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Article

Simulating Weather Events with a Linked Atmosphere-Hydrology Model

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Abstract

This study aims at assess the importance of a conceptual representation of hydrological processes when modelling atmospheric circulation. It compares results from a regional atmospheric model that interprets land surface hydrological processes based on parameterizations with results from a two-way coupled atmosphere-hydrological model that has a process-based approach to the land surface hydrological cycle. These numerical models were applied to a region covering the Rio Grande basin, Brazil. The same input data, initial and boundary conditions were used on a 31-day simulation period. Results obtained from these simulations were compared to visible satellite images and gauging rainfall stations for three case studies that included a cold front, deep convective clouds and stable atmospheric conditions. Both models could reproduce regional patterns of air circulation and rainfall influenced by the orography of the basin. However, atmospheric processes driven by spatial gradients of land surface temperature or local surface heating were spatially better represented by the atmospheric-hydrological modelling system rather than the regional atmospheric model. Since areas characterized by spatial gradients of land surface temperature and local surface heating were closely associated with convergent air flows near land surface and strong vertical motion in the mid troposphere, this finding enhanced the role of a good representation of land surface hydrological processes for a better modelling the atmospheric dynamics.

Keywords: Earth surface dynamics, weather events, atmosphere-hydrology models, land surface modeling.

Simulação de Eventos Atmosféricos com um Modelo de Interface Atmosfera-Hidrologia

Resumo

Este estudo tem como objetivo avaliar a importância de uma representação conceitual dos processos hidrológicos na modelagem da circulação atmosférica. Ele compara os resultados de um modelo atmosférico regional que interpreta os processos hidrológicos da superfície terrestre por meio de parametrizações com os resultados de um modelo que tem uma interface hidrologia-atmosfera. Ambos os modelos numéricos foram aplicados a uma região que cobre a bacia do Rio Grande. Os mesmos dados de entrada e de condições inciais e contorno foram usados para um período de simulação de 31 dias. Os resultados obtidos a partir dessas simulações foram comparados com imagens de satélite visíveis e medições de estações pluviométricas para três estudos de caso que incluíram: uma frente fria, nuvens convectivas e condições atmosféricas estáveis. Ambos os modelos conseguiram reproduzir padrões regionais de circulação de ar e precipitação influenciados pela orografia da bacia. No entanto, os processos atmosféricos impulsionados por gradientes espaciais de temperatura da superfície da terra ou aquecimento local da superfície foram melhor representados espacialmente pelo modelo de interface Atmosfera-Hidrologia do que pelo modelo atmosférico regional. Como áreas caracterizadas por gradientes espaciais de temperatura da superfície terrestre e aquecimento local da superfície estão associadas a fluxos de ar convergentes perto da superfície terrestre e forte movimento vertical na troposfera média, esta descoberta reforçou o papel de uma boa representação dos processos hidrológicos da superfície terrestre para uma melhor modelagem da atmosfera.

Palavras-chave: dinâmica da superfície terrestre, eventos atmosféricos, modelo de interface atmosfera-hidrologia, modelagem da superfície terrestre.

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1. Introdução

Interactions associated to natural fluxes between biosphere and atmosphere have been highly discussed (Sellers *et al.*, 1997; Pielke *et al.*, 1998; Sutton *et al.*, 2007). Among these natural exchanges, the water cycle stands out for its complexity and relevance to all other physical processes (Stohlgren *et al.*, 1998). The water cycle incorporates a wide range of processes within soil, surface and atmosphere that are closely interconnected to each other. For a better understanding of these processes and how they are interrelated, many alternatives and strategies have been developed to estimate water fluxes between soil, surface and atmosphere at different spatial and temporal scales (Liang *et al.*, 1994; Schaake *et al.*, 1996; Wilson *et al.*, 2001; Pitman, 2003; Balsamo *et al.*, 2009). In this context, numerical models are widely recommended as tools capable of quantifying, predicting and assessing the soil, surface and atmospheric water budgets (Arnold *et al.*, 1993; Maxwell and Miller, 2005; Bittelli *et al.*, 2010).

In general, numerical models have successfully been used for estimating the exchange of water within the hydrosphere, and among surface water, soil water and groundwater. A groundwater model, for instance, have recently been applied by Singh (2013) to evaluate the impacts of a waterlogged area on groundwater level and recharge rates. Besides finding that a small increase in the net recharge might implicate an expansion of waterlogged areas, that study also indicates that numerical models are an effective tool for groundwater simulations. Raza *et al.* (2013) used a numerical model to analyse the influence of three types of land use on soil water dynamics. Results obtained from simulations were compared to field experiments and, revealed that the numerical model could satisfactorily reproduce the water content in the soil profile.

Regarding surface water, numerical models have systematically been developed and upgraded (Todini, 1996; Lohmann *et al.*, 1998; Panday and Huyakorn, 2004). Among these models, hydrological models are frequently used for a large range of applications spanning from runoff simulation to flood forecasting (Nijssen *et al.*, 1997; Toth *et al.*, 2000). Although hydrological models are able to physically represent most of the water balance by integrating soil and surface water processes, they do not have any atmospheric module to deal with exchange of water between surface and atmosphere; hence, estimates of runoff depend on how dense the rainfall gauge network is (St-Hilaire *et al.*, 2003) or on the resolution of the atmospheric model used to estimate or forecast precipitation.

On the other hand, atmospheric models present a detailed and complex approach of atmospheric processes that includes estimation of carbon, heat, energy and water fluxes between surface and atmosphere based on energy balance. By using a suite of regional climate model (RCM) scenarios, for instance, Morales *et al.* (2007) estimated climate impacts on carbon cycling across Europe. Their study found that projected changes in carbon balance depended on the choice of the general circulation model (GCM) providing boundary conditions to the RCM rather than the choice of RCM. RCM simulations were also conducted by Seneviratne *et al.* (2002) in order to investigate thermodynamic processes such as exchange of sensible/latent heat between land surface and atmosphere under a warmer climate. Among many other findings, their results underline the importance of land surface processes in climate integrations. RCMs were also evaluated by Hagemann *et al.* (2004) on their ability to estimate water budgets over Europe. Their study showed that all RCMs presented either prominent summer drying or overestimation of rainfall throughout the year except during the summer. They claimed that the model deficit and systematic errors may be related to deficiencies in the land surface parametrization. Moreover, parameterization schemes usually apply prescribed values of parameters based on their probability density functions. This assumption does not consider land use and soil characteristics as continuous distributions, and hence, mixtures in soil and vegetation within an area of interest are not captured. This may lead to errors in spatial distribution when estimating land surface processes (Vidale *et al.*, 2003; Molders, 2000). Simultaneously, an alternative approach proposes to optimize the performance of hydrological and atmospheric numerical models by coupling them into integrated modelling systems (Walko *et al.*, 2000; Seuffert *et al.*, 2002). In this context, a two-way coupled atmospheric-hydrological modelling system have been implemented and presented in Pereira *et al.* (2014). It proved to be able to estimate the exchange of fluxes between surface and atmosphere considering their feedback loops. In this study, comparisons between this integrated modelling system and a regional atmospheric model have been made in order to evaluate the influence of a process-based representation of land surface hydrological processes on regional atmospheric models.

As the atmospheric-hydrological modelling system includes a distributed hydrological model, its domain simulation is restricted to river basins. In this case, the Rio Grande basin, Brazil, was chosen as study area due to convenience in the data acquisition and previous experience with the area.

2. Data and Methods

We compared results of relative humidity, vertical motion, surface temperature and instantaneous rainfall as computed from a regional atmospheric model and a linked atmosphere-hydrology model.

The numerical experiment consisted of a short-term run of 31 days over which a variety of weather events occurred, including fronts and local convection. The first run was carried out with the regional atmospheric model (BRAMS) operationally used at the Brazilian Center for Weather Prediction and Climate Studies (CPTEC) whereas the linked atmosphere-hydrology model by Pereira (2014) was used in the second run. Based on atmospheric activities detected by the presence/absence of cumulus clouds in visible satellite images, three case studies were selected representing a cold front passage, local strong convections and stable atmospheric conditions. Finally, the influence of a better representation of land surface hydrological processes was individually evaluated by analysing the performance of each model in reproducing each study case.

2.1. Input data

As the atmospheric-hydrological coupled modelling system is composed by BRAMS and MGB-IPH models, input data for both models were needed. For MGB-IPH, input data vary according to whether running in simulation or calibration mode. As in the integrated modelling system MGB-IPH is always ran in simulation mode, its input data include land use, soil and elevation maps together with air temperature, sunshine, relative humidity, wind speed and atmospheric pressure time series.

Similarly to MGB-IPH, the BRAMS input data includes topographical and land use features. Its input data contain normalized difference vegetation indexes (NDVI), soil moisture distribution, sea surface temperature, soil texture classes, land use and elevation maps. Besides input data, BRAMS requires time-dependent boundary conditions which are derived from general circulation models. For the Rio Grande basin, input data and boundary meteorological observations were collected from different sources, from online databases to personal communication. The whole data collection procedure is described as follows.

A digital elevation model (DEM) was freely obtained at Department of Ecology of the Federal University of Rio Grande do Sul. Their DEM preprocessing includes data gap filling and mosaicking of SRTM database, not only, for the Rio Grande basin but also for all Brazilian territory (Hasenack *et al.*, 2010).

The soil map of the Rio Grande basin was derived from a soil survey data created by RADAM Brasil project (RADAMBRASIL, 1982) at scale of 1:1000000. Although at a coarser scale than RADAM Brasil soil survey data, digitalized soil maps (1:3000000) from the Food and Agriculture Organization of the United Nations (Food and of the United Nations, 1974) were resampled and used to overcome missing data. The RADAM Brasil database that includes over 12 different types of soils in the Rio Grande basin, (FAURGS, 2007) was reclassified into two groups as deep and shallow soils according to their hydrological behavior.

Meteorological data sets from three stations were provided by CPTEC. They comprise monthly time series of air temperature, sunshine, relative humidity, wind speed and atmospheric pressure. The location of these stations may be seen in Fig. 1.

Normalized difference vegetation indexes (NDVI), soil moisture distributions and weekly sea surface temperature are available at CPTEC website (CPTEC, 2020).

2.2. Initial and boundary conditions

Initial and boundary conditions were separately set for BRAMS and MGBIPH models. In the BRAMS, a

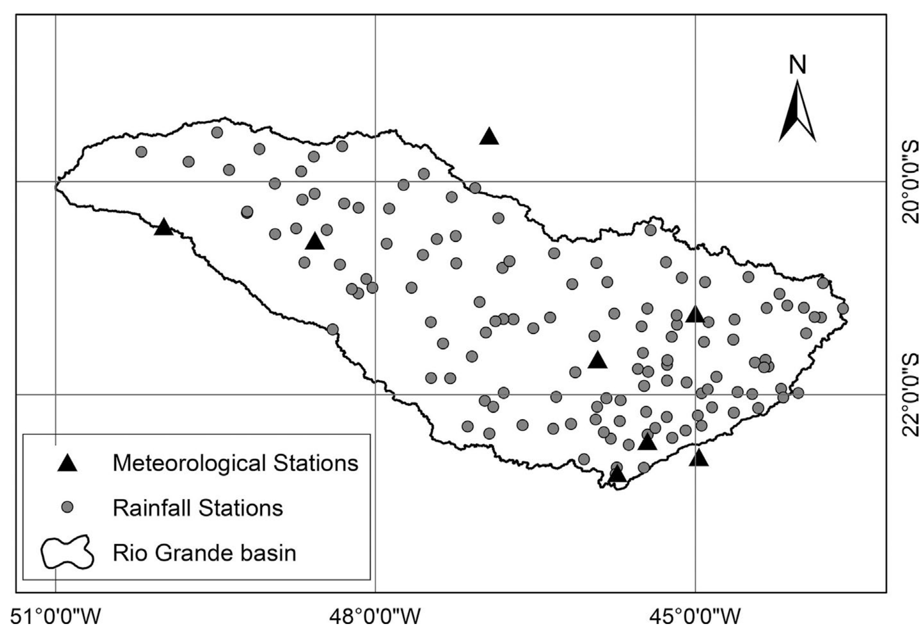

Figure 1 - Rainfall gauges and meteorological stations used in this study.

four-dimensional data assimilation technique described by Umeda and Martien (2002) was used to interpret atmospheric boundary conditions provided every 6 h by global atmospheric analyses. In addition, initial soil moisture conditions were calculated using global analyses of monthly precipitation derived from satellite and surface measurements. For doing so, a hybrid model (Gevaerd and Freitas, 2006) which estimates soil moisture based on the Global Precipitation Climatology Program (GPCP) and the Tropical Rainfall Measuring Mission (TRMM) has been used. Moreover, soil temperature was considered as vertically homogeneous and its value was set equal to the value of air temperature near land surface.

In the MGB-IPH, initial conditions were set by changing interception and infiltration stores. An initial hot start for interception and infiltration stores was adopted according to simulations performed by Farias Pereira *et al.* (2013). This hot start is reasonable since a warming-up period has been made in the beginning of each run and, therefore, errors due to this assumption were gradually attenuated.

2.3. Rainfall gauge network and satellite images

Rainfall depths were selected from the Agencia Nacional de Aguas (ANA) database (http://hidroweb.ana.gov.br/). Daily precipitation values were obtained from observations on 483 precipitation stations over the Rio Grande basin and its surroundings. Out of these 483, 136 stations had rainfall records for January 2009, the selected wet period for the model runs. The position of these stations is indicated in Fig. 1.

Visible satellite images were used to analyse the presence/absence of cumulus clouds in the upper and middle levels of the atmosphere. These images were captured by two different geostationary satellites that provide coverage for South America, the Geostationary Operational Environmental Satellite10 (GOES-10) and the Meteosat-9. The first one was operated by the the National Oceanic and Atmospheric Administration (NOAA) and it was used to support hurricane forecasting efforts in South America whereas Meteosat-9 was designed by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) to support weather forecasting in Europe and Africa. Despite the coverage area of Meteosat-9 partially includes South America, GOES-10 visible images are preferably used for analyses. When not available, the preference criterion for satellite images considers Meteosat-9 visible images, followed by false-color GOES-10 and Meteosat-9 images.

In this study, all the visible and false-color images were freely downloaded from the Satellite Division and Environmental Systems website (DSA, 2020).

3. Short-Term Runs

Two different runs were performed for a simulation period of 31 days. The first run corresponds to the control run and, only BRAMS was applied to the Rio Grande basin while the second run was carried out using the atmospherichydrological modelling system.

One of the aspects evaluated by this study was the capability of reproducing rainfall events by better representing land surface hydrological processes. In order to assess the formation of rainfalls, a wet weather period was chosen due to its high probability of rainfall occurrence. Austral summer is the rainy season at the Rio Grande basin, therefore the chosen simulation period spans 1st January trough 31st January 2009.

Prior to each run, a warning-up period of 10 days was considered for the initialization of the physical variables (Benoit *et al.*, 2000). Thus, all comparisons presented in this study refer to results obtained from the last 20 days of simulation, which means, between 11th to 31st January 2009.

In general, atmospheric models provide outputs every 6 h (Baron *et al.*, 1998; Onogi *et al.*, 2005). Depending upon the purpose of the study, this value may become smaller or larger. Here, as the influence of land surface hydrological processes on the atmosphere was carefully investigated for atmospheric processes that occur at different time scales, the interval between outputs was assumed equal to 3 h for both runs. Since satellite images were captured every 3 h, this is the shortest interval which could be adopted for comparisons with observed data.

4. Criteria for Selection of Case Studies

Outputs from both the atmospheric-hydrological modelling system and the regional atmospheric model were compared to each other and analysed towards the formation of clouds and rainfall derived from convergence at the surface layer. In this study, significant atmospheric activities were selected according to the following procedure.

Firstly, convergences at the surface layer (1000 hPa) were identified by plotting zonal and meridional wind fields. Convergence was used as indicator of atmospheric activities in the upper layers. Secondly, vertical motions higher than 1 m/s at 500 hPa over the convergence zones pointed to possible convection development.

Finally, convection occurrence was validated by the visible satellite images.

According to this procedure, three convection developments were observed on 21 January at 2100 UTC, 22 January at 1800 UTC and 25 January at 2100 UTC from model results. All these three events are described and discussed in section 5.

5. Results and Discussion

Here, results from the short-term simulations performed by the atmospherichydrological model system are compared to outputs from the regional atmospheric model, satellite images at visible spectrum and daily rainfall data for the specific cases identified in section 4.

5.1. Case studies

5.1.1. 21 January at 2100 UTC

On January 21st , a false-color Meteosat-9 image captured at 2100 UTC shows a cold front passing over the Rio Grande basin (Fig. 2a). In the image, the front is detected by the presence of brighter cumulus clouds. Since brightness of clouds in visible satellite images is related to their top heights (Song *et al.*, 2004), Fig. 2a is an indicator of vertical motion upwards which may have caused high cloud tops and increased their reflectance in the image.

Daily observed rainfall over the basin ranged from 0 to 80 mm. Although the satellite image indicates developing and mature cumulus clouds all over the basin due to the passage of this front, the highest values of rainfall depth were observed mostly concentrated in the eastern part of the basin as shown in Fig. 2b. This spatial rainfall distribution is primarily associated with the orography of the Rio Grande basin.

As the satellite image and observed daily rainfalls have different time scale, they were compared to results obtained from the short-term runs in a way to enhance the performance of each model in reproducing spatial alignment and distribution of the front rather than estimating rainfall intensity values.

The spatial alignment and distribution of fronts are generally characterized by shifts in wind directions, and sharp temperature and air moisture content changes over short distances (Ahrens, 2007). Therefore, temperature, zonal and meridional wind fields calculated by the integrated system and regional atmospheric model were compared to the spatial alignment and distribution of the front observed in the visible satellite image (Figs. 2 and 3). Moreover, Figs. 2b and 2c show computations of vertical motion at 500 hPa (shaded) using the regional atmospheric model and integrated system, respectively.

As presented in Figs. 2b and 2c, zonal and meridional wind fields estimated by both models indicated convergent air flows over the Rio Grande basin. However, the convergence zone is placed by the coupled system in better accordance to the shape of the front observed in the

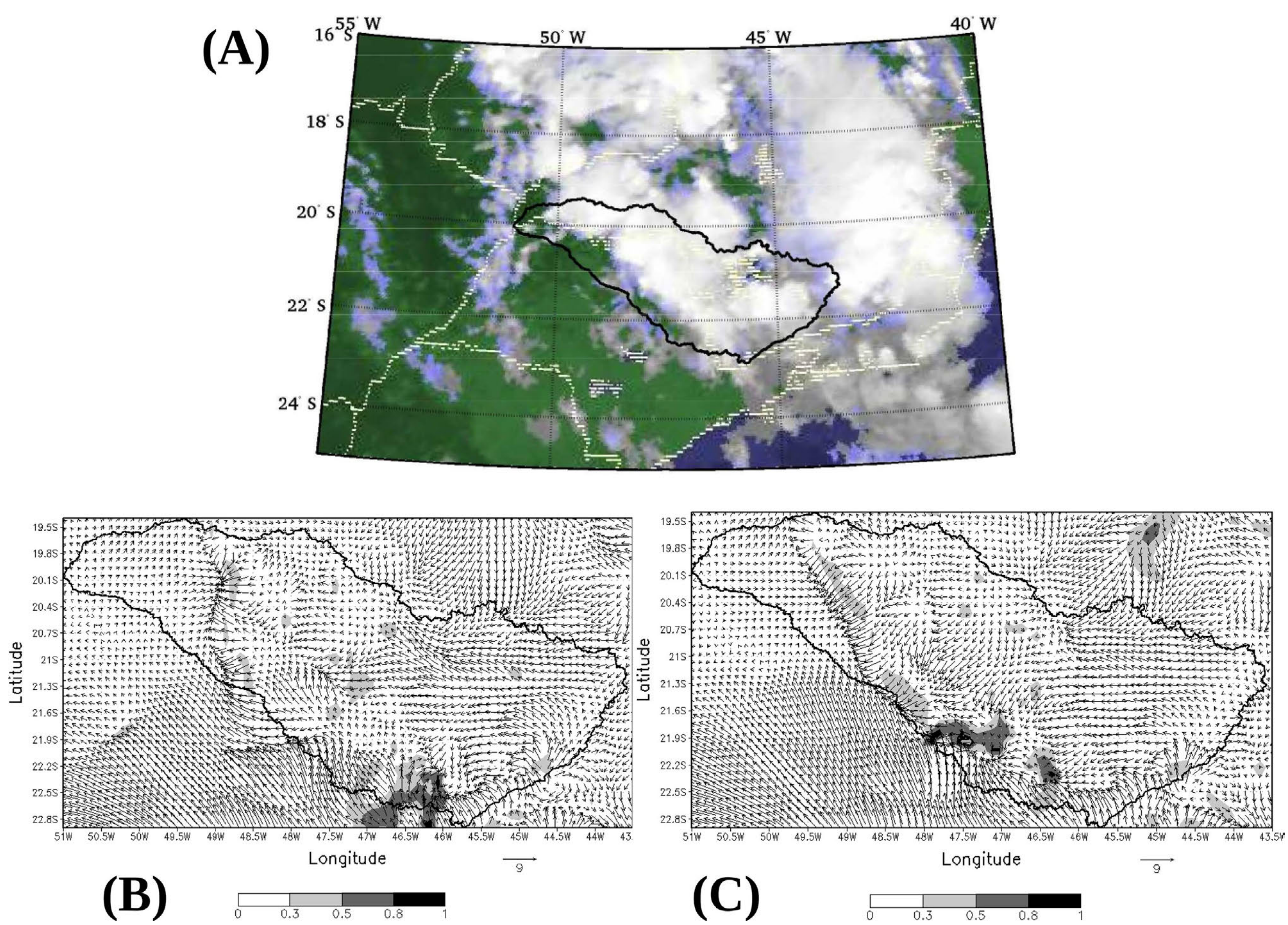

Figure 2 - The false-color Meteosat-9 image captured on January 21st at 2100 UTC over the Rio Grande basin (a). Compared to the regional atmospheric model (b), the spatial alignments to the air flow field calculated by the coupled model (c) showed a good agreement with the visible satellite image.

satellite image than by the regional atmospheric model. According to Jacobson (2005), convergence zones derived from fronts related to abrupt variations of land surface temperature. In this context, the process-based representation of land surface hydrological processes proposed by the integrated system yielded a good agreement between spatial gradients of land surface temperature and spatial alignment of the front (Fig. 3b). In contrast, spatial distribution of abrupt variations of land surface temperature estimated by the regional atmospheric model presented neither the same pattern as the coupled system nor the spatial alignment of the front (Fig. 3a).

Differences in spatial distribution of land surface temperature between the atmospheric model alone and the coupled system resulted also in different placement of areas of deep convection. Zones of deep convection were identified by upward vertical motion higher than 0.7 m.s -1 at 500 hPa (Jorgensen and Lemone, 1989) and are presented as shaded areas in Figs. 2b and 2c. Comparing to the satellite image, Fig. 2c shows that despite zones of deep convection by the coupled system did not fully match the alignment of the front, they were placed in accordance with the occurrence of brighter cumulus clouds in the satellite image. On the other hand, zones of deep convection indicated by the regional atmospheric model alone were neither associated with the alignment of the front nor with any cumulus cloud observed in the satellite image.

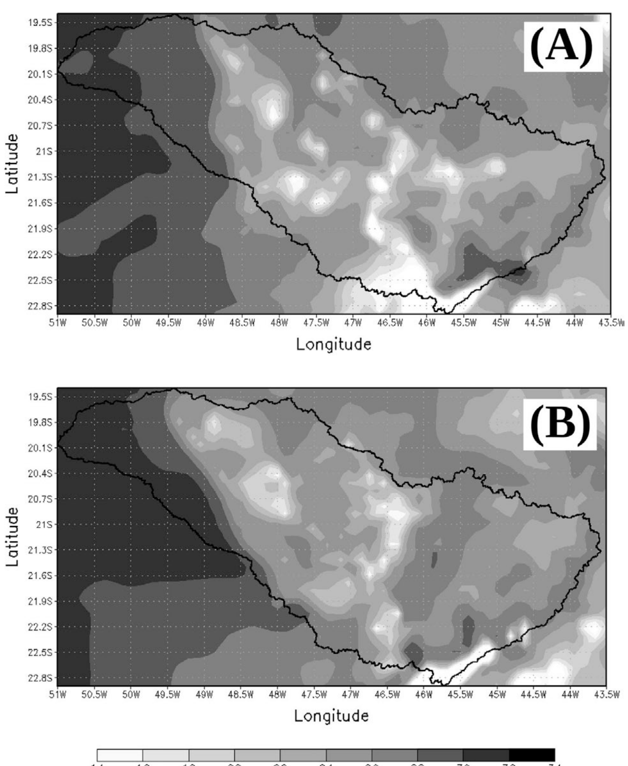

Figure 3 - Temperature rates showed a better spatial representation of the cold front using the coupled model (b) than the regional atmospheric model (a).

Although estimates of rainfall by regional atmospheric models are yet not accurate enough for realistic representation of rainfall intensity (Kendon *et al.*, 2012), observed daily rainfall data were compared to 24 h-accumulated rainfall in order to capture the spatial rainfall distribution. Figure 4 presents observed daily rainfall (4a) and 24 h-accumulated rainfall estimated by the regional atmospheric model (Fig. 4b) and the coupled system (Fig. 4c).

According to Fig. 4, the same spatial patterns of rainfall were identified for the regional atmospheric model and integrated system. Moreover, both of them presented the same range of values, from 0 to 80 mm.d^{-1}, and similar location of wet and dry regions in the Rio Grande basin. Except for some local rainfall events in the dry regions, most of the rainfall gauging stations with values larger than 70 mm.d^{-1} were located in the wet region pointed by the models. It means that, in terms of regional hydrological behaviour of rainfall, the models had a good agreement with the daily rainfall data when representing the front.

5.1.2. 22 January at 1800 UTC

Even though cumulus clouds have been observed in the GOES-10 visible image captured in the early evening

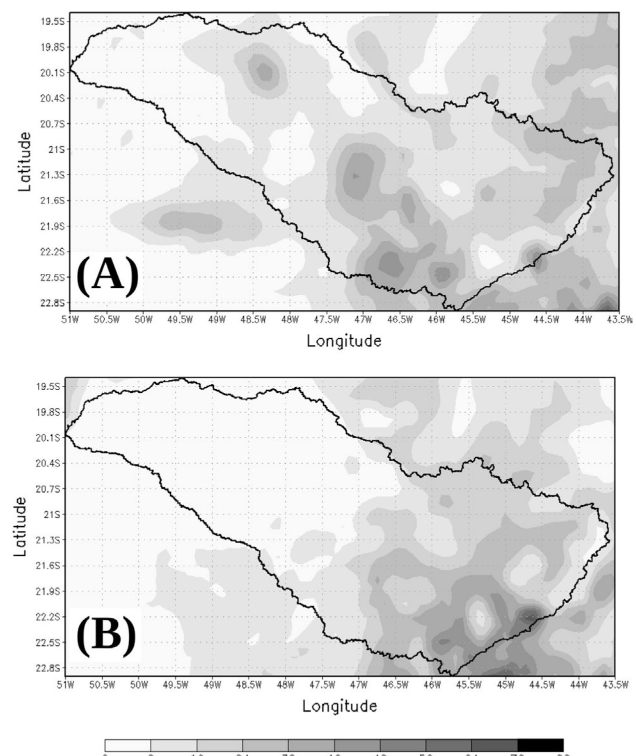

Figure 4 - 24-h accumulated rainfall fields estimated by the models presented the same regional trend as observed daily rainfall, where high intensities of rainfall were concentrated in the southeastern part of the Rio Grande basin. This regional trend was directly associated with the orography of the basin.

on January 22nd, they were only used as support to the presence of convective activities in the atmosphere. Therefore, one cloudy region containing developing and mature cumulus clouds was selected within the Rio Grande basin and is shown in Fig. 5a. This cloudy region was identified as an area of deep convection where rainfall is possible or probable (hereafter referred to as rainfall potential area). Despite many other cumulus clouds may be found in the satellite image, their reflectance indicated that they have lower cloud-top heights.

Although convective activities occur at short-time scale to be compared to observed daily rainfall, comparisons between the rainfall potential area and daily rainfall observations (Fig. 5b) were made with respect to extreme values and/or presence of outliers, which indicate convective rainfall events.

Figure 5 shows that daily rainfall observations presented values larger than 70 mm at two rain gauge stations (highlighted in Fig. 5b) over the rainfall potential area. These indicators were used as evidence of a strong convection in this area. Moreover, the performance of each model in representing the rainfall potential area were evaluated by comparing its spatial distribution to relative humidity, land surface temperature, vertical motion, instantaneous rainfall, zonal and meridional wind fields estimated by the models (Figs. 6 and 7).

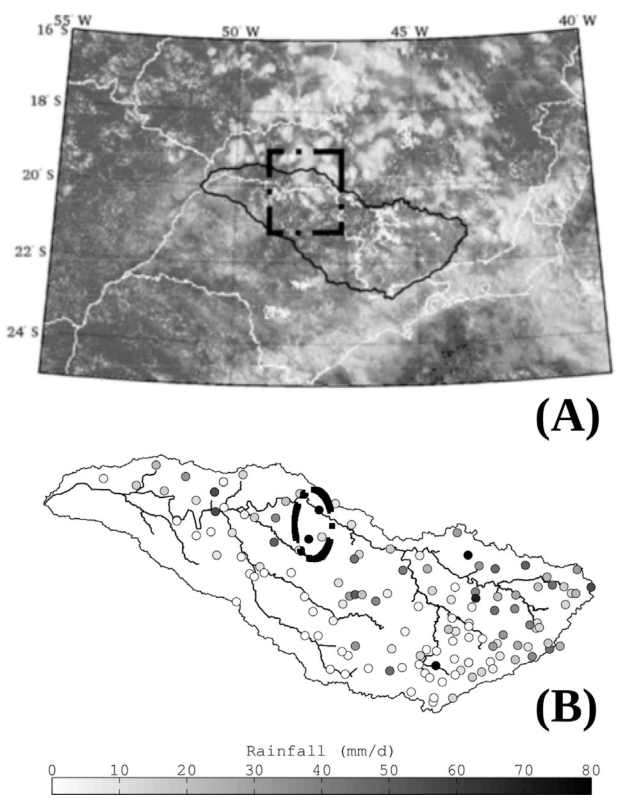

Figure 5 - One cloudy region containing developing and mature cumulus clouds observed in the GOES-10 visible image (rectangle) captured on January 22nd at 1800 UTC (a) and daily rainfall observations at each rainafall gauging station (b). The ellipse indicates two rainfall gauging stations which may have been affected by convective rainfalls derived from the developing and mature cumulus clouds in (a).

Figure 6 reveals a close relationship between spatial gradients of land surface temperature and convergence at low level. According to results from both models, a combination of these two indicators of convection were presented over two regions within the Rio Grande basin (rectangles in Figs. 6a and 6b). The larger one corresponds to the same region as the rainfall potential area whereas the smaller one represents a local convection near the border of the basin.

For the region characterized by the local convection, both models estimated values of vertical motion at 500 hPa higher than 0.7 $m.s^{-1}$. However, neither mature nor developing cumulus clouds were observed in the satellite image (Fig. 7). As values of relative humidity calculated by the models were lower than 70% in the region of this local convection (Figs. 7a and 7b), the absence of mature and developing cumulus clouds in the satellite image indicates that the amount of water vapour in the air was a limiting factor for the formation of cumulus clouds.

On the other hand, in the first region defined as the rainfall potential area, values of relative humidity reached 100%; which, together with vertical motion upwards, may have induced the formation of the mature and developing cumulus clouds observed in the satellite image and highlighted in Fig. 5a.

The ability of each model to simulate convective rainfall events was investigated using instantaneous rainfall fields. Convective rainfall events were identified over the Rio Grande basin and are shown in Figs. 7c and 7d (shaded). These convective rainfalls were defined as instantaneous rainfall rates higher than 3.5 $mm.h^{-1}$ according to studies on the variability of rainfall events in the State of So Paulo carried out by Leibmann *et al.* (2001). As shown in Figs. 7c and 7d, two main convective rainfall events were detected using instantaneous rainfall fields estimated by the models. The first convective rainfall event was characterized by the orography of the basin whereas the second convective rainfall event, located towards the middle of the basin, was derived from spatial gradients of land surface temperature.

According to results obtained from the simulations, both models estimated the same values of relative humidity, instantaneous rainfall and vertical motion at 500 hPa for the two convective rainfall events. Moreover, values of vertical motion at 500 hPa revealed that the second convective rainfall event, exclusively induced by land surface processes, reached the upper layers of the troposphere unlike the first convective event. This explains the matching of the second convective rainfall event and the presence of cumulus clouds in the satellite image. In terms of spatial distribution and intensity of convective rainfall

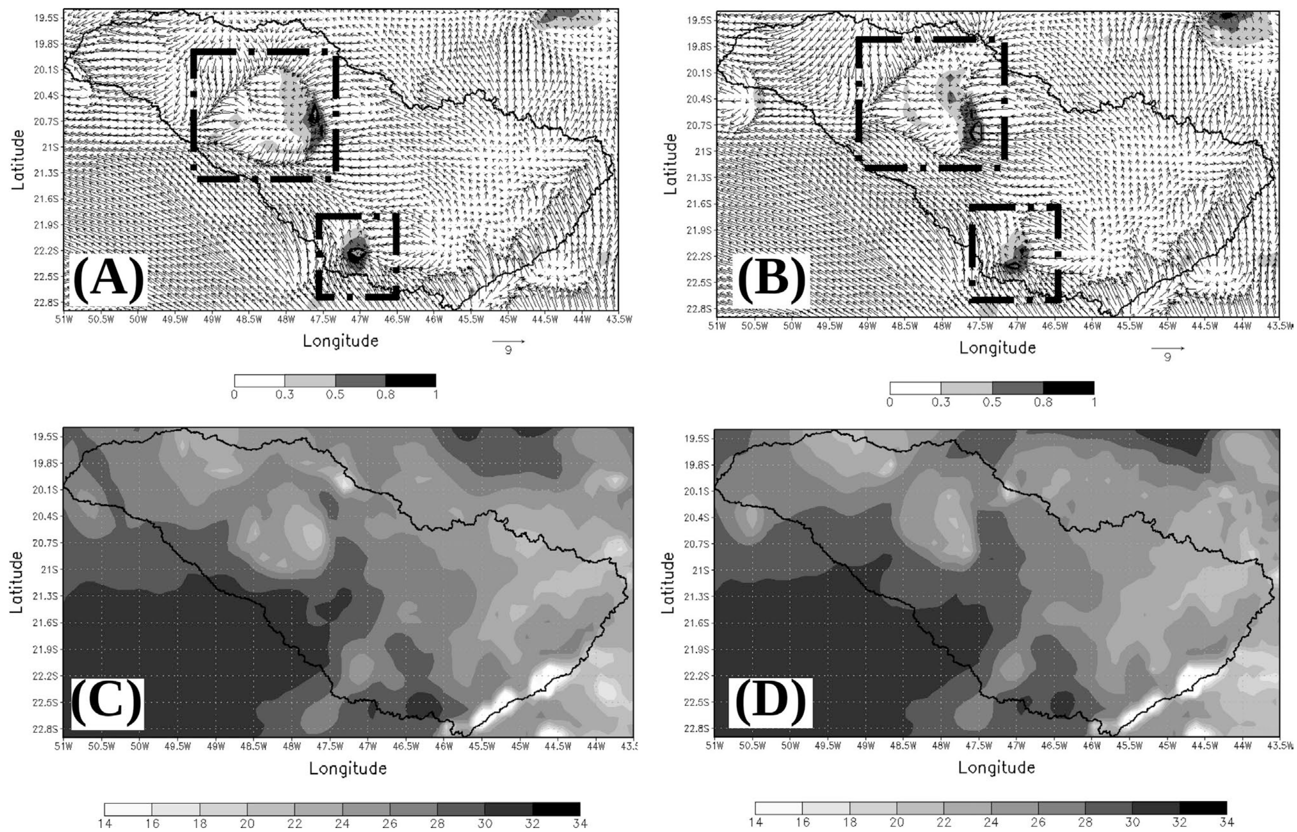

Figure 6 - Temperature (c and d) and air flow (a and b) fields near land surface calculated by both models. In a and b, rectangles indicate zones of convection. The larger one corresponds to the same region as the rainfall potential area whereas the smaller one represents a local convection near the border of the basin.

events within the basin, results obtained from both models showed a good agreement.

In this study case, relative humidity, temperature, instantaneous rainfall, zonal and meridional wind fields estimated near land surface by the integrated system and regional atmospheric model showed roughly the same spatial distribution, thereby differences on how to represent land surface hydrological processes were not as significant as they were for the study case of the cold front. A possible reason for that is the different spatial scale between the front in the previous study case and the convection of this case. While the front covered much of the Rio Grande basin, convection only represented a small portion of it. Besides, the study case of the front presented variations of surface temperature greater than the convection, which implied to higher contributions from land surface processes to the atmosphere.

For both models, zonal and meridional wind fields could capture convergent air flows derived from the orography of the basin and spatial gradients of land surface temperature. Although very few differences were noted between results obtained from the integrated system and regional atmospheric model, this study case showed that relative humidity, temperature, zonal and meridional wind calculated near land surface were important factors for the formation of cumulus clouds and areas where convective rainfalls are possible or probable. These results agree with what Pielke (2001) has proposed as triggering mechanisms of convection.

5.1.3. 25 January at 2100 UTC

This study case is characterized by the absence of brighter clouds in the GOES10 visible image captured at 25th January 2100 UTC. Among many other factors, cloud brightness is also associated with cloud thickness and cloud water content (Song *et al.*, 2004; Love *et al.*, 2001). Based on this concept, neither local convective rainfall events nor storms were observed in the visible image (Fig. 8a). Since observed values of daily rainfall were lower than 20 mm.d^{-1} over the whole basin (Fig. 8b), they corroborated with the low rainfall profile indicated by the satellite image.

This study case evaluates the capability of the models in representing atmospheric processes under stable atmospheric conditions. In this sense, temperature, zonal and meridional wind fields computed near land surface were investigated as indicators of atmospheric activities. In addition, vertical motion at 500 hPa was used to evidence the effects of possible atmospheric activities pointed by the models (Fig. 9).

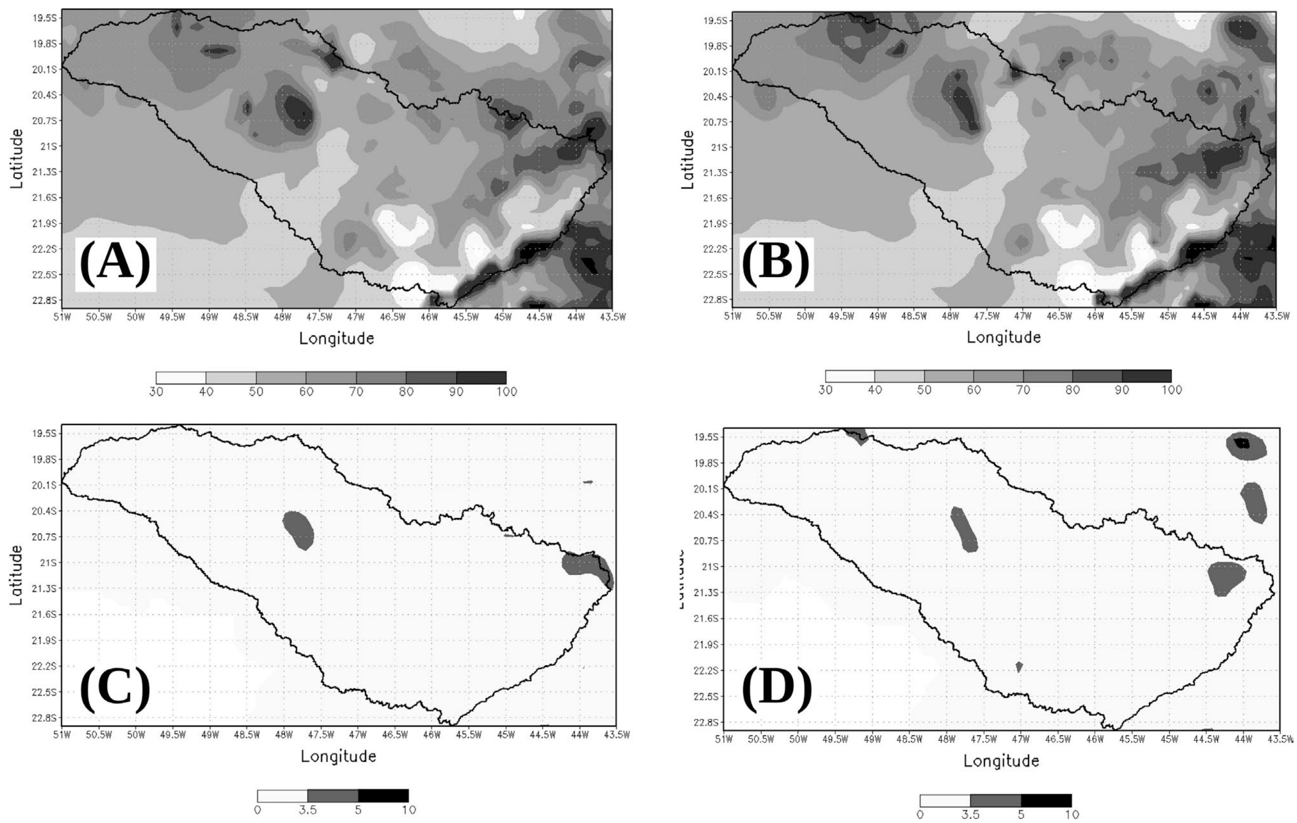

Figure 7 - Relative humidity (a and b) and instantaneous rainfall (c and d) fields near land surface estimated using the regional atmospheric model and the coupled model.

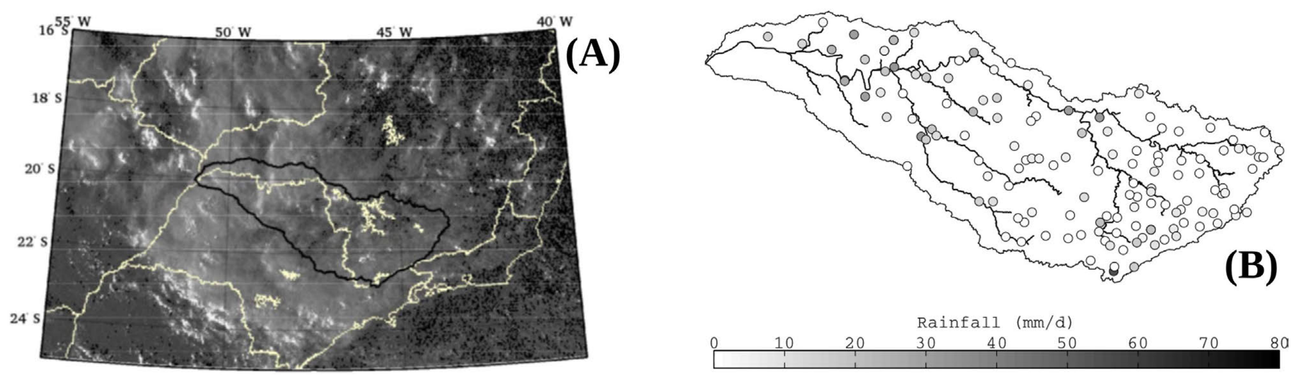

Figure 8 - Case study characterized by stable atmospheric conditions in the GOES-10 visible image (a) and low rainfall profile measured in the rainfall gauging stations (b).

According to Figs. 9a and 9c, results from the regional atmospheric model revealed a strong convection in the centre of the Rio Grande basin characterized by convergent air flow and abrupt variations of temperature over short distances. Since values of vertical motion were larger than 1 $m.s^{-1}$ over this area, it has been interpreted by the regional model as a trigger mechanism to generate a convective rainfall event.

On the other hand, evidences of atmospheric activity (as defined in section 4) were not detected based on temperature, vertical motion, zonal and meridional wind fields calculated by the integrated system (Figs. 9b and 9d). Although values of temperature near land surface varied in the same range as the ones estimated by the regional atmospheric model, spatial gradients of temperature by the coupled system were lower than those from the regional model. Moreover, the integrated system suggested convergent flow in many areas across the basin. However, in accordance with the satellite image, values of vertical motion at 500 hPa below 0.5 $m.s^{-1}$ did not indicate strong convective activity.

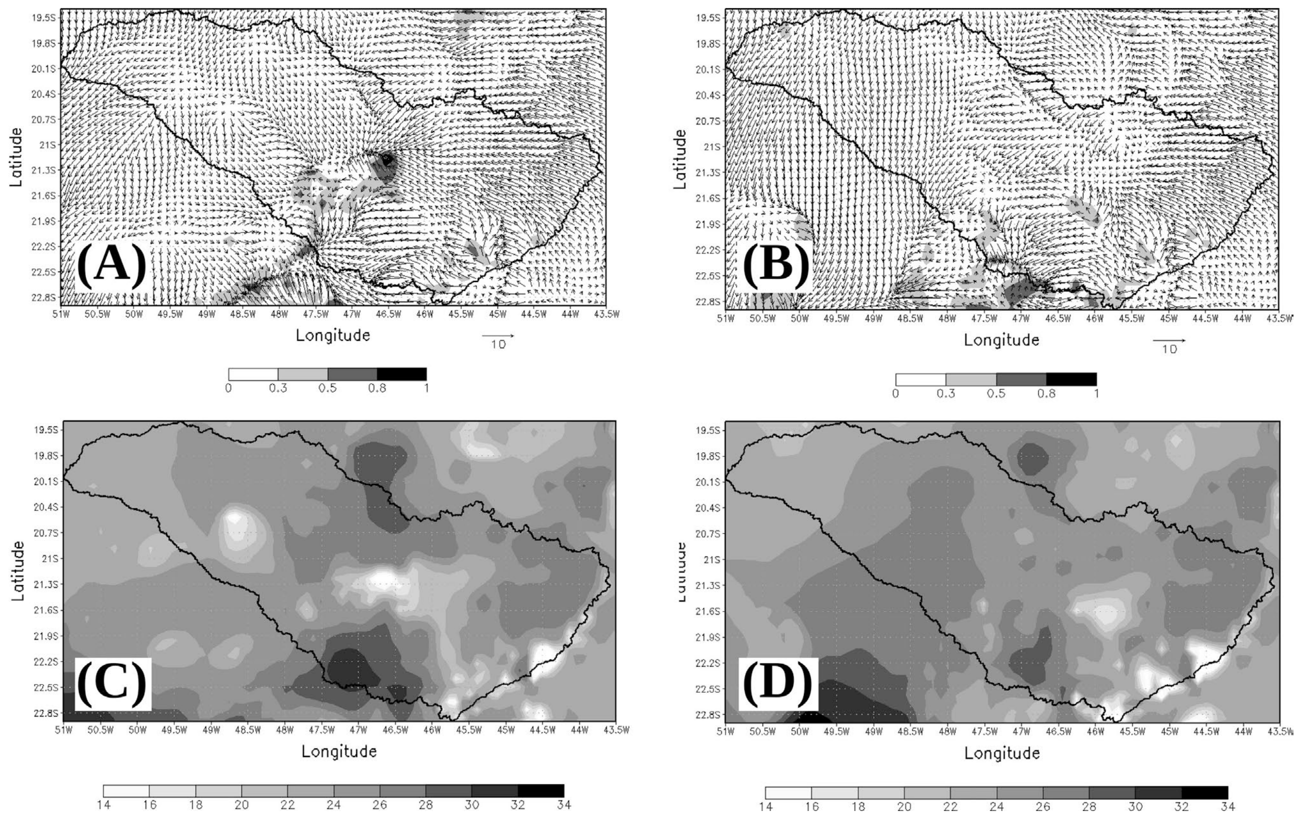

Figure 9 - Temperature (c and d) and air flow (a and b) fields near land surface calculated by both models.

6. Summary and Conclusions

This study outlines the role of a better representation of land surface hydrological processes in regional atmospheric models. For doing so, comparisons were made between a regional atmospheric model and a two-way coupled atmospheric-hydrological modelling system. The major difference between these models is that the atmospheric-hydrological coupled system incorporates a distributed hydrological model for representing land surface hydrologic processes while the regional atmospheric model interprets hydrologic processes based on land surface parameterizations (Avissar and Pielke, 1989; Lee and Abriola, 1999). In order to assess the performance of each model in representing atmospheric processes, simulations were performed and three study cases were selected to evaluate how the models behave in three distinct situations: reproducing a cold front, representing formation of deep convection and at stable atmospheric conditions. Results obtained from these simulations led to findings which have been separately described for each study case. For the cold front, convergent flows and high gradients of land surface temperature estimated by the two-way coupled atmospheric-hydrological modelling system well represented the spatial alignment of the front observed in the visible image. Although the regional atmospheric model alone have also detected the front, convergent flows and gradients of land surface temperature did not match the spatial distribution of the front observed in the satellite image. However, in terms of daily rainfall, comparisons between simulated values of 24-h accumulated rainfall and daily rainfall data revealed that both models regionally captured wet and dry regions over the Rio Grande basin.

Concerning the study case composed of convective activities, high cloudtop observed in the satellite image, associated either with surface heating or orography of the basin, were represented by convergent flows and high instantaneous rainfall rates by both models. In this study case, both approaches presented similar patterns of land surface temperature, zonal and meridional wind over the Rio Grande basin, thereby rainfall potential areas estimated by the models were similar to each other and, were located at the areas suggested by the satellite image and gauging rainfall stations. Under stable atmospheric conditions, estimates of land surface temperature and air circulation by the regional atmospheric model indicated convergent flows and abrupt variations of temperature which resulted in convective unstable zones in the mid troposphere. On the other hand, despite air circulation estimated by the atmospheric-hydrological modelling system having presented convergent flows over the basin, high values of vertical motion in the mid troposphere were not associated to them. Moreover, in accordance to the satellite image, the integrated system did not present any strong convective activity over the basin.

Overall, the replacement of land surface parameterizations by processbased hydrological modelling implied improvement in temperature, air water content, zonal and meridional winds calculated near land surface. According to investigations made towards the implications of these changes on the atmosphere, convergent flows and abrupt variations of temperature calculated by the coupled system were better related to the spatial alignment and distribution of the front than the regional atmospheric model. Under stable atmospheric conditions, results from the regional atmospheric model revealed a non-existent development of convection in response to a local surface heating. As the positioning of the front and development of convection are highly associated with temperature gradients, it indicates that the coupled system provides a better support to weather forecasting when simulating atmospheric processes driven by local surface heating or sharp temperature gradients.

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