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Original paper

A case study of a winter heavy rainfall event over the Serra do Mar in Brazil

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Resumen

La "Serra do Mar" es una estrecha cadena montañosa costera, localizada en el sudeste de Brasil, que abriga importantes ciudades, puertos, industrias y vías de comunicación. Esta región resulta muy vulnerable a las avalanchas de lodo y piedras, debido a sus inclinadas laderas y a las frecuentes e intensas lluvias. En el presente trabajo se estudia un caso de ocurrencia de avalanchas durante el período de invierno, es decir durante la estación seca, que sorprendió a las autoridades de la Defensa Civil y provocó la muerte de varias personas. El objetivo de la investigación es indagar las causas que condujeron a las avalanchas, con el fin de apoyar la tarea de los pronosticadores y los organismos tomadores de decisiones. Las lluvias fueron de tipo estratiforme y estuvieron asociadas a la presencia de un frente frío relativamente intenso que permaneció en la región alrededor de 6 días. Ese sistema se tornó estacionario en la costa del Estado de San Pablo, mientras que el anticiclón post-frontal, inicialmente frío, fue adquiriendo paulatinamente características barotrópicas. Esa situación originó vientos persistentes del sur y sudeste en superficie, que eran ascendidos por la Serra do Mar. El pasaje de una vaguada de onda relativamente corta en los niveles altos de la atmósfera, si bien no fue la causa principal de las lluvias, contribuyó a incrementar la inestabilidad termodinámica y, por lo tanto, a aumentar la intensidad de las lluvias creando condiciones favorables para la ocurrencia de avalanchas.

Palabras clave: fuertes lluvias, derrumbamientos, orografía, Brasil.

Abstract

Serra do Mar is a mountainous region vulnerable to landslides due to frequent summer heavy rainfall and steep slopes. These mountains are located in Southeastern Brazil and lie along the coastal region. Major cities, industries, roads and pipelines are established in the Serra do Mar. A reference of landslides occurred in the winter of 2004. This is a rare case in the dry season and the civil defense was caught unprepared. We investigate the causes of these landslides in order to provide some guidance to forecasters and policy makers. Rain was mainly from stratiform clouds associated with a relatively intense cold front which persisted for about 6 days in the region. The cold front became stationary on the coast of the State of Sao Paulo as the post-frontal anticyclone, which was initially cold, acquired a barotropic structure and, consequently, a semi stationary behavior. The large scale circulation determined the persistence of southerly and southeasterly winds near the surface. After reaching the continent, these winds were lifted by the Serra do Mar mountain chain. The progression of a shortwave trough to upper levels was not the major cause of heavy precipitation, but contributed to enhance the thermodynamic instability and increase rainfall, which caused the landslides in the Serra do Mar.

Key words: heavy rains, landslides, orography, Brazil.

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Introduction

The Serra do Mar mountain range extends along the coastline of Brazil, from Rio de Janeiro state to Santa Catarina state (see Figure 1 for geographical location), ranging from 700 to 1,500 m. This narrow mountain range is a set of festoon scarps, which exhibits one face that decline abruptly toward the ocean, while the opposite face declines very gently inland. Geologically it is composed of metamorphic and igneous rocks related to the Precambrian Basement Complex, such as granites, schists, gneisses, and migmatites. Important civil works, such as highways, railways, pipelines, and high-power lines cross these mountains. Major cities and industrial complexes are also located in the influence area of these mountains. Marginally constructed housing and small villages are generally established on the slopes of the Serra do Mar Mountains where heavy rains and subsequent landslides frequently occur during summer. This area has a history of mass movement events and accidents. Superficial processes such as mass movements, floods, erosion, creeps, silting and mud-debris flows are geological hazards responsible for major social and economic damages in Brazil. Shallow landslides are the most frequent type of mass movements occurring in Serra do Mar. There are significant portions with high natural susceptibility and high mass movement risks.

The climate of the Serra do Mar region is classified as a humid tropical climate with dry season. The overall average annual rainfall ranges from 1,500 to 2,500 mm, but values around 4,000 mm can be locally observed in the Itapanhau Valley (at about 23,5° S; 46,0° W), being one of the largest annual rainfall in Brazil. Rainfall is concentrated during summer, which amounts for 70% of the annual total, while winter months (June to August) are characterized as the dry season, with monthly precipitation around 100 mm.

Seluchi and Chou (2009) carried out a synoptic climatology study to investigate the large scale patterns related to these landslide events during the summer season. The presence of the South Atlantic Convergence Zone, a feature of the South American Monsoon (Vera *et al.*, 2006), associated with blocking systems over the Atlantic Ocean depicts a situation favorable to landslides in the Serra do Mar region. On average, landslides occur after at least two days of rain concomitant with the progression of an upper-troposphere short wave that enhances precipitation.

According to the Institute for Technological Research (IPT) data, more than 85% of landslides events occur during the summer season, between November and April. For this reason, it is difficult to perform statistical analyses of heavy rain events during winter. However, although heavy precipitation and landslides are concentrated in summer, they could be present during winter, the dry season. This kind of phenomenon is rare, and due to its low frequency (about 1 case every 3 to 4 years, on average), they are less studied, which makes it more unknown and challenging for forecasts and early warnings. These events are statistical outliers and their conditions are generally overlooked by forecasters. Therefore, this work tries to give some insight on the environmental conditions favorable to these rare events that cause landslides and deaths.

The objective of this work is to investigate the major mechanisms responsible for the heavy rains which occurred between 19 and 20 July 2004 in Serra do Mar. This event represents one of the most extreme landslide events in the past 15 years in the region. The identification of the atmospheric patterns related to these hazardous situations would help operational meteorologists and policy makers to mitigate the negative impacts and reduce loss of human lives.

Few references in the literature can be found on orographic heavy rains in Brazil, particularly during winter months. Severo (1994) carried out a climatological study of synoptic weather systems that produce heavy rainfall events during the whole year in the Itajai Valley, southern Brazil. He identified five different typical large scale patterns related to those events: cold and warm frontal systems, upper level cyclonic vortices, storm track configuration and low level jets. Haas *et al.* (2002) investigated a case of heavy rains in the mountain area of Santa Catarina, south of Brazil about 29°S. These rains were caused by a deep upper-level cyclonic vortex. Sias and Silva-Dias (2002) studied a convective event which occurred during winter 1989 in São Paulo city. In this work, they found that winter precipitation over 50mm/day occurs, on average, once in every ten years and it is mainly related to the passage of cold fronts. In particular, studies focusing the analysis of landslide events in the Serra do Mar region during winter were not identified in the literature.

The South Atlantic Convergence Zone is a common feature during summer in South America and has been identified by Seluchi and Chou (2009) as frequently responsible for heavy rain events during summer. However, as this feature does not form during austral winter, a different mechanism should be responsible for the rare winter heavy rainfall event. The purpose of this work is to contribute to the understanding of processes and weather systems associated with heavy rains and landslides in the Serra do Mar region during the dry season of southeast Brazil.

The results are expected to guide meteorologists and civil defense organisms in order to take early mitigating actions, since the winter meteorological patterns associated with these situations are still not well understood and identified.

Data and methodology

This case study was chosen because of the rare heavy rain event which registered casualties by landslides. The synoptic conditions were analyzed using NCEP (National Centers for Environmental Prediction) reanalysis data (Kalnay *et al.*, 1986), with a 2.5° horizontal resolution, interpolated to the resolution of the limited area model (40 km). This data set has been widely used for diagnostic studies as, despite its relatively low resolution, they usually capture the meteorological patterns at least at synoptic scale. In addition, the subsynoptic scale mechanisms responsible for the heavy rains were investigated by means of numerical simulations with a mesoscale model. The Eta/CPTEC model was included in the study as a tool to understand the physical processes that cause the large amount of rains. The model offers advantage compared to re-analyses because it allows description of the dynamical processes with higher horizontal and vertical resolutions. The Eta/CPTEC model was configured with 40-km horizontal grid size and 38 vertical layers. The numerical integration was carried out for 168 h starting at 1200 UTC on 16 July 2004, using NCEP reanalyzes as initial and lateral boundary conditions.

The Eta Model uses the eta vertical coordinate, developed by Mesinger (1984), which has the property of reducing errors in the calculation of horizontal derivate terms near topography when compared to sigma coordinate. The Eta/CPTEC has complete representation of the physical processes, which includes convective (Janjic, 1994) and explicit precipitation (Zhao and Carr, 1997), the OSU land surface scheme (Chen *et al*., 1997), the GFDL radiation package, with short (Lacis and Hansen, 1974) and longwave (Fels and Schwarzkopf, 1975) radiation, and turbulence scheme of the type Mellor-Yamada 2.5 (Mellor and Yamada, 1974). Further model details can be found in Black (1994) and in the Appendix B of Pielke (2002). The Eta Model has shown to be appropriate for simulations of weather systems affected by orography in South America (Viale 2010; Viale and Norte, 2009; Seluchi *et al.*, 2006; Seluchi *et al.*, 2003).

Results

Synoptic overview

In the period between 16 and 22 July 2004, moderate and persistent rains occurred along the Brazilian coast, particularly in the São Paulo State, between 26°S and 23°S. Over 200 mm of rain were accumulated in this 7-day period in some observational sites. Figure 1 shows the total accumulated precipitation near the coastal regions during the whole period under consideration. The numbers between parentheses are maximum

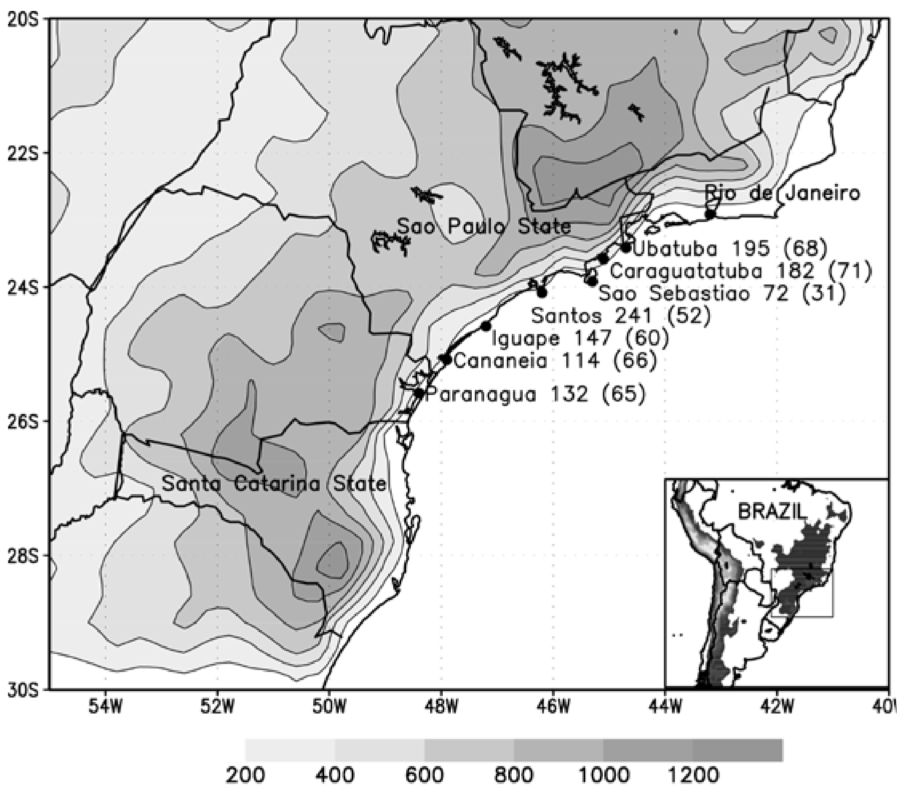


Figure 1. Orography of the region under study (elevations higher than 200 m are shaded) and location of the meteorological stations. Numbers close to station identification correspond to observed accumulated precipitation between 16 and 22 July 2004, at 1200 UTC, while those between brackets represent accumulated precipitation between 19 and 20 July 2004, at 1200 UTC.

values accumulated in 24 hours. As a reference for climatological total for July we can take the 112 mm for Ubatuba, a town located at the foot of Serra do Mar, at 23.5°S (see Figure 1). As a consequence of the rains, landslides occurred in many surrounding areas with casualties and houses destroyed, especially in Caraguatatuba, a neighbor town to the southwest of Ubatuba.

The rains were associated with the displacement of a cold front, which was located in Southern Brazil on 16 July 2004 (Figure 2 upper panels). In general, the frontal system exhibited typical winter characteristics, with enhanced baroclinicity, indicated by the strong wind shear, especially over the Atlantic Ocean, and the presence of an intense post-frontal anticyclone which was elongated in the meridional direction. The sharp moisture contrast between two air masses is clear in Figure 2 (right-upper panel). An interesting feature worth mentioning is that the frontal zone progressed in meridional direction, to the east of the Andes, associated with moderate southerly winds, similar to the case described by Seluchi *et al.* (2006), while the frontal zone displacement was slower along the coastal regions.

On 17 July (Figure 2 central panels) the frontal zone became gradually stationary over the coast of São Paulo, in comparison with the previous day, whereas typical winter cold fronts progress northeastward or eastward. The major post-frontal anticyclone exhibits a shortwave trough deepening over the central region of Brazil, about 25°S and 55°W, which configured two regions of maximum anticyclonic curvature, one located over the Bolivian low plains and the other in Southern Brazil and adjacent Atlantic Ocean. Although this latter anticyclonic branch extends northwards and reaches São Paulo region, the wind convergence occurred to the south of Sao Paulo, leaving the coastal region of Serra do Mar Mountains immerse into the moister air mass.

The synoptic situation became more stationary and less baroclinic on 18 July (Figure 2 bottom panels) as can be seen by the 500-hPa horizontal gradient of geopotential height between 20°S and 30°S. During this period, a shortwave trough approached from the west, at about 25°S, and an opposite phase wave, a ridge, displaced to the south of 30°S. On 19 July (Figure 2_continuation, upper panels), the cold front started to dissipate as the southeasterly winds resume in most part of the Brazilian coast and the near-surface moisture and temperature contrasts start to weaken. At upper levels, the progression of the trough, of shorter wavelength and more intense than the previous day, caused an expansion of the raining areas and an increase of about 300% in rain intensity (as seen in Figure 4) over southeastern Brazil.

Rain attained maximum intensity over the northern coast of São Paulo on 20 July (Figure 2_continuation bottom panels), when the shortwave trough passed through the region. Simultaneously with the displacement of the trough, an upper-level ridge positioned over the surface anticyclone and established an equivalent barotropic system. The anticyclone, with blocking characteristics remained stationary in the following 3 days (21, 22 and 23 July) (figures not included), blowing easterly winds at most of Brazilian coast, and favoring rains from Paraná to Bahia, from 26°S up to about 15°S. Due to the progression of the upper level trough toward the east in this period, precipitation along the coast was weak and of stratiform type. After 23 July, rains gradually decreased due to the displacement of the anticyclone to the east, over the Atlantic Ocean.

The role of large scale forcing

The causes of the rains that produced landslides in the coastal region of São Paulo were investigated with the aid of numerical simulations carried out using the Eta Model. In order to validate the simulations, Figure 3 shows the simulated and observed precipitation during the period of intense precipitation. Figure. 3c shows the distribution of the stations available for precipitation analysis of the case. Despite the limitations of the scarce observations for the comparison, it can be noticed that the model positioned correctly the maximum precipitation in the coastal region and showed the strong contrast of accumulated values from the coastal area to the inland areas of the Serra do Mar region. The quantitative precipitation can be considered well simulated as model values exceeded 240 mm, whereas the recorded values in Santos, coastal town around 24°S, reached 241mm. Because this is a non-WMO listed station, its report did not get into the operational database to be shown in Figure 3a. Unfortunately, only few synop stations were reported to the north, in Rio de Janeiro. The Paranagua station, along the coast at 25.5°S, may be uncertain, as differences with stations nearby are large.

Figure 4 shows the time series of mean precipitation taken in a rectangle around the area of interest, between 23°S-24°S and 44°W-46°W. Figures 3 and 4 show that the Eta Model succeeded in simulating reasonably well the spatial and temporal distribution of the rains. As precipitation is a result of complex interactions between dynamic and thermodynamic processes, the result can suggest that those mechanisms are correctly captured in the model simulation. Another independent corroborating evidence of the model accuracy can be provided by comparing satellite images to model outputs. Figure 5 shows

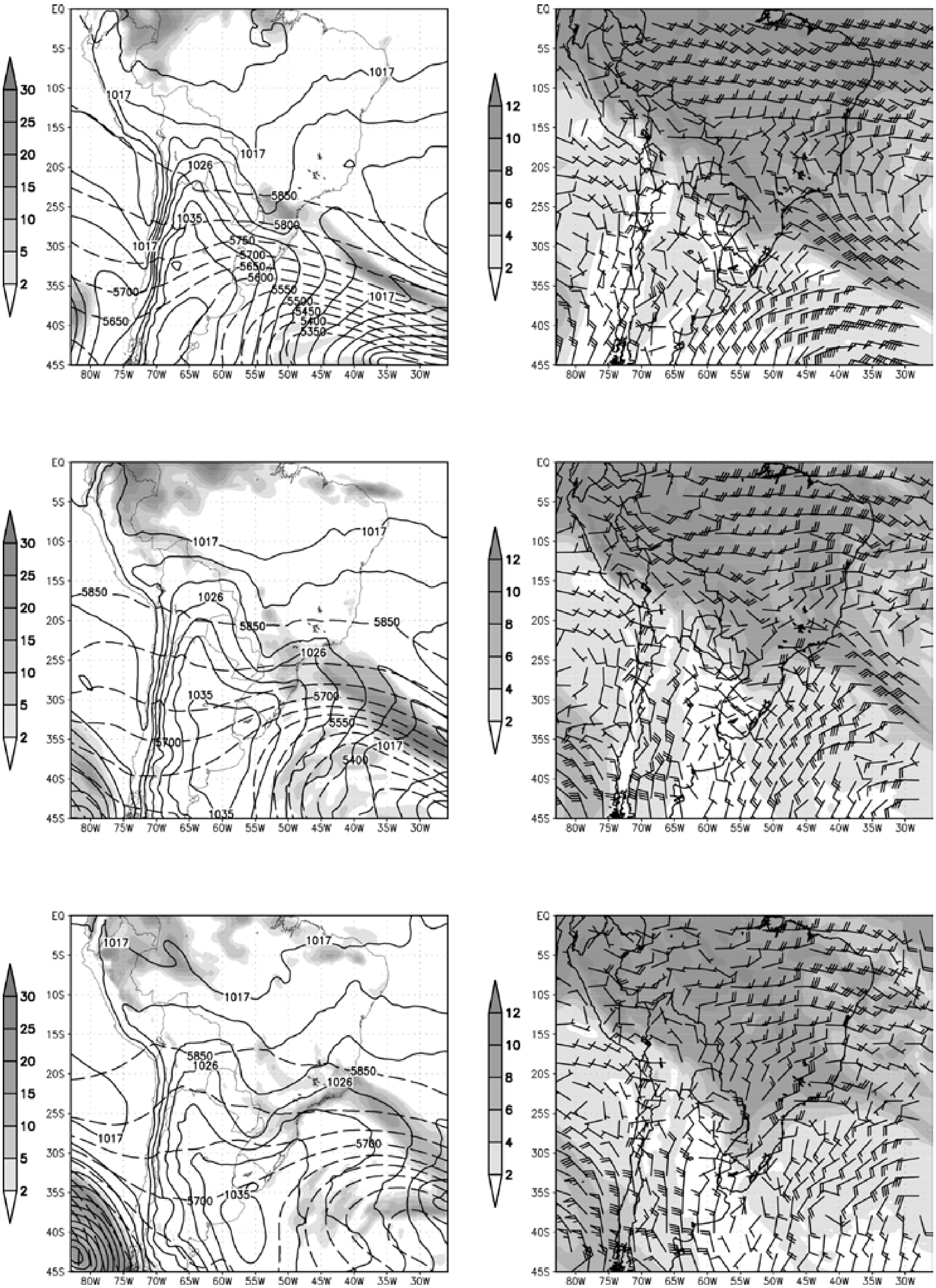


Figure 2. Synoptic conditions on 1200 UTC, 16 July (upper panels), 1200 UTC, 17 July (middle panels) and 1200 UTC, 18 July 2004 (lower panels), derived from NCEP reanalyses interpolated to the Eta-CPTEC model resolution and domain: mean sea level pressure (hPa, solid contours), 500 hPa geopotential height (gpm, dashed contours) and 24-h accumulated precipitation simulated by the Eta Model, to the left; and 850-hPa specific humidity (g/kg, shaded) and winds (barb in m/s), to the right. In all cases model simulation was initiated at 1200UTC, 16 July 2004.

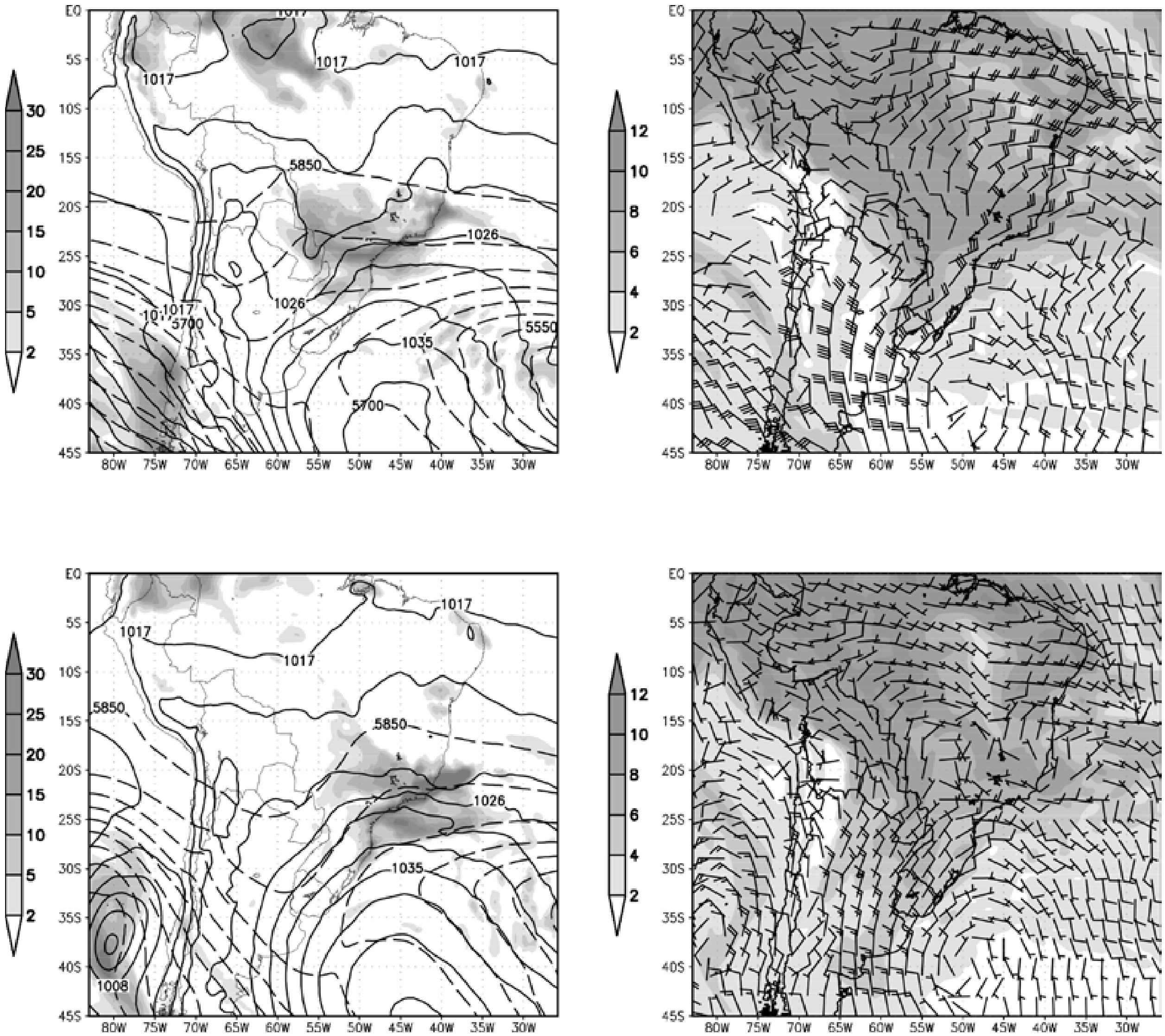


Figure 2._continuation: Synoptic conditions on 1200 UTC, 19 July (upper panels), 1200 UTC, 20 July 2004 (lower panels), derived from NCEP reanalyses interpolated to the Eta-CPTEC model resolution and domain: mean sea level pressure (hPa, solid contours), 500 hPa geopotential height (gpm, dashed contours) and 24-h accumulated precipitation simulated by the Eta Model, to the left; and 850-hPa specific humidity (g/kg, shaded) and winds (barb in m/s), to the right. I all cases model simulation was initiated at 1200 UTC, 16 July 2004.

the GOES-12 Infrared image taken at 2345 UTC July 19 2004, near the moment of maximum precipitation intensity. The total cloud cover from 84-h Eta-CPTEC Model simulation is shown for comparison with satellite image. Mean sea level pressure and 500-hPa geopotential height (contours) are also plotted for completeness of the synoptic conditions. The similarities between observed and simulated cloudiness patterns are evident. In particular, the overcast conditions over Serra do Mar region, the adjacent Atlantic Ocean and most of the southern Brazilian coast as well the inland cloud penetration north of Rio de Janeiro State are well captured by the Eta-CPTEC Model, even after 3.5 days of numerical integrations. Other features, such as the cloud band related to the frontal zone over the Atlantic Ocean, and the two extratropical disturbances detected over both the Atlantic and the Pacific Oceans were correctly simulated. A closer inspection reveals that the open cells observed to the south of the frontal zone are captured by the model in the region of stronger baroclinicity.

As consequence, it can be inferred that the simulation adequately captures the major mechanisms responsible for precipitation occurrence, at least at regional scale, thus denoting that the model is a useful tool for the subsequent investigation.

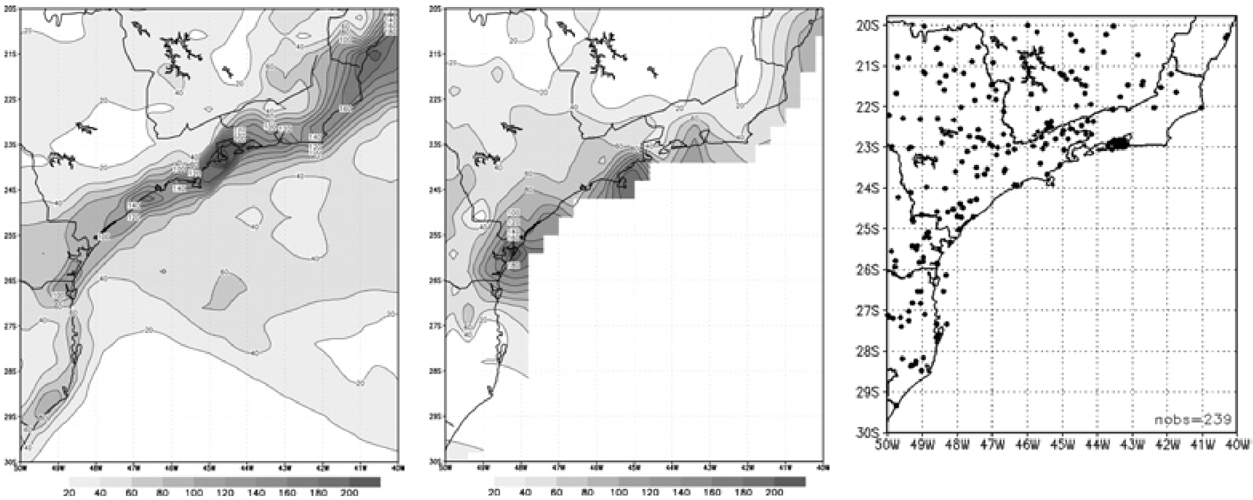


Figure 3. Simulated accumulated precipitation (mm) between 16 and 22 July 2004, at 1200 UTC (left panel) and observed from surface synop stations (center panel) interpolated to the model output grid. Right panel shows meteorological station network used for interpolation.

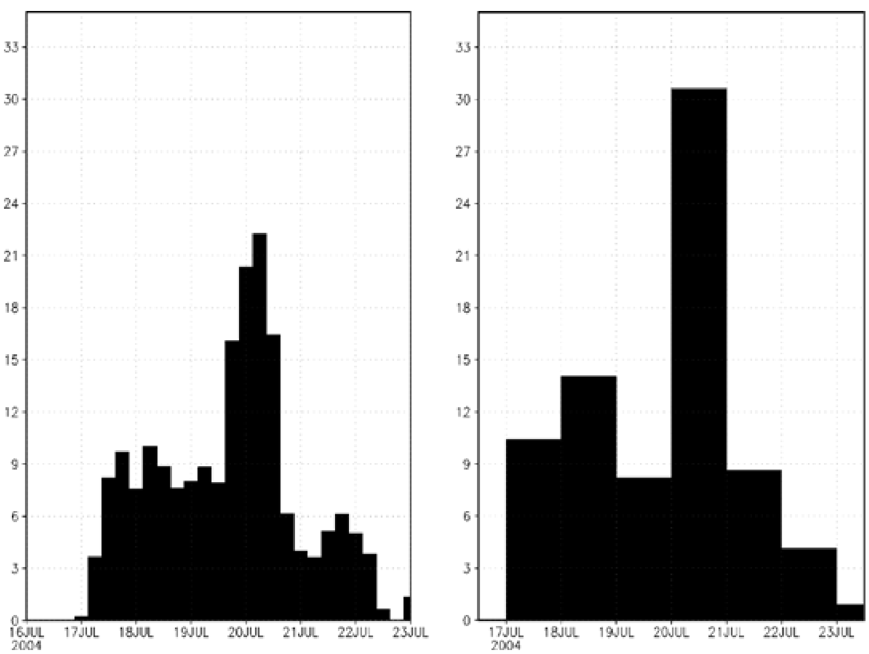
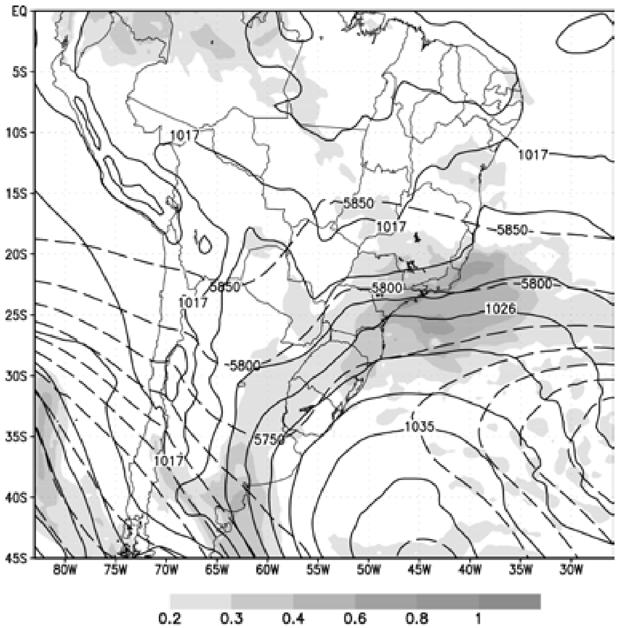


Figure 4. Time evolution of precipitation averaged in the coastal region of São Paulo, between 23°S-24°S and 44°W-46°W (see Figure 7c for station location). (a) 6-h accumulation from Eta Model simulation (mm/6h) and (b) 24-h accumulated precipitation from surface observations (mm/day).

The progression of the shortwave trough and the simultaneous increase of precipitation on 19 and 20 July (Figure 2), indicates that this system may be the primary cause of the intense precipitation. In order to further investigate this aspect, the vertical velocity (Omega) at 700 hPa and the difference in divergence between 300 and 900 hPa (300-hPa minus 900-hPa divergence) are shown in Figure 6. Generalized ascent motion is observed over the Serra do Mar region and also in some portions of southeast Brazil and adjacent ocean. These regions coincide with areas of positive difference of mass divergence (shaded) which indicates more divergence (or less convergence) at upper levels than at lower troposphere. However, in the narrow region of the São Paulo and Rio de Janeiro coasts, the vertical motions do not seem to respond to this dynamical mechanism, as the positive divergence differences are negligible.



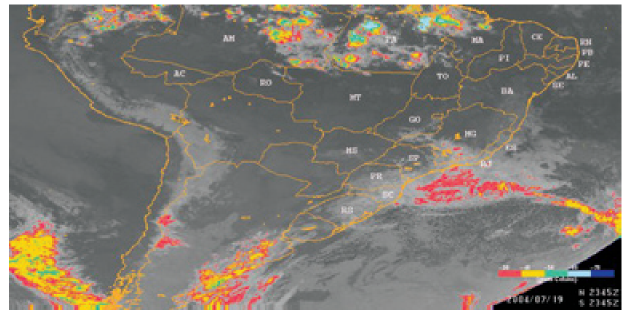


Figure 5. Left panel: Synoptic conditions on 0000 UTC, 20 July 2004 derived from 84-h Eta-CPTEC model simulations including sea level pressure (hPa, solid contours), 500-hPa geopotential height (gpm, dashed contours) and total cloud cover (shaded, from 0 (clear sky) to 1 (overcast). Right panel: GOES-12 Infrared satellite image corresponding to 2345 UTC July 19 2004. Shading indicates cloud top temperatures (°C).

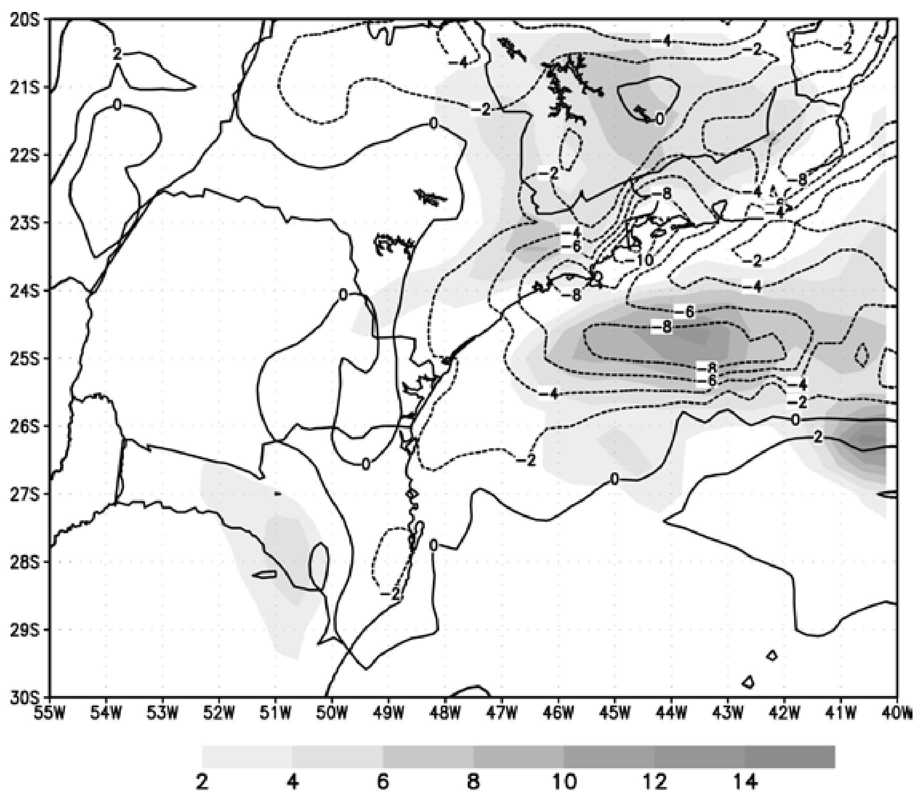


Figure 6. 96-h Simulated 700-hPa vertical motion (Pa/s, contours) and difference: 300-hPa minus 900-hPa divergences ($10^{-5}s^{-1}$, shaded) at 0000 UTC, 20 July 2004.

A supplementary diagnostic is based on the Q vector and Q-vector divergence (Sanders *et al.*, 1990) in combination with the vertical motion at 700 hPa. The convergence of Q vector indicates regions of large-scale forcing and in particular large-scale upward motion. Various areas of significant Q-vector convergence are shown in Figure 7. However, the strong upward motion along the coastal region of São Paulo cannot be explained by this large-scale forcing.

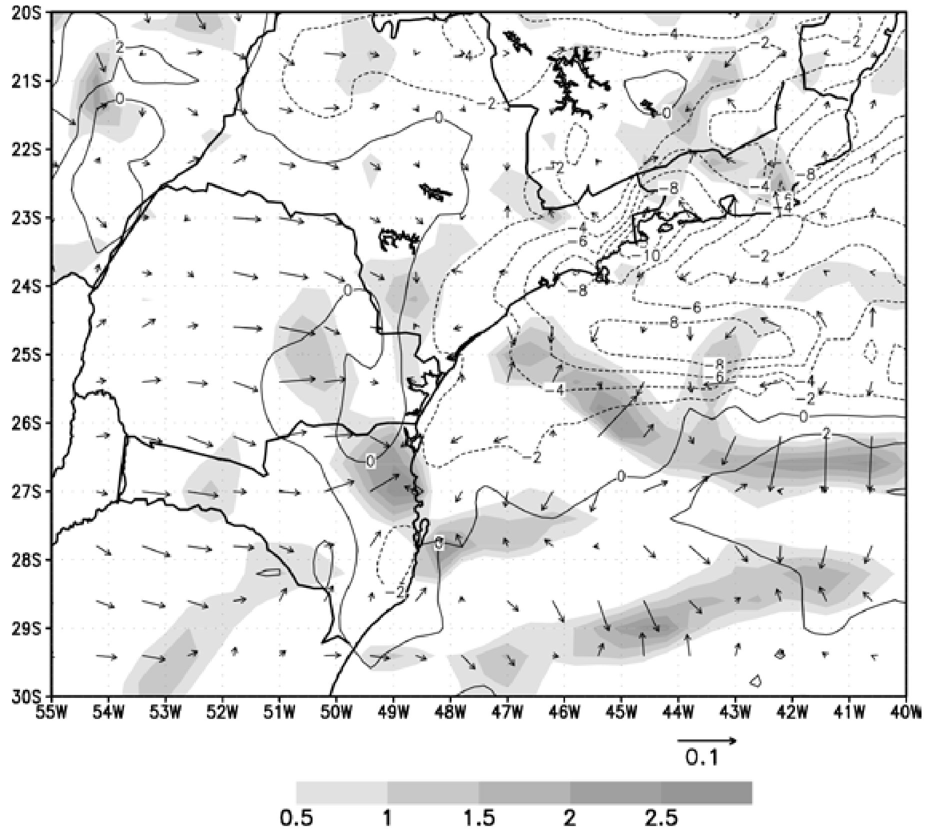


Figure 7. 96-h Simulated 700-hPa vertical motion (Pa/s, contours), Q vector (arrows) and Q-vector convergence (J K Pa m-2 s-1, shaded) on 0000 UTC, 20 July 2004.

For further detailed investigation, Figure 8 shows 24-h accumulated precipitation and the vertical motion at 700 and 850 hPa on 20 July, 000 UTC, when the most intense precipitation occurred. It is important to note the high spatial coherence between precipitation and 850-hPa vertical air ascent which indicates major contribution of the vertical motions from low troposphere in the rain production. Figure 9 shows that convective precipitation mostly occurred inland and in northern part of the coast. Consistently, in the coastal areas of São Paulo model simulations showed that 80% of the precipitation was from stratiform cloud type. This fact can be corroborated with the aid of satellite images (for example as seen in Figure 5) that exhibit low level cloudiness over the coast and the adjacent ocean near the Serra do Mar.

The role of topography

The previous section analysis showed that rains in the coast of São Paulo were associated with upward motion in the lower troposphere, and not due to upper level dynamical processes. This result points to topography as one of the major causes of the large amounts of accumulated precipitation.

To verify this hypothesis, a numerical experiment removing mountains higher than 500 m was carried out. As a consequence, the Serra do Mar Mountains and the central Brazilian plateau were removed as shown in Figure 10. Other characteristics of the model setup were kept the same in the simulation.

In general, the synoptic situation produced by the simulation with modified topography shows the cold front moving faster northeastward and a significant reduction of the rains in the region. Figure 11 depicts mean sea level pressure, 500-hPa geopotential height and accumulated precipitation at 1200 UTC, 19 July 2004. The surface anticyclone and the associated southerly and southeasterly winds have penetrated more inland in comparison with Figure 2_continuation (upper panels) as a consequence of the reduced barrier effect of the mountains. Figure 12 is similar to Figure 3a but produced from the reduced mountain height simulation. Rain has significantly reduced, and represents about 20% of the original amount. They are more evenly spread between inland and the coastal areas and precipitation rates were more uniform in the period and occurred in shorter time, from July 17 to July 21.

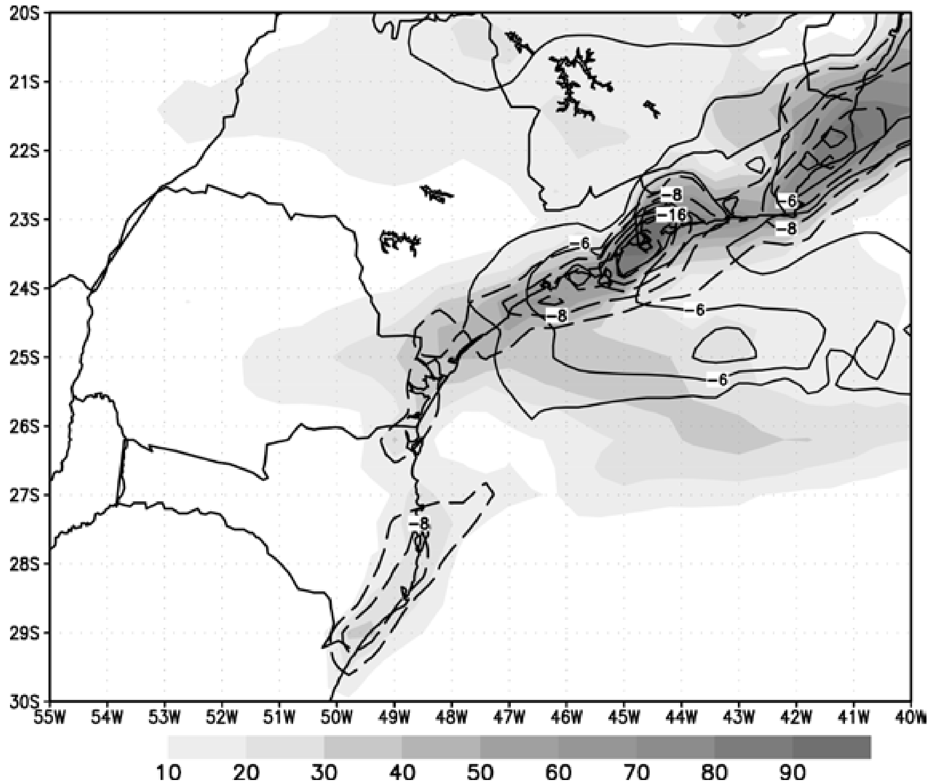


Figure 8. 96-h Simulations of precipitation (mm/day, shaded), 700-hPa (solid contours) and 850-hPa (dashed contours) vertical motions (Pa/s) on 000 UTC, 20 July 2004.

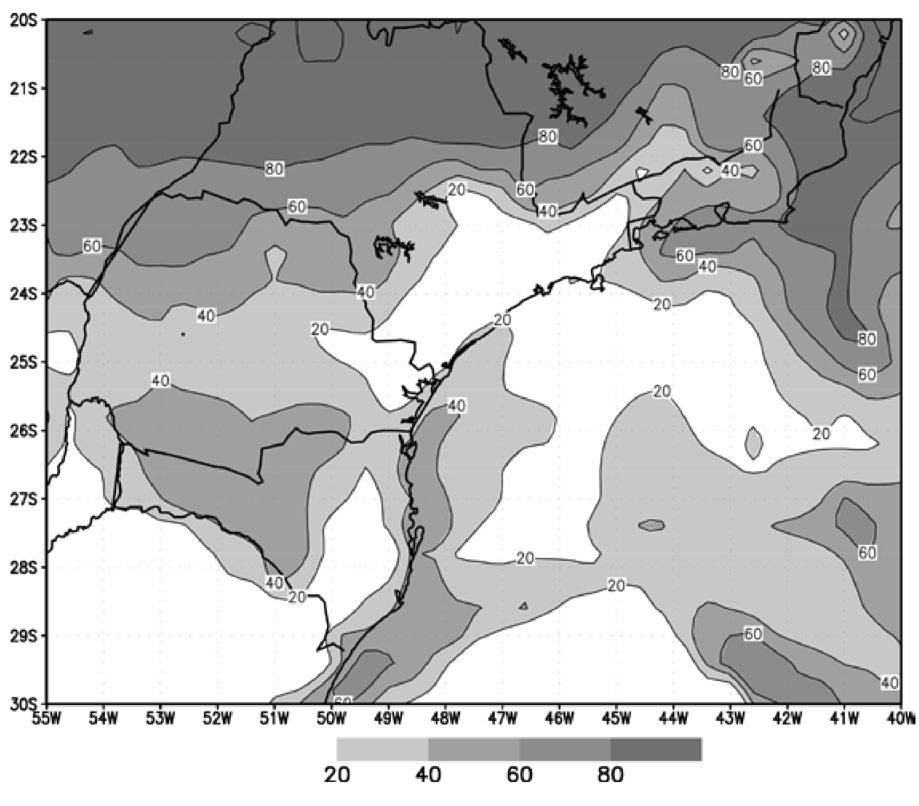


Figure 9. Percentage of convective precipitation with respect to total precipitation, simulated between 16 and 22 July 2004.

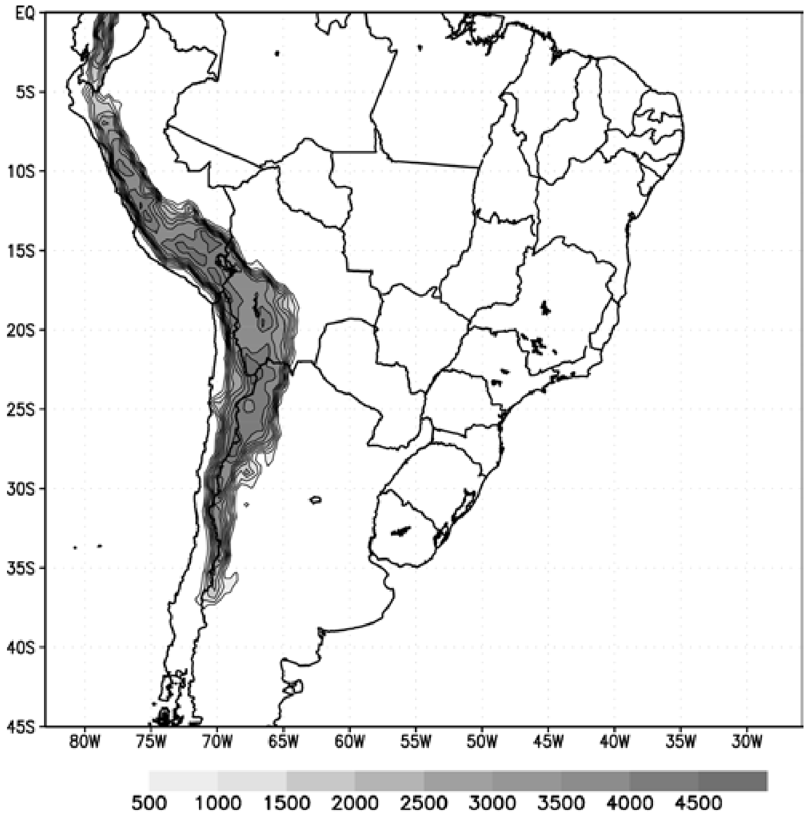


Figure 10. Topography (m, shaded) of the experiment in which elevations over 500 m in Serra do Mar and Central Brazilian Plateau were suppressed.

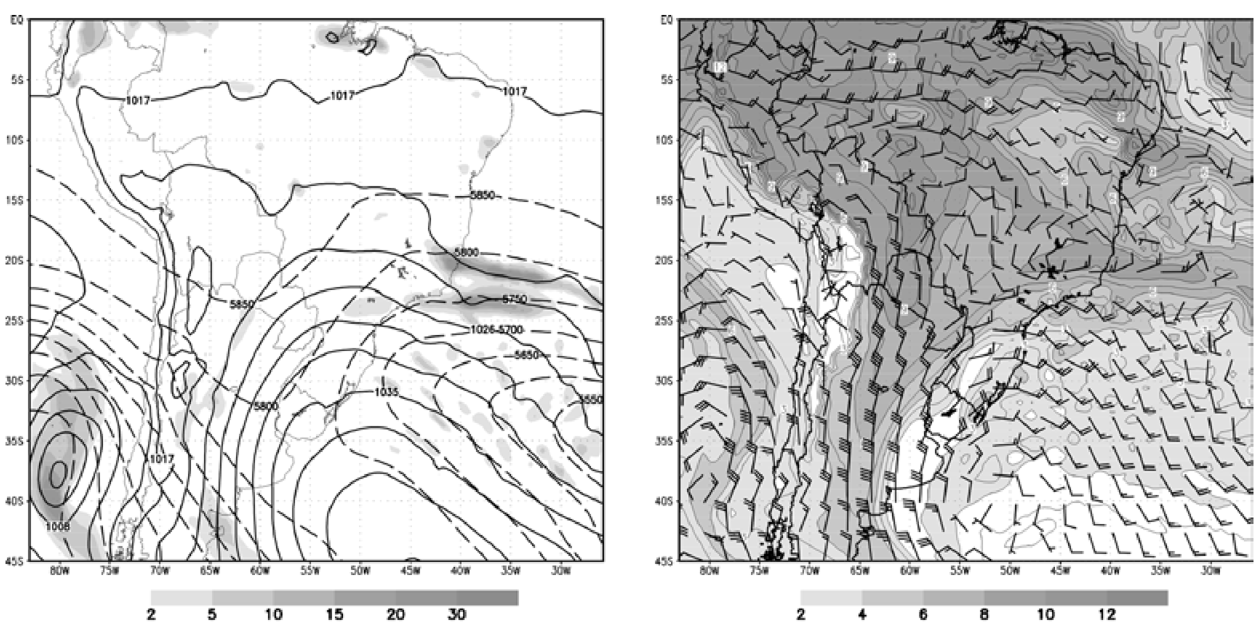


Figure 11. Synoptic conditions on 1200 UTC, 19 July 2004 derived from 84h-Eta Model simulations with reduced mountain elevations: mean sea level pressure (hPa, solid contours), 500-hPa geopotential height (gpm, dashed contours) and 24-h accumulated precipitation simulated by the Eta Model, to the left; and 850-hPa specific humidity (g/kg, shaded) and winds (barb in m/s), to the right.

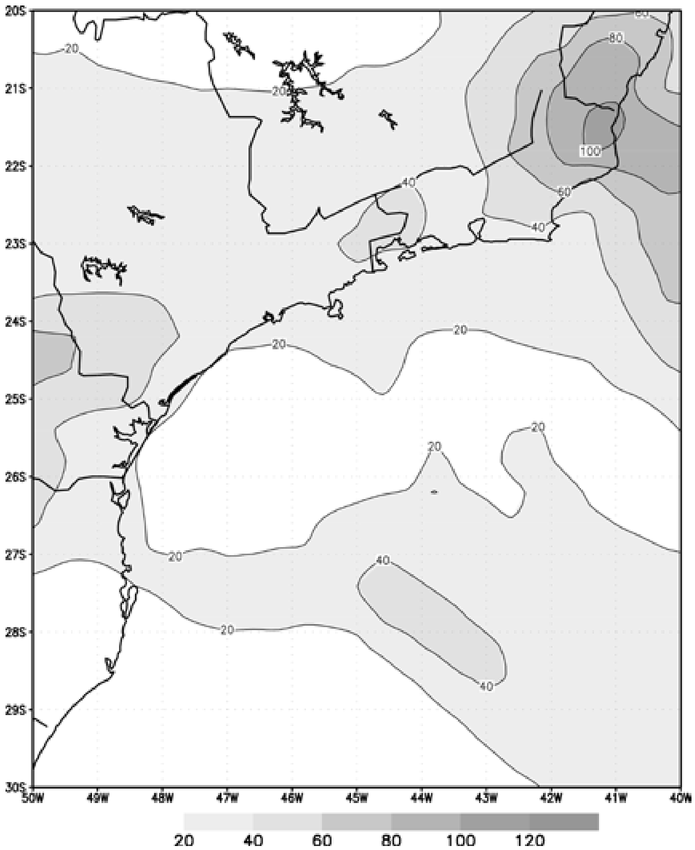


Figure 12. Simulation of accumulated precipitation (mm) in the period between 16 and 22 July 2004 from the experiment with reduced mountain elevations.

Figure 13 shows the difference of vertical motion and mass divergence between the control run and the experiment with modified mountains, that is, control minus experiment runs. In the horizontal plane, Figure 13a shows that the Serra do Mar creates upward motion along the coast, from about 30ºS up to about 20°S, and downward motion in the downwind side of the mountains. This causes a large contrast of accumulated precipitation amounts across the mountains. Besides the change to vertical motion, orography also produces changes to the direction and velocity of the low level winds causing mass convergence on the coastal side and divergence on the inland side of the mountains. The cross section performed at 45°W (Figure 13b) illustrate that, in spite the relatively low altitude of the Serra do Mar, the impact on the vertical velocity attain the medium troposphere favoring upward (downward) motion to the upwind (lee) side of the mountains. Patterns of omega and divergence differences reveal that the Serra do Mar induces a mountain-type circulation with ascending motion and convergence (divergence) near surface (near the 850 hPa level) close to the continent and an opposite behavior off-shore. Positive/negative centers of divergence difference also suggest horizontal wind acceleration (decrease) toward the coast at low (850 hPa) levels and determines maximum vertical wind acceleration near the level of 900 hPa.

As a consequence of the synoptic conditions, it can be stated that the Serra do Mar plays major role in concentrating and enhancing significantly the accumulated precipitation along the coast of Sao Paulo and also to extend the rainy period, causing landslides and floods.

However, it is not clear the role of the short wave trough on the increase of precipitation on July 19 and July 20. Figure 14 shows time evolution of the area average vertical cross section, over the rectangle 44°W and 45°W, and 23°S and 24°S, shown in Figure 13a, obtained with the control run. The upward motion is more intense in the actual mountain run (shaded) and extends vertically in all troposphere on days 19 and 20 July, which coincides with the passage of the shortwave trough. In particular, the drop of the lifted index (solid thick line in Figure 14) in that period indicates a temperature drop at 500 hPa, which is a con-sequence of the transient trough approach. Therefore, the increase of thermodynamic insta-bility favored the intensification of rains which acquired a more convective character. In fact, according to the control run, the days 19 and 20 July registered convective rains which repre-sented almost 50% of the total precipitation volume. This shows that the short wave trough passage played an important role in causing the landslide events by creating the necessary ther-modynamic conditions

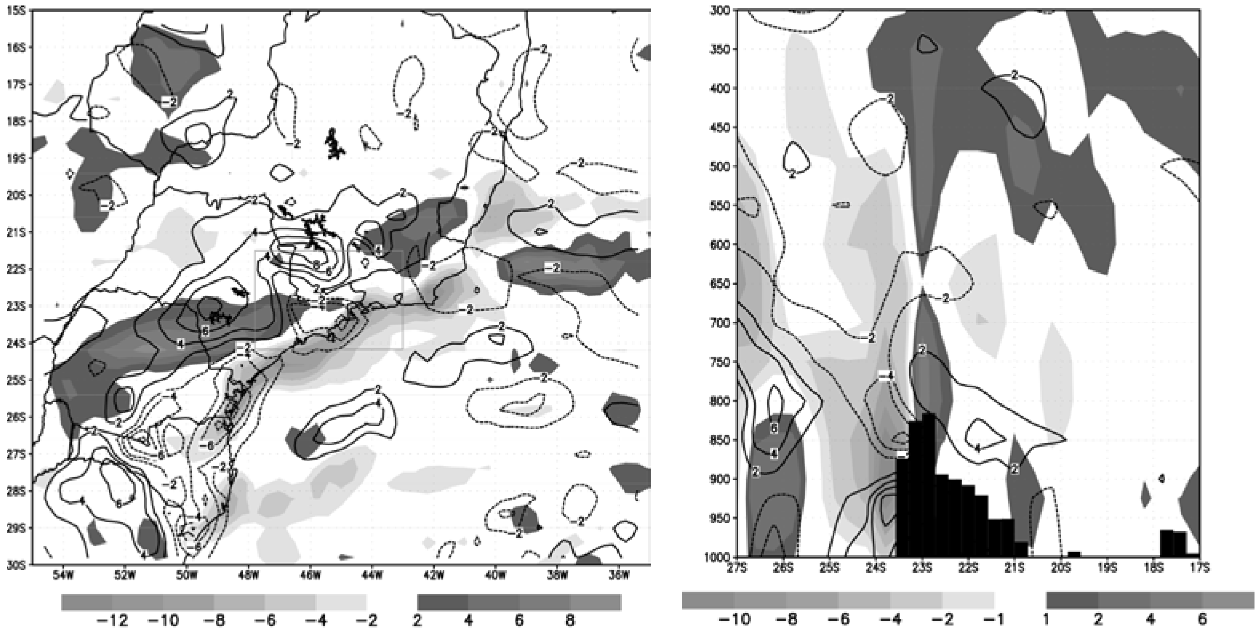


Figure 13. Differences between runs (84-hr simulation) with actual mountain elevations and reduced topography (control run minus reduced mountains run) of mass divergence (10-5 s-1, shaded) and vertical motion (Pa/s, contours) on 1200 UTC, 19 July 2004 at a) the 850-hPa level (left panel) and at b) 45ºW (cross section, right panel). Dark bars in Figure 13b represent model topography (control run). Dark box in Figure 13a is used in Figure 14 to area averaged values.

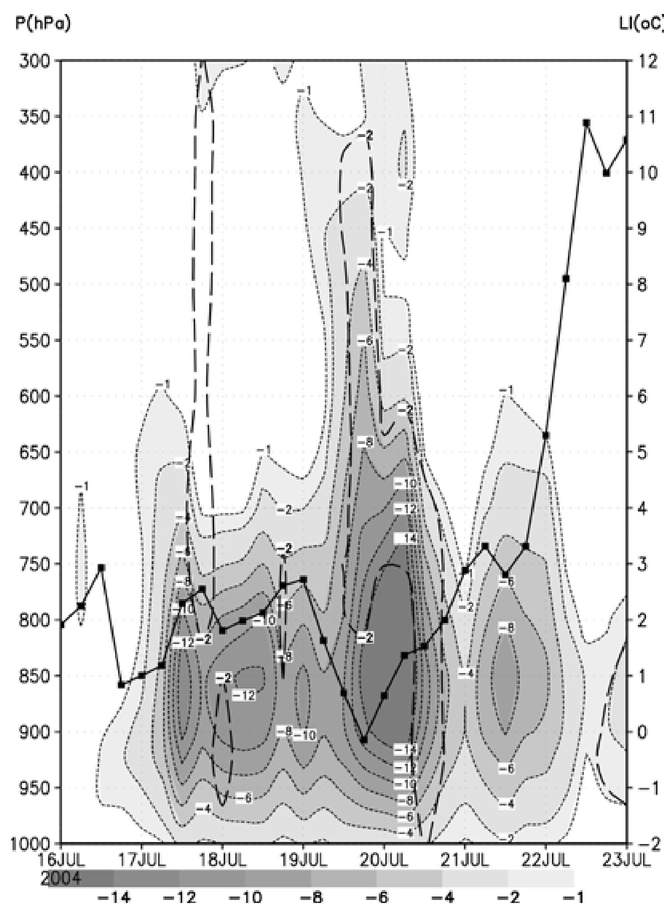


Figure 14. Time evolution of the area average vertical cross section, over the box 44°W and 46°W, and 23°S and 24°S (shown in Figure 13), obtained with the control run of simulated upward motion (10^3 Pa/s, shaded). The left hand side axis refers to pressure levels. The solid line is the simulated lifted Instability Index (°C, right hand side axis). The dashed line is the -2 x 10^3 Pa/s upward motion taken from the run with reduced mountain elevation.

to significantly increase the rain volume. It is interesting to note that in the simulations with modified topography, upward motion in the mid troposphere, indicated by the dashed contour of -2x10^3 Pa/s in Figure 14, reveals the passage of the shortwave trough, although the air lifting at low levels is weaker, occurred in short period of time and immersed in a drier air mass.

These results show the coupling of vertical motion associated with orography at lower levels with the flow generated by the passage of a perturbation in mid and upper troposphere. Besides, the Serra do Mar produced concentration of moisture in the upwind side of the mountains and increase of convective instability during the passage of the transient perturbation.

Horizontal resolution

Increase of horizontal resolution was carried out in order to verify the related numerical effects on the precipitation distribution and intensity. Figure 15 shows the accumulated precipitation between 16 and 22 July 2004, at 1200 UTC, same as Figure 3a but for model setup at 20-km resolution. The accumulated precipitation amounts are very similar to the run with 40-km resolution. The position of the maximum values are better located and most of rain lies along the coast whereas its reduction inland is evident. The increase of horizontal resolution can dip the valleys and increase the mountain peaks, with respect to a lower resolution model setup, but causing small changes to the precipitation pattern and the progression of the frontal system.

Conclusions

In the period between 16 and 22 July 2004 moderate and persistent precipitation occurred in the coastal region of Sao Paulo which caused landslides and floods in Serra do Mar region. Heavy rains are frequent in the summer season, when tropical South America is dominated by a monsoon-type circulation, but almost absent during winter season. Landslide events induced by rains during winter are unexpected and represent a challenge to the forecasters.

The synoptic situation was characterized by a cold and intense frontal passage, which weakened and reached the subtropical latitudes, and became stationary around Southeastern Brazil. The post-frontal anticyclone, initially cold, acquired barotropic equivalent characteristics during this period, and moderate and persistent

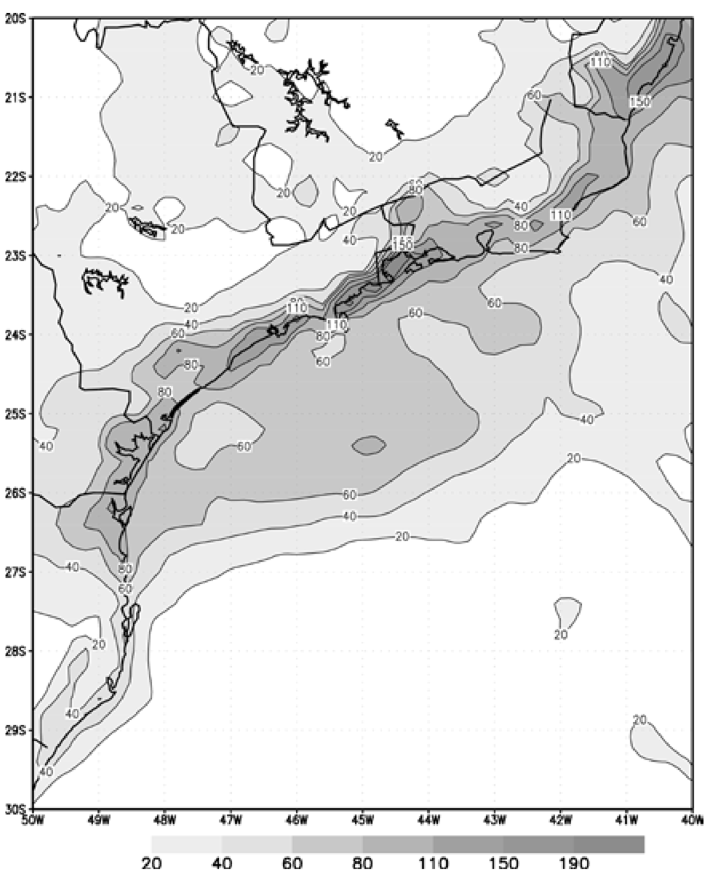


Figure 15. Same as Figure 3a but for model at 20-km resolution.

winds blew from the ocean toward the land at the coast of Sao Paulo. Due to the synoptic conditions in combination with the persistent southerly and southeasterly winds, rains were caused by orographic effects of the Serra do Mar, which caused an increase in low level convergence of relatively warm and moist air.

The progression of a shortwave baroclinic perturbation, although it was not the major cause of persistent rain, contributed to increase the thermodynamic instability with the decrease of temperature at middle levels, and led to heavier rains on 19 and 20 July, thus favoring conditions for landslides.

In general heavy rains are associated with strong dynamical forcing, such as frontal activity or midlevel disturbances. In this case, the most relevant aspect was the persistence of the low level circulation whose direction was almost perpendicular to the mountains, increasing the orographic effect. In this situation, a critical point was the location and persistence of the blocking anticyclone over the Atlantic Ocean. Another important aspect is that the region affected by landslides was embedded in a moist air mass, which enhanced the precipitation efficiency. This kind of orographic effect in the region is rare since low-level winds over the subtropical Brazilian coast, originated from the semi-permanent Atlantic Anticyclone, are usually weak and blow rather parallel to the Serra do Mar.

From a geological point of view, the moderate and persistent rainfall allowed deep infiltration of water into the rather shallow soil of the Serra do Mar slopes. During extreme and abrupt rain showers the accumulated water tends to drain superficially, but moderate precipitation tends to penetrate into the soil. In the case under study, rain was weak to moderate during the first three days (July 16th to July 18th), which caused the soil saturation, and became moderate to intense on July 19th, and causing landslides.

The dry month situation investigated in this work has some characteristics similar to the patterns identified by Seluchi and Chou (2009) for the rainy season, for example, the barotropic anticyclone which gave the general stationary and persistent character of the event. Another example is the interaction of a shortwave trough at upper levels which contributed to rain intensification. For forecast purposes, these results suggest that the persistence and configuration of the low-level circulation would play a more important role that the middle troposphere dynamics and the thermodynamic instability. This a novel information for forecasters since numerical models usually have some difficulties to predict thermodynamic conditions or to detect short wave disturbances, but they are more accurate to forecast the regional scale low-level circulation.

A possible future work is the investigation of the role of the Serra do Mar and of the central Brazilian plateau in modifying the character of the cold frontal systems that passes these subtropical latitudes in higher resolution simulations and to test the precipitation sensibility to different numeric and physic setup.

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