INTENSE RAINFALL OVER THE REGION OF SERRA DO MAR - BRAZIL

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ABSTRACT: Expressive amounts of rainfall may occur during the summer season along all the extension of the mountainous region known as Serra do Mar, which encompasses portions of four states in Brazil – Santa Catarina, Paraná, São Paulo and Rio de Janeiro –, causing landslides and floods. Inter-annual and intra-seasonal oscillations with significant variability in spatial location and range of coverage can be observed, when the phenomenon is analyzed at the appropriate scale. The hazards vary according to geomorphology and land use and the severity of the associated disasters increases with disordered urban occupation. In December 2013 an extremely heavy rainfall occurred over the states of Espírito Santo (ES) and Minas Gerais (MG), killing 45 people and leaving more than 10.000 homeless. These two states are near the region of Serra do Mar forming with it a wider region where the South Atlantic Convergence Zone (SACZ) episodically acts increasing significantly the amount of rainfall during spring and summer. The event of December 2013 resulted from the configuration of some SACZ episodes acting in a sequence over the same area, with little spatial variation from one to the following episode. In this work the frequency of the event is evaluated using data observed in different gages within the region and available Intensity–Duration–Frequency (IDF) curves from a study performed for the whole country in the 1950's. The rainfall amounts registered during the event by 64 available automatic gauging stations and observed at other 127 daily gauging stations are compared to Tropical Rainfall Measuring Mission (TRMM) data sensed over the affected area. The representativeness of the existing monitoring network was evaluated as the TRMM data were validated using time wavelet transform methodology and a multi-resolution analysis (MRA).

Key Words: Natural disasters, representative monitoring network, intense rainfall.

1. INTRODUCTION

Heavy rainfalls are common during summer in the Southeast region of Brazil specially due to the phenomenon known as South Atlantic Convergence Zone (SACZ). Depending on the exact place where an episode occurs and for how long it stays over the place severe disasters may develop. Along all December 2013 heavy rainfall occurred over the states of Minas Gerais (MG) and Espírito Santo (ES), causing severe damage to the inhabitants of many cities, 45 in ES and many others in MG, summing up around 50 casualties. The event of December 2013 was caused by a sequence of SACZ episodes that varied very little in position, in reality persisting over one area for the whole month.

The SACZ have been monitored since 1987 in Brazil by CPTEC/INPE with reports published in *Climanálise* bulletin until February 2013 (CPTEC, 2013), and from then on in *Síntese Sinótica Mensal* bulletin (CPTEC, 2014). Some characteristics of the SACZ are already known so that it is possible to identify its episodes.

Referring to the association of extreme precipitation events to the behavior of SACZ episodes, the spatial and time variability of precipitation features, based on point observational data at gauging stations and spatial TRMM satellite data, is examined using the wavelet transform methodology which allows the assessment of the representativeness of both sets of data. In this sense this work shows a new vision of integrate assessment of available precipitation data allowing to identify features of the activeness of precipitation phenomena within different spatial and time scales.

2. THE RAINFALL OF DECEMBER 2013

Precipitation is monitored by the National Meteorology Institute (INMET) in hourly basis at 64 gauging stations within the state of ES and the portion of MG that belongs to the Doce river basin. Daily precipitation is monitored in the same region by the Geological Survey of Brazil (CPRM) in a partnership with the National Water Agency (ANA), at hundreds of gauges, but for December 2013 data from 127 gauges were available. These data revealed a really extreme event, what the consequences have already shown in numbers of homeless people and casualties. Data from the Tropical Rainfall Measuring Mission (TRMM) were also obtained and were summed up for several duration periods along the whole event.

2.1 Data from gauging stations

Observational data showed intense precipitation for the duration periods of 24h, 48h, 72h, 96h (4d), 144h (6d), 192h (8d), 240h (10d) till 360h (15d). As rainfall with these duration periods can be analyzed from daily data it was possible to increase the number of investigating points to 191 filling in gaps occurred in the automatic monitoring and enlarging the spatial coverage.

From the daily data, four events of intense rainfall persisting along 4 days or three persisting for 7 days were encountered. The verified intensity of the rainfall was much higher than the threshold to be considered intense, 55mm for 24h (Pfafstetter, 1982), as shown in Figure 1 for most of the days.

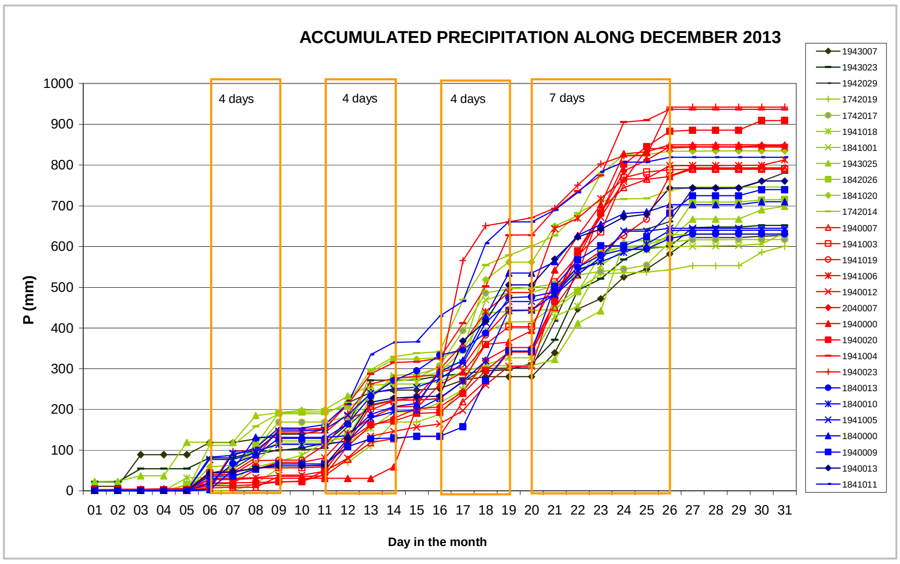

Figure 1: Evolution of precipitation in December 2013

2.2 Comparison to historical records - magnitude and frequency of similar events

Comparing data of maximum total precipitation along 24 hours from the climatology for the region (INMET, 1979 and DNMET,1992) to the maximum 24 hours precipitation at Vitoria station in December 2013, it is easily verified that values of the magnitude of those occurred in 2013, once in November and again in December, have already occurred there as shown in Figure 2. On the other hand the total accumulated in only 6 days in December 2013 was much higher than any of the mean monthly values averaged over 30 years, as seen in Figure 3. The continuity of the precipitation at critical standards is what certainly has contributed to the hazards.

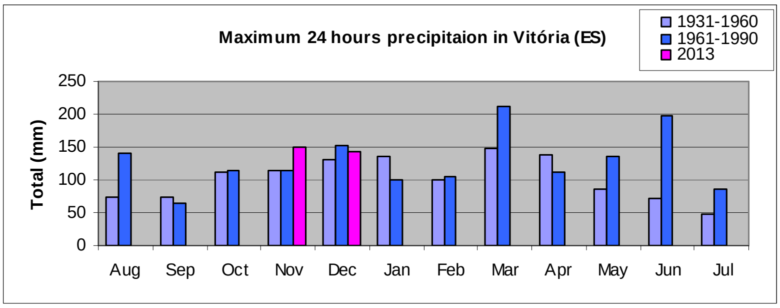

Figure 2: Maximum 24 hours precipitation in December 2013

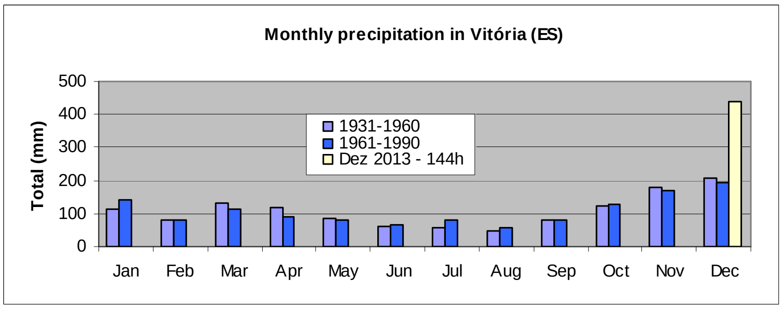

Figure 3: Maximum total 6 days precipitation in December 2013 and monthly figures

The study of Pfaffstetter (1982) was considered for estimating the return time (or time of recurrence) of the event of 2013 for several durations of precipitation within it, as shown in Table 1. The maximum 6 days precipitation over Vitoria (ES) seems to have been really extreme as the estimated TR exceeds 600 years.

Table1: Estimates of TR for the event of December 2013

Duration(h)	P obs (mm)	TR (years)
24	149.2	9
48	185.4	12
72	254.2	43
96	269.0	39
144	439.2	**622**

Events such as the one of December 2013 may be more frequent than expected and this could be confirmed if a regional analysis can be performed for the region over which the SACZ normally acts, instead of using a local or point approach estimate. The magnitude of the events seems to be increasing with time as the proportion of the associated disasters are increasingly higher, although for such a conclusion it should be considered also the increase in occupation of vulnerable areas.

2.3 Data from Tropical Rainfall Measuring Mission (TRMM)

TRMM data were obtained for each 3 hours and also summing them up for 4d, 6d, 7d, 10d, 14d and 17d duration for the period from 2013/12/05 to 2013/12/27, the most intense in rainfall. These data were tested comparing them with the observed figures. Figure 4a and Figure 4b show how broadly was the event of 2013 and its persistency over the central region of ES and the Doce river basin in MG.

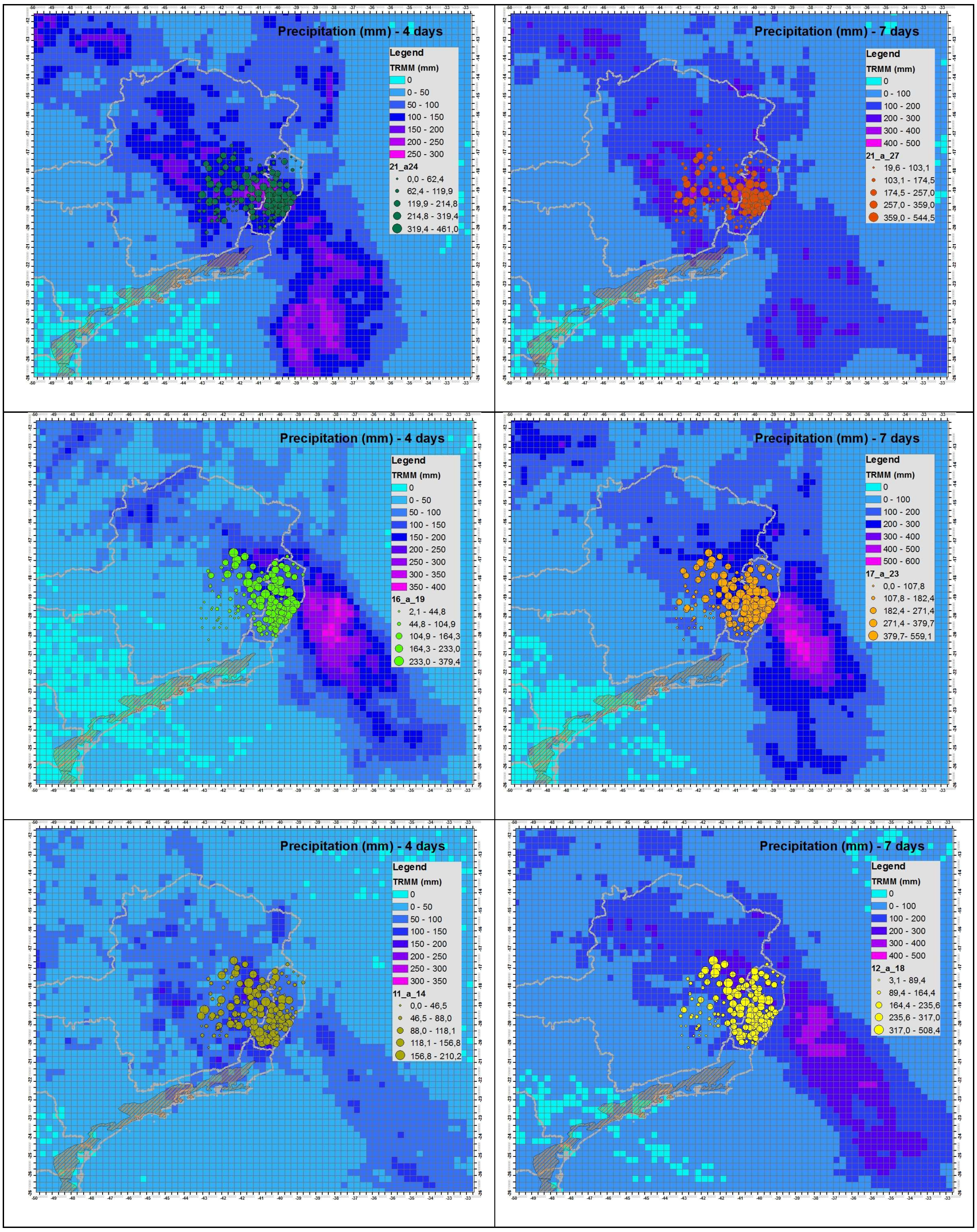

Figure 4a: Evolution of the 4 days long (left) and 7 days long events (right) - Accumulated precipitation - TRMM and observational data depicted with proportional symbols - from 11 to 27th December 2013.

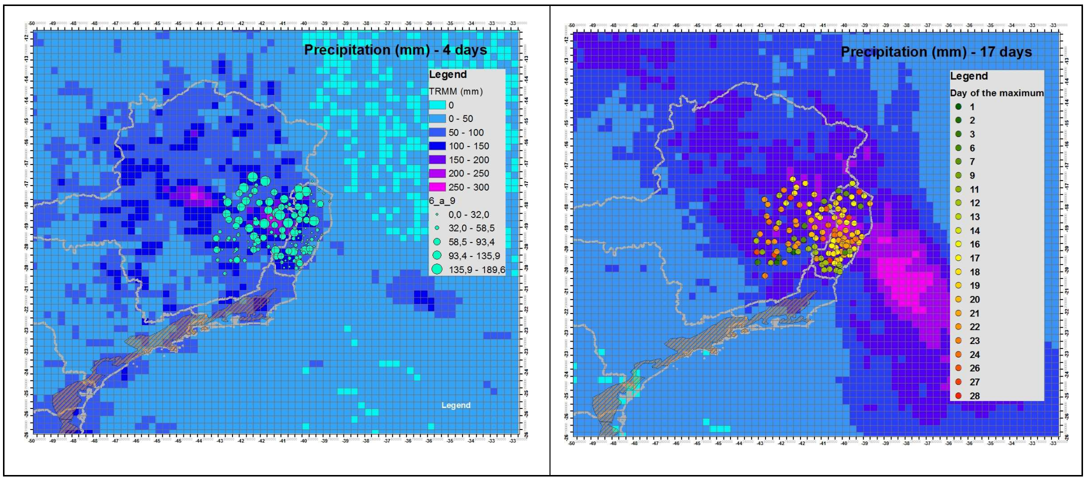

Figure 4b: Coverage and magnitude of the 4 days accumulated precipitation from 6 to 9th December 2013 - TRMM and observational data depicted with proportional symbols (left). Day of the maximum precipitation in each gauging station over the image of the accumulated 17 days precipitation sensed by TRMM (right).

3. MULTIRESOLUTION ANALYSIS OF THE TEMPORAL VARIANCE AND CORRELATION OF GRIP TRMM AND DATA METEOROLOGICAL STATIONS

The time series of the Tropical Rainfall Measuring Mission (TRMM) and meteorological station were subjected to a multiresolution analysis (MRA) based on the maximum overlap continuous wavelet transform (Daubechies, 1992) and the Haar wavelet (Haar, 1910). For the wavelet analysis the area of study was divided into four quadrants and the stations within the quadrants had their hourly data compared to the 3 hours TRMM data. Figure 5 shows the quadrants, the selected stations within them and the closest TRMM pixels considered in the analysis.

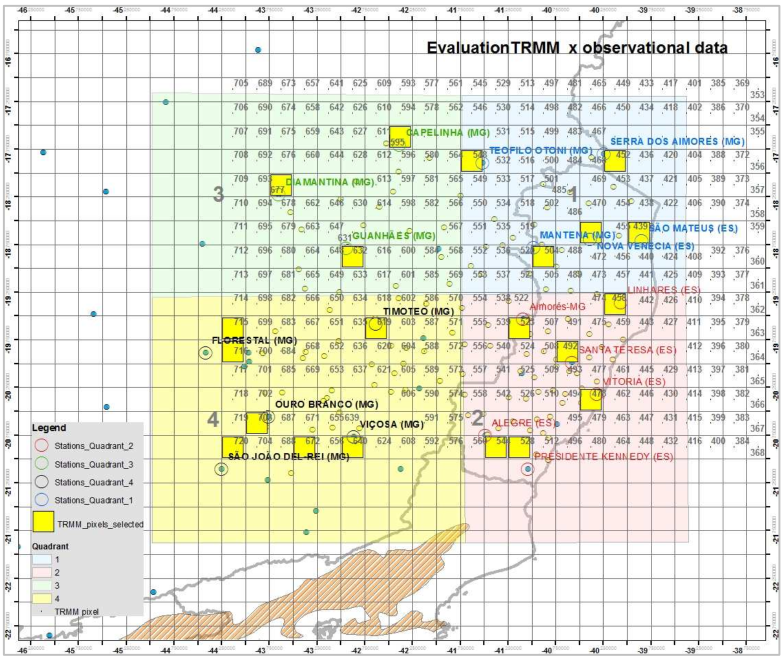

Figure 5: Quadrants and selected TRMM pixels and stations for comparison of figures

Adopting the division of the data base into four sets, following the quadrants shown in Figure 5, the time series of 3 hours precipitation observed at hourly gauging station and the TRMM data of the same period from 12/11/2013 3:00 to 12/31/2013 21:00 were analyzed for validation.

The basic objective of the wavelet transform is to achieve a complete time-scale (or shift-scale) representation of a localized and transient phenomena occurring at different time scales. Multiresolution wavelet analysis (Mallat, 1998) allows the decomposition of a function or signal into a progression of successive approximations and details, corresponding to different scales. The scale *j* corresponds to a time scale 2^{-j} relative to Δt present in the real signals. For example, if Δt = 3 hours, *j*=1 corresponds to a time scale of 6 hours and *j* = 2 corresponds to a time scale of the 12 hours.

The effects of the averaging over time on the variance of the time series and on the correlation of TRMM and meteorological station are studied here. Figure 6(a,b,c,d) shows the scale- dependent variance of the wavelet details D_j, J є {1, 2, ...,6} for the TRMM grid and the meteorological stations data, normalized to the total variance of the full 3 hours resolution time series in the Quadrants 1, 2, 3 and 4. This normalization has been chosen to ensure better comparability between the values of TRMM and meteorological stations data, by removing the effects of a non-unity slope in an assumed linear relation between both quantities. Both time series exhibit a very different time scaling behavior:

Figure 6a shows the scale dependence for the levels of decomposition j = 1 to 6 (D_1- 6h; D_2-12h; D_3-24h, D_4-48h, D_5-96h, D_6-192h) of the TRMM pixel closest to each of four stations representative of Quadrant 1, for time scale of 3 hours. It is possible to notice that that TRMM data greatly overestimate precipitation at the stations Nova Venécia and Serra dos Aimorés, where lower amounts were registered. For São Mateus and Teófilo Ottoni, where the registered amounts of precipitation were higher, TRMM data also overestimate the registered amounts of precipitation at the stations but the values were closer to each other. It is also visible through the normalized variance that the correlation between the time series of stations and TRMM pixels is better at the levels of decomposition *j* = 4 to 6 (D_4-48h, D_5-96h, D_6-192h), that is, it gets better with time integration at the four stations.

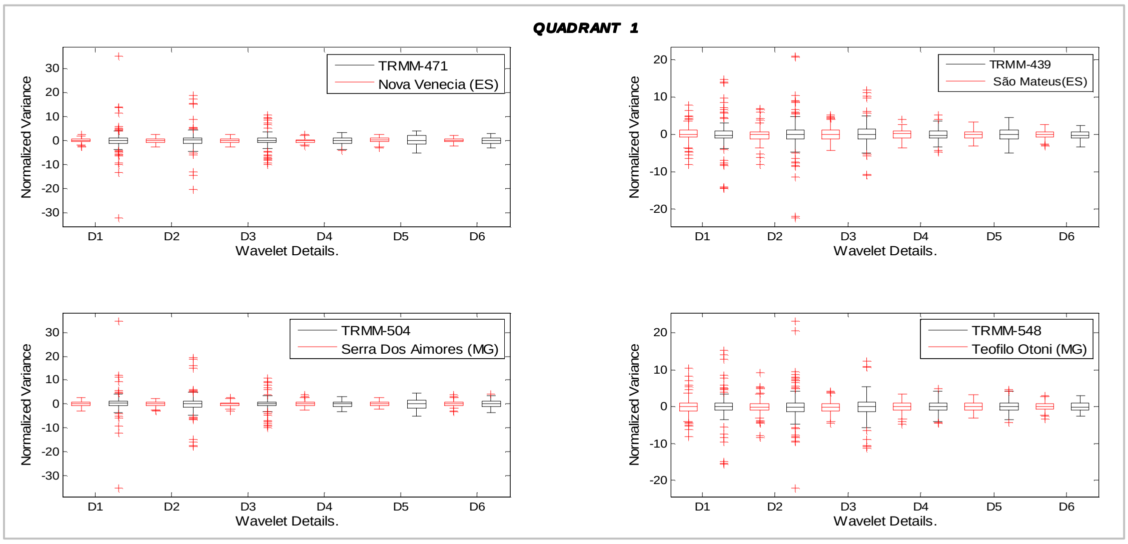

Figure 6a. The variance for the wavelet details (D_1- 6h; D_2-12h; D_3-24h, D_4-48h, D_5-96h, D_6=192h) of the data of the closest TRMM pixel and the data of each of four rain gauge stations located in Quadrant 1, normalized to the total variance of the original time series.

Figure 6b shows the scale dependence for the levels of decomposition *j* = 1 to 6 of the TRMM pixel closest to each of six stations representative of Quadrant 2: Alegre, Linhares, Presidente Kennedy, Santa Teresa, Vitoria and Aimorés. The TRMM data overestimate the registered amounts of precipitations but the values are closer, leading to the conclusion that where the precipitation is heavier the estimates of TRMM are better. The stations in Quadrant 2 are those in red symbols in Figure 1. As observable for

Quadrant 1, it is also visible through the normalized variance that the correlation between data at stations and TRMM pixels is better at the levels of decomposition j = 4 to 6 (D_4-48h, D_5-96h, D_6-192h), that is, it gets better with time integration at the six stations.

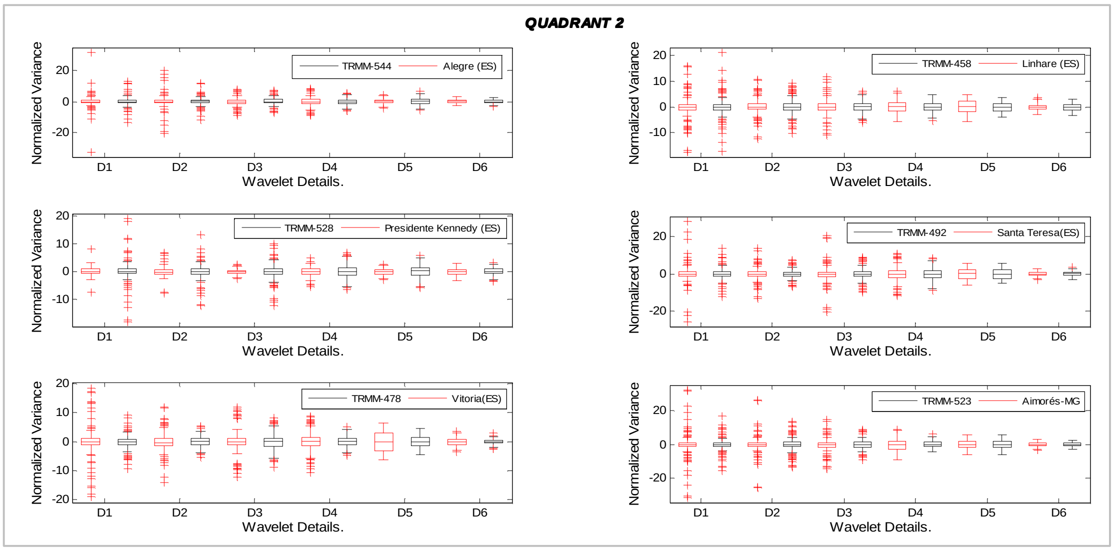

Figure 6b. The variance for the wavelet details (D_1- 6h; D_2-12h; D_3-24h, D_4-48h, D_5-96h, D_6-192h) of the data of the closest TRMM pixel and the data of each of six rain gauge stations located in Quadrant 2, normalized to the total variance of the original time series.

Figure 6c shows the scale dependence for the levels of decomposition j = 1 to 6 of the TRMM pixel closest to each of three stations representative of Quadrant 3: Capelinha, Diamantina and Guanhães. The TRMM data also overestimate the registered amounts of precipitations but the values are closer, leading to the conclusion that where the precipitation is heavier the estimates of TRMM are better, as the area of quadrant 3 was also significantly affected by the catastrophic event. As observable for quadrants 1 and 2, it is also visible through the normalized variance that the correlation between data at stations and TRMM pixels is better at the levels of decomposition j = 4 to 6 (D_4-48h, D_5-96h, D_6-192h), that is, it gets better with time integration at the three stations.

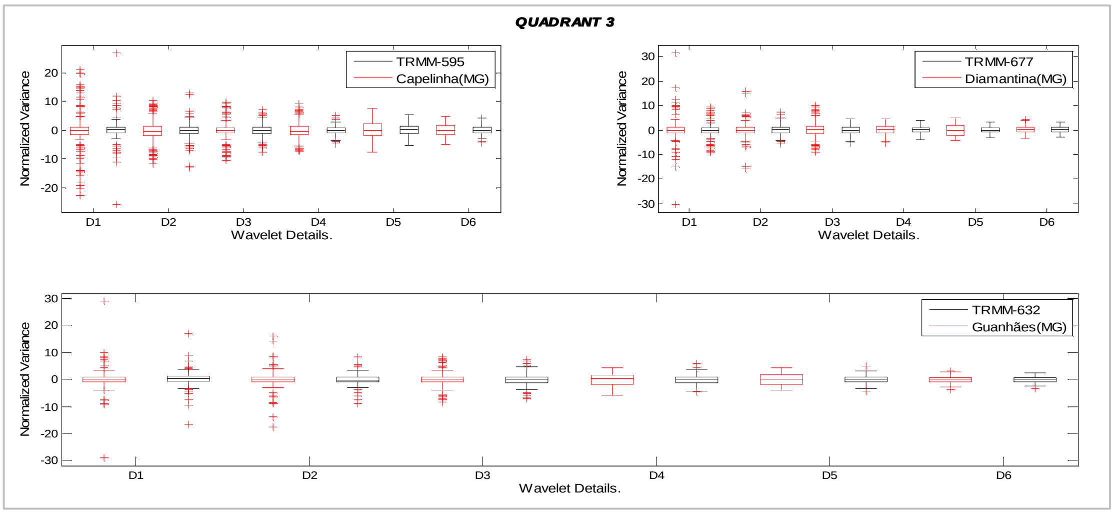

Figure 6c. The variance for the wavelet details (D_1- 6h; D_2-12h; D_3-24h, D_4-48h, D_5-96h, D_6-192h) of the data of the closest TRMM pixel and the data of each of three rain gauge stations located in Quadrant 3, normalized to the total variance of the original time series.

Figure 6d shows the scale dependence for the levels of decomposition *j* = 1 to 6 of the TRMM pixel closest to each of five stations representative of Quadrant 4: Floresta, Ouro branco, São João del Rey, Timóteo and Viçosa. The TRMM data also overestimate the registered amounts of precipitations. Confirming what is observable for Quadrants 1, 2 and 3, it is also visible through the normalized variance that the correlation between data at stations and TRMM pixels is better at the levels of decomposition *j* = 4 to 6 (D_4-48h, D_5-96h, D_6-192h), that is, it gets better with time integration at the five stations.

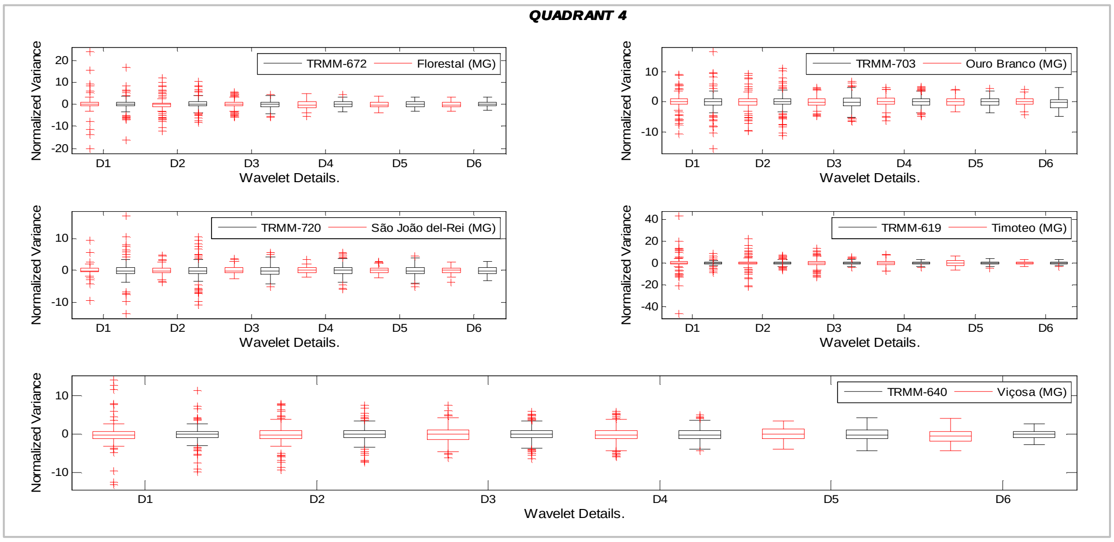

Figure 6d. The variance for the wavelet details (D_1- 6h; D_2-12h; D_3-24h, D_4-48h, D_5-96h, D_6-192h) of the data of the closest TRMM pixel and the data of each of five rain gauge stations located in Quadrant 4, normalized to the total variance of the original time series.

The analysis revealed interesting features of the spectral behavior of the precipitation data. It is possible to conclude that, depending on the number of hours of accumulated precipitation, different adherence patterns may result between observational data and TRMM data. In special for the two quadrants where the amount of precipitation was greater (3 and 2), the adherence was stronger. In general, considering the different duration times, the adherence was stronger from the second day on for all quadrants (Figures 6a, 6b, 6c and 6d). In the case of extreme events, data on hourly basis present similar distribution among each other.

The study demonstrates that the multiresolution analysis (MRA) well suits the investigation of scaling properties of time series and the scale-dependent correlation of related quantities. We have successfully applied it to quantify the influence of time averaging along different periods on quality of the retrieved data and to obtain validation statistics.

4. CHARACTERISTICS OF A SOUTH ATLANTIC CONVERGENCE ZONE (SACZ) EPISODE

The SACZ is defined as a persistent cloudiness and precipitation band oriented northwest- southeast from the southeast of Amazonia towards southwest of the Atlantic area (Kodama 1992 e 1993; Carvalho *et al*., 2002 e 2004).

Kodama (1992, 1993, 2002) presented several characteristics that distinguish the Baiu frontal zone (BFZ), which takes place in East Asia, from the Intertropical Convergence Zone (ITCZ) and the polar frontal zones and showed the common features shared by the BFZ, the SACZ and the South Pacific Convergence Zone (SPCZ), which are significant precipitation zones in the summer Southern Hemisphere. Some common characteristics of BFZ, SACZ and SPCZ are as the following:

- commonly form along the subtropical jet on the eastern side of a quasi-anchored trough;

- rainfall amount attains ~400 mm/month when they are active;
- are characterized by convergence zones with an interior thick moist layer and baroclinic zones with an upper subtropical jet; and
- quasi-stationarity continuing for about ten days.

The active period of the SACZ is, in general, December-January-February, but it may occur from October to March as well. The characteristics of the extreme precipitation related to the SACZ are: seven days of continuous precipitation of which total exceeds 40% of the monthly climatology and presents at least one day of precipitation amount above 20% of the monthly climatology (Ferraz and Ambrizzi, 2006). These features are verified in the event of 2013, as the maximum 24h precipitation 142,4mm observed in Vitória exceeded the 20% of climatologic features, so happening to the maximum 6 days total precipitation 439,2mm that greatly exceeded the mean monthly totals in Vitoria as seen in Figures 2 and 3.

Because of the high amount of precipitation produced by BFZ, SACZ and SPCZ, Kodama (1992) referred to them as Subtropical Precipitation Zones (SPZs). To investigate their large-scale characteristics the referred author utilized geopotential height, temperature and wind at 8 levels, from 100mb to 1000mb or surface, and relative humidity or dew point temperature from 400mb to surface. The configuration of the SPZs and rainfall activities were studied from twice-daily OLR (outgoing longwave radiation) data for eight years, from 1979 to 1986, and station data of precipitation to investigate the rainfall amount from December 1978 to November 1979 but no observation stations were found at appropriate sites to discuss the rainfall amount of the SACZ (Kodama, 1992).

By the ORL data Kodama (1992) showed the SACZ in 1979 stagnated around 20º W, between 20ºW and 40ºW with much cloudiness before the first ten days in February, then it weakened between to second ten days in February and the first ten days in March, and became migratory around 20ºW after the second ten days in March. All these are showed along the latitude of 30ºS where there is no land and therefore only sea with no observational data.

It would be interesting to compare the event of 2013 with the extreme event occurred in the same region, ES and MG, between January and March 1979, considered to have been the most catastrophic ever in the region until December 2013. Possibly the event of 1979 was caused by an episode of SACZ acting over the coast. It is possible that the SACZ episode has had similar characteristics in spatial distribution acting over the ocean and over the continent just as it happened in 2013.

The 1979 precipitation data were analyzed in this work identifying two periods of great intensity of precipitation one from 5 to 8th of January and other from 18th of January to 8th of February, having more intensity the periods of 6d and 10d of duration between 30th of January and 5th or 8th of February 1979. These periods are in accordance with the activity of the SACZ described by Kodama (1992) for the region of the parallel 30º S.

Carvalho *et al*. (2002) studied the anomalies of ORL depicting less than 220 $W.m^{-2}$, which is a threshold usually related to high clouds in the tropics, in order to evaluate the occurrence of extreme precipitation over São Paulo. They analyzed the spatial variability of the convergence defining three main regions or fractions: amazonic, coastal and oceanic. It is clear that maximum spatial variability occur during December, January and February over the coastal and oceanic fractions. The SACZ may sometimes stretches from the Amazonia to the Atlantic Ocean and other times reaches only the Southeast region. The intense activity with extent to the Atlantic intensifies the precipitation over Serra do Mar (Carvalho *et al*., 2004).

This work highlights that the most rainy trimesters are November-December-January (CPRM, 2011) in the region studied, for which the climatology reveals total amounts varying from 450 to 850mm. Figure 5 shows the isohyets of the most rainy trimester (NDJ), together with accumulated precipitation data from TRMM along the period 10^{th} to 27^{th} of December 2013, revealing that the total amount of 17 days are comparable to the climatology of the whole most rainy trimester.

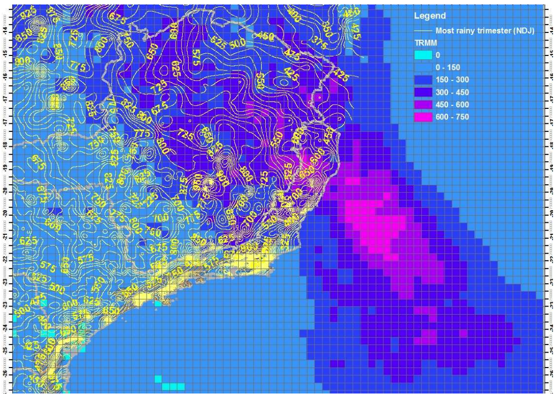

Figure 7: Isohyets for NDJ and total 17 days amount of precipitation in December 2013.

5. CONCLUSION

The TRMM data estimate adequately the precipitation during the occurrence of episodes of SACZ in the Southeast of Brazil. This could be checked against observational data at 191 stations. The catastrophic event of December 2013 in MG and ES was composed by at least four episodes of SACZ, having duration from 4 to 7 days, all days with amounts much higher than the threshold 55mm/24h considered intense by Pfafstetter (1982), at most part of stations. It is also possible to consider that the event persisted for 17 days. The SACZ episodes were marked by intervals of no precipitation at most part of the stations or of less intense precipitation at the other part, as seen for 10th, 15th and 20th of December in Figure 1.

The SACZ is a phenomenon that happens every year, although presenting a certain inter-annual or intra-seasonal variability in space and time along the continental or coastal Southeast region and over the ocean. It is possible to detect the presence of the SACZ by its identifiable characteristics what helps in forecasting precipitation over the region although it is still not possible to preview the intra-seasonal variability and so to be precise in the forecasting of the heavy rainfall events.

The climatologic features of the most rainy trimester in the South and Southeast regions may be used to delimitate the wide path along which SACZ is frequently active as the isohyets are based on the registers of the observed rainfall averaged over time and the most frequent events influence more in its configuration. Due to the characteristics of the SACZ of producing concentrated intense rainfall during a few days the mean amounts of the trimesters may have occurred during periods of 15 days when the SACZ may have been active over the region.

The return period estimate for the rainy event of December 2013 was based on a study which considered precipitation data observed until 1950, so relatively short time series had been used in it, and the return period for the precipitation of 6 days duration was estimated in more than 600 years. This means that such rainfall magnitude could be rather rare. If a regional approach for all the area where the SACZ may be formed is used instead of a local one the results may be different.

The magnitude of the associated disasters seems to be increasing with time as the number of affected people is always greater then in past events, but any conclusion on this point should take into account the increase in occupation of vulnerable areas. To minimize natural disasters and their consequences it is mandatory to consider the geomorphology of the region to determine areas not to be occupied as they are vulnerable areas such as steep slopes and flood plains, as intense precipitation over the region where the SACZ acts is the rule not the exception being a question of short time to occur at critical standards, over any occupied area along the path of the SACZ.

There are several studies dedicated to determine the possible mechanisms that activate the SACZ, its structure, the position and persistence of its episodes, but is still not possible to preview the exact location where it will occur, the intra-seasonal variability and the persistence of the episodes over the same area.

The present work explores the spatial-temporal relation of observational precipitation data and estimates based on TRMM data using wavelet transforms. The results show that depending on the amount of rainfall, different time scales are activated. The adherence between data of the different sources for short intervals of duration is weak, specially for less significant precipitation amounts. It is also showed that, for intervals greater than 48 hours (or two days) of persistent rainfall, the adherence is stronger between spatial (remote sensing) and point observational data.

From this diagnosis, new guidelines for research may be pointed out in order to provide an integrated assessment in the spatial and in the frequency domains to estimate precipitation associated to uncertainties of occurrence along time, with consequences for regional analysis of hydrometeorological information and its corresponding impacts on the watershed.

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