Implementation of a two-way coupled atmospheric-hydrological system for environmental modeling at regional scale

Fábio Farias Pereira, Marcio A. E. de Moraes and Cintia Bertacchi Uvo

ABSTRACT

This work describes the two-way coupling performed between the regional atmospheric model Brazilian Regional Atmospheric Modeling System (BRAMS) and the hydrological model MGB-IPH. As a first step of the atmosphere-hydrology coupling, only the water balance variables were coupled. Differences in temporal and spatial scales between MGH-IPH and BRAMS were analyzed. By default, MGB-IPH has a daily time step whereas BRAMS uses smaller time steps. Thus, accumulated rainfall values from BRAMS were used to feed MGB-IPH. On the other hand, daily values of evapotranspiration from MGB-IPH were provided to BRAMS. This procedure was assumed as a daily loop in the simulations. Differences in spatial scales were avoided by using the same grid size (10 × 10 km) in both models, in such a way that neither upscaling nor downscaling was necessary. The coupled system was tested for the Rio Grande basin situated in south-eastern Brazil by comparing results from BRAMS with results from the coupled system for the same period, with the same input data. Outputs from the runs were compared to water vapor satellite images. The results from the coupled model tests indicated that its predictions of rainfall distribution were more accurate than BRAMS.

Key words | atmospheric model, distributed hydrological model, two-way coupling

Fábio Farias Pereira (corresponding author)
Cintia Bertacchi Uvo
Department of Water Resources Engineering,
Lund University,
Lund,
Sweden
E-mail: *fabio.pereira@tvrl.lth.se*

Marcio A. E. de Moraes
National Institute for Space Research (INPE), São José dos Campos,
SP,
Brazil

INTRODUCTION

Interactions between land surface and atmosphere induced by human activities and natural environmental dynamics act on a time scale that varies from seconds to millions of years. By exchanging heat, water, energy and carbon, land surface and atmospheric processes are closely interrelated and influence each other in reciprocal ways (Pielke *et al.* 1998; Betts 2007; Field *et al.* 2007). Therefore, estimating the exchanges of heat, water, energy and carbon between land surface and atmosphere considering their interplay is an important step towards the understanding of the impacts of anthropogenic actions as potential forcing mechanisms for climate regime shifts.

In this context, several numerical models have systematically been developed and enhanced to better represent land surface/atmosphere feedback loops (Benoit *et al.* 2000), and, among them, regional climate models (RCMs) stand out by including a wide range of transfer processes between land surface, atmosphere and oceans, from root water uptake to transport of atmospheric aerosols (Liston & Pielke 2000). One disadvantage of such models is that their local surface hydrology does not consider the river routing; thereby estimates of soil moisture content are underestimated in areas close to the drainage network (Graham *et al.* 2007). Yet another issue is associated with land surface parameterizations used by RCMs, since parameterization schemes usually apply prescribed values of parameters based on their probability density functions. This assumption does not interpret land use and soil characteristics as continuous distributions, and hence, mixtures in soil and vegetation within an area of interest are not captured (Walko *et al.* 1995; Beven & Freer 2001).

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In an attempt to simulate surface runoff on a daily basis, Hay *et al.* (2002) proposed a one-way coupling of a RCM and a distributed hydrological model. Their approach suggests that outputs of precipitation and temperature from the RCM are used as input to the hydrological model. This methodology incorporates the effects of the drainage network when calculating the soil moisture content, and replaces land surface parameterizations by a process-based method to estimate daily surface runoff; though feedback effects of land surface dynamics from the hydrological model are not included in calculations of precipitation and temperature time series provided by the RCM.

Therefore, the need for better representation of land surface hydrological processes and their feedback mechanisms into RCMs has been strongly suggested by several numerical studies (Baron *et al.* 1998; Bartholmes & Todini 2005; Lin *et al.* 2006; Messager *et al.* 2006; Haggag *et al.* 2008). In this sense, a more sophisticated approach proposed by Walko *et al.* (2000) presents a two-way coupling of a RCM and a hydrological model. Their coupled system includes turbulent and radiative exchange of heat and water between soil, vegetation, canopy air and atmosphere. However, sensitivity tests of this coupled system are only performed in idealized model simulations. Moreover, Walko *et al.* (2000) use a parametric model developed by Louis (1979) to represent fluxes of water vapor between land surface and atmosphere. This parametric model assumes that momentum roughness length is equal to heat transfer roughness length, and the height of the lowest model level is much larger than momentum roughness length. These assumptions are well supported by experimental evidence for smooth surfaces (Phelps & Pond 1971; Högström & Smedman-Högström 1974), although are not valid for rough surfaces and/or mountainous regions (Van Den Hurk & Holtslag 1997; Kot & Song 1998).

A similar approach has been used by Seuffert *et al.* (2002) to evaluate the influence of land surface hydrology on the predicted local weather. However, their study consists of a two-way coupling between a RCM and a hydrological model through a coupling strategy that, firstly, supposes that the hydrological model estimates the turbulent diffusion coefficients of heat and momentum more realistically than the RCM, and, secondly, replaces values of albedo from the RCM with those calculated by the hydrological model. Despite their results revealing that the two-way coupled model improved the predicted energy fluxes and rainfall in comparison with predictions made by the RCM during a 3-day forecast period, evapotranspiration rates are not only dependent on albedo but also on leaf area index, rooting depth and bulk stomatal resistance. Also, values of evapotranspiration may be over- or underestimated after a longer period of simulation.

In order to bridge this gap, this study presents the implementation of an atmospheric modeling system composed of a two-way coupling between the Brazilian Regional Atmospheric Modeling System (BRAMS; Freitas *et al.* 2009) and the hydrological model for large basins (MGB-IPH; Collischonn 2001) in a way to optimize their respective strengths. Since MGB-IPH incorporates a process-based approach to estimate evapotranspiration rates considering values of albedo, leaf area index, sunshine hours, relative humidity, atmospheric pressure and wind speed, this coupling methodology uses estimates of evapotranspiration by MGB-IPH in BRAMS. On the other hand, BRAMS provides daily precipitation as input to MGB-IPH. Spatial and temporal mismatches associated with the coupling methodology are also presented. As a case study, the atmospheric-hydrological modeling system is applied to the Rio Grande basin, Brazil.

MATERIAL AND METHODS

The implementation of the atmospheric-hydrological modeling system consists of a two-way coupling of BRAMS and MGB-IPH models. Besides the experience of the authors with them, the choice of these models was also based on their successful use in previous studies in the Rio Grande basin (Nóbrega *et al.* 2011; Bender & de Freitas 2013). Prior to implementing this integrated modeling system, a brief description of BRAMS and MGB-IPH including how land surface hydrological processes are interpreted by each of the models, and what kinds of ecosystems these models have successfully been applied to are presented in order to figure out the best coupling approach between BRAMS and MGB-IPH.

Once a proper two-way coupling strategy has been defined, spatial and temporal mismatches are adequately addressed as part of the implementation procedure. As BRAMS and MGB-IPH present their own spatial-temporal discretizations, which count on their respective grid generation and time step settings, the two-way exchange of variables between BRAMS and MGB-IPH is incorporated together with an algorithm that solves temporal and spatial mismatches.

The atmospheric-hydrological modeling system is then evaluated by means of comparisons of amount of instantaneous rainfall between results from two short-term runs of 31 days each performed for a wet period when the atmosphere is dominated by fronts, and local convection. The first run was carried out using the regional atmospheric model whereas the atmospheric-hydrological modeling system was applied in the second run. Based on atmospheric activities detected by the presence/absence of clouds in visible satellite images, two case studies were selected representing a cold front passage and local strong convection over the Rio Grande basin.

MGB-IPH hydrological model

The large-scale hydrological model MGB-IPH (Collischonn 2001) is a distributed model based on the LARSIM (Bremicker 1998) and VIC-2L (Liang *et al.* 1994) models, that consist of modules for calculating soil water budget, evapotranspiration, flow propagation within a cell, and flow routing through the drainage network (Collischonn *et al.* 2007). MGB-IPH has been tested and used in several South American basins, from rapid-response ones of southern Brazil and Uruguay to very low-response ones such as the Pantanal, the large wetland in the Upper Paraguay river basin. It also has been applied for several purposes, such as flow forecasting (Tucci *et al.* 2008) and to estimate daily water balance in large basins (Collischonn *et al.* 2008).

MGB-IPH divides each computational cell into hydrologic response units (HRUs) based on its land use/cover and soil distribution. HRUs are then defined by intersecting land use and soil groups within a computational cell. Once all computational cells are classified into different groups with similar hydrological response, MGB-IPH calculates the soil water budget, evapotranspiration and flow propagation (Collischonn *et al.* 2007). Evapotranspiration is estimated using the Penman-Monteith equation and routing through the river network uses the Muskingum-Cunge method. Meteorological conditions are prescribed based on interpolation of nearby measurement stations. By default MGB-IPH is employed using a daily time step; however depending on the purpose of study, it might become smaller or larger.

The MGB-IPH parameters are related to classes of physical characteristics, such as soil type, land use, geology and vegetation.

BRAMS atmospheric model

BRAMS is part of the operational weather prediction system of the Center for Weather Forecast and Climate Studies (CPTEC), belonging to the National Institute for Space Research (INPE) in Brazil (http://brams.cptec.inpe.br). The BRAMS is a multipurpose, numerical prediction model designed to simulate atmospheric circulations spanning from hemispheric scales down to large eddy simulations of the planetary boundary layer (Walko *et al.* 2000; www.atmet.com). The model is equipped with a multiple grid nesting scheme, which allows the model equations to be solved simultaneously on any number of interacting computational meshes of differing spatial resolution. It has a complex set of packages to simulate processes such as radiative transfer, surface-air water, heat and momentum exchanges, turbulent planetary boundary layer transport, and cloud microphysics. The initial conditions can be defined from various observational data sets that can be combined and processed with a meso-scale isentropic data analysis package. For the boundary conditions, a four-dimensional data assimilation technique described by Umeda & Martien (2002) is used to interpret atmospheric boundary conditions provided every 6 h by global atmospheric analyses. BRAMS features used in this system include an ensemble version of a deep and shallow cumulus scheme based on the mass flux approach and soil moisture initialization data. The surface-atmosphere water, momentum and energy exchanges are simulated by the Land Ecosystem Atmosphere Feedback model (LEAF-3), which represents the storage and vertical exchange of water and energy in multiple soil layers, including the effects of freezing and thawing soil, temporary surface water or snow cover, vegetation, and canopy air (Lee & Pielke 1992).

In order to merge the capabilities of several numerical weather codes, BRAMS was implemented using the concept of 'plug-compatible' modules given by Pielke & Arritt (1984). Although this concept allows the easy incorporation of improvements between the sub-routines of the model, it also stimulates the use of parameterizations by the developers and users of the model.

To represent surface layer fluxes of water vapor into the atmosphere, LEAF-3 uses a parametric model developed by Louis (1979). Similarly to any other trace gas, such as ozone (O_3) and carbon dioxide (CO_2), his parameterization scheme estimates the fluxes of water vapor using Businger's profile functions (Businger *et al*. 1971). Once computed, the fluxes of water vapor are interpreted by BRAMS as the lower boundary for the atmosphere.

Two-way coupling methodology

In the two-way coupling of BRAMS and MGB-IPH, process-based estimates of evapotranspiration rates by MGB-IPH replace fluxes of water, from canopy air to atmosphere, calculated using land surface parameterizations in the LEAF-3 routines of BRAMS as shown in Figure 1. Figure 1 shows a schematic of components of the LEAF-3 routine and their interactions with MGB-IPH, where atmosphere (A), vegetation cover (V), canopy air (C) and two soil layers (G1 and G2) are divided into multiple vertical layers. Moreover, vertical fluxes of heat, water and long wave radiation are represented by their subscripts h, w and r as well as the source and receptor (g for ground, s for snow, v for vegetation, c for canopy air, and a for free atmosphere). Therefore, evapotranspiration rates from MGB-IPH are equivalent to WCA (Water between Canopy air and Atmosphere) in LEAF-3.

On the other hand, daily accumulated rainfall estimated by BRAMS is provided as input to MGB-IPH. However, unlike the stand-alone version of BRAMS, the flux of water from canopy air to atmosphere incorporates feedback from a process-based approach to land surface hydrological processes given by MGB-IPH into calculations of daily accumulated rainfall. In this process-based approach to land surface hydrological processes, MGB-IPH calculates fluxes of water from land surface to atmosphere based on air temperature, relative humidity, long wave radiation and wind speed, and hence, it is considered more accurate and comprehensive than land surface parameterizations used by LEAF-3.

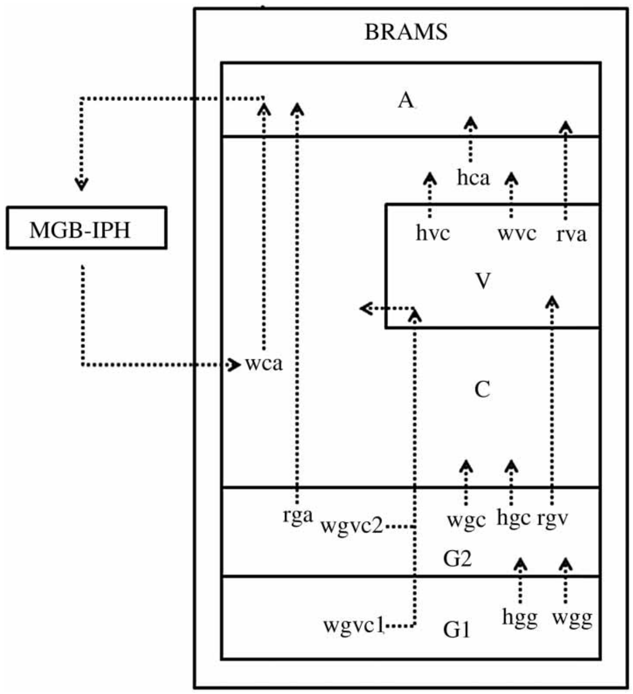

Figure 1 | A schematic of components of the LEAF-3 and their interactions with MGB-IPH over an entire column (adapted from Walko *et al*. (2000)).

As both models present their own surface grid and time step, the two-way exchange of variables between BRAMS and MGB-IPH includes two strategies to solve spatial and temporal mismatches. These strategies are separately described as follows.

Strategy for solving temporal mismatches

Due to numerical stability constraints, BRAMS runs with a smaller time step than the daily time step often used by MGB-IPH at basin scale. Therefore, the two-way exchange of variables between BRAMS and MGB-IPH presents a temporal coupling in a way that MGB-IPH is employed as a subroutine of BRAMS which is called every 24 simulation-hours as depicted in Figure 2. Specifically, at this time step, calculations of flux of water between canopy air and atmosphere in LEAF-3 are switched off. Complementarily, observed daily rainfall was not given as input to MGB-IPH at any time step. Thus, errors in energy and water balance computations owing to modifications arising from the two-way coupling methodology are not incorporated into the coupled model.

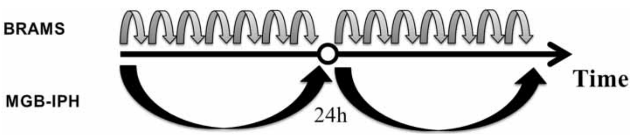

Figure 2 | Temporal coupling of BRAMS and MGB-IPH. As MGB-IPH runs on a daily basis while BRAMS uses shorter time steps, coupling variables are exchanged every 24 h.

Strategy for solving spatial mismatches

Although the two-way coupling methodology avoids upscaling and downscaling issues by running both models on the same grid cell size, BRAMS and MGB-IPH output variables are calculated at their own computational cell centers that do not always match each other. In order to correctly address the two-way exchange of variables between BRAMS and MGB-IPH, an algorithm has been developed to calculate and rank the distances between BRAMS and MGB-IPH computational cell centers. It also sorts these distances in ascending order, and identifies the nearest computational cell centers for the two-way exchange of variables. Figure 3 illustrates this two-way exchange according to the procedure carried out by the algorithm.

Model application

The Rio Grande basin was used as a case study for evaluating the two-way coupled system. The Rio Grande basin is located in the eastern upper Paraná basin (Figure 4). The basin is also formed by important subsidiaries rivers such as rivers Pardo and Mogi-Guaçu. Approximately 60% of

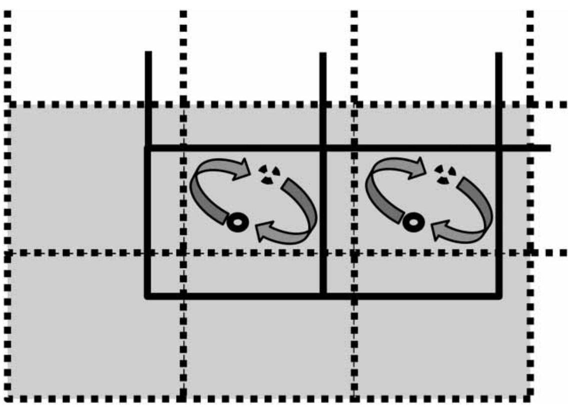

Figure 3 | Scheme of the two-way exchange of variables between BRAMS and MGB-IPH computational cell centers. An algorithm selects the nearest computational cell centers before exchanging the coupling variables.

hydroelectric power generation in Brazil is provided by the Paraná River basin, of which approximately 12% comes from the 15 hydropower plants in the Rio Grande basin (Agência Nacional de Energia Elétrica (ANEEL) 2005). The altitude in the basin varies from 300 to 2,700 m.a.s.l. and the land use is composed mostly of agriculture and pasture in the low lands and forest in the high lands.

The simulation domain corresponds to an area of 120 × 100 km that covers the Rio Grande basin. The horizontal and vertical grid spacing were defined equal to 10 km. The atmospheric variables were driven at the lateral boundaries using reanalysis from the Eta/CPTEC model. Weekly sea surface temperature (SST) was assumed on a one-degree grid (Reynolds *et al.* 2002) and topographic data from the US Geological Survey (USGS) were interpolated to the coupled model resolution.

Model runs

Two different runs are performed for a simulation period of 31 days. The first run corresponds to the control run and, the stand-alone version of BRAMS is applied to the Rio Grande basin while the second run is carried out using the atmospheric-hydrological modeling system.

This study evaluates the capability of each model to reproduce rainfall occurrence. For doing so, instantaneous rainfall fields from the BRAMS and the coupled model are compared to satellite images with respect to spatial distribution of rainfall and presence of clouds with high water content. Thereby, a wet weather period was chosen due to its high probability of rainfall occurrence. According to Nóbrega *et al.* (2011), austral summer is the rainy season at the Rio Grande basin, therefore the chosen simulation period spans 1st January through 31st January 2009.

Prior to each run, a warming-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, from 11th to 31st January 2009.

Criteria for selection of case studies

Outputs from both the atmospheric-hydrological modeling system and BRAMS are compared to each other and

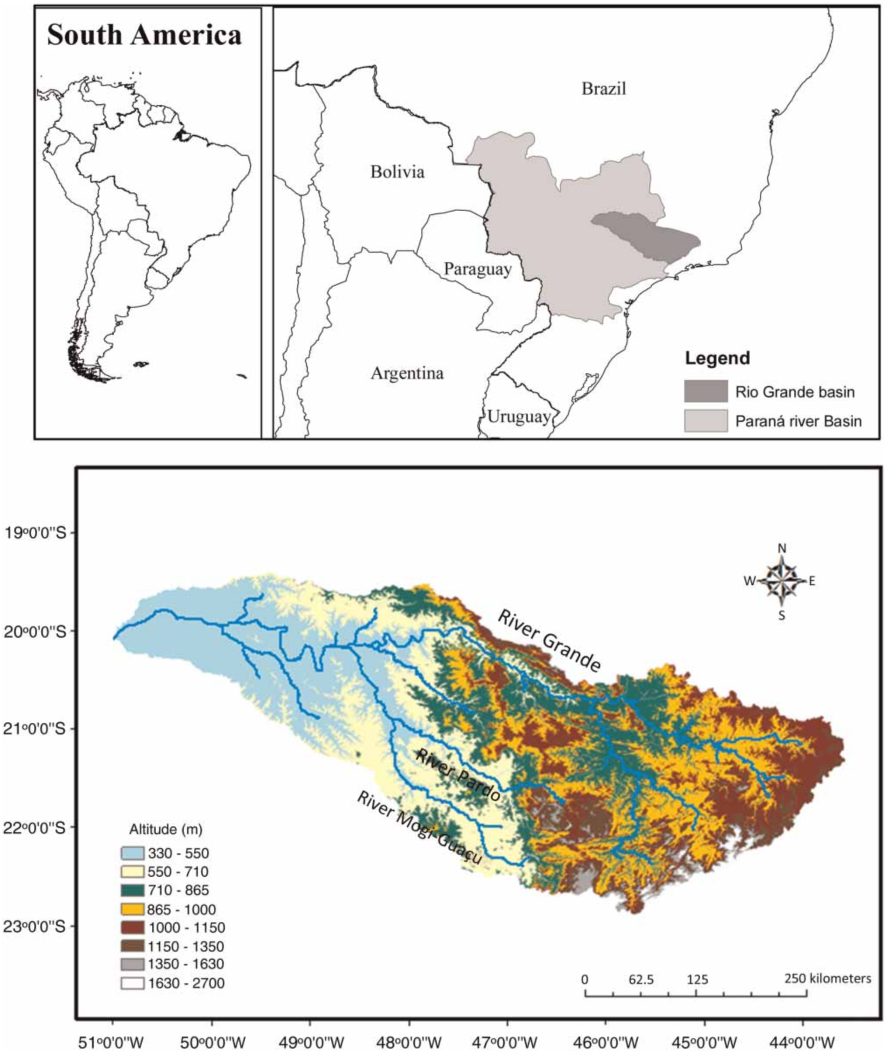

Figure 4 | Maps of Paraná river basin and Rio Grande basin with its main tributaries (i.e. Rivers Grande, Pardo and Mogi-Guaçu) and Rio Grande basin topography (see online version for colours: http://www.iwaponline.com/nh/toc.htm).

analyzed for the formation of clouds and precipitation occurrence. Since brightness of clouds in satellite images is related to their water content (Song *et al*. 2004), the presence of brighter clouds is used as indicator of precipitation occurrence.

In this study, visible satellite images were used to analyze the presence/absence of brighter clouds in the atmosphere. These images were captured every 6 h for the period of simulation after the warming-up period, 10th January 2009 to 31st January 2009. Four out of 160 satellite images clearly present brighter clouds over the Rio Grande basin, which represent two distinct events. The first event consists of a cold front passage that spans from 22nd January at 0000 UTC (Coordinated Universal Time) to 23rd January at 0000 UTC. The second one is characterized by a local strong convection on 15th January at 1200 UTC. These two events are then selected as case studies.

Assessment of the coupled model

The performance of each model is evaluated with respect to its capability of representing the spatial distribution of instantaneous rainfall. Since satellite coverage is continuous over most regions of the Earth surface and several satellite-based rainfall estimation techniques have proved that rainfall occurrence is closely associated with brightness of visible images (Adler & Andrew 1988; Porcú et al. 1999; Todd et al. 2001; Coppola et al. 2006; Lintner et al. 2011), the spatial distribution of instantaneous rainfall given by BRAMS and the coupled model are compared to visible satellite images captured by a geostationary satellite focused on South America and operated by the National Oceanic and Atmospheric Administration (NOAA), the geostationary operational environmental satellite 10 (GOES-10).

Although there is a time difference before the probable rain (i.e. brighter clouds in GOES-10 visible images) falls to the surface (from 5 to 8 min; Jakob & Klein 2000), it is assumed that precipitating clouds do not move out of computational cells of 10×10 km in this small time interval. This assumption is valid for comparisons made between satellite images and instantaneous rainfall fields (O'Sullivan et al. 1988). However, since rainfall observations from the Tropical Rainfall Measurement Mission (TRMM) and rain gauge stations are respectively 3 h and daily accumulated data, they are not used for comparisons due to their temporal resolution. Moreover, TRMM estimates are given at a 0.25-degree by 0.25-degree spatial resolution, thereby quantitative comparisons between these estimates of rainfall and simulated values from the models would be affected by upscaling/downscaling approaches.

Once the spatial distribution of instantaneous rainfall fields estimated by BRAMS and the coupled model match probable rains in GOES-10 visible images, the order of magnitude of instantaneous rainfall rates are compared to values of rainfall obtained from studies on the interannual variability of extreme events in the same study area carried out by Leibmann et al. (2001). For the Rio Grande basin, their analysis defines as convective rainfalls, rainfall events higher than 3.5 mm h^{-1}.

RESULTS

In this section, results from the models runs for each case study are presented. The case studies represent two particular atmospheric events driven by different physical processes. In the first case study, for instance, the ability of each model to reproduce instantaneous rainfall derived from a cold front passage is evaluated, while the second case study assesses the models when representing local rainfalls formed from convections. As rainfall is a response of the atmosphere to sharp variations of air temperature, atmospheric pressure, relative humidity and air flow, the agreement between instantaneous rainfall fields and satellite images is used to evaluate the performance of the models as done by McMurdie & Katsaros (1996) and O'Sullivan et al. (1988).

Figure 5 shows the spatial distribution of precipitating clouds (first column) and instantaneous rainfall fields estimated by BRAMS (second column) and the coupled model (third column) on 22nd January 2009 00:00 UTC, 06:00 UTC, 12:00 UTC and on 23rd January 2009 00:00 UTC for the first case study.

According to Figure 5, the presence of precipitating clouds indicates convergences all over the Rio Grande basin, which characterizes a cold front passage on 22nd January 2009 at 00:00 UTC and 23rd January 2009 at 00:00 UTC. In addition, stable atmospheric conditions are observed on 22nd January 2009 at 06:00 UTC and 18:00 UTC and they are used to investigate possible numerical instabilities in the coupled model when the atmosphere shifts from unstable to stable conditions, and vice versa.

Under stable conditions, interactions between atmosphere and land surface slow down and the amount of instantaneous rainfall is lower than 0.5 mm h^{-1} over the Rio Grande basin for both models. Accordingly, instantaneous rainfall fields calculated by BRAMS and the coupled model present the same low rainfall profile as observed in satellite images. It means that, despite passing through unstable atmospheric conditions due to a cold front, the coupled model converges to the same rainfall patterns as BRAMS and satellite images. Moreover, this case study shows that changes proposed by the two-way coupling strategy do not affect rainfall under stable atmospheric conditions.

Nevertheless, on 22nd January 2009 at 00:00 UTC and 23rd January 2009 at 00:00 UTC, estimates of maximum instantaneous rainfall obtained from the coupled model and BRAMS vary at different rates. While estimates of maximum values of instantaneous rainfall by BRAMS are higher than 5 mm h^{-1}, instantaneous rainfall rates from the coupled model vary between 0 and 4 mm h^{-1} over the Rio Grande basin. However, the spatial distribution of instantaneous rainfall calculated by the coupled model is

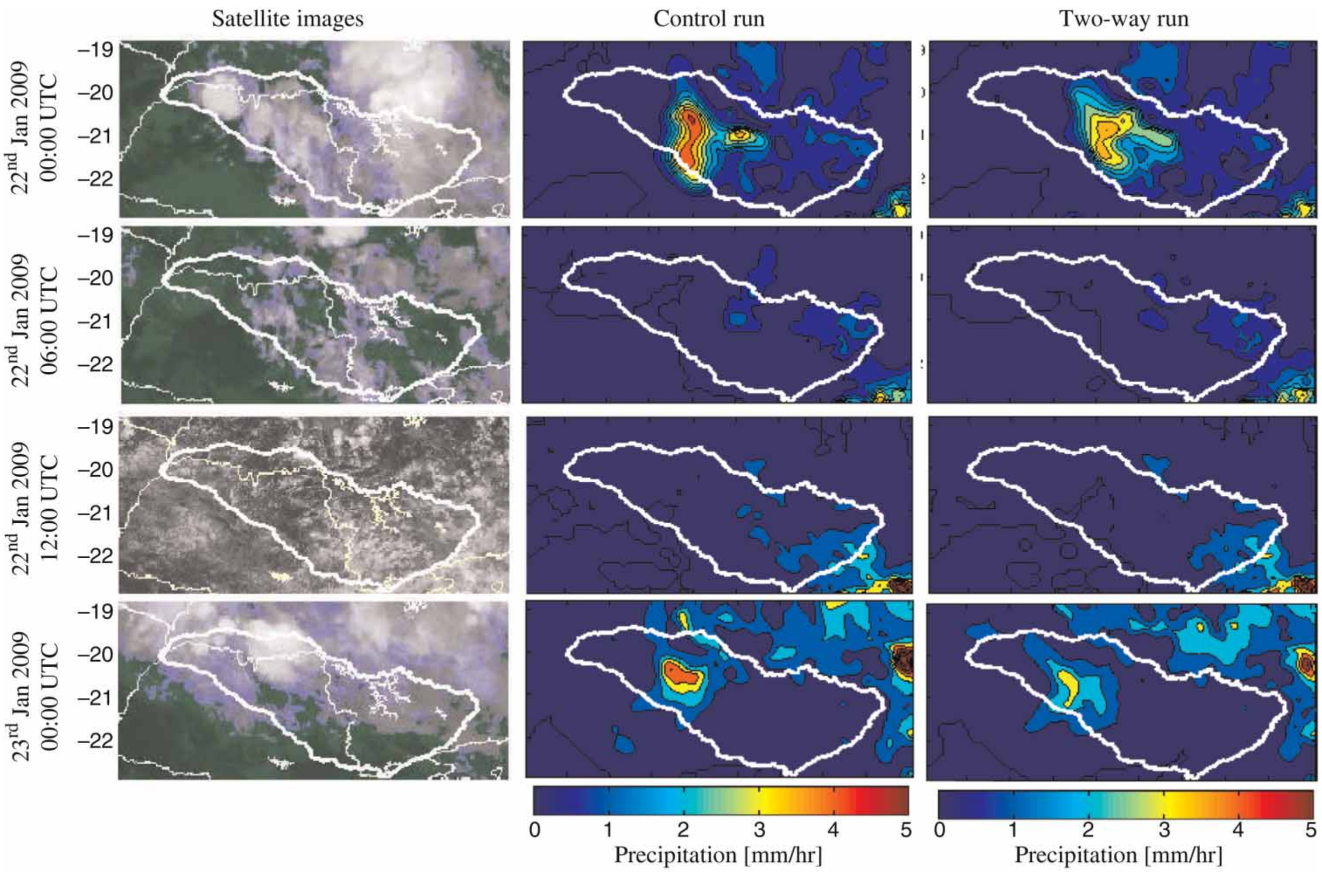

Figure 5 | Simulated precipitation fields at 00:00, 06:00, 12:00 UTC 22 January and 00:00 UTC 23 January for the BRAMS model without any changes (control run), with the two-way coupling (two-way run), and with the water vapor observations from GOES-10. The marked line indicates the Rio Grande basin (see online version for colours: http://www.iwaponline.com/nh/toc.htm).

well-distributed over the basin and, by comparing to the satellite image, it shows a better agreement with precipitating clouds than the one proposed by BRAMS.

Regarding the second case study, results from the coupled model and BRAMS are examined using satellite image, instantaneous rainfall fields and differences between those estimated by BRAMS and the coupled model (Figure 6). These differences are calculated in a way that negative values of instantaneous rainfall imply estimates of instantaneous rainfall by the coupled model higher than those by BRAMS.

As shown in Figure 6, precipitating clouds observed in the satellite image indicate probable convective rainfalls towards the north-eastern part of the Rio Grande basin. Also, despite both models estimating the amount of instantaneous rainfall within the range suggested by Leibmann *et al.* (2001), instantaneous rainfall fields present different patterns of spatial distribution over this region. Comparing to the spatial distribution of precipitating clouds in the satellite image, the spatial distribution of instantaneous rainfall from the coupled model reveals a better agreement than the one from BRAMS. According to differences between instantaneous rainfall fields, zones of probable convective rainfalls present values up to $-5\,\mathrm{mm\,h^{-1}}$, which means that BRAMS may underestimate convective rainfall events.

Since convective rainfalls are driven by local surface heating, which increases evapotranspiration rates, a better representation of this case study suggested that a process-based approach to land surface hydrological processes proposed by the two-way coupling strategy improves the ability of regional atmospheric models to represent atmospheric events governed by the local hydrology.

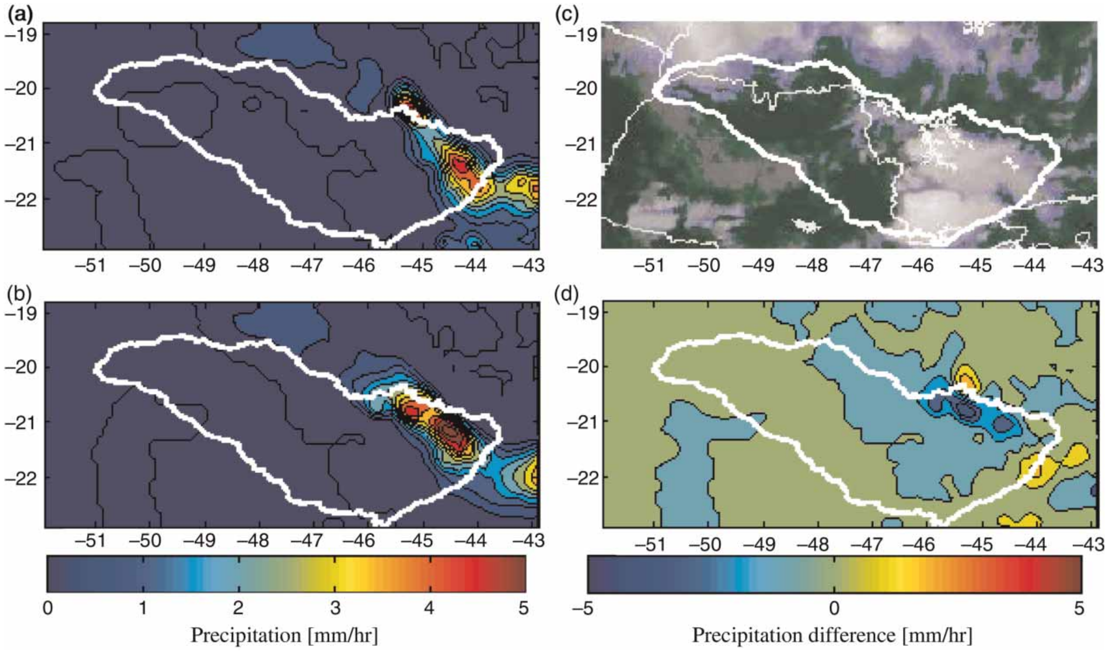

Figure 6 | Precipitation fields calculated by BRAMS (a), the coupled model (b) and water vapor observations (c). Differences between precipitation fields simulated with BRAMS and the coupled model (d) (see online version for colours: http://www.iwaponline.com/nh/toc.htm).

CONCLUSIONS

This work presents the implementation of a two-way coupling between the Brazilian Regional Atmospheric Modeling System (BRAMS) and the model for large basins (MGB-IPH) in order to develop an atmospheric-hydrological modeling system capable of estimating interactions between land surface and atmosphere considering their feedback loops. This coupled system aimed to use the process-based approach to estimate evapotranspiration provided by MGB-IPH instead of evapotranspiration calculated from land surface parameterizations in BRAMS. Unlike Walko *et al.* (2000), results from the coupled system and BRAMS were compared to two atmospheric events captured by a geostationary satellite and characterized by variations of evapotranspiration in the land surface, namely, a cold front passage and a local surface heating. These results led to findings which are discussed below.

Cold fronts are derived from sharp gradients of temperature and pressure over short distances; and although two different approaches to land surface processes were used to reproduce the cold front passage, modifications arising from the coupled system did not have the same order of magnitude as interactions between land surface and atmosphere during the front passage. Therefore, BRAMS and the coupled model presented similar patterns of spatial distribution of instantaneous rainfall. Another characteristic found in this atmospheric event was the capability of representing the transition from unstable to stable atmospheric conditions. Even though the coupled system incorporates a two-way exchange of variables between BRAMS and MGB-IPH at a particular time step, this case study revealed that effects of this exchange of variables did not lead to numerical instability; since the coupled system and BRAMS converged to the same solution after unstable atmospheric conditions caused by the cold front.

On the other hand, the coupled system and BRAMS indicated different areas of convective rainfall induced by the local surface heating. Differences between instantaneous rainfall fields revealed that areas of convective rainfall proposed by the coupled system matched precipitating clouds observed in satellite images rather than those suggested by BRAMS. Since convective rainfalls are responses to warmer temperatures in the land surface, the case study of the local surface heating evidenced that a process-based approach to land surface hydrological processes used by the coupled system increased BRAMS ability to reproduce convection; thereby, the coupled system appears to be an alternative method for issues related to simulating convective events at regional scale (Moncrieff 1995; Bernardet *et al*. 2000; Lang *et al.* 2007; Anabor *et al*. 2009).

Ongoing researches are being conducted on the development of an integrated modeling system capable of assessing the interplay between land use, hydrology, and atmosphere in ecosystems under climatic and land use changes. Therefore, future improvements of the atmospheric-hydrological modeling system will incorporate air temperature, relative humidity, surface pressure, wind speed, and turbulence coefficient as well as solar and long wave radiation as coupling variables provided by BRAMS to MGB-IPH. In addition, the river routing scheme from MGB-IPH may be included in calculations of soil moisture rates by BRAMS.

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