weather stations (12 localities), MCC associated precipitation was solely responsible for surpassing the three-month normal. The MCC rainfall contribution averaged 63%, varying from 41% (Pelotas) to 82% (Santa Vitória do Palmar). These findings show that two thirds of the precipitation, between October and December, was produced from MCC events in spring 2003. Figures 4 and 5 show the spatial distribution of MCC events and the participation percentages in relation to total monthly averages.

The spatial distribution of the MCC related precipitation for the month of October showed rainfall concentrations in the northeastern, mid-eastern and far western sectors of RS. These sectors had MCC associated precipitation values of approximately 150 mm, with some localities having greater values, such as Cachoeirinha, Cruz Alta, Veranópolis, Farroupilha, Porto Alegre, Caxias do Sul, Encruzilhada do Sul, Santa Maria, Cambará do Sul and Uruguaiana (Figure 4a).

With relation to MCC precipitation contribution for the month of October, the northeastern, mid-southern, southeastern (including the Greater Porto Alegre), and far western sectors of RS registered the largest MCC contributions, where approximately 70% of the rain was produced from MCC events in October 2003 (Figure 5a).

November MCC precipitation reached approximately 100 mm for a large part of state. The resulting 100 mm isohyet virtually divided the state in two sections (east and west), with ≤ 100 mm rainfall in the east and ≥ 100 mm in the west (Figure 4b). MCC contribution was more pronounced in the far south (Figure 5b), where Santa Vitória do Palmar had a 96% MCC event precipitation share, the largest value for the whole study period. The far north (Iraí), mid-east (Santa Maria) and the northern coast (Maquiné) each recorded at least 80% MCC contributions.

The month of December showed a clear concentration of MCC precipitation in the northern half of the state, creating a west-east 100 mm isohyet (Figure 4c). A great number of weather stations located in the northern half, the highlands of

RS (Caxias do Sul, São Borja, Ijuí, Passo Fundo, Santa Maria, Ibirubá, São Luiz Gonzaga and Júlio de Castilhos), registered precipitation totals of 200 to 350 mm. The mid-northern and northwestern sectors received > 60% of their total precipitation from MCCs in December (Figure 5c).

In Figure 4d, with the exception of the coastal plains regions and the far south, the three-month accumulated precipitation showed that MCC precipitation affected practically all of RS, reflecting both larger total precipitation and MCC event associated values of December. The MCC contribution to the total precipitation for December had the highest concentrations in the mid-northern, far western, far southern and eastern sectors of the state (Figure 5d).

5. CONCLUSIONS

The main goal of this study was to investigate the participation of MCCs and their associated precipitation in RS, for October, November and December of 2003. Twenty-two MCC events contributed to the precipitation totals for the period, also causing a series of damages and hazards to local populations. Almost two thirds of the registered precipitation (63%) was associated with MCC events. December showed the largest accumulated average (152 mm) yet the smallest MCC contribution among the total precipitations of the three months (61%). Alternatively, November registered the smallest average MCC precipitation (90 mm) and the largest MCC contribution

Table 4 - Main characteristics of MCCs that affected RS, from October to December of 2003.

Date-Hour start MCC (LT)	Date-Hour max. extent MCC (LT)	Date-Hour end MCC (LT)	Duration MCC (h)	Days of MCC associated precipitation	Size A at hour of max. extent (km^2)	Size B at hour of max. extent (km^2)	Eccentricity at hour of max. extent
03/Oct 04:45	03/Oct 14:45	03/Oct 15:45	11.0	2 and 3/Oct	479,344	147,840	0.8
03/Oct 16:15	03/Oct 20:45	04/Oct 03:15	11.0	3/Oct	674,064	85,840	0.7
04/Oct 04:15	04/Oct 05:45	04/Oct 14:15	10.0	3 and 4/Oct	766,928	280,256	0.7
21/Oct 01:15	21/Oct 12:45	21/Oct 15:15	14.0	20 and 21/Oct	683,536	143,136	0.8
24/Oct 18:15	25/Oct 01:15	25/Oct 02:45	8.5	24/Oct	589,840	256,864	0.9
25/Oct 06:45	25/Oct 23:15	26/Oct 10:45	28.0	24 and 25/Oct	2,209,456	1,063,216	1.0
31/Oct 16:15	31/Oct 18:45	01/Nov 01:15	9.0	31/Oct	849,472	177,840	0.8
10/Nov 20:45	11/Nov 06:45	11/Nov 21:15	24.5	10 and 11/Nov	1,080,064	460,032	0.8
12/Nov 15:45	12/Nov 20:45	12/Nov 21:45	6.0	12/Nov	953,136	415,616	0.7
15/Nov 15:45	15/Nov 22:15	16/Nov 00:45	9.0	15/Nov	342,528	159,312	0.7
16/Nov 11:15	17/Nov 12:15	17/Nov 12:15	25.0	16 and 17/Nov	2,122,976	732,672	1.0
17/Nov 14:15	17/Nov 18:45	17/Nov 21:45	7.5	17/Nov	1,104,016	548,000	0.7
25/Nov 08:45	25/Nov 14:45	25/Nov 14:45	6.0	25/Nov	651,696	279,680	1.0
26/Nov 03:45	27/Nov 01:45	27/Nov 02:45	23.0	25 and 26/Nov	2,055,312	1,096,048	0.7
07/Dec 15:45	09/Dec 03:45	09/Dec 06:45	39.0	7 and 8/Dec	3,427,360	901,296	0.7
12/Dec 20:15	13/Dec 12:45	13/Dec 15:15	19.0	12 and 13/Dec	654,816	129,600	0.7
14/Dec 01:45	14/Dec 03:45	14/Dec 15:15	13.5	13 and 14/Dec	342,576	160,992	0.7
14/Dec 17:45	15/Dec 03:45	15/Dec 07:15	13.5	14/Dec	330,208	221,936	0.7
14/Dec 20:15	15/Dec 09:15	15/Dec 15:15	19.0	14 and15/Dec	840,768	159,104	0.7
20/Dec 09:45	20/Dec 15:45	21/Dec 10:45	25.0	19 and 20/Dec	1,076,864	309,680	1.0
21/Dec 08:45	22/Dec 08:15	22/Dec 08:15	23.5	20 and 21/Dec	1,362,112	769,296	0.7
25/Dec 17:45	27/Dec 02:45	28/Dec 10:45	65.0	25, 26 and 27/Dec	1,387,088	650,880	0.7

(65%). October registered intermediate values (119 mm) for MCC associated precipitation and contribution (64%).

The spatial distribution of the MCCs and their associated precipitation demonstrated that such events had a very significant contribution at some localities in RS. The largest accumulated percentages were found for the western, mid-northern and far southern sectors of RS, with MCCs contributing more than 60% to the precipitation totals. The prevalence of MCC events in the northern half of RS, represented by the average accumulation, reflected the high values found for December - the month with the largest accumulated precipitation totals.

Some of the main physical characteristics of MCCs described in the literature were confirmed (life cycle, starting time, maximum extension and event ending), but the results also determined that the average size of MCC events was double that found for SA by Velasco and Fritsch (1987), although these authors employed narrower temperature thresholds (–42°C and –62°C). This may have led these authors to underestimate MCC events. The present study found that MCC average size was approximately three times larger than such events studied by Maddox (1980) in the US, showing an average size of 300 x 103 km^2.

The ForTraCC application was found to be efficient at calculating the physical parameters proposed by Maddox (1980) to classify MCC events, although the present study found twice the number of MCCs in December than Climanálise (2003c), eight and four, respectively. It is important to note that the CTT criteria for this work follows Maddox (1980). This discrepancy may be related to the difference in defining the parameter of MCC event analyses. This study considers that the end of the MCC events occurs when it ceases to comply with the established size criteria (Size A and B). This could happen due to dissipation, separation or fusion with other ongoing events. This is the case for the events registered from December 12 to 15, where this work defined four MCCs, but Climanálise (2003c) only showed one MCC on December 13.

This work only evaluated the physical characteristics identifying MCC events (Size A and B), and did not consider the

Table 5 – MCC total precipitation (mm) and contribution relating to monthly and three month precipition totals in percentages (%).

		October/2003			November/2003			December/2003			3 month Accumulation		
Nº	weather station	Total (mm)	MCC (mm)	Contrib (%)	Total (mm)	MCC (mm)	Contrib (%)	Total (mm)	MCC (mm)	Contrib (%)	Total (mm)	MCC (mm)	Contrib (%)
1	Bagé	187	117	63	193	124	64	107	77	72	487	318	65
2	Bom Jesus	219	147	67	122	49	40	330	162	49	671	357	53
3	Cachoeirinha	199	150	75	108	79	74	207	139	67	513	368	72
4	Cambará do Sul	232	186	80	72	23	31	218	116	53	523	325	62
5	Campo Bom	204	134	66	102	57	56	215	141	65	521	332	64
6	Caxias do Sul	226	170	75	155	93	60	335	215	64	716	478	67
7	Cruz Alta	227	155	68	214	121	57	328	196	60	769	472	61
8	Encruzilhada do Sul	225	175	78	143	110	77	184	87	47	552	372	68
9	Farroupilha	217	170	78	104	74	72	299	196	65	620	440	71
10	Ibirubá	219	133	61	187	107	57	395	245	62	801	485	61
11	Ijuí	190	50	26	131	72	55	432	233	54	753	355	47
12	Iraí	271	132	49	142	119	84	341	184	54	754	434	58
13	Júlio de Castilhos	195	130	67	172	93	54	364	324	89	731	548	75
14	Lagoa Vermelha	192	144	75	123	78	63	256	154	60	571	377	66
15	Maquiné	147	100	68	79	64	80	158	88	56	385	252	65
16	Passo Fundo	268	148	55	138	86	63	392	243	62	797	477	60
17	Pelotas	58	39	68	81	38	47	75	11	14	213	88	41
18	Porto Alegre	236	170	72	92	60	65	185	105	57	512	336	66
19	Quaraí	144	94	66	181	130	72	161	120	75	486	345	71
20	Rio Grande	51	30	59	80	62	78	59	9	15	190	101	53
21	Santa Maria	232	177	77	192	165	86	356	243	68	779	585	75
22	Santa Rosa	161	45	28	159	59	37	312	179	57	631	283	45
23	Santa Vitória do Palmar	50	28	56	182	176	96	55	31	57	287	235	82
24	Santana do Livramento	60	32	53	175	117	67	205	83	41	439	232	53
25	São Borja	177	100	56	181	130	72	318	230	72	676	459	68
26	São Gabriel	116	62	53	89	50	56	171	96	56	376	207	55
27	São Luiz Gonzaga	176	80	45	202	144	71	343	254	74	721	478	66
28	Taquari	238	133	56	115	91	80	237	171	72	589	395	67
29	Torres	148	98	66	50	11	21	186	95	51	384	204	53
30	Uruguaiana	246	200	81	146	100	68	176	109	62	567	409	72
31	Veranópolis	225	167	74	164	105	64	397	183	46	787	455	58
	Average	185	119	64	138	90	65	251	152	61	574	361	63

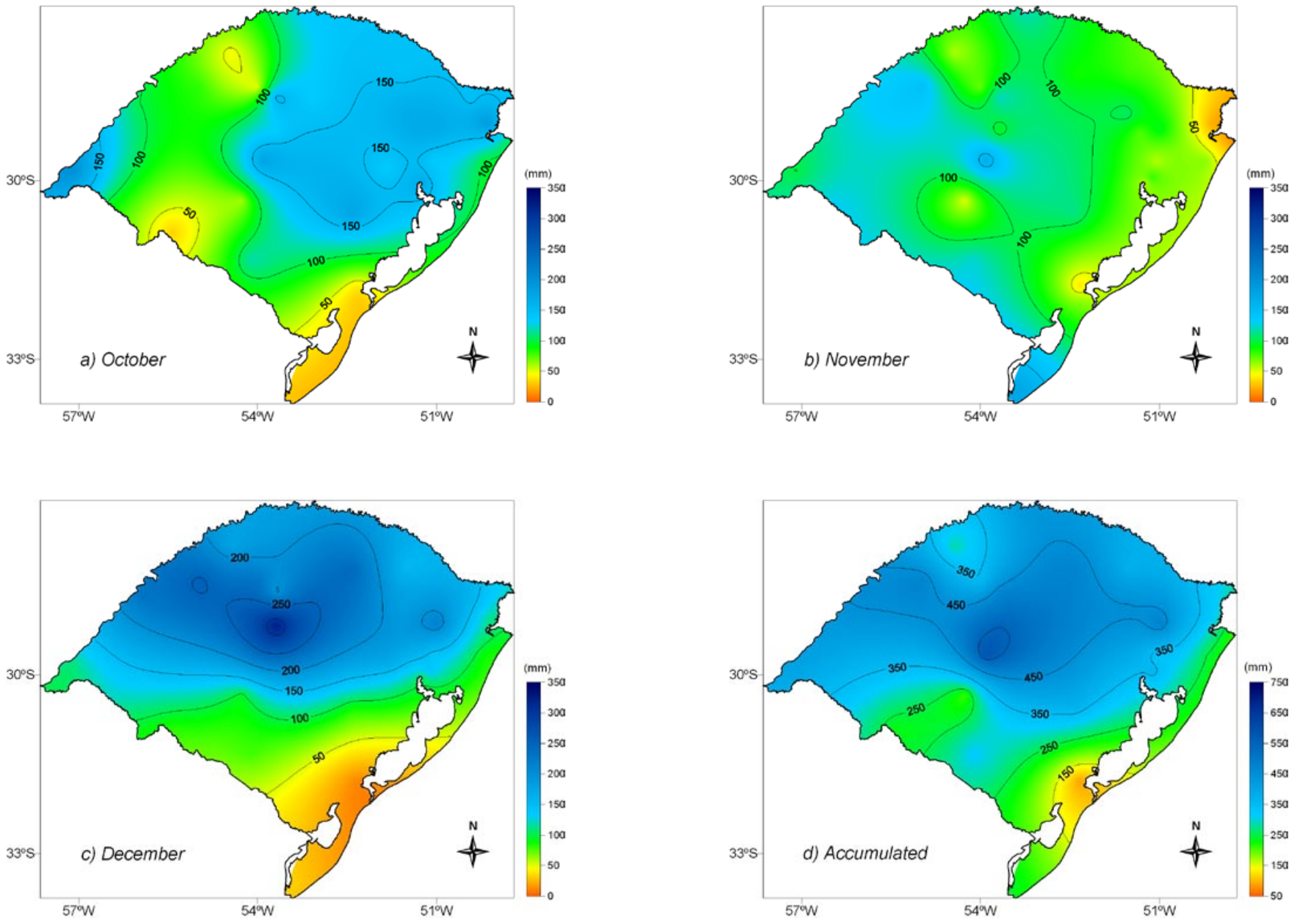


Figure 4 – MCC related precipitation (mm) for RS: October (a), November (b), December (c) and three-month accumulated values (d).

associated synoptic conditions. Although such conditions were not explicitly considered, it was observed that some of the MCCs developed under pre-frontal conditions, where the advance of a cold air mass may have acted as a valley-mountain breeze driver, triggering the convection. Therefore, the differences in results between this work and Climanálise (2003c), regarding the MCC events of December, 2003, may be linked to such atmospheric conditions.

The methodology to evaluate MCCs in RS could be improved, given the operation of a greater number of weather stations with better spatial and temporal resolution. The ideal situation would be the access of hourly observations, but few automatic weather stations, of both official observing systems in RS (INMET and FEPAGRO), operate at this resolution. Thus, the option was to use the maximum number of weather stations, allowing the best spatial coverage for the present study.

6. ACKNOWLEDGMENTS

We thank the team at Divisão de Satélites Ambientais (DSA) from Instituto Nacional de Pesquisas Espaciais (INPE) for all their assistance with the FORTRACC data and images. We also greatly thank Thomas Mote and the anonymous referees for their contributions to this paper.

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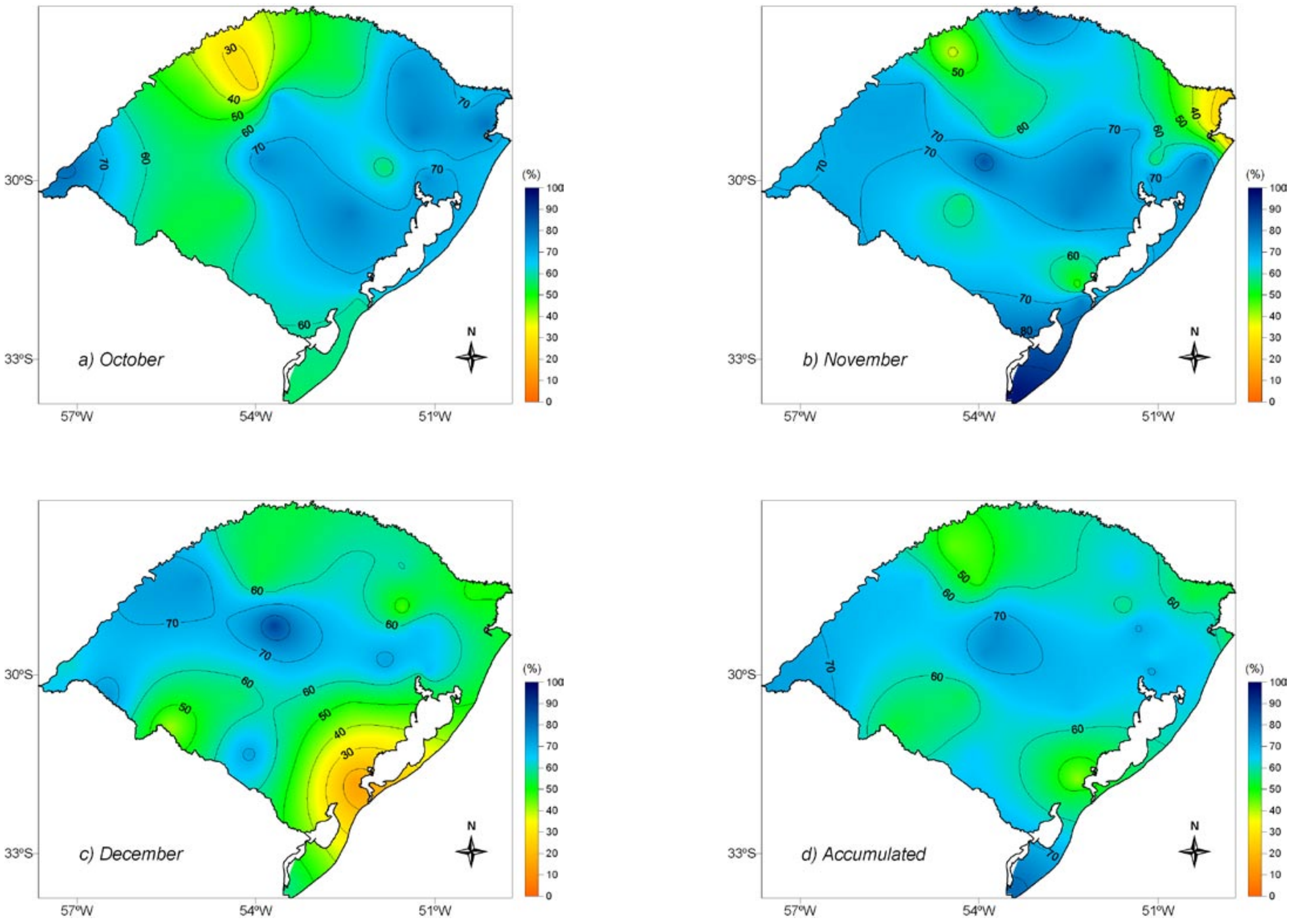

Figure 5 – MCC related precipitation contribution (%) for RS, relative to monthly totals: October (a), November (b), December (c) and the accumulated three months (d).

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