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The Brazilian Global Atmospheric Model (BAM). Performance for Tropical Rainfall forecasting and sensitivity to convective scheme and horizontal resolution

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ABSTRACT

This article describes the main features of the Brazilian Global Atmospheric Model (BAM), analyses of its performance for tropical rainfall forecasting, and its sensitivity to convective scheme and horizontal resolution. BAM is the new global atmospheric model of the Center for Weather Forecasting and Climate Research (CPTEC), which includes a new dynamical core and state-of-the-art parameterization schemes. BAM's dynamical core incorporates a monotonic two-time-level semi-Lagrangian scheme, which is carried out completely on the model grid for the tridimensional transport of moisture, microphysical prognostic variables, and tracers. The performance of the Quantitative Precipitation Forecast (QPF) from two convective schemes, Grell-Dévényi (GD) scheme and its modified version (GDM), and two different horizontal resolutions are evaluated against the daily TRMM Multi-satellite Precipitation Analysis over different tropical regions. Three main results are: a) the QPF skill was improved substantially with GDM in comparison to GD; b) the increase in the horizontal resolution without any ad-hoc tuning improves the variance of precipitation over continents with complex orography, such as Africa and South America, whereas over oceans there are no significant differences; and c) the systematic errors (dry or wet biases) remain virtually unchanged after 5 days forecast. Despite improvements in the tropical precipitation forecast, especially over southeastern Brazil, dry biases over the Amazon and La Plata remain in BAM. Improving the precipitation forecast over these regions remains a challenge for the future developments of the model to be used not only for Numerical Weather Prediction over South America but also for global climate simulations.

1. Introduction

Substantial progress has been made during the last decade in the development of Earth System Models (ESMs) and simulation of many important features of the present global climate. Nevertheless, most current models still have serious deficiencies in simulating the tropical precipitation during the wet season over the Southern Hemisphere (December to February- DJF). The largest errors are found over the six regions depicted in Fig.1a, which are: Central Africa, Indian Ocean ITCZ (Intertropical Convergence Zone), South Pacific Convergence Zone (SPCZ), Amazon Basin, South Atlantic Convergence Zone (SACZ), and La Plata Basin. For instance, results from the Coupled Model Intercomparison Project phase 5 (CMIP5) show that most models tend to underestimate rainfall over the Amazon Basin (e.g., Yin et al. 2013; Mehran et al. 2014; Gulizia et al. 2014) and exhibit persistent errors in simulating the South American Monsoon System (SAMS) (Jones and Carvalho 2013). Over Africa and Australia, models also show poor skill in precipitation simulation (Mehran et al. 2014) and the SPCZ is still poorly simulated in CMIP5 models (Hirota and Takayabu 2013; Grose et al. 2014). Moreover, as rainfall is a highly nonlinear phenomenon, it is difficult to trace-back the origin of errors by using full Earth System Models.

Xie et al. (2012) and Ma et al. (2014) examined the correspondence between short- and long-term systematic errors in atmospheric models and found that most of the systematic errors in precipitation of climate simulations develop within the first few days (~5 days) of simulation. Therefore, it is believed that improving quantitative precipitation forecasts (QPF) in short-time integrations (1-7 days), for instance, may be useful for improving climate variability simulation. With this perspective, the Brazilian Global Atmospheric Model (BAM) has been developed at Center for Weather Forecasting and Climate Studies (CPTEC) of the National Institute for Space

Research (INPE) for use in time scales ranging from days to seasons and horizontal resolutions *O*(10-200 km). The strategy was to develop a seamless framework for weather/climate prediction. Hence, the same global atmospheric model used in deterministic NWP (1-10 days) or, coupled to an ocean model, in probabilistic extended NWP (1-4 weeks) is designed to be used also in a full ESMs (global coupled atmosphere-ocean-land-cryosphere) for seasonal climate prediction and climate change studies.

A comprehensive performance analysis of the BAM model in NWP and climate predictions is yet to be documented. The present work is focused on evaluating seven-day tropical precipitation forecasts produced by BAM during the austral summer (DJF) of 2012/2013 over the Southern Hemisphere, against the daily Tropical Rainfall Measuring Mission (TRMM) and Multi-satellite Precipitation Analysis (TMPA). The aim of this paper is to provide (a) a brief description of the dynamical and physical processes in BAM; (b) a QPF skill evaluation of the new model with two different convective parameterization schemes: the Grell and Dévényi (2002, GD) ensemble scheme and its modified version (GDM) developed at CPTEC against the TMPA data set; and (c) an evaluation of the impact of increased horizontal resolution (from 45 to 20 km) on the QPF skill. Although the importance of other physical processes such as radiation, vertical diffusion, microphysics, and surface processes for tropical precipitation cannot be overlooked, our main focus lie on deep convection, which is crucial for rainfall prediction (Fritsch and Carbone 2004), and on the impact of increasing horizontal resolution on precipitation forecasts.

Although this study evaluates the performance of the model over all the tropics, our main attention lies over southeastern Brazil, where the maximum seasonal precipitation occurs during DJF; and where large metropolitan areas (e.g., Sao Paulo, Rio de Janeiro and Belo Horizonte) rely on precipitation for water supply and food production. Therefore, development of a stable global atmospheric model and its validation are important for practical use in weather forecasting over Brazil, as well as the atmospheric component of the Brazilian Earth System Model – BESM (Nobre et al. 2013) for the seasonal climate prediction and climate change studies. Hence the importance of this study is to identify strengths and weaknesses of BAM for its use as operational NWP model and for further developments of the model. This paper is organized as follows. In Section 2, the physics and dynamics formulations of the new model are briefly described. Section 3 describes the design of the experiments; precipitation dataset and methodology used. Evaluation of the QFP over the tropical region with two different convective schemes and the evaluation of the impact of increased horizontal resolution on the QPF skill are described in Section 4. Section 5 summarizes our results.

2. Overview of model formulation

The dynamical core and physics parameterizations in BAM are quite different from those used in the previous CPTEC atmospheric global model (referred hereafter as AGCM3 or old model). We describe here briefly the novelties and the motivations leading to the new model. The original version of AGCM3 was adapted from the Center for Ocean–Land–Atmosphere Studies (COLA) AGCM during the nineties (Cavalcanti et al. 2002). The evolution CPTEC/COLA AGCM, which led to AGCM3 has been reported in, for example, Figueroa et al. (2006), Panetta et al. (2007) and Barbosa et al. (2008) (see Table 1 for a summary). AGCM3 has been extensively used in previous years for deterministic and probabilistic global operational NWP (e.g., Cunningham et al. 2014), and has been coupled to an ocean model for seasonal climate prediction and climate studies (e.g., Nobre et al. 2009; Nobre et al. 2013). Nevertheless, many systematic errors in NWP and climate simulations were found for horizontal resolutions *O*(10-100 km), such as an excess of oceanic tropical precipitation, wet biases over Andes and spurious precipitation near the mountains at high latitudes, among others that will be shown later in this article. These errors motivated the development of a new global atmospheric model, which included a new dynamical core and state-of-the-art parameterization schemes.

a. Dynamics core

The dynamical core in BAM is a hydrostatic semi-implicit spectral model, based on a U-V formulation, with a sigma/hybrid vertical coordinate, incorporating a monotonic two-time-level semi-Lagrangian scheme for the tridimensional transport of moisture, microphysical and tracers prognostic variables. This transport scheme, which can be used with both the Eulerian and the semi-Lagrangian code options for the dynamics, is carried out on the model grid, with moisture variables having no spectral representation. This dynamical core aims to be used for weather and climate prediction at horizontal resolutions from 200 down to 10 km. In the next subsections, some physical processes incorporated in BAM are described, with others are listed in Tab.1. The documentation of the new model (dynamical core and physics formulations) will be available as a technical report.

b. Surface layer processes

The land surface scheme is the Integrated Biosphere Simulator-IBIS version 2.6 (v.2.6) of Foley et al. (1996) and Kucharik et al. (2000), which was improved at CPTEC by Kubota (2012). This scheme is a dynamic global vegetation model, which represents a wide range of processes, including land surface physics, canopy physiology, plant phenology, vegetation dynamics and competition, and carbon and nutrient cycling. The evaluation studies of this scheme over the Amazon (e.g., Costa et al. 2007, Costa and Piris, 2010), and over the Brazilian Northeast (Cunha et al. 2013) have shown the capability of this scheme well represents the physical, physiological, and ecological processes occurring in vegetation and soils. Therefore, this scheme coupled to the atmosphere is a useful tool for rainforest, land use, deforestation, and climate change studies, especially over the Amazon.

c. Cloud microphysics

The double-moment bulk microphysics Morrison scheme (Morrison et al. 2005, Morrison et al. 2009) with predicted droplet concentration and coupling with the specified background aerosol/cloud condensation nuclei (CCN) spectra is used. This scheme predicts the mass and number mixing ratios of five hydrometeor categories (x): cloud droplets, rain, cloud ice, snow, and graupel. The size distributions are represented by gamma functions: $N_x(D_x) = N_{0x} D_x^{\mu_x} \exp(-\lambda_x D_x)$, where D_x is the particle diameter, and N_{0x}, λ_x, and μ_x are the intercept, slope, and shape parameters of the size distribution respectively. The shape parameter is assumed zero (μ_x=0) for cloud ice and precipitation species. For cloud droplets, μ is calculated as a function of the droplet number concentration following Martin et al. (1994). The slope and intercept parameters are derived from the predicted mass (q_x) and number (N_x) mixing ratios and specified μ_x. Equations for the time tendencies of q_x and N_x are similar to those in Morrison et al. (2005), except for graupel, q_g and $N_g$are given by Reisner et al. (1998). This scheme is coupled to the turbulent mixing scheme, which provides a sub-grid vertical velocity for droplet activation and mixing of the cloud droplet and ice number mixing ratios, as well as to the radiation scheme described in the next section using the predicted cloud droplet and ice effective radii.

d. Radiation and cloud properties

The shortwave (SW) and longwave (LW) radiation scheme used in BAM is the Rapid Radiative Transfer Model for GCMs (RRTMG, Iacono et al. 2008) developed at the Atmospheric and Environmental Research, Inc. (AER), and which is a modified version of a rapid and accurate radiate transfer model (RRTM, Mlawer et al. 1997). This scheme includes the Monte-Carlo independent column approximation (McICA) technique (Pincus et al. 2003), which is an efficient statistical method for sub-grid cloud characterization. The RRTMG-SW and RRTMG-LW calculate fluxes and heating rates for the shortwave (14 bands, from 0.2 μm to 12.2 μm) and longwave (16 bands, from 3.1 μm to 1.0 mm) respectively. The effects of gaseous absorption and particle scattering into RRTMG-SW include water vapor, carbon dioxide, ozone, methane, oxygen, nitrogen, clouds, aerosols, and Rayleigh scattering, while the molecular species treated into RRTMG-LW are water vapor, carbon dioxide, ozone, methane, nitrous oxide, oxygen, nitrogen, and the halocarbons CFC11 and CFC12. On the other hand, the cloud properties (cloud optical depth, emissivity, etc.) used in this new model are similar to those used in the NCAR Community Atmosphere Model (CAM 5.0) described in Neale et al. (2012). The aerosol optical properties are specified. The implementation of a dynamic aerosol model in BAM is in progress, and is expected to be available in the next model version.

e. Convection

Shallow convection scheme in BAM is from Park and Bretherton (2009), which was developed at University of Washington (UW). The cloud-base mass flux is calculated using

Turbulent Kinetic Energy (TKE) and Convection Inhibition Energy (CINE), and the entrainment and detrainment into cumulus updraft are calculated using a buoyance-sorting algorithm. Two deep convection schemes have been implemented in BAM. The multi-closure, Grell and Dévényi (2002) ensemble scheme (GD) and its modified scheme (GDM) developed at CPTEC/INPE (which is briefly summarized in Appendix). Below, we briefly describe the GD scheme focusing on the cloud-base mass flux.

Following Arakawa and Shubert (1974, hereafter AS) the cloud-work function (A) is the rate of generation of kinetic energy due to work done by buoyancy force (B), or an integral measure of the buoyance force with weighing by a normalized mass flux profile (η). The change of A can be written as $\frac{\partial A(t)}{\partial t} = \left(\frac{\partial A(t)}{\partial t}\right)_{LS} + \left(\frac{\partial A(t)}{\partial t}\right)_{CU} m_b$, where the subscripts LS and CU represent changes of the work function due to effects of the large-scale forcing (F), and due to the convective clouds (K) normalized by cloud base flux m_b, respectively. The Grell closure (Grell 1993, G1) assumes the AS convective quasi-equilibrium assumption between large-scale forcing and convection. This AS quasi-equilibrium assumption requires that $\frac{\partial A(t)}{\partial t} \ll F$. This means that convective tendencies are fast compared to the net or observed tendency, $\frac{\partial A(t)}{\partial t} \approx 0$, then the mass flux base m_b in G1 closure can be calculated as $m_b - F/K = -(A'(n+1) - A(n))/K\Delta t$, where A' is the work function calculated with updated (at time-step $n+1$) thermodynamics variables (ψ^{n+1}) after modifications by model tendencies (radiation, surface and PBL processes and dynamics) and A is calculated from thermodynamics variables at the present state (ψ^{n}) and K is calculated as in G1. The GD scheme implemented in BAM uses five different methods to calculate m_b. Three are stability closures. G1 (1) is described above. For AS (2), the closure from the GFS physics suite is used that uses climatological cloud work functions instead of calculating A. KF-Type (3) removes stability over a specified time period (such is used in Kain and Fritsch 1992). Kuo-type (4) uses a Krishnamurti type closure (Krishnamurti et al. 1983), relating the integrated vertical advection of moisture to m_b. The final closure (5) uses a relationship between low level omega and m_b (Brown 1979). Three perturbations are then applied for G1, FC_type, Kuo_type and omega, and four perturbation for AS. These are allowed to interact with 9 members from static control (3 precipitation efficiencies and 3 cap strengths), giving a total 144 sub-grid members.

3. Experiments, data and methodology

a. Experimental design

Four experiments have been performed. The first experiment (Exp1) uses AGCM3 and the other three use BAM with two convective parameterizations, GD and GDM, which are referred to as BAMa and BAMb respectively. Further details are given in Table 2. In the first experiment, global precipitation from AGCM3 and BAM are compared (Section 4a). The QPF evaluation over the tropics, sensitivity of precipitation forecast from the new model (BAM) with two convective parameterizations (Exp2 and Exp3) and sensitivity to increasing the horizontal resolutions (Exp4) are evaluated in two parts: Part 1 (Section 4b) - over the global tropics, SPCZ, and over three land regions; and Part 2 (Section 4c) - over Brazil which was divided into 5 regions. The experiments at 20 km horizontal resolution were carried out with SL and Eulerian advection schemes, but the results were similar (figures not shown). Therefore, we will focus only on the SL results.

The period of simulation is from November 20, 2012 to February 28, 2013. This period was chosen for the present study because during that specific period, i.e., austral summer, many heavy rainfall events were observed. For instance, during DJF 2012/2013, 13 cold fronts over La Plata, and 5 well-defined SACZ episodes occurred over southeastern Brazil (Climanálise 2012, 2013a and 2013b). Starting at every day in that period, the models were integrated for 7 days using the same initial conditions used in the NCEP/GFS operational model, at 12 UTC. The 7-days output total precipitation forecast was used for model evaluation. We use the initial conditions from GFS to evaluate the performance of the new dynamic and physical processes involved in BAM, rather than using our own assimilation system, to allow for a clear comparison with precipitation forecast from GFS. In order to filter the spurious high-frequency oscillations produced during the first time-steps of the forecast due to the unbalanced initial conditions, a diabatic nonlinear normal-mode initialization (NNMI) scheme based on Machenhauer (1977) and Kitade (1983) is used with the first five vertical modes, period cutoff of 48 h and two interactions. In this scheme, the initial tendency of the faster modes is set to zero and the corresponding fields of these waves are replaced by a new balanced fields obtained interactively. This initialization process can alleviate the problem of surface pressure tendency spin-up during the first few hours of integration.

b. Data for QPF verification

The daily observed rainfall for the tropical QPF evaluation is derived from TMPA (Huffman et al. 2010) 3B42 version 7, 3-hourly $0.25^{o} \times 0.25^{o}$ lat/long grid resolution rainfall data for the period December 2012-February 2013. Previous studies have evaluated the TMPA product over different tropical regions, e.g., over Australia (Chen et al. 2013) and over the Andes (Ochoa et al. 2014). These studies reveal that the TMPA product shows, in general, a good correspondence with rain gauge data sets. In addition to TMPA, for evaluating the global precipitation and surface latent heat fluxes for DJF 2012/2013, the daily Global Precipitation Climatology Project (GPCP-v.2.2) $1^{o} \times 1^{o}$ lat/long grid (Huffman et al. 2009) product and the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim (ERA-Interim) product (Dee et al. 2011) are used, respectively. For comparison of QPF from BAM and other global NWP operational models, 7-days precipitation forecast data from the operational GFS (September 2012 version, horizontal resolution ≈ 27 km and 64 vertical levels) is used, which are available on the NCEP website. Finally, the output precipitation data from all experiments were gridded to the observed data resolution (e.g., tropical model precipitation to the TMPA dataset resolution, 0.25°; and global model precipitation to the GPCP dataset resolution, 1°). For this interpolating, the *remapcon* utility from the CDO (Climate Data Operators) package is used that performs first-order conservative remapping.

d. Methodology and statistics

For evaluating the QPF in each region we used standard continuous and categorical statistical measures. The continuous statistics scores used to evaluate the accuracy of different models are: unconditional bias ($BIAS$), root mean square error ($RMSE$), unbiased root mean square error (URMSE), standard deviation (σ) and Pearson correlation coefficient (R). Following Murphy (1988), the uncentered total RMSE can be decomposed in two components, due to the systematic errors (BIAS) and related to the pattern error (URMSE). The URMSE (once the unconditional biases are removed from the total error) can be interpreted as a measure of non-systematic model errors due to errors in amplitude (σ) and phase (R). We use the Taylor (2001) diagrams to graphically summarize the normalized unbiased RMSE ($URMSE^{*}$), the normalized standard deviations forecast (σ_f^{*}) and the correlation coefficient (R_{fo}). This method is also used to compare the performance of models to the observations.

The categorical forecast verification measures used here are: frequency bias score (FBS), and the Gilbert skill score (GSS) also known as the Equitable Threat Score (ETS) (Mesinger and Black 1992). The FBS and GSS are among the different categorical scores recommended by WMO (2009) for assessing the skill of deterministic precipitation forecast. The threshold values used for plots are similar to those used by Mesinger (1998) except in mm/day. Four different rainfall categories, based on thresholds of precipitation intensity (in mm/day), are used in this paper: very light rain (0.1-2.5), light rain (2.6-7.5), moderate rain (7.6-35.5) and heavy rain (>35.6). These four rainfall categories have been adapted from the Indian Meteorology Department-IDM glossary (http://www.imdpune.gov.in/weather_forecasting/glossary.pdf).

4. Results

a. Global precipitation from AGCM3 and BAM

In this section we evaluate the 24 h global DJF average precipitation and surface latent heat fluxes from AGCM3, and BAM at 45 km horizontal resolution with two convective parameterizations GD and GDM. Figure 1 shows the seasonal mean precipitation rate obtained from GPCP and the 24 h model forecasts from the first three experiments (left) and the corresponding surface latent heat fluxes (right). The comparison of surface latent fluxes is included in this section, in order to identify the possible cause of the excessive tropical precipitation in AGCM3. The spatially averaged RMSE and correlation coefficient values are shown on the top right corners of the panels, and the zonal mean precipitation and surface latent heat fluxes corresponding to Fig. 1 are shown in Fig. 2. An eyeball comparison of the results from the old model (Fig. 1b) with the observations (Fig.1a) clearly shows large spurious precipitation over the mountains in high latitudes (e.g., the Rocky, Himalayan, Greenland, and Antarctic mountains), and large wet biases over the tropical region, especially over Africa, South America, SPCZ, and ITCZs. Large differences over high and low latitudes between the old model and GPCP can be vividly observed in Fig. 2a. These errors in AGCM3 are probably caused by the horizontal diffusion applied to moisture and temperature computed in spectral space along pressure surfaces. The new treatment of moisture in the new dynamic spectral core of BAM with a semi-Lagrangian scheme for horizontal and vertical advection carried out completely in grid-point space eliminated this problem (compare Fig.1c with Fig.1b over high latitudes). In the new dynamical core, no horizontal diffusion is applied to moisture, microphysics prognostic variables and trace constituents. In addition, the semi-Lagrangian advection scheme employs a monotonic quasi-cubic interpolation method, preventing the occurrence of over- or under-shootings. In particular, positive quantities remain positive.

On the excessive ocean tropical precipitation present in the old model, which was reduced drastically in BAMa, a comparison of the surface latent heat fluxes over tropical regions (Fig. 1b') with Era-Interim (Fig. 1a') suggests that the origin of this wet bias is probably linked to the errors in the surface fluxes formulation over the oceans. Although the forecast of global precipitation in BAMa is improved (compare Fig. 1b with Fig. 1c, even more clearly in Fig. 2a) wet biases still remain over the Pacific and Atlantic ITCZs, as well as over Africa and South America. However, in BAMb (with GDM convective scheme), these errors are reduced substantially (compare Figs. 1d and 1c), i.e., the wet biases over ITCZs, Africa, South America, are largely reduced. On the other hand, while the surface latent heat fluxes do not change significantly between BAMa and BAMb zonal averages, they do overcorrect for the excess surface heat flux of AGCM3 (Fig. 2b). The precipitation patterns from 48 and 72 h forecast (figures not shown) are similar to the ones in Fig.1 and 2. In brief, the GDM scheme in BAM improved DJF global precipitation compared to the GD scheme and AGCM3, as can be clearly seen in Fig. 2a, yet it is necessary to compare the daily forecast statistics from both convective schemes for 7 day forecasts in order to conclude which convective scheme is better for QPF. In the next sections we will not consider AGCM3 for the QPF evaluations anymore; instead, we will mainly focus on the performance of BAM with two convective parameterizations (GD and GDM) and two horizontal resolutions (45 and 20 km) against observations. Additionally, the performance of BAM is compared with GFS results.

b. Quantitative Precipitation Forecast over the Tropics

In this section we focus on the QPF evaluation from Exp2 (45 km) and from Exp3 (45 km) and Exp4 (20 km) over the Tropics and GFS products against daily rainfall data from TMPA. Initially, we analyze the first 24 h forecast mean precipitation (Fig. 3) by comparing the output from BAMb at two horizontal resolutions and GFS against the observed precipitation dataset to illustrate short-term precipitation forecast pattern over the Tropics. The left panel in Fig. 3 shows that there are no substantial differences between BAMb at low (Fig. 3b) and high (Fig. 3c) horizontal resolutions and GFS (Fig. 3d) (compare spatial root mean square and the correlation coefficient values), and they appear quite similar to the observations (Fig. 3a). However, in the right panel of Fig. 3, we can identify regions with dry and wet biases. The similarity of dry and wet biases on all three panels on Figure 3’ are noteworthy especially over the mouth of the Amazon River, and southward anomalous displacement of the Atlantic ITCZ. The main differences between BAMb at low and high resolutions (Figs. 3b’ and 3c') are observed over Africa and South America regions with complex topography, where the precipitation forecasts are slightly increased at higher resolution (more details in Section 4c), whereas over oceans there are no noticeable differences. In the case of GFS, major errors (overestimation) are found over South America (e.g. the Andes), Central Africa and the tropical and north Pacific Ocean, whereas minor errors are found over the maritime continent in comparison to BAM with both resolutions. This visual evaluation over different tropical regions will be analyzed later by their statistical metrics for the 7 days forecast, which will show that the systematic errors over some regions observed in Fig. 3 for the 24 h forecast remain for the next 2-7 days forecast, and over other regions these errors change during 4'days forecast, but remain virtually unchanged from 5 to 7 days forecast.

To analyze the QPF over the tropics, we have chosen 5 areas shown in Fig. 3a: global Tropics (A1); three tropical continental areas: Africa (A2), northern Australia (A3) and South America (A5); and SPCZ (A4). Figure 4 displays the time series of precipitation for models and TMPA to illustrate the daily rainfall forecasts at lead times of 24 and 72 h, and Fig. 5 shows the BIAS (left) and unbiased URMSE (right) for 1-7 days forecast. Figure 4a shows that the precipitation amount over the global tropics for the 24 and 72 h forecast are overestimated by BAMa and GFS whereas BAMb shows minor biases, which can be seen clearly in Fig. 5a. This figure also shows that the precipitation bias observed during the first days remains similar for the medium range forecast 5-7 days. The unbiased RMSE analyzed over the global tropics (Fig. 5a') also shows minimum errors for BAMb compared to GFS and BAMa. The BIAS analysis in specific regions shows (Fig. 4 and 5) that BAMa and GFS overestimate over Africa and South America, while BAMb slightly underestimates precipitation. Over Australia and SPCZ the precipitation biases undergo changes during the first 3 days forecast. Notwithstanding these changes, the precipitation biases for 5 to 7 days forecast remain virtually unchanged (e.g., over SPCZ) or they are enlarged (e.g., GFS and BAMb over Australia). In short, the systematic errors from these models over tropical regions occur within the first five days of forecast. The unbiased RMSE analyzed over different regions shows that BAMa has larger pattern errors than GFS and BAMb.

The precipitation time series for BAMb at 20 km horizontal resolution (figure not shown) are similar to that for BAMb at 45 km shown in Fig. 4, except over Africa and South America, where the model at high-resolution increases the precipitation amount, shown in Fig. 5b and 5e. However, there are no clear differences in RMSE at both resolutions. The average dry biases over South America (Fig. 5e) are slightly improved at high horizontal resolution (more details in Section 4c).

Figure 6 depicts the GSS along with the FBS of QPF with the 72 h forecasts from BAMa, BAMb and GFS. The frequency bias score is useful to know whether the model overpredicted ($FBS > 1$) or underpredicted ($FBS < 1$), i.e., indicating whether the model predicted either more or fewer events than observed (it is different from the unconditional bias used before). A perfect score of 1 means, that the forecast frequency is equal to the observed events regardless of forecast accuracy. On the other hand, GSS is commonly used to evaluate the precipitation forecast skill across different regimes, with GSS equal to 0 indicating no skill, 1 indicating a perfect score and <0 a worse forecast than random. However, this score should be used in combination with FBS (or by adjusting with bias score), because higher GSS scores can result from FBS inflated beyond unity (Mesinger 2008). The analysis of FBS (Figs. 6a-e) and GSS (Figs. 6a’-e’) over the global tropics as well as over different tropical regions at low resolution shows that BAMb performs much better than BAMa, with major skill improvement over SPCZ for light and moderate rainfall. There are no significant differences in GSS scores over all regions as the horizontal resolution is increased. However, a substantial improvement in FBS (values near 1) with increased horizontal resolution for moderate and heavy rainfall over Africa (Fig. 6b) and South America (Fig. 6e) is noted.

To further evaluate the models' performance for amplitude and phase of precipitation patterns over the five areas of study, Taylor diagrams were computed and are shown in Fig. 7. These diagrams allow for the intercomparison of unbiased RMSE, correlation coefficient, and standard deviation for 1, 3, 5 and 7 days forecasts. In these diagrams, the radial distance (dotted lines) from the origin to any given forecast point indicated by number (from 1 to 7 days forecast) is the normalized standard deviations (σ_f^*), and their cosine of the azimuthal angle related to the horizontal axis, gives the correlation coefficients (R_{fo}). The distance from the reference point (black star) on the horizontal axis to any given forecast points is unbiased RMSEs ($URMSE^*$) described in Section 3d. Fig. 7 shows, first, that BAMb performs better than BAMa over Africa, Australia, South America and SPCZ in terms of RMSE, correlations and amplitude of spread (standard deviation) with the lead time of 1 to 7 days consistent with the previous analyses. Secondly, the results from BAMb at high resolution are similar to the results at low resolution, except over Africa (Fig. 7b) and South America (Fig. 7e), where at 20 km an improvement in the standard deviation is seen. These last results over Africa and South America are consistent with FBS improvement over these regions, discussed later, and with the improvement in rainfall intensity shown in Fig. 5. We speculate that this improvement, over regions with complex terrain, can be attributed to improved representation of topographical forcing in high-resolution models. It is interesting to see that over Australia and SPCZ, from Fig. 7c and 7d, errors increase (and correlations diminish) as the lead time increases (in both resolutions and especially from 5 to 7 days). Although these results are obtained from an AGCM not coupled to an ocean model, they also indicate that the precipitation predictability for medium range time scales in some equatorial regions (e.g., Australia and SPCZ) can be higher than that at high latitudes, as has been suggested by Stern (2011), Zhu et al. (2014) and Stern and Davidson (2015).

In summary, the QPF evaluation from different versions of BAM shows that BAMb at 45 km gives better performance than BAMa (in terms of FBS, GSS, RMSE, BIAS, standard deviation and correlations) over all tropical regions analyzed here. On the other hand, the bias scores of moderate and heavy rain (both intensity and standard deviation) are improved at high-resolution over Africa and South America, which indicate the importance of resolution to improve the representation of extreme precipitation events over these regions. An additional result is that systematic errors (bias) in the model over tropical regions occur within the first 5 days of forecast.

c. Quantitative Precipitation Forecast over Brazil

To evaluate the performance of BAM for QPF over Brazil up to 7 days, we have chosen 5 regions covering the country, namely, B1, B2, B3, B4 and B5 shown in Fig. 8. Region B5 includes northern Brazil where the Brazilian Amazon basin (hereafter called Amazon) is located; region B4 includes most of northeastern Brazil (referred here as Northeast); region B3 includes central-west Brazil, eastern Bolivia and northern Paraguay (Central-West); region B2 includes most of southeastern Brazil and surrounding oceanic areas (referred here as Southeast), where the large Brazilian cities are located (e.g., Rio de Janeiro, São Paulo and Belo Horizonte); and B1 represents approximately the La Plata Basin, which includes most of southern Brazil, Uruguay, northeastern Argentina, and southern Paraguay (hereafter called La Plata).

Before analyzing the QPF from BAMb, we will review briefly the main features that affect the daily precipitation over regions B1 to B5 focusing on the period DJF 2012/13. Fig. 9 shows the time series of precipitation for the models and TMPA to illustrate the models' daily precipitation forecast for 24 h (left) and 72 h (right) over the regions defined in Fig. 8 in comparison to observations.

The systems that affect the daily precipitation over La Plata region during DJF are frontal systems (Garreaud and Wallace 1998), mesoscale convective systems (MCSs) and cyclogenesis (e.g., Salio et al. 2007, Romatschke and Houze 2010, Boers et al. 2015, Rasmussen et al. 2016). The La Plata basin is a preferred region over southern South America for tropical-extratropical interactions between the large-scale synoptic baroclinic waves (upper-level jet streams and their associated fronts) and warm and moist low-level advection by the low-level jet (LLJ) on the eastern side of the Andes from the Amazon region, generating the majority of MCSs observed in this region (e.g., Berbery and Barros 2002, Salio et al. 2007, Rozante and Cavalcante 2008, Arraut and Barbosa 2009, Arraut and Satyamurty 2009, Boers et al., 2014, Rasmussen and Houze 2016). Although the occurrence of some MCSs over this region do not relate to the frontal systems, the most numerous and intense MCSs tend to occur in connection with LLJ and cold fronts passing over the southern Andes and arriving to the northern Argentina, Uruguay and Southern Brazil (Romatschke and Houze 2010, Rasmussen and Houze 2016).

During DJF 2012/2013, 13 cold fronts were identified over the region (Climanálise, 2012, 2013a, and 2013b), which is indicated by letter F in Fig. 9a (from to F_1 to F_{13}), giving an average of a cold front passage every 7 days. We can see that all models forecasted these systems 24 and 48 h in advance, although with different intensities.

Among the main systems that produce rainfall over the Southeast (B2) (e.g. the SACZ, frontal systems, MCSs, squall lines; and land-sea breeze circulation), the SACZ (a quasi-stationary meteorological perturbation that lasts for 3 to 7 days, approximately) is the most important synoptic systems directly affecting the Region. In addition, this system indirectly affects the weather conditions over South, Central-West, North, and Northeast regions of Brazil during DJF (Nogués-Peagle and Mo (1997). SACZ's origin is not fully understood. However, preliminary modeling studies suggest that interaction between intense convection over the Amazon (as local forcing) with large-scale westerly winds (e.g., Figueroa et al. 1995) or frontal system (e.g., Ferreira, et al. 2013) could be a possible cause of SACZ initiation. The dynamics of enhanced cloudiness and rainfall over cooler SST associated to the SACZ could be better explained by the use of coupled ocean-atmosphere models and direct observations (e.g., De Almeida et al. 2007).

Despite this fact, the 5 SACZ episodes identified during DJF 2012/2013 (Climanálise, 2012, 2013a and 2013b), indicated by the letter S in Fig. 9b (from S_1 to S_5) were well predicted by BAMb as well as GFS, both their duration and intensity, 24 and 72-h in advance. Only in the S4 event, at the end of January (around day 60), precipitation amount was underestimated by BAMb. A comparison of Fig. 9a and 9b shows an alternation between the extreme precipitation events over the SACZ and La Plata regions, which is known as the South American dipole (Nogués-Paegle and Mo, 1997).

When intense and persistent SACZ events occur over Southeast (e.g. during January 2013, days 32-63), the precipitation over the La Plata region is drastically reduced. Conversely, when persistent intense precipitation occurs over La Plata (e.g., in December, days 1-31), the development of intense SACZ events are inhibited. This dipole-like precipitation structure on intraseasonal time scales between La Plata and southeastern Brazil, identified in many observational studies (e.g., Nogués-Paegle and Mo, 1997), were reproduced well by the BAMb and GFS models, but overestimated by BAMa. While SACZ is a quasi-stationary system, the cold fronts arriving in this region from southern Brazil are transient perturbations, and the convective bands associated with them rapidly move northeastward (Lima et al. 2009). Most of the intense MCSs over this region are linked to these frontal incursions (Siqueira and Marques, 2010). Also, these transient systems are responsible for maintaining or intensifying the convective activity in the SACZ driving extreme precipitation events over this region.

Weather conditions over Central-West region (B3) are also affected by squall lines, MCSs, SACZ (mainly over the eastern part of this region) and frontal systems that occasionally reach the southern part of this region. The maximum seasonal precipitation over the Northeast (B4) occurs during March-April-May (MAM), and is linked to the Atlantic ITCZ southernmost annual displacement (Moura and Shukla 1981; Nobre and Shukla 1996). However, weather conditions during DJF over the southern Northeast are affected by convective activity associated with the upper-level cyclonic vortices, easterly waves, land-sea breeze circulation (over coastal regions of B4), as well as occasional cold fronts and SACZ reaching the southern part of this region (Chaves and Cavalcanti 2001). For instance, intense precipitation during the last 15 days of January (days 45-60) over the Northeast (Fig. 10d) was related to SACZ events (compare Fig. 9d with Fig. 9b). Finally, weather conditions over the Amazon (area B5) during DJF are affected by convection organized by SACZ (Vieira et al. 2012), MCSs, and squall lines, which originate on the northern coast of Brazil and propagate toward the Amazon, although these systems are more frequent during MAM (Cohen et al. 1995). The time series of TMPA precipitation estimated over the Amazon (Fig. 9e) shows a large rainfall variability during the intense SACZ events over Southeast (days 45 to 75), although the maximum precipitation values over Amazon and SACZ regions do not occur simultaneously.

Similar to Figure 4 (left), Figure 10 (left) shows that the tendencies of the systematic errors (e.g., dry bias over the Amazon and La Plata) remain unchanged from 5 to 7-days forecast. The RMSE (Fig. 10, right panel) shows that BAMb (at both 45 and 20 km resolution) performs much better than BAMa. Figure 11 depicts the GSS (right) along with FBS (left) at 72-h lead time for the areas defined in Fig. 8. A visual inspection of the frequency bias (Fig.11a-e) shows that BAMa overpredicts moderate and heavy rainfall events over all regions, except over the Amazon, whereas BAMb at 45 km underpredicts. However, it is improved (FBS values near 1) at high resolution, mainly over the Southeast. The GSS analysis shows that BAMb at 45 km is superior to BAMa for light and moderate rainfall over the Southeast and La Plata, whereas over other regions there are not clear differences. Over La Plata Fig. 11a and a), GFS performs much better than BAMb in terms of GSS, however in FBS analysis all models overpredict of occurrence of light and moderate rainfall. Major improvement of BAMb (FBS and GSS) at high resolution for moderate and heavy rainfall compared to BAMa at 45 km is found over the Southeast (Fig. 11b, Fig. 11b'), even beyond 72 h forecast (not shown). On the other hand, over the Amazon all models display lower Gilbert skill score (Fig. 11e'). Improvement in QPF skill over this region will remain a great challenge.

A comparison of precipitation forecast statistics using the Taylor diagram (Fig. 12) and Biases (Fig.11, left) shows that BAMb is generally superior to BAMa for 1 to 7 day lead time forecasts (smaller URMSE*, higher correlations and smaller BIAS), except over the Amazon and La Plata; where they have similar performance. On the other hand, the comparisons between GFS and BAMb for 1 to 7 day forecasts at 45 km show similar URMSE* and correlations over La Plata, Southeast, Central-West and Northeast, notwithstanding the magnitude of the daily variability is better forecast by GFS. The performance of BAMb at high-resolution is similar to that at 45 km, except over the Southeast (B2) and Central-West (B3) (compare red and black color numbers in Fig. 12). Over these regions, one can see the improvement of the spread (standard deviation) of precipitation at high-resolution, which is more noticeable over Southeast. These results are consistent with the improvements in precipitation intensity, frequency bias and Gilbert skill score for moderate and heavy rainfall over Southeast as discussed before.

In summary, the version of BAM with the GDM scheme outperforms the model with the GD scheme for QPF over the regions depicted in Fig 8. A comparison of results from low and high horizontal resolutions shows that the frequency bias as well as the Gilbert skill score are improved for moderate and heavy rainfall over the Southeast as the horizontal resolution increases (Fig. 11b and 11b'). The variance of precipitation over the Southeast also improves at high horizontal resolution (Fig.12d). Finally, the systematic forecast errors in precipitation (dry or wet biases) over the regions shown in Fig. 8 remain practically unchanged from 5 to 7 days forecast.

5. Summary and conclusions

The Brazilian Global Atmospheric Model (BAM) has been developed to overcome a number of shortcomings present in the previous CPTEC atmospheric global model (AGCM3) for the use over time scales ranging from days to seasons and horizontal resolution *O*(10-100 km). BAM's dynamical core incorporates a monotonic two-time-level semi-Lagrangian scheme for the transport of moisture and microphysics prognostic variables, and tracers, which are carried out completely on the model grid space. Some state-of-art physical parameterization schemes included in BAM are two convective parameterization schemes: GD and GDM, among the others (listed in Table 1).

The QPF skill from BAM with GD and GDM schemes and sensitivity to increasing the horizontal resolutions are evaluated against the daily TRMM Multi-satellite Precipitation Analysis (TMPA) over the tropical region for up to seven days lead time during austral summer 2012/2013. Three main results are summarized here: a) the QPF skill was improved substantially with GDM in comparison to GD (smaller biases, smaller unbiased RMSE, higher correlations, improved frequency bias score-FBS and Gilbert skill score-GSS) over all tropical regions evaluated (defined in Fig. 3a and Fig. 8); (b) the increase in horizontal resolution from 45 to 20 km, without any ad-hoc tuning, enhances the intensity and variance of precipitation, and improves the frequency statistics of moderate and heavy rainfall events over the tropical continents with complex orography, such as Africa and South America, mainly over southeastern Brazil. Nevertheless, there was little difference between low and high resolutions over the oceans; and (c) the systematic errors (dry or wet biases) seen during the first-day forecast over some tropical regions remained similar or increased with time (e.g., Central Africa, Amazon, La Plata), whereas in other regions there were changes during the first 1-4 days forecast. However, these errors remain virtually unchanged after 5 days forecast.

From the first result stated above, we conclude that improving the convective parameterization in BAM (for which the Single- Column Model and Cloud Resolving Model were useful tools) is a key to improving the QPF over the tropics. From the second result, we conclude that increasing the horizontal resolution in BAM from 45 to 20 km can benefit operational NWP over tropical continents with complex topography for predicting extreme rainfall events (e.g. during the SACZ events), mainly over Southeastern Brazil.

Two caveats to this evaluation are pointed out. (a) The quality of forecast from BAM can be affected by the use of initial conditions produced from other data assimilation systems (i.e., NCEP/GFS). However, using the same initial condition as the NCEP/GFS forecast system has made the model comparison more robust. (b) The period of evaluation, 7 days forecast for 3 months might not be enough for drawing conclusions regarding the performance of the new model for precipitation forecast. Further, QPF and other variables (e.g., wind, temperature, radiation, clouds, etc.) evaluation for different seasons of the year and for different years using CPTEC's data assimilation system is necessary. Yet, the present exercise served to show relevant improvements of precipitation forecast by the new convective scheme GDM compared to the original GD scheme, as well as to explore the benefits of using 20 km horizontal resolution of CPTEC global model in operational NWP. Based in this study, the semi-Lagrangian TQ666L96 ($\approx 20\ km$ and 96 vertical levels) BAM has become operational on January 01, 2016, (after being used in experimental mode for one year), replacing the previous operational TQ299L64 ($\approx 45\ km$ and 64 vertical levels).

Although tropical precipitation forecasts have been improved with BAM, especially over the southeast of Brazil, the total rainfall and its variance over the Amazon and La Plata regions are still underestimated. In the next paper, we will show that similar systematic errors are found in BAM climate simulations with prescribed sea surface temperature. Improving the precipitation forecast over these regions remains a challenge for the future BAM developments.

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APPENDIX

The modified Grell and Dévényi convective scheme (GDM)

We have found in our experiments that by using GD scheme in BAM (either ensemble and individual closures), the rainfall over ITCZs, Africa and South America, mainly over the Andes are systematically overestimated (Fig.1c) which is discussed in Section 3. The large wet biases over the Andes have been investigated using BAM Single-Column Model (BAM-SCM) and the System of Atmospheric Modeling (SAM, Version 6.8.2) Cloud Resolving Model (CRM) developed by Khairoutdinov and Randall (2003). Based on these results, the original GD scheme described above was modified considering two important aspects: 1) AS, KF_type , Kuo_type and Omega closures were excluded and instead an undiluted CAPE (convective available potential energy)-based closure described in Zhang (2002) and Zhang (2009) was included; and 2) the original entrainment rate scheme ($\varepsilon = \frac{0.2}{R}$) was replaced by a new simplified scheme ($\varepsilon = \frac{\epsilon_0}{z(k)-z(kb-1)}$), where R is the radius of the rising plume (12000 m), $z(k)$ is the height at model level k, $z(kb)$ is the height at cloud base level ($z(k) > z(kb-1)$), and ϵ_0 a tunable parameter of $O(10^{-2})$. In Table A1, we summarized the closures and parameters used in this scheme, which is referred here as GD modified (GDM) scheme. Its performance in global NWP compared to GD scheme (e.g., Fig.1d and Fig.1c) is discussed in Section 4. The details of this modified scheme, and its impact on the improvement of precipitation simulation over the Andes will be reported in a separate article (paper in preparation). The remainder of this section describes how GD scheme was modified using SAM and BAM-SCM, and the main reason for the improvement of the simulated precipitation over the Andes with the modified scheme.

The averaged large-scale forcing (temperature and humidity advections, pressure, wind and vertical velocity) used for the CRM (1 km × 1 km horizontal grid spacing, 144 × 144 grid points and with the two-moment Morrison microphysics scheme, Morrison et al. 2009) and SCM simulations (BAM-SCM with parameterization physics described in Table 1), were calculated from the 6 hourly NCEP/GFS analysis for the period 01 to 30 January 2013, over an $5^{o} \times 5^{o}$ (latitude-longitude) area centered approximately over the Peru-Bolivian Plateau (16.5^{o} S - 69^{o} W). First, the precipitation from CRM was compared with the daily precipitation estimated by satellite (TMPA, database details in Section 3) then results from BAM-SCM were compared with the CRM simulations.

The CRM simulates the precipitation reasonably well in comparison to TMPA with maximum values around 10 mm/day, although uncertainties exist in precipitation and large-scale forcing estimated over complex topography. The results from BAM-SCM show (figure not shown) that the daily precipitation patterns and intensity are poorly simulated when using the original GD scheme in comparison to CRM and observations, in contrast results from GDM are similar to CRM. Overall the GD scheme overestimates TMPA by approximately three-fold. We found that results were much improved when we only used G1 and Zhang as closures, so all other closures were excluded in GDM. The averaged (January 2013) mass-flux profile from CRM/SAM, BAM-SCM with the GD scheme and 1D with the GDM scheme shows (figure not shown) that the mass-flux from GD is almost three times higher than from CRM (maximum value from CRM is around 0.02 $kg/m^2/s^2$), whereas that from GDM, at least in the first 6 km above cloud-base, is close to the CRM results. The improvement in GDM simulation is attributed mainly to: a) the exclusion of some closures b) addition of the CAPE-based closure and; c) inclusion of the new simple entrainment scheme with ϵ_0 tuned using CRM/SAM results.

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Table 1. Summary of the dynamic and physics configurations in AGCM3 and BAM

Dynamics and Physics	*CPTEC/AGCM3 (old)*	*CPTEC/BAM (new)*
Dynamics	*Spectral Eulerian or semi-Lagrangian semi-implicit model, with hydrostatic approximation, sigma vertical coordinates, full or reduced gaussian grids, fully parallel (MPI + OPenMP)*	*Spectral Eulerian or semi-Lagrangian semi-Implicit model, with hydrostatic approximation, sigma/hybrid vertical coordinates, full or reduced gaussian grids, semi-Lagrangian monotonic transport scheme (on the model grid) of moisture, microphysics prognostic variables and tracers, fully parallel (MPI + OPenMP)*
Land surface process	*Simplified Simple Biosphere (SSiB) scheme, Xue et al. (1991)*	*Dynamic vegetation model, the Integrated Biosphere Simulator -IBIS (Foley et al. 1996 and Kucharik et al. 2000), implemented, adapted and improved by Kubota (2012)*
Sea-air surface fluxes	*The bulk transfer coefficients are determined by analytical functions (Sato et al. 1989)*	*The bulk transfer coefficients are determined by using the Monin–Obukhov theory and the Tropical Oceans Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) data (Zeng et al. 1998)*
Vertical diffusion	*Local Mellor-Yamada (1982), coupled to SSiB equations*	*Modified the Mellor-Yamada (1982) scheme by adding the counter-gradient adjustment term to the eddy diffusion equation*
Gravity-wave Drag	*Alpert et al. (1988) scheme without low-level blocking*	*Webster et al. (2003) scheme with low-level blocking*
Cloud microphysics	*Single-moment Microphysics scheme (Rasch and Kristjansson, 1998)*	*Double-moment Microphysis scheme (Morrison et al. 2009)*
Radiation Short and long-wave	*CLIRAD, Chou and Suarez (1999) and modified by Tarasova and Fomin (2000)*	*RRTMG, Iacono et al. (2008, developed at Atmospheric and Environmental Research, Inc. (AER)*

Shallow Convection	*Tiedtke (1983) diffusion scheme*	*University of Washington (UW) Shallow convection (Park and Bretherton, 2009)*
Deep Convection	*Grell and Dévényi (2002) ensemble scheme (GD)*	*-Grell and Dévényi (2002) ensemble scheme (GD)* *-Modified the GD scheme (GDM), described briefly in this paper (Appendix).*

Table 2. Experiments description.

Exp.	*Quadratic grid horizontal resolution with a reduced Gaussian grid*	*Time Step (s)*	*Dynamics: Model version-Eulerian (EU) or semi_Lagrangian (SL)*	*Physics: Model version, Except deep convection*	*Deep Convection*	*Model version-dynamics-resolution*
Exp 1	T_Q299 $(0.4^o \approx 45\ km)$	*240*	*AGCM3-EU*	*AGCM3*	*GD*	*AGCM3-EU-45 km*
Exp 2	T_Q299 $(0.4^o \approx 45\ km)$	*240*	*BAMa-EU*	*BAMa*	*GD*	*BAMa-EU-45 km*
Exp 3	T_Q299 $(0.4^o \approx 45\ km)$	*240*	*BAMb-EU*	*BAMb*	*GDM*	*BAMb-EU-45 km*
Exp 4	T_Q666 $(0.18^o \approx 20\ km)$	*400*	*BAMb-SL*	*BAMb*	*GDM*	*BAMb-SL-20 km*

Table A1. Brief overview of mass fluxes and parameters used in the GDM ensemble scheme. In this scheme 6 different closures (3 perturbations for Grell closure and 3 perturbations for CAPE-based closure) from the dynamic control are allowed to interact with 9 members from the static control (3 efficiencies and 3 cap strengths), giving a total of 54 sub-grid members.

Dynamic and Static control	*Definition of the type of Closures in dynamic control and parameters in static control*	*Number of variations*	*Mass flux (dynamic control) or parameters (static control)*
Dynamic control	**Grell closure**: Assume AS quasi-equilibrium between large-scale forcing (LS) and convection (Grell, 1993).	*3*	$m_b = -\frac{1}{K}\left(\frac{\partial A}{\partial t}\right)_{LS}$ $A = \int_{z_b}^{z_t} \eta(z)\, B(z)\, dz$
Dynamic control	**CAPE-based closure**: Assumes that quasi-equilibrium exists between convection and the large-scale process in the free troposphere (Zhang 2002 and Zhang 2009). Note, $CAPE_{env}$ is similar to the work function definition, but without weighing by a normalized mass flux profile (η), and the buoyancy force B can be calculated with and without dilution.	3	$m_b = -\frac{1}{K}\left(\frac{\partial CAPE_{env}}{\partial t}\right)_{LS}$ $CAPE_{env} = \int_{z_b}^{z_t} B(z)\, dz$
Static control feedback	**Precipitation efficiency (f) perturbations**. The convective rainfall (R) is defined as a function of precipitation efficiency (f), integrated condensate in the updraft (I), which depends on the total water that is rained out (S_u) and m_a (Grell and Dévényi , 2002).	3	$R = fI\, m_a$, $I(\lambda) = \int_{z_b}^{z_t} n_u(\lambda, z) S_u dz$ $f = (0.25, 0.5, 0.75)$
Static control feedback	**Maximum depth of capping ($CapMax$) perturbations**. The scheme does not allow convection until the lifting required for parcels to reach their level of free convection becomes less than specified $CapMax$ ($25\, mb < CapMax > 25\, mb$)	3	$CapMax = (60, 90, 120)$

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Fig. 1. Precipitation (left) and surface latent heat fluxes (right) averaged over DJF 2012-2013 from GPCP (a), Era-Interim reanalysis (a′), and the 24 h forecast of the models. Old model AGCM3 (Exp1) (b, b'), new model BAMa (Exp2) (c, c') and new model BAMb with GDM convective scheme (Exp3) (d-d'). Model identifications are indicated in the bottom-left corner of the panels; while spatially-averaged *RMSE* and correlation coefficient (*CORR*) are given in the top-right corner of the panels. Boxes defined in (a) indicate approximately the regions with intense precipitation during DJF over Southern Hemisphere. Africa (1), Indian Ocean ITCZ (2), South Pacific Convergence Zone (SPCZ, 3), Amazon Basin (4), South Atlantic Convergence Zone (SACZ, 5), and La Plata Basin (6).

Fig. 2. Zonal mean precipitation (a) and surface latent heat fluxes (b) corresponding to Fig. 1 for 24 h forecasts by different models indicated in the panels.

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Fig. 4. Daily mean precipitation for the period 01 December 2012 to 28 February 2013 from 24 h (left) and 72 h (right) forecasts for the areas defined in Fig.3a from TMPA and three NWP models indicated in the panel.

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Fig.3a.

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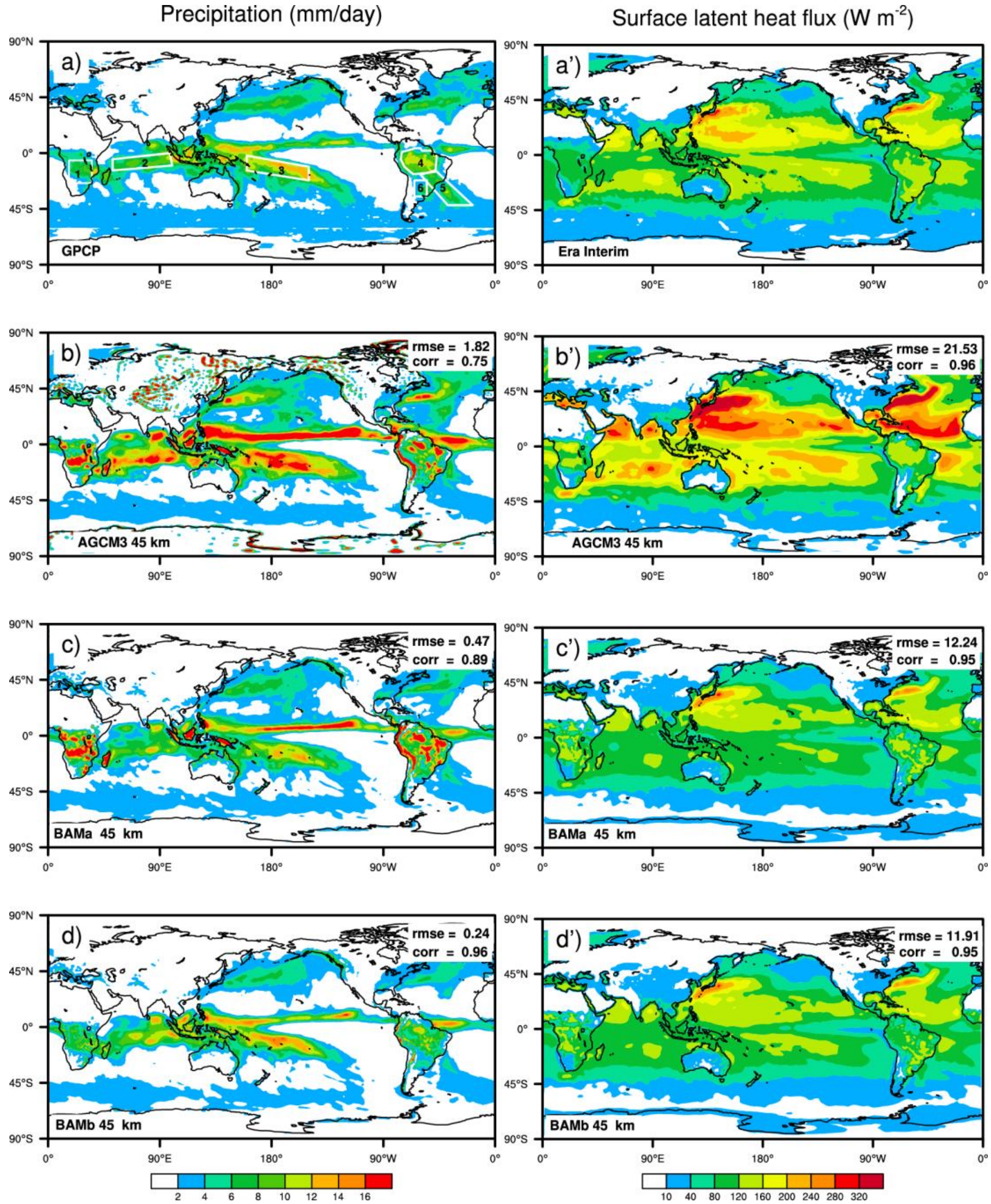
Fig. 8. Map of South America with the geographic regions of Brazil (shaded). Boxes B1 to B5 are considered for model evaluation. B1 represents approximately La Plata Basin (which includes Southern Brazil, Northeast Argentina, Southern Paraguay and Uruguay). The boxes B2, B3, B4 and B5 represent approximately the Southeast, Central West, Northeast and North regions of Brazil. B5 also represents approximately the Brazilian Amazon Basin (referred to as Amazon).

Fig. 9. Daily mean precipitation for the period 01 December 2012 to 28 February 2013 from 24 h (left) and 72 h (right) forecasts for the areas defined in Fig. 8 from TMPA and three NWP models indicated in the panel. The letters F in (a) and S in (b) indicate cold fronts over La Plata and SACZ events over Southeast respectively.

Fig. 10. As Figure 5, except for the areas defined in Fig. 8.

Fig. 11. Same as in Fig. 6, except for the areas defined in Fig. 8.

Fig. 12. Same as in Fig. 7, except for the areas defined in Fig. 8.



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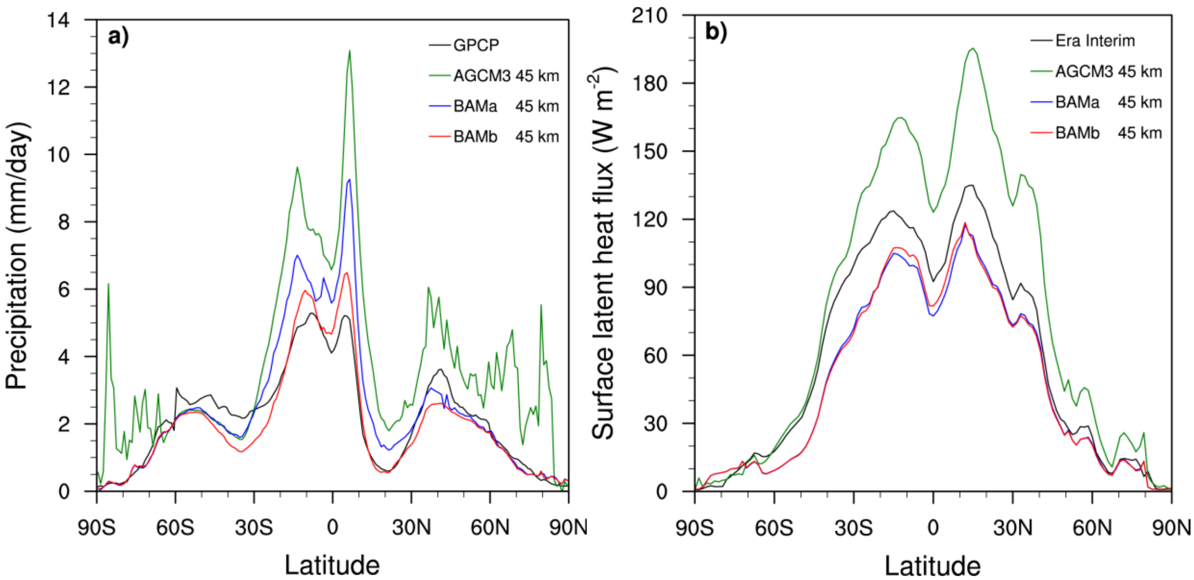

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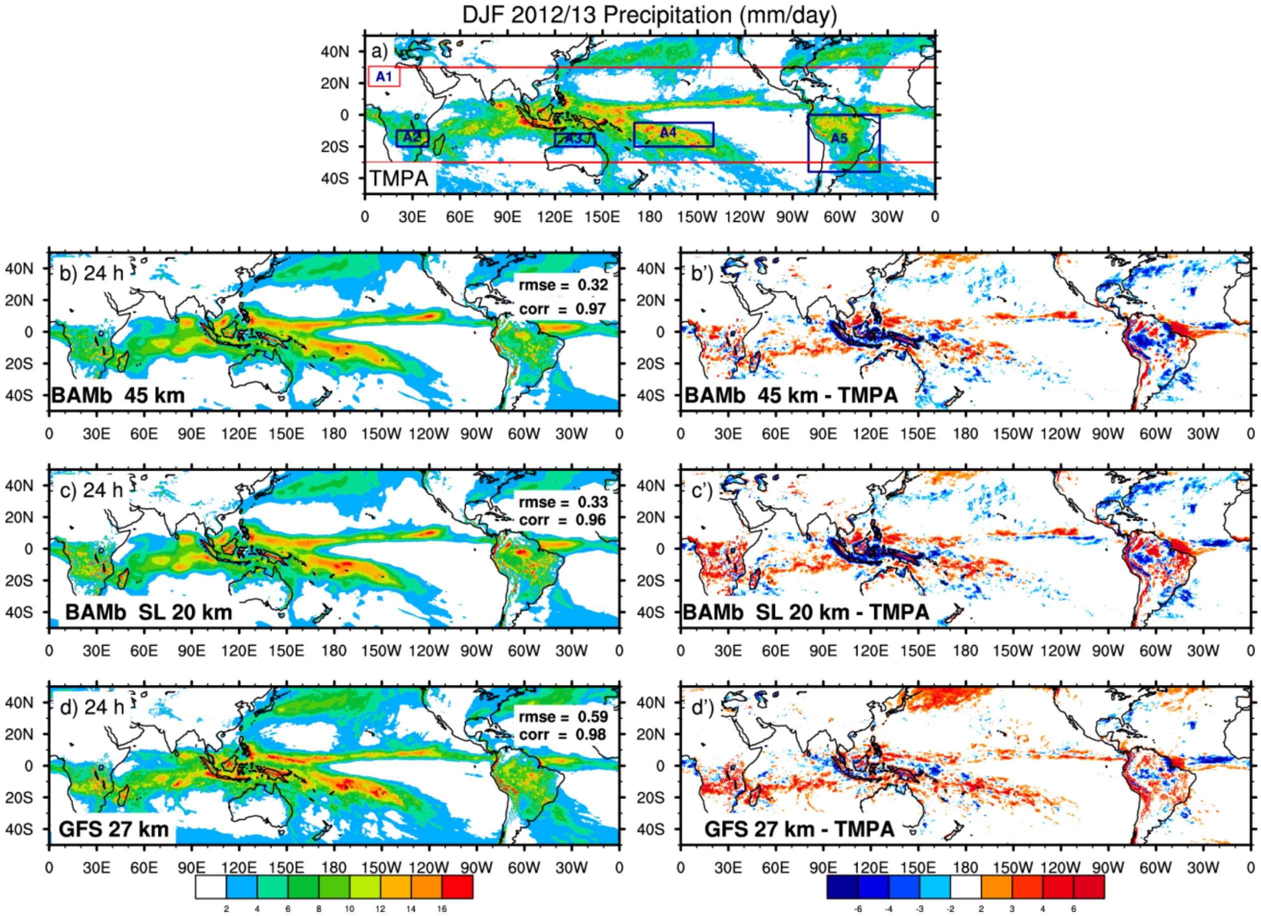

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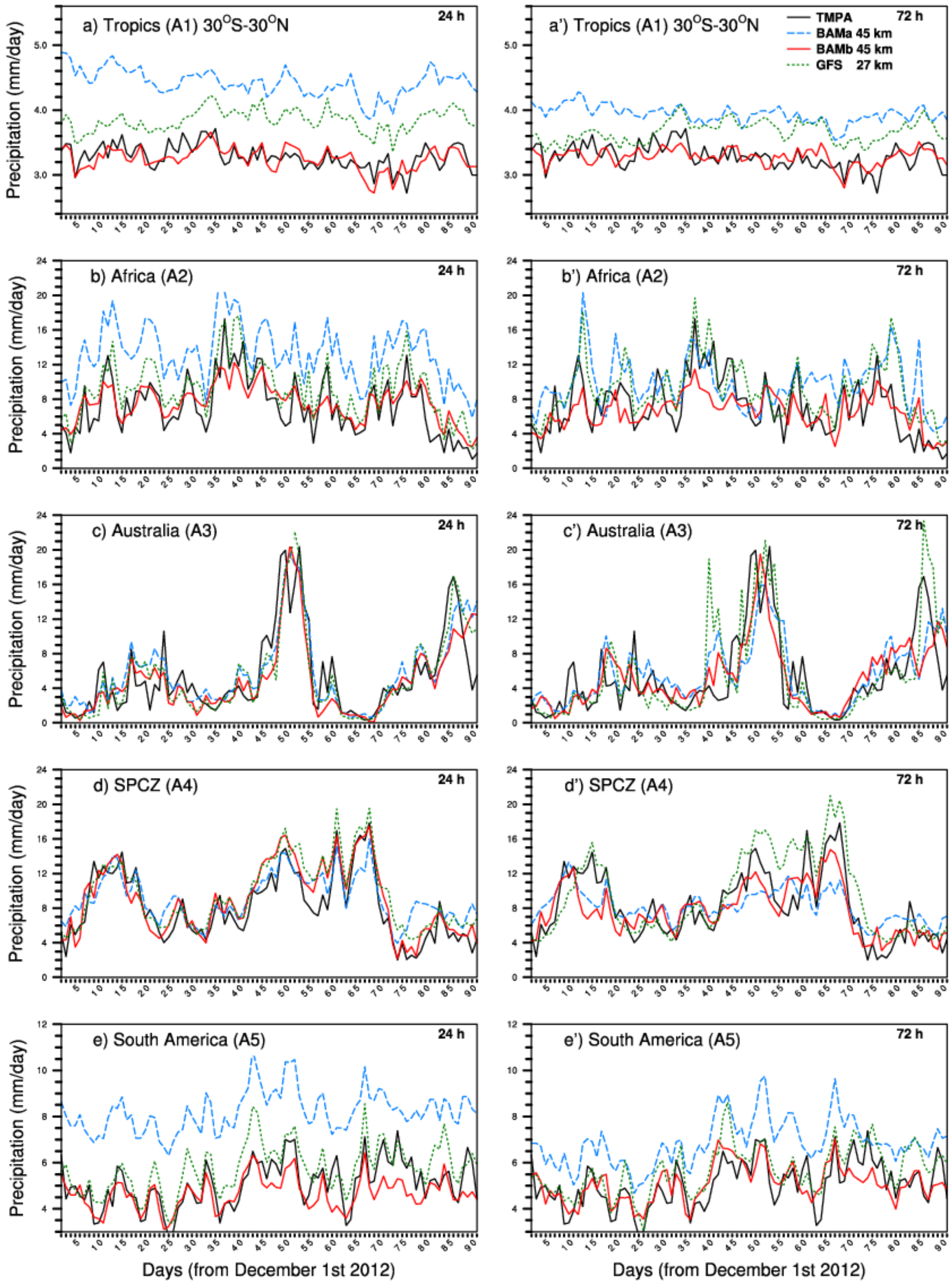

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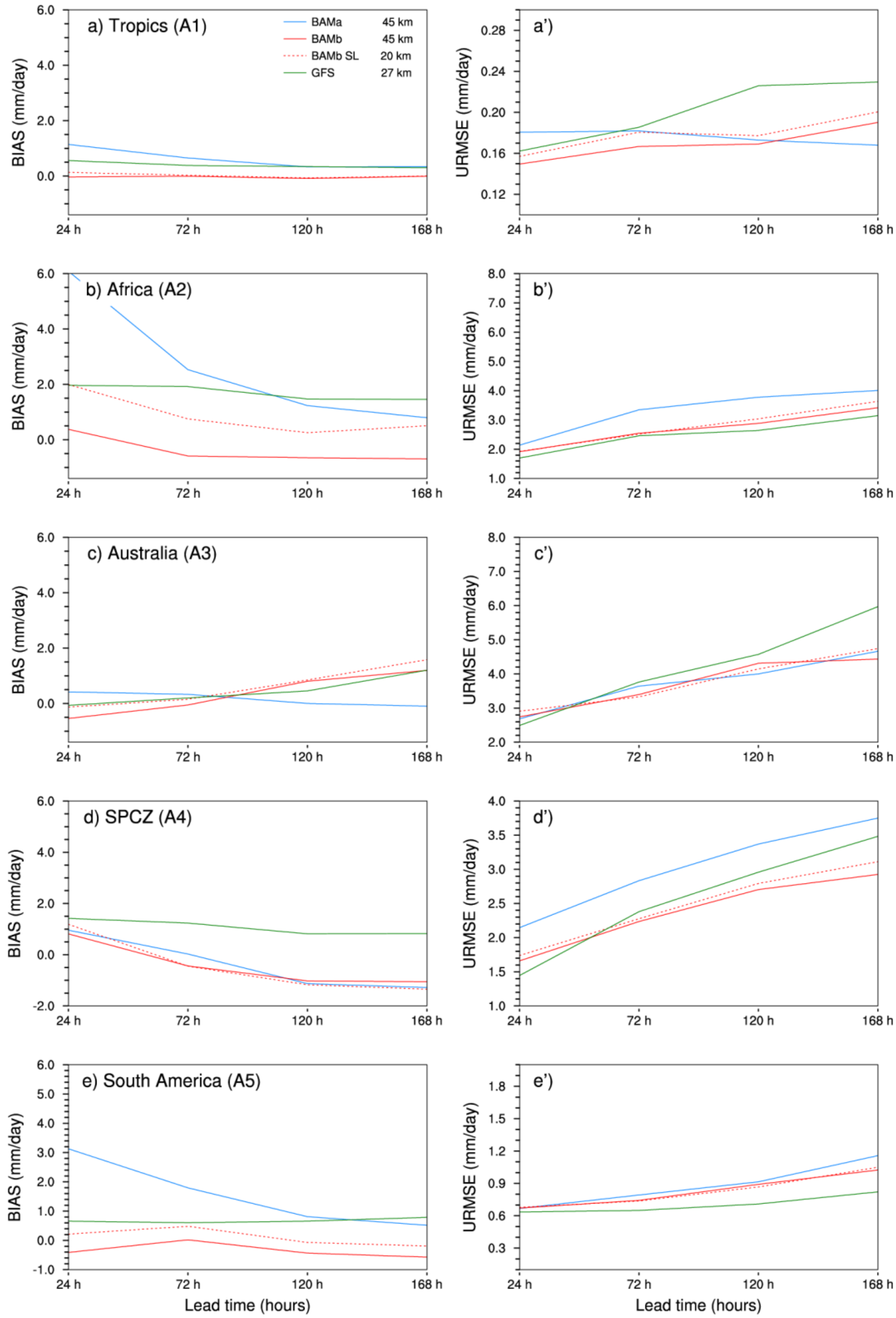

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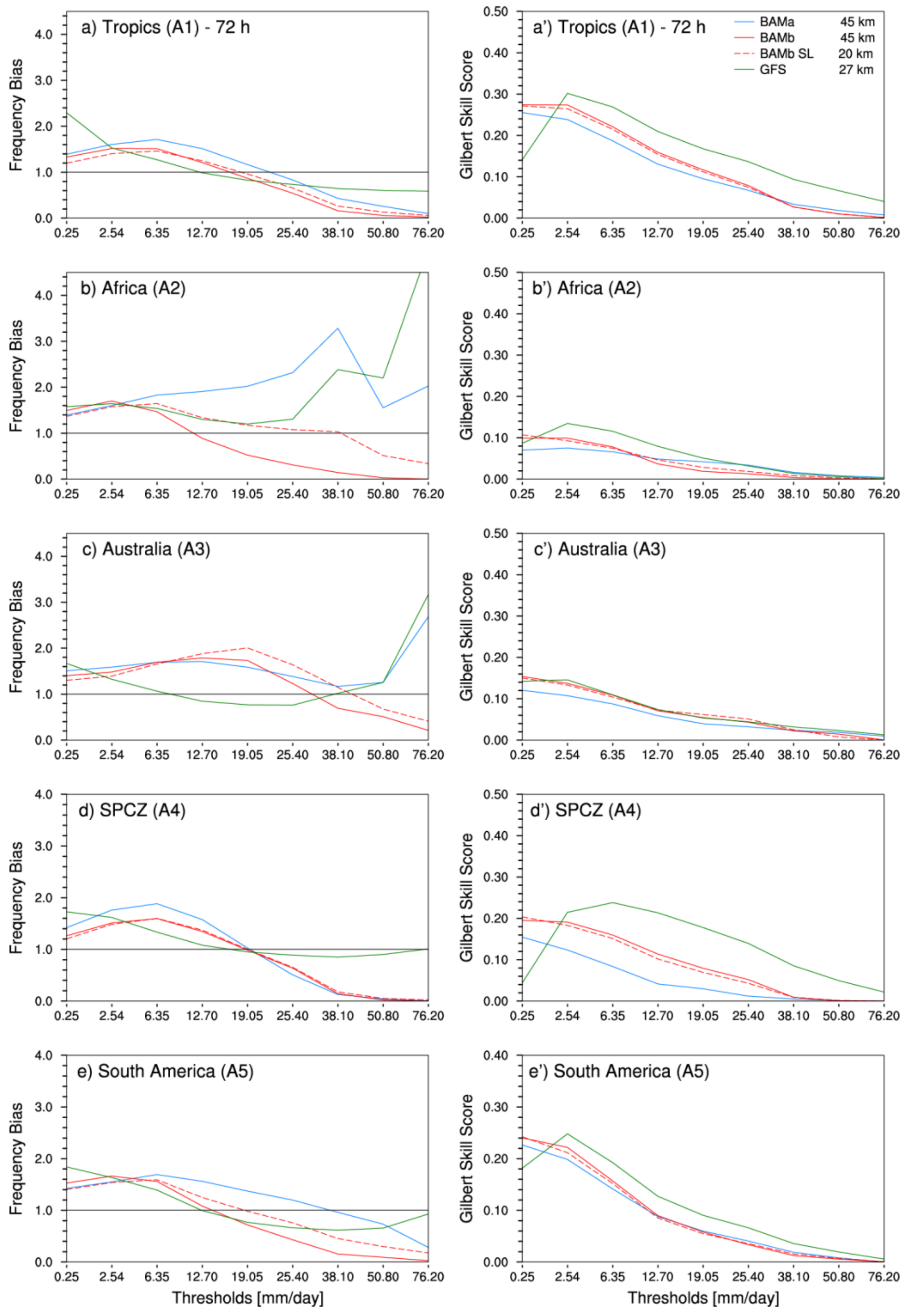

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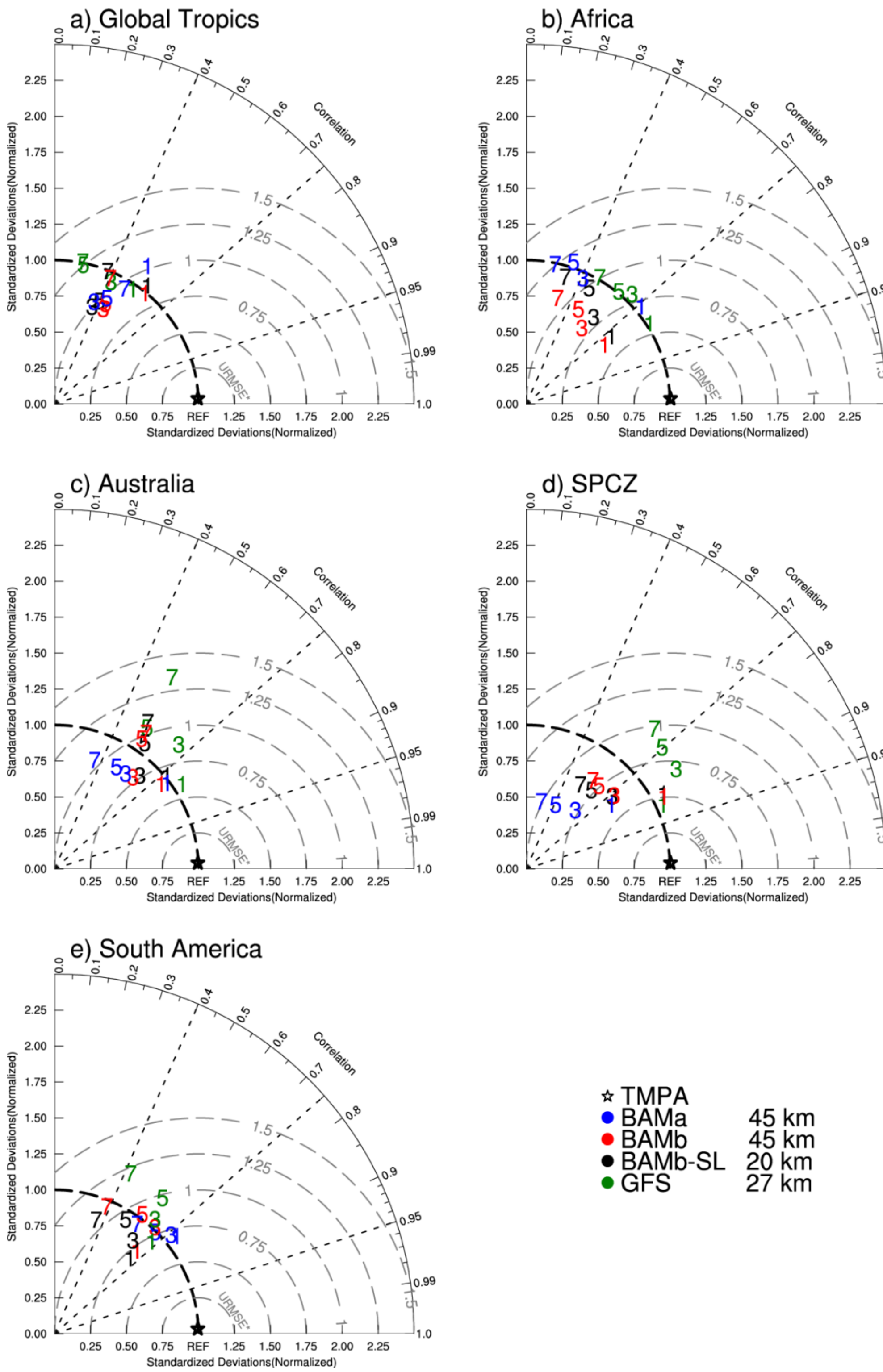

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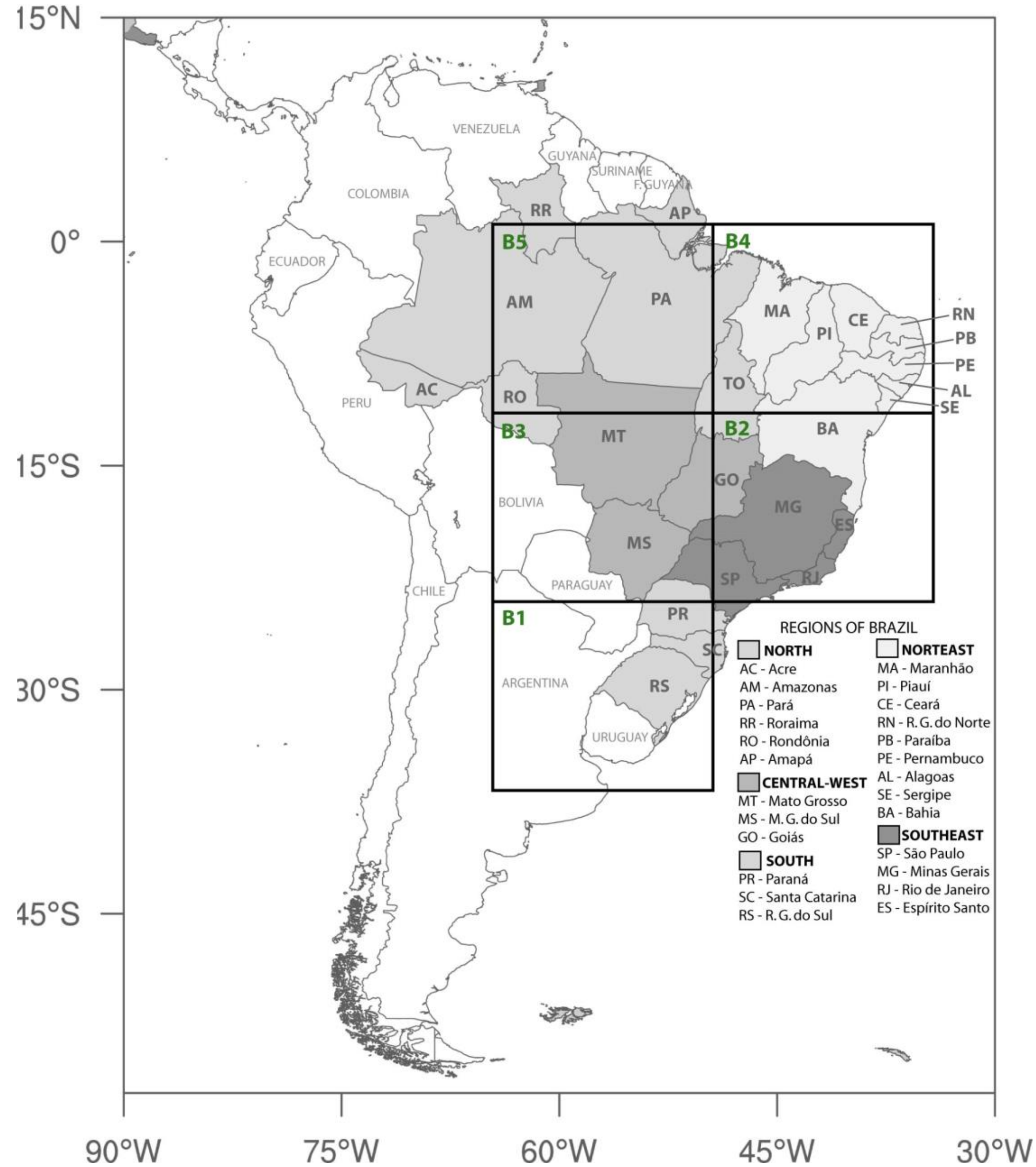

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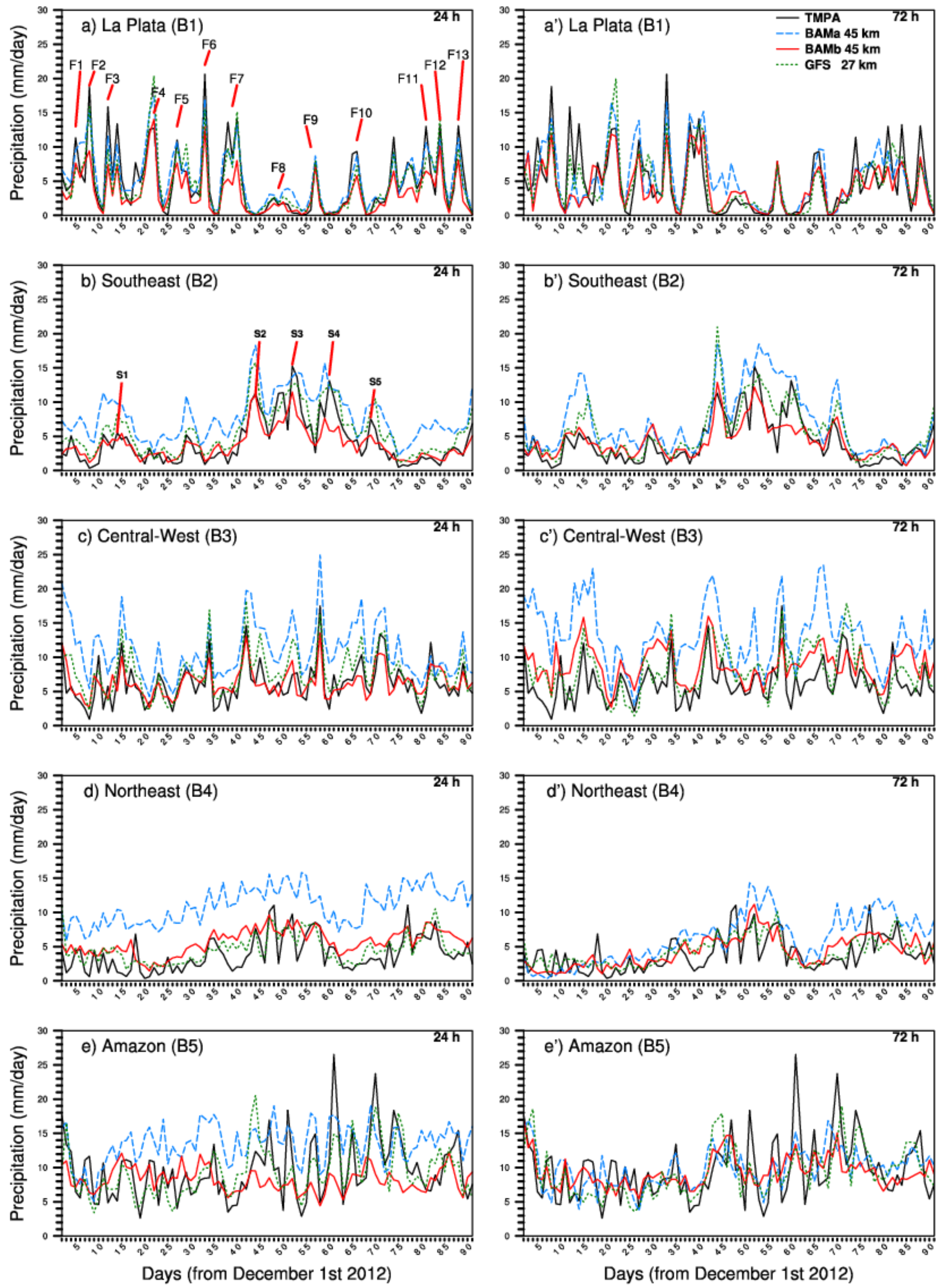

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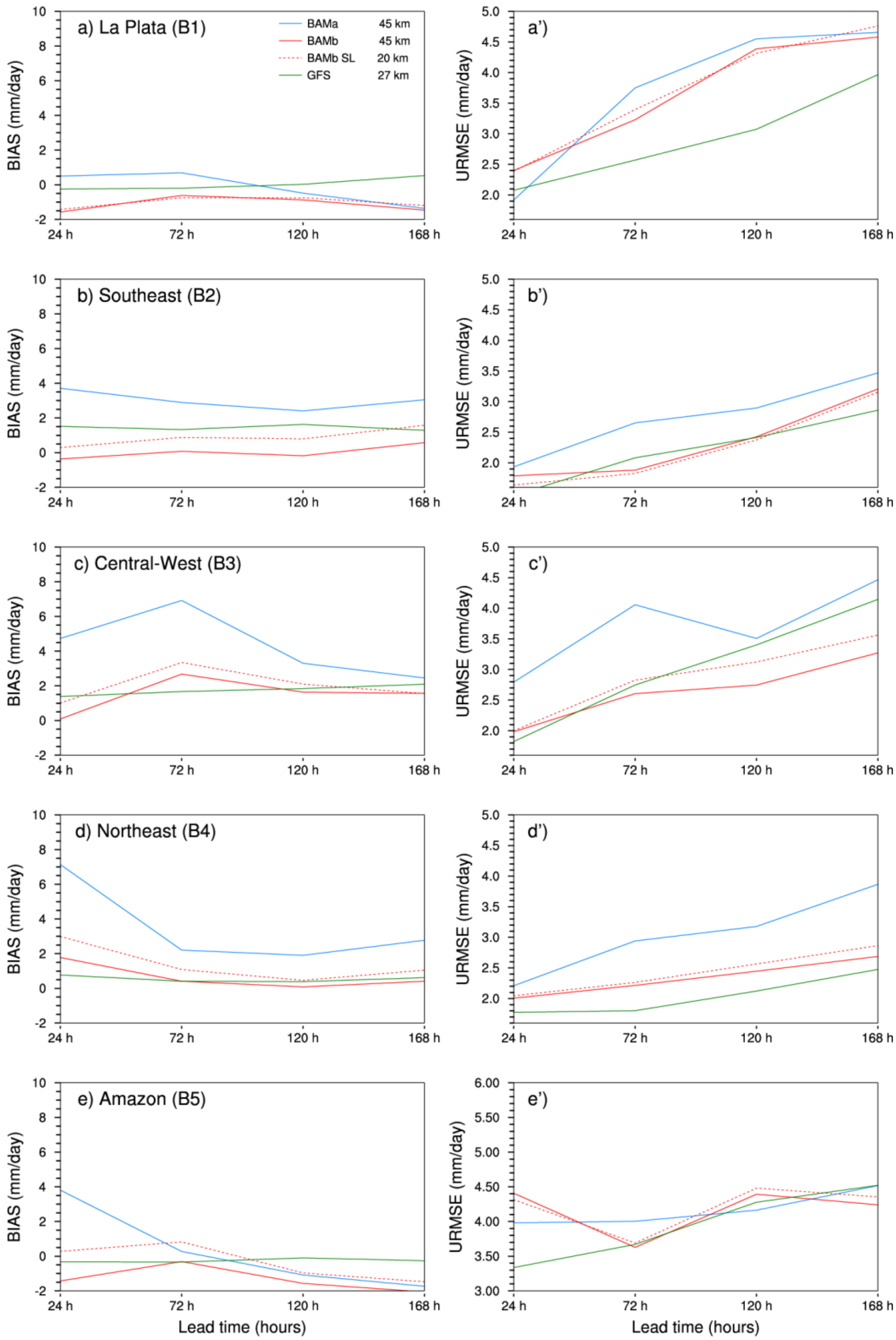

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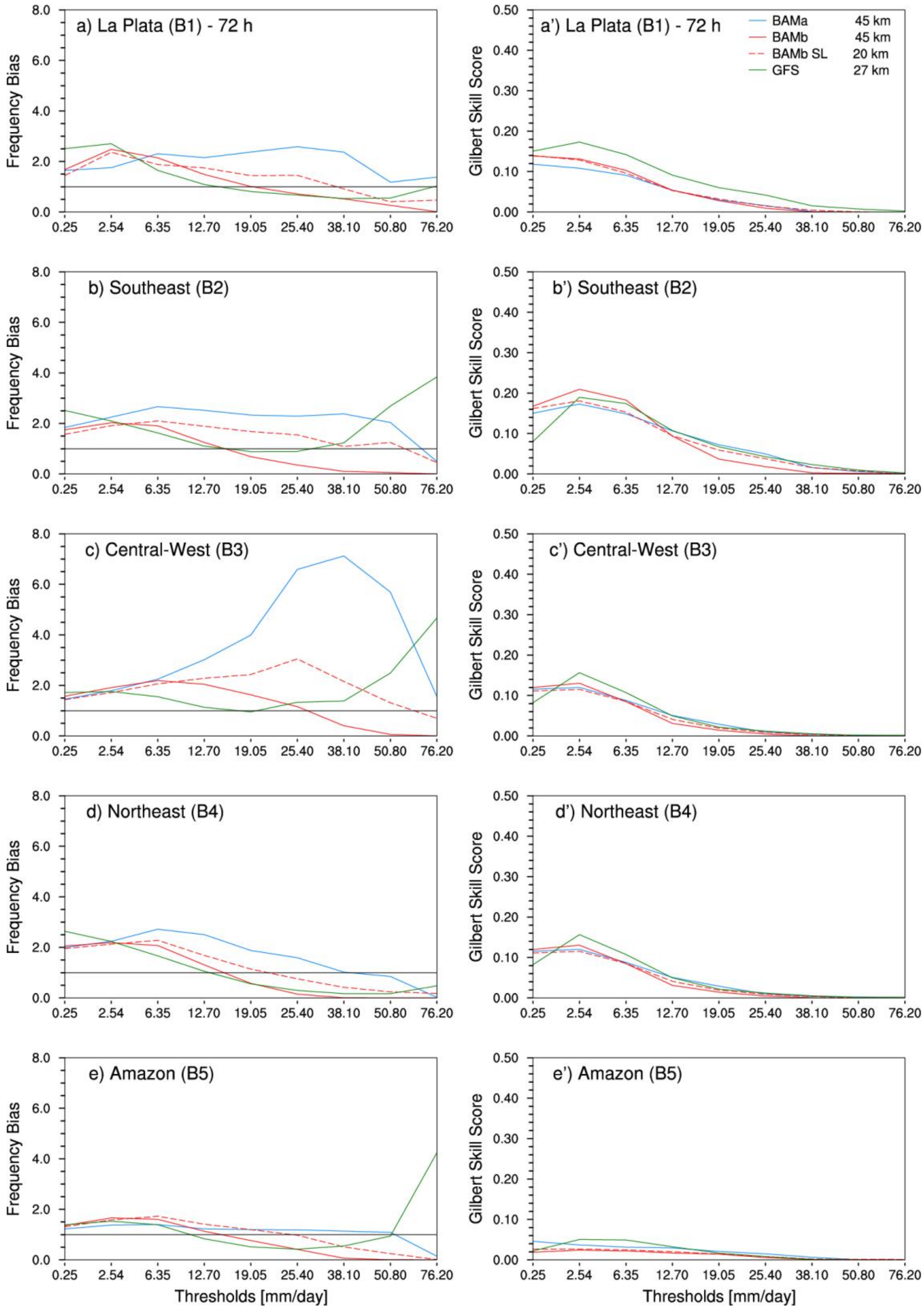

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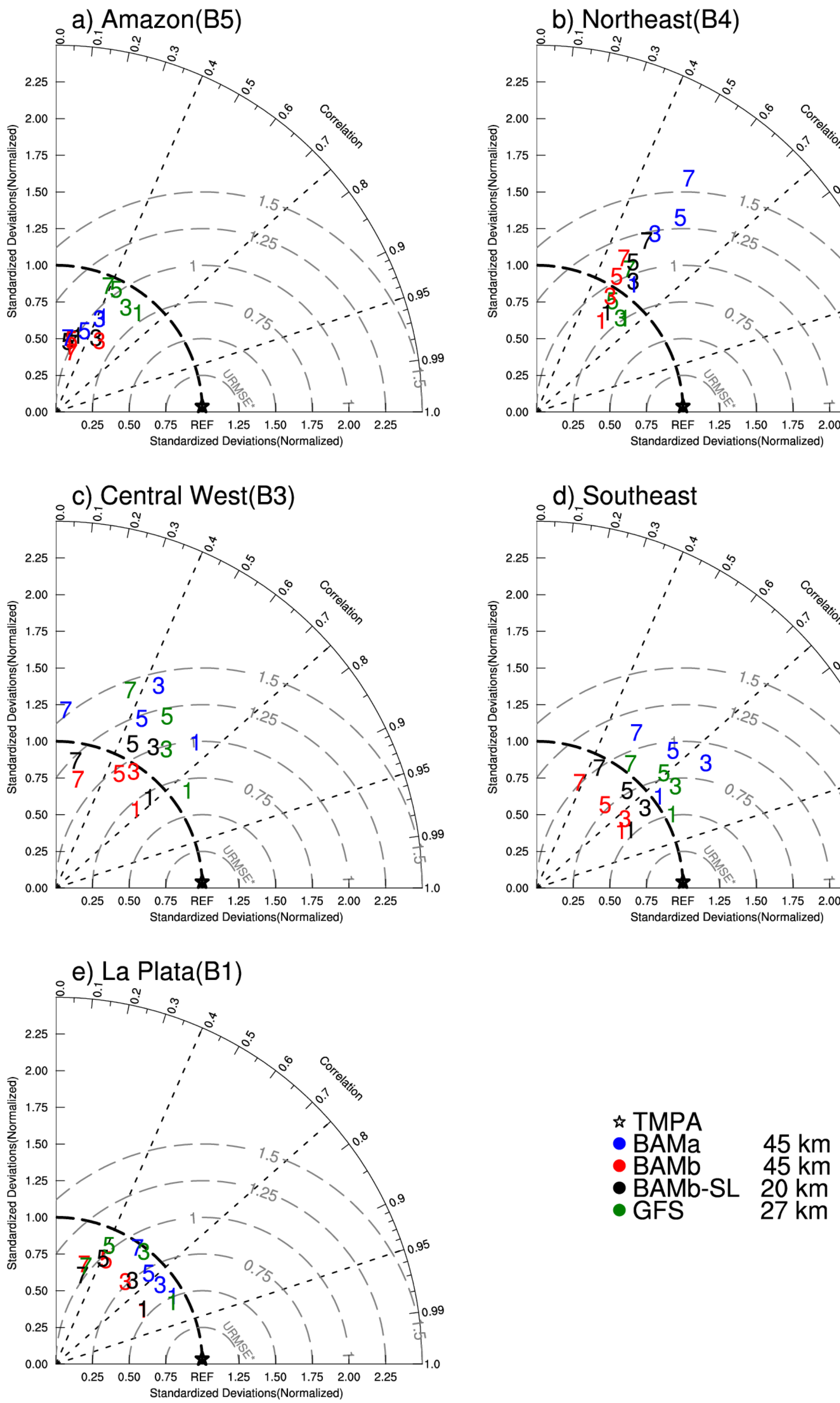

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