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Impact of increased horizontal resolution in coupled and atmosphere-only models of the HadGEM1.1 family upon the climate patterns of South America

Maria de Souza Custodio^{1,2}, Rosmeri Porfírio da Rocha¹, Tércio Ambrizzi¹, Pier Luigi Vidale³ and Marie-Estelle Demory³

Affiliation 1: Departamento de Ciências Atmosféricas, Universidade de São Paulo, São Paulo, Brazil

Affiliation 2: Departamento de Física, Universidade Estadual Paulista, Bauru, Brazil

Affiliation 3: Department of Meteorology, National Centre for Atmospheric Science, University of Reading, UK.

Corresponding author: Maria de Souza Custodio, e-mail: maria.custodio@iag.usp.br, Phone number: +55 11 30912836, Fax number: +55 11 3091-4714

1 ABSTRACT

2 This study analyzes the impact of increased horizontal resolution in coupled and atmosphere-only climate
3 models on the simulation of climate patterns in South America. To this end, we analyze models of the
4 HadGEM1.1 family with three different horizontal resolutions in the atmosphere - 135, 90 and 60 km - and in
5 the ocean – 1-1/3° and 1/3°. In general, the coupled simulation with the highest resolution (60 km) has smaller
6 systematic errors than the atmosphere-only models for seasonal fields over SA (precipitation, temperature and
7 circulation). The simulations, both coupled and atmosphere-only, represent observed spatial patterns related to
8 the seasonal march of the Intertropical Convergence Zone (ITCZ), formation and positioning of the South
9 Atlantic Convergence Zone, and the subtropical Atlantic and Pacific highs; nevertheless they overestimate the
10 rainfall rate, especially for the ITCZ and over the western border of the higher-elevation areas such as southern
11 Chile. For the Atlantic ITCZ and the continental branch of the SACZ in particular, the coupling combined with
12 higher resolution results in a more realistic spatial pattern of rain. All simulations correctly represent the phase
13 and amplitude of the annual cycle of precipitation and air temperature over the most subdomains in South
14 America. The results show that despite some problems, increasing the resolution of the HadGEM1.1 family of
15 models results in a more realistic representation of climate patterns over South America and the adjacent oceans.

16 Keywords: South America, coupled, atmospheric, resolution

17

18 **1. Introduction**

19 South America (SA) is a continent with great latitudinal extension, with a diversified surface physiography and a
20 large mountain range, the Andes, located on its western side, extending from 60°S to the tropics. The continent
21 has tropical, sub-tropical and extratropical characteristics, and because of its large area, it is influenced by
22 various dynamic systems with different spatial and temporal scales, resulting in differing climatic regimes in its
23 sub-regions. Prominent among the wide variety of systems that determine the climate of SA are the South
24 Atlantic Convergence Zone (SACZ; Satyamurty et al 1998; Kodama 1992; Carvalho et al., 2004), the
25 Intertropical Convergence Zone (ITCZ; Uvo 1989a; Waliser and Gautier 1993), mesoscale convective systems
26 (SCMs; Machado and Rossow 1993; Sakamoto et al. 2011), upper-level vortices – VCANs (Gan and Kousky
27 1986), and the Bolivian High – BH (Gutman and Schwerdfeger 1965; Lenters and Cook 1997). It is also
28 important to highlight the El Niño/Southern Oscillation (ENSO) phenomenon and the sea surface temperature
29 (SST), which directly affect the climatic variability of SA and are among the main challenges for climate
30 modeling (Grimm and Silva Dias 1995; Ambrizzi et al. 1995; Cavalcanti et al. 2009).

31 The large-scale seasonal patterns of meteorological variables are constantly being analyzed across the globe, and
32 a more realistic representation of their characteristics still remains a challenge for climate modeling. Among the
33 systems that determine the climate variability and are not yet well simulated by climate models, despite having
34 well defined seasonal cycles, are the zones of convergence. Simulations of these systems are constantly being
35 evaluated in order to understand model errors. For example, errors in intensity, position and displacement of the
36 convergence zones acting over SA have been discussed by Custodio et al. (2012) and Bombardi and Carvalho
37 (2009). Furthermore, in the case of coupled models, common errors are the breaking up of the ITCZ (Yu and
38 Mechoso 1999; Ma et al. 1996; Cavalcanti et al. 2002; Biasutti et al. 2006; Silva et al. 2014), as well as
39 representation of circulation patterns and of the rain in the highlands of the Andes. There is general agreement
40 that the global climate models still need constant evaluation in order to identify errors in simulations and to
41 indicate directions for improvement.

42 Proceeding from the AR4 (IPCC, Solomon et al. 2007) and from the errors shown in the climate models of
43 CMIP3, climate models have been improved, and their resolutions refined as shown in the IPCC AR5 report
44 (IPCC, 2013). Here the IPCC showed that the ability of these models to simulate surface temperatures had
45 increased in many, but not all, aspects with respect to the AR4. For the mean annual rainfall in the AR5, models
46 also showed an improvement compared to those of the AR4, with an increase in global spatial correlation

47 between simulations and observations. However, on a regional scale, precipitation continues to present large
48 errors, and evaluation of this scale remains difficult due to observational uncertainties (Hegerl et al. 2015).

49 Increased horizontal resolution of global models is constantly being tested in climate modeling centers around
50 the world (Shaffrey et al. 2009; Mizielinski et al. 2014). However, few studies have evaluated how increased
51 resolution, both in the ocean and in the atmosphere (in the case of coupled models) impact simulations in
52 specific regions of the globe. One of the first initiatives to simultaneously increase the resolution in the
53 atmosphere and ocean in coupled models took place with in the UK High Resolution Global Environmental
54 Modelling (HiGEM) project at the National Centre for Atmospheric Science (NCAS, Shaffrey et al. 2009) and
55 the UK-Japan Climate Collaboration (Roberts et al. 2009) in Yokohama, Japan.

56 According to Roberts et al. (2009), increased horizontal resolution in the HadGEM1.1 family of models
57 improved some aspects of the simulations such as tropical instability waves and their interaction with the tropical
58 atmosphere. These authors point out that the interaction between the tropical instability waves and the response
59 of near-surface winds impact the average state of the equatorial Pacific Ocean and therefore the average global
60 climate and ENSO. The ability of the atmosphere to respond to small-scale structures in the SST in a more
61 realistic way was apparent in studies of Shaffrey et al. (2009) and Roberts et al. (2009) with models from the
62 HadGEM1.1 family. For the atmosphere, high-resolution simulations have shown significant improvements in
63 the representation of storm trajectories and in the distribution of precipitation over Europe, where orographic
64 effects are important (Pope and Stratton 2002; Junge et al. 2006). As for the case of the oceans, the resolution
65 affects the representation of ocean eddies, which can result in improvements in wind direction, circulation and
66 westerly currents (originating from the west; Shaffrey et al. 2009).

67 In SA, general circulation models (GCMs) have shown some ability to predict seasonal rainfall especially in the
68 northeast of Brazil, due to its strong relationship to SST anomalies (Nobre et al. 2001; Moura and Hastenrath
69 2004). In the case of coupled general circulation models some major problems in the simulation of rainfall in SA
70 are linked to the discrepancy in the intensity and location of the SACZ and its seasonal evolution, as well as
71 problems in the exact quantification of the seasonal precipitation over the major basins of the continent (Vera et
72 al. 2006b). The coupled general circulation models used in the IPCC AR4, do not reproduce, for example, the
73 rainfall maximum observed over southeastern South America (SESA) during the cold season (Seth et al. 2010;
74 Vera et al. 2006b). According to Cavalcanti et al. (2002) the global model CPTEC-COLA underestimates
75 (overestimates) the rainfall in the tropical (subtropical) sectors of the convergence zones. On the other hand, over

76 the Andes and in northeastern Brazil this model overestimates the precipitation, while a large deficit of rainfall
77 was observed in the interior of the South American continent, including the Amazon basin.

78 The coupled models of the HadGEM1.1 family with finer horizontal grids (135 and 90 km) were previously
79 analyzed over South America by Custodio et al. (2012), albeit with a slightly different physical formulation
80 (version 1.2) and pointed out some improvement in the representation of migration and positioning of the ITCZ
81 and Pacific and Atlantic subtropical highs. Furthermore, the models reproduce the location and seasonal
82 evolution of the SACZ, indicating significant improvements over the coarse horizontal resolution models (Vera
83 et al. 2006b; Seth et al. 2010). In contrast, the Brazilian climate model (BESM-OA2.3) developed by
84 CPTEC/INPE, with intermediate horizontal grid (1.875 degrees in the atmosphere), analyzed by Nobre et al.
85 (2013), showed errors similar to those of other coupled models, such as a double ITCZ displaced to the south
86 and with the South Pacific Convergence Zone (SPCZ) almost absent. In addition, the BESM-OA2.3 simulated
87 excessive rainfall over the oceans and a deficit over the continent, especially over the Amazon basin.

88 The objective of the present study is to evaluate the impact of horizontal resolution in global coupled and
89 atmosphere-only models on the climatology of SA. The simulations were performed using the high-resolution
90 model of the HadGEM1.1 family at three different horizontal grid spacings in the atmosphere (~135, 90 and 60
91 km at 50°N) and two in the ocean (1-1/3° and 1/3°). Basically two important aspects are addressed. First, if and
92 how refining the horizontal resolution in this model impacts the simulated climate over South America, and
93 second, what is the impact of SST on this climatology.

94 **2. Materials and Methods**

95 **2.1. Model**

96 The simulations described in this paper share a common model formulation, HadGEM1 (Johns et al. 2006;
97 Martin et al. 2006; Ringer et al. 2006). The model has three components: atmosphere, ocean, and sea ice.
98 HadGEM1 was used in the IPCC Fourth Assessment Report with horizontal grid spacing of 1.25° latitude x
99 1.875° longitude (N96) for the atmosphere, and 1° x 1° in the ocean (augmented to 1/3° meridionally near the
100 equator). From HadGEM1, two higher-resolution configurations were developed: HiGEM (Shaffrey et al. 2009)
101 and NUGEM, in the context of high-resolution programs developed in partnership between the Natural
102 Environment Research Council (NERC) and the Met Office Hadley Centre. NUGEM was developed in the
103 context of the UK-Japan Climate Collaboration and its configuration is fully detailed in Strachan et al. (2013).

104 HiGEM and NUGEM were developed based on a number of small modifications in the dynamics core of the
105 (parent) HadGEM1, necessary for enabling the increased resolution in the ocean and atmosphere (Roberts et al.
106 2009), but they share identical physical parametrizations to allow a clean comparison of the effect of resolution.
107 After these high-resolution numerical experiments were completed, a low-resolution version was produced for
108 full consistency and it is commonly referred to as HadGEM1.1. The lowest-resolution results shown in this paper
109 are from HadGEM1.1, but for brevity this model configuration is referred to as HadGEM in Table 1 and
110 subsequent text. The horizontal resolution of HiGEM is 0.83° latitude \times 1.25° longitude (N144) in the
111 atmosphere, and $1/3 \times 1/3^\circ$ globally for the ocean and sea ice. The ocean/sea ice model in NUGEM are identical
112 to those used in HiGEM.

113 The atmospheric component of HadGEM family models has a non-hydrostatic dynamical core with semi-
114 Lagrangian transport, where the equations are discretized on the Arakawa C grid. In addition, the model includes
115 an iterative scheme for aerosols. The parameterizations of the boundary layer and convective schemes are
116 virtually identical to those used in HadCM3 (Pope et al. 2000). HadGEM has 38 vertical levels with the top of
117 the model set at 39 km; thus the stratosphere is not completely resolved. HadGEM uses the second version of the
118 UK Met Office Surface Exchange Scheme (MOSES-II; Cox et al. 1999; Martin et al. 2006) to represent the
119 surface processes allowing the description of the heterogeneous coverage of the earth's surface by use of nine
120 different types of surface.

121 The oceanic component of the HiGEM/NUGEM, follows that used in the HadGEM (Johns et al. 2006), but with
122 a higher horizontal resolution and some additional improvements. The oceanic model is formulated on a
123 spherical latitude-longitude grid, with 40 vertical levels spaced unevenly, with higher resolution near the surface
124 to better address the mixed layer and the ocean-atmosphere interaction processes. The maximum ocean depth is
125 5,500 m. A more detailed description of the ocean model can be obtained in Shaffrey et al. (2009).

126 As with the other components, the formulation for the sea ice also follows that used in HadGEM. However, the
127 values of some parameters and the introduction of subschemes for space and time for the ice dynamics were
128 changed. Rather than existing as a separate sub-model, part of the ice is treated within the ocean model, and a
129 small part is resolved by the atmospheric model. The ocean model addresses the dynamics, redistribution
130 mechanics, and thermodynamics of the sea ice, while the atmospheric model calculates the ice-air fluxes and the
131 temperature of the ice surface using the time step of the atmosphere to allow the representation of the diurnal

132 cycle of the ice. Mean fields are then transferred to the ocean model at each coupling time step (once a day).
133 Further details on the sea ice component of HadGEM can be obtained in McLaren et al. (2006).

134 **2.2. Simulations**

135 The present study analyzed and compared six simulations of the HiGEM series using the same dynamic core,
136 and the same physical parameterization and radiative forcing. All simulations used the radiative forcing (e.g.
137 greenhouse gases and aerosol climatologies) for the year 1990, with the model running freely in response to this
138 forcing. The simulations differ only in being either coupled or atmosphere-only and in terms of horizontal grid
139 spacings in the atmosphere and ocean (see details and nomenclature in Table 1). In the atmosphere-only models,
140 SST and sea ice are prescribed by the data from the Atmospheric Model Intercomparison Project (AMIP II;
141 Gates et al. 1999), with horizontal resolution of $1^\circ \times 1^\circ$ latitude/longitude.

142 The characterizations of austral summer (December-January-February - DJF) and austral winter (June-July-
143 August - JJA) climates are analyzed over all of SA, while the annual cycle is evaluated in the five subdomains
144 shown in Figure 1. The regions are identified as: AMZ (Amazon), NDE (Northeast), SESA (Southeastern South
145 America), Andes (AND) and Patagonia (PAT). The climate patterns are classified as to precipitation,
146 temperature and circulation at low and high levels.

147 **2.3. Data**

148 The climate simulations are compared to different analyses of observations, which have different spatial and
149 temporal resolutions. For seasonal climatology and annual precipitation cycle the analyses used were: (a)
150 Climate Prediction Center - Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996) with horizontal
151 resolution 2.5° (period 1979-2008); (b) Climate Research Unit (CRU; Mitchell and Jones 2005) horizontal
152 resolution 0.5° (period 1979-2002); (c) Global Precipitation Climatology Project (GPCP; Quartly et al. 2007)
153 with horizontal resolution of 2.5° (period 1979-2008); (d) Climate Prediction Center (CPC; Chen et al. 2008)
154 horizontal resolution of 1° (period 1979-2005); (e) Tropical Rainfall Measuring Mission (TRMM; Bookhagen B,
155 in review) horizontal resolution of 0.04° (period 1998 to 2009) product 3B31. In the validation of air temperature
156 the analyses used are: (a) the National Centers for Environmental Prediction (NCEP; Kalnay et al. 1996)
157 horizontal resolution of 2.5° (period 1979-2008); (b) European Centre for Medium-Range Weather Forecasts
158 (ECMWF) ERA-Interim, hereafter ERAIN on a horizontal grid of 1.5° (Dee et al. 2011; period 1979-2008); (c)
159 and CRU. Circulation at high and low levels is compared with the ERAIN reanalysis. The ensemble of analyses

160 used in the validation of the seasonal pattern and the annual cycle represents mean values of the CMAP, GPCP,
161 CRU and CPC analyses for precipitation and of ERAIN, CRU and NCEP for air temperature.

162 **3. Results**

163 **3.1. Seasonal climatology: Precipitation and air temperature**

164 According to Figures 2 and 3, the seasonal march of the ITCZ in the coupled simulations is similar to that
165 observed (TRMM and ensemble), although there are some differences between the simulations and observations
166 in the intensity of the rain from this system. Comparison of the global coupled models to the ensemble in the
167 summer (Fig. 2) and winter (Fig. 3) shows overestimation (underestimation) of rain intensity to the north (south)
168 of the ITCZ over the Pacific. In comparison to TRMM, which has high spatial resolution, the differences
169 between simulations and analysis (or errors) are smaller. The north-south shifting of the ITCZ is correctly
170 simulated by the coupled models as well as the atmosphere-only models. However, in some cases, for example
171 Figure 3g, in the atmosphere-only models, the north-south extent of the ITCZ near the north coast of SA is
172 greater. In the austral summer, over the Atlantic Ocean the ITCZ is positioned further south, near the north-
173 northeastern coast of Brazil in the coupled models.

174 However in DJF, as is shown by the analyses (Figs. 2a-b) for the ITCZ over the Atlantic, there is only one
175 maximum of rain, centered at $\sim 25\text{-}30^\circ\text{W}$, -5°N , and in the Pacific this rain band is more intense toward the west
176 but weakens near the west coast of Central America. In both basins, the spatial pattern of rain in the ITCZ
177 simulated by NUGEM (Fig. 2e) is closer to the analyses (Figs. 2a, b) than in other simulations. This indicates the
178 importance of both the horizontal resolution and the ocean-atmosphere coupling in the organization of the rain in
179 the ITCZ. In addition, comparing NUGEM to NUGAM, there is a clear indication that the high-frequency
180 temporal variability of the SST, resulting from the coupling in NUGEM, appears to be more important for
181 reproducing the observed pattern of rain than the prescription of the average observed monthly SST value in
182 NUGAM. In terms of intensity, simulated rainfall by NUGEM in the ITCZ and the Atlantic and Pacific has
183 values closer, respectively, to the ensemble (Fig. 2a) and TRMM (Fig. 2b). The rain area in the Atlantic ITCZ is
184 centered at $\sim 3\text{-}4^\circ\text{N}$ and 30°W in NUGEM, which corresponds to the latitude of convergence of the trade winds
185 in the lowermost troposphere (the layer between 1000-900 hPa), that is, in the coupling-resolution combination,
186 rain was responding to the correct positioning of the large-scale convergence at low levels (figure not shown)
187 and the associated convective systems. Using a coupled regional model of high resolution (1/4 deg), Seo et al.

188 (2008) obtained similar results to those of the NUGEM, i.e., a more realistic ITCZ in the tropical Atlantic.
189 According Seo et al. (2008), this occurs provided that the convection associated with the East African waves
190 reinforces the ITCZ precipitation in an environment in which large-scale convergence at low levels is also more
191 intense.

192 Simulations from coupled models used in this study, HadGEM and HiGEM, show a break in the Pacific ITCZ in
193 summer (Figs. 2c,d), a common error in global models, which can be attributed to their adjustment in the mass
194 flux. Since much rain is produced in a particular region, between $\sim 5-10^\circ\text{N}$, the model then generates
195 compensating subsidence, which dries a nearby region (Cavalcanti et al. 2002; Gandu and Silva Dias 1998).
196 Some studies, such as Ma et al. (1996), Yu and Mechoso (1999) and Li et al. (2002) also attribute the double
197 ITCZ to the underestimation of the stratus cloud cover on the Peruvian coast in the southeast Pacific, a common
198 problem in atmosphere-only GCMs that directly affects the simulation of the ITCZ. In NUGEM, with increased
199 horizontal resolution, there is a much less significant break in the ITCZ. In the atmosphere-only models, the
200 equatorial Pacific ocean rainfall in the ITCZ is less intense, thus reducing the double ITCZ. In these models the
201 spatial pattern of the ITCZ shows little change with increasing horizontal resolution, with the bias suffering only
202 a slight increase in NUGAM. The double ITCZ was also identified in the study by Custodio et al. (2012) with
203 version 1.2 of the HadGEM family of models. Nevertheless, with respect to the intensity of the ITCZ, especially
204 over the Atlantic Ocean, version 1.2 models show higher wet biases than those of version 1.1.

205 In DJF (Fig.2), the presence of the SACZ in the analyses (TRMM and ensemble) is indicated by a region of high
206 rainfall values that extends from southern Amazonia to the subtropical Atlantic Ocean, where its oceanic branch
207 is situated on the southeast coast of Brazil (Kodama 1992; Carvalho et al. 2004; Carvalho et al. 2002;
208 Satyamurty et al. 1998). As for the flow at 850 hPa (Fig. 4), northwest winds carry moisture from the Amazon
209 region to the subtropics of SA, which together with the western branch (northeast wind) of the South Atlantic
210 Subtropical High favor the release of intense convective activity in the tropics and subtropics of South America.
211 Figure 2 makes it clear that the coupled simulations produce a spatial pattern of the SACZ that is closest to the
212 observations of TRMM as well as the ensemble. Analyzing the differences due to the horizontal resolution in
213 coupled simulations (Fig. 2), the refinement in the grid in NUGEM implies greater similarities to TRMM
214 observations in the representation of the northwest/southeast extent of the continental SACZ. In addition,
215 compared to TRMM, in NUGEM the wet bias in the continental branch of ZCAS is smaller than in other
216 coupled simulations (HadGEM and HiGEM). In atmosphere-only models, the highest horizontal resolution in

217 NUGAM acts only to increase SACZ rainfall in both the continental and oceanic branch, thereby increasing the
218 wet bias of the simulation.

219 During the winter, the spatial pattern of rain in the oceanic branch of the ITCZ simulated by the coupled models
220 is closer to the analysis than in atmosphere-only models (Fig. 3). As in the analysis, the coupled models simulate
221 heavier rainfall in the eastern sector of the tropical Atlantic basin, while the atmosphere-only models simulate a
222 maximum of rain in the western sector of this basin. In general, atmosphere-only models underestimate the rain
223 in the ITCZ in the southwest sector of the North Atlantic Ocean, near the west coast of Africa, both when
224 compared to the ensemble and TRMM. This error in atmosphere-only models in simulating the Atlantic ITCZ is
225 common among uncoupled global climate models. Biasutti et al. (2006) identified a similar pattern, which was
226 attributed to the difficulty of atmosphere-only models in representing the correct relationship between SST and
227 precipitation in the Atlantic region. Basically, since SST is warmer in the southwestern equatorial Atlantic,
228 models tend to simulate the maximum precipitation over this region, indicating a direct relationship between the
229 two, which affects the convergence surface and thus the location of the ITCZ (Biasutti et al. 2006).

230 Both the coupled and atmosphere-only models simulate the extensive dry area on the continent, from
231 the northeast to the southeast of Brazil (north of 20°S) in winter (Fig. 3), with some differences in the size of this
232 dry area. The coupled models excel in simulating the extent of this area similarly to the ensemble and slightly
233 less than in TRMM. On the narrow band in eastern of northeastern Brazil heavier rainfall occurs during JJA,
234 both in simulations and in observations (Fig. 3). According to Kousky (1980) this rain would result just from the
235 convergence of the trade winds and the nocturnal land breeze. However, more recent studies indicate a major
236 contribution to the rain in this area from easterly waves propagating over the tropical Atlantic (Kayano 2003;
237 Diedhiou et al. 2010; Torres and Ferreira 2011; Gomes et al. 2015). On the continent in JJA, the areas with the
238 greater rainfall rate are situated in northwest and southeast SA (SESA) in all simulations, agreeing with the
239 pattern present in the observations (Figure 3). In the latter region, much of the rain results from
240 passage/development of extratropical cyclones and associated frontal systems, which are more frequent during
241 the winter (Gan and Rao 1991; Reboita et al. 2010b). In northwestern SA precipitation is mainly organized by
242 the action of the ITCZ. In both areas, the spatial pattern of rainfall (location of maxima/minima) simulated by
243 NUGEM is closer to TRMM than simulated by NUGAM, indicating the importance of ocean-atmosphere
244 coupling in the reproduction of observed patterns.

245 As mentioned, in winter there is also a strong correlation between the spatial patterns of simulated rain and
246 observed dataset (ensemble and TRMM). However, the rain rate is overestimated in some regions, especially the
247 western edge of mountainous regions such as the south of Chile. This is a common feature of many models that
248 block the flow from the west and force upward motion with consequent intense precipitation, i.e., incorrectly
249 simulating the circulation and precipitation patterns associated with elevated topographies (Stern and Miyakoda
250 1995; Cavalcanti et al. 2002). In addition, owing to the small number of direct observations (stations) as well as
251 the poor quality of estimates via satellite in the Andean region, the validation of rain becomes difficult in this
252 area. From the observational point of view, the analysis of rain in extratropical mountainous regions needs to be
253 improved, so that models can be correctly evaluated. Comparison of Figures 2 and 3 indicates that the increase in
254 horizontal resolution in coupled models (HiGEM and NUGEM) helps to reduce the excessive rainfall simulated
255 by HadGEM over the mountainous Andes region (from 25° to 10°S, especially in summer).

256 Another important factor in seasonal fields of precipitation is that in much of Amazonia, coupled simulations
257 represent the rain similarly to the ensemble and TRMM in the two seasons, with small systematic errors, except
258 in its northernmost portion. This represents a significant improvement compared to other GCMs, such as the
259 MCGA (atmospheric GCM) of CPTEC-COLA (Cavalcanti et al. 2002), ECMWF (Brankovic and Molteni 1997)
260 and NCAR-CCM3 (Hurrell et al. 1998), which show a significant rain deficit over the Amazon region during the
261 summer. Atmosphere-only models during the summer have, in general, higher systematic errors than coupled
262 models in the Amazon.

263 Comparison of the seasonal maps shows that coupled models (Figs. 2-3 c, d, e) produce a spatial pattern similar
264 to the analyses and TRMM and in some seasons increased horizontal resolution helps to reduce the bias of the
265 simulation. Examples of this occur over the center-west of Brazil during the winter (Fig. 3), in addition to
266 subtropical and tropical areas of the Andes throughout the year. In general, coupled models, although
267 overestimating precipitation, have smaller systematic errors in seasonal fields than do the atmosphere-only
268 models. These results indicate that the increase in resolution associated with ocean-atmosphere coupling which
269 includes diurnal variation of the SST, results in more realistic simulations of precipitation over SA and the
270 tropical sector of tropical oceans than do the models of the HadGEM family.

271 The spatial distribution of temperature in summer (Fig. 4) and winter (Fig. 5) over the oceans in the atmospheric
272 and coupled simulations is similar to that of the ensemble, while over the continent the differences between the
273 simulations and the ensemble are larger. The models simulate a warmer and colder atmosphere, respectively,

274 over north-central and south-central SA. In the atmosphere-only models, systematic errors are smaller than in the
275 coupled models in northern and in southeast-central parts of SA. Over the oceans atmospheric simulations are
276 slightly warmer than the ensemble, including the region of the ITCZ in the Northern Hemisphere. The better
277 performance of the atmosphere-only models in representing the air temperature is consistent with the fact that
278 these are forced with the observed SST, which acts as a direct regulator for the simulation of temperature.

279 In summer (Fig. 4), both in the coupled and the atmosphere-only models, higher temperatures (above 22°C)
280 occur in the latitudinal belt 5°N-30°S, while in the winter (Fig. 5) such temperatures have a smaller north-south
281 extent, 5°N-20°S. Temperatures below 20°C already occur over the Andes and the higher latitudes south of 35°S
282 and south of 25°S, respectively, in summer and winter, in both atmospheric and coupled simulations. The
283 simulated hot and cold regions in these models agree with the results obtained by Collins et al. (2009) who
284 analyzed the seasonal pattern of the NCEP/NCAR reanalysis for two periods, 1948-1975 and 1976-2007.

285 In summer, coupled models were colder than the ensemble in their simulation of the Pacific equatorial region
286 (Fig. 4b-d), but among these simulations HiGEM (Fig. 4c) shows the lowest systematic errors. In the Atlantic
287 Ocean, HadGEM and NUGEM underestimate the temperature in relation to the ensemble in the summer, not
288 simulating a temperature above 26 °C anywhere in a region that extends all the way to the Brazilian northeast
289 coast. HiGEM is the only one that shows elevated temperatures from the Brazilian east coast to Africa in the
290 equatorial region. In contrast, NUGEM has the lowest error in the southern part of the Atlantic, where
291 temperatures are below 24°C. In winter (Fig. 10) the coupled models are also colder than the ensemble in the
292 equatorial Pacific and Atlantic oceans. In the equatorial Pacific the existence of a cold bubble (centered at the
293 equator) elongated toward the west may result from more intense trade winds (Fig. 7) with the consequent
294 intensification of upwelling in the coupled simulations. The ensemble shows a region on the continent in
295 northeastern SA with temperatures above 26°C, which in the coupled models is not properly simulated. Only
296 HiGEM and NUGEM simulations show elevated temperatures in this region, though with a much smaller extent
297 than the ensemble. The model with low horizontal resolution (HadGEM), in addition to not simulating this warm
298 region in winter on the continent, is cooler by 2°C (or more) in the equatorial Pacific (Fig. 10b).

299 Blazquez and Nuñez (2012) showed that in the summer, fall, and spring the high-resolution global atmospheric
300 model of the Japanese Meteorological Agency (JMA/MRI), underestimates the temperature by up to 4°C in
301 eastern Argentina, western Uruguay, southern Chile and tropical latitudes. In comparison, the errors both in the
302 coupled and the atmospheric simulations analyzed here are much smaller (bias of less than +0.5°C in these

303 regions) than those obtained in Blazquez and Nuñez (2012). The JMA/MRI model used a grid spacing of 20 km
304 (TL959), i.e., higher than the horizontal resolution of the models discussed here, and even so it presents
305 significant errors in the simulation of seasonal temperature. This indicates that in addition to increasing the
306 resolution of climate models, the physical parameterizations of these models are also of great importance in
307 reducing simulation errors over SA.

308 The results indicate that increasing the resolution helped to reduce errors in the simulation of temperature,
309 especially over the oceans in atmosphere-only models. In general, the largest systematic errors occur over oceans
310 and northern SA. The equatorial region of the Pacific Ocean is also identified in the seasonal analysis of
311 precipitation (Figs. 2 and 3) as having a break in the ITCZ. The results show that the coupled models also have
312 relatively large errors in air temperature over the ocean. This indicates the need for improvements in the
313 simulation of SST, which has a direct impact on air temperature over the ocean due to the turbulent processes at
314 the air-sea interface.

315 **3.2 Seasonal climatology: Circulation at low and upper levels**

316 As for the circulation at low levels during the austral summer (Fig. 6), some characteristic systems such as the
317 trade winds and the Pacific and the Atlantic subtropical highs, are identified and properly represented by both
318 coupled and atmosphere-only models. However, there were some differences in intensity in relation to ERAIN.
319 The deflection by the Andes toward the tropics of the northeast trade winds coming from the North Atlantic is
320 closer to ERAIN in the simulations with higher horizontal resolution. In the equatorial Atlantic near the northern
321 coast of SA the wind speed errors are smaller in NUGEM. At high latitudes (south of 40°S), the westerly flow
322 over the Pacific Ocean and Atlantic is present in all simulations (Fig. 6b-g), but with speeds closer to ERAIN in
323 NUGEM. Still in the circulation patterns at low levels, in all simulations the Pacific and Atlantic subtropical
324 high are properly positioned and have strengths close to those in the reanalysis.

325 The flow at 850 hPa shows that the maximum northwest wind speed east of the Andes, which characterizes the
326 low level jet, is more intense in summer (Fig. 6) than in winter (Fig. 7) in ERAIN. In this analysis, the LLJ
327 undergoes a meridional displacement between winter and summer, being centered further north in summer
328 (northern Bolivia) and further south in winter (northern Paraguay). The coupled and atmosphere-only models
329 correctly simulate these characteristics observed in the LLJ in ERAIN. In winter, the winds at 850 hPa on the
330 northeast coast of SA are stronger in atmosphere-only models than in the coupled models and ERAIN (Fig. 7).

331 This pattern in the atmosphere-only models can explain the greater intensity of the ITCZ in this area (Fig. 3),
332 since the deceleration of the trade winds induces greater convergence and increased rainfall.

333 With the increase of the horizontal resolution in the coupled models, the LLJ intensifies as shown in Figure 8, a
334 vertical cross section of the wind speed at 17.5°S latitude in summer, the season during which the LLJ is quite
335 typical (Marengo et al. 2004). Furthermore, with the increased resolution the core of the LLJ is moved west,
336 closer to the Andes, i.e., the jet is centered at ~61°W in HadGEM and ~63°W in NUGEM. This indicates a direct
337 impact of the more realistic topography used by NUGEM, and in this simulation the position of the LLJ is closer
338 to that of ERAIN. On the other hand, with the increase in resolution, the core of the LLJ occurs at higher
339 pressure levels (~8.5 m/sec at 800 hPa in NUGEM) and is more intense than in ERAIN (~4.5 m/sec at 850 hPa).
340 The intensification of the LLJ with increased horizontal resolution in coupled simulations can result in increased
341 moisture transport from the Amazon region to southeastern SA. This jet upon decelerating, induces greater
342 convergence of moisture flux in the region and increases the precipitation rate in NUGEM. It is noteworthy that
343 in the summer period the Amazon region is a large moisture source with direct impact on the organization of
344 convective activity in southeastern South America. In the atmospheric simulations, in both the intensity of the
345 core of the LLJ as well as the vertical level of its top speed, there is virtually no change with increased horizontal
346 resolution of the models (Fig. 8). In these three simulations, the core of the LLJ is located at higher pressure
347 levels (~700 hPa in NUGAM and 725 hPa in HadGAM) than in ERAIN (~850 hPa). However, the maximum
348 speed of the LLJ is smaller than that in coupled simulations and closer to that of ERAIN. Besides the LLJ,
349 simulations adequately reproduce the speed maxima in the lowermost troposphere (between 1000-900 hPa)
350 associated with the subtropical anticyclones in the Pacific (west of 75°W) and Atlantic (east of 45°W).

351 ERAIN shows in Figure 9 the circulation at 200 hPa over SA, where the two characteristic systems that are
352 prominent during the summer are the Bolivian High (AB - centered at ~22°S-60°W) and the trough over
353 northeastern Brazil (CN - axis at ~20°W). The coupled and atmosphere-only models simulate these two systems
354 as similar to ERAIN in position and intensity. The AB is a quasi-stationary anticyclone which in ERAIN is
355 centered at ~20°S, 70°W. Although the simulations correctly represent the position of the AB, it worth noting
356 that this system is simulated closer to ERAIN in NUGEM than in other simulations. The small error in
357 positioning the AB in the simulations can be explained by the realistic representation of rain in the Amazon
358 basin since numerical studies indicate that this system would be a response to the heat source associated with
359 convection in this basin (Lenters and Cook 1997; Gandu and Geisler 1991). The CN is also represented in the six

360 analyzed simulations, although the coupled as well as the atmosphere-only models locate it east of its position in
361 ERAIN. Even in summer, the models show a pattern similar to ERAIN in the simulation of the speed maximum
362 in the westerly flow over the southeast sector of the South Atlantic Ocean (east of $\sim 30\text{-}20^\circ\text{W}$ and centered on
363 45°S latitude) and the weakening of the subtropical jet over the south Pacific and South America (Fig. 9).
364 NUGEM simulates both factors of the 200 hPa flow at mid-latitudes more closely to ERAIN.

365 **3.3. Regional climatology: annual cycle and biases**

366 The annual cycles of precipitation and temperature for five subdomains of South America are shown in Figures
367 10 and 11. In region AMZ (Fig. 10a), the rainy season in the ensemble occurs from December to March
368 (maximum of 10 mm day^{-1}) while the dry season occurs from June-August (minimum of 1 mm day^{-1}). All
369 simulations correctly represent the phase of the annual cycle of rain in the region, which is reflected in high
370 correlation coefficient values (between 0.98 and 0.99) as shown in Fig. 10b. However the simulations are wetter
371 over a large part of the year (mainly from January to March) than the ensemble, except NUGEM in some months
372 of the year. The refinement of the grid in coupled models (NUGEM) contributed to a smaller bias (0.2 mm day^{-1}),
373 while for the atmosphere-only models (NUGAM) the bias increases with the increase in resolution (1.4 mm
374 day^{-1}). Fig. 10b also shows that the simulated standard deviation is close to the ensemble, especially in NUGEM
375 and HiGEM. This would indicate the importance of ocean-atmosphere coupling and grid refinement for realistic
376 simulations of rain over AMZ.

377 As pointed out by Custodio et al. (2012), who analyzed version 1.2 of the HadGEM and HiGEM (coupled
378 models), version 1.2 of the coupled and atmosphere-only models of the HadGEM1 family did not have the dry
379 bias in the region of the Amazon basin that is pointed to as a common error in many climate models in the region
380 (Cavalcanti et al. 2002; Li et al. 2002; Marengo et al. 2003; Seth and Rojas 2003; Seth et al. 2007; Ma et al.
381 2011). This error is usually attributed to the smoothing of the Andes in global climate models. For the models of
382 the HadGEM family, although versions differ from one another in their configurations, these differences did not
383 alter significantly the representation of the annual cycle of precipitation in AMZ.

384 The observations show that the rainy season in NDE is concentrated in the months from January-April, with a
385 peak in March, due to the shift to the south of the ITCZ (Fig. 10c). In the following months the rain decreases
386 abruptly, reaching minimum values (1 mm day^{-1}) in August-September (Fig. 10c). The coupled and atmosphere-
387 only models are in phase with the observed annual cycle of rain with correlation of greater than 0.95 (Fig. 10d),

388 but there are some differences in intensity. Among coupled models (Fig. 10c), those with lower resolution
389 (HadGEM and HiGEM) present the highest relative biases (47% and 37%, respectively) for the region since they
390 are wetter (drier) than the ensemble during the rainy (dry) season. The larger amplitude of the annual rain cycle
391 in these simulations is reflected in the larger values of the standard deviation (Fig. 10d). NUGEM remains drier
392 than the ensemble throughout the year, and among the coupled simulations provides the lowest relative bias (-
393 25%) and standard deviation, similar to that of the ensemble. In the NDE region, the biases of precipitation in the
394 atmosphere-only models (13% in HadGAM, +3% in HiGAM, and 5% in NUGAM) are smaller than in the the
395 coupled models. The best performance of atmosphere-only models in simulating the annual cycle of precipitation
396 in the NDE is directly related to incorrect positioning of the ITCZ over northern SA in HadGEM and HiGEM
397 (see Figures 3c-d). The increase of the horizontal resolution in the coupled models lessens the overestimation of
398 rainfall in NDE while correctly positioning the ITCZ (see Fig. 3e).

399 During the rainy season the wet bias in NDE occurs in most simulations (atmospheric and coupled) indicating
400 little association with the SST. Possibly these errors are related to the local scale physical processes that are not
401 being correctly resolved in the models of the HadGEM family such as, for example, parameterization of
402 convection. By comparing our results with those of Custodio et al. (2012) it can be seen that the changes
403 between coupled versions 1.1 and 1.2 of the HadGEM family do not present a clear trend since in the rainy and
404 dry seasons the bias decreases and increases, respectively, in version 1.2.

405 In the analysis (ensemble), the rainy and dry seasons occur from June to August and from October to April,
406 respectively, in the SESA region (Fig. 10e). This pattern is correctly simulated by coupled and atmosphere-only
407 models, although they overestimate the rainfall rate throughout most of the year. In this region only the coupled
408 model with lowest resolution (HadGEM) remains drier than the observation ensemble from January to April. For
409 annual rainfall, the relative biases in SESA range from +20% in HiGEM and HiGAM to values close to zero in
410 HadGEM and HiGAM, in other words, values always less than 0.85 mm day^{-1} . In this region increasing the
411 resolution increases the rainfall rate and the relative bias. However, in all simulations the biases are much lower
412 than previously reported for other global models (Seth et al. 2010; Blazquez and Nuñez 2012) and regional
413 models (da Rocha et al. 2014) in a similar area. Compared to Custodio et al. (2012), the version assessed here
414 (1.1) does not change the representation of the annual cycle of precipitation in the SESA. In addition, these
415 results represent an improvement compared to the nine coupled models of the CMIP3 project (Seth et al. 2010)
416 and some of the CMIP5 models, which that underestimate the spring rainfall by 50% (da Rocha et al. 2014).

417 Together with the small annual bias in all simulations the phase and amplitude of the annual precipitation cycle
418 is similar to the ensemble, as indicated by the high correlation (between ~0.8 and 0.9) and similar standard
419 deviations in SESA (Fig. 10f). By comparison, in this region, the atmosphere-only, as well as the coupled
420 simulations, represent a great improvement over the CMIP3 models, which are very dry (bias ~ -3 mm day⁻¹)
421 during the winter and do not simulate the observed phase of the annual cycle of precipitation, principally the
422 peak rainfall in April.

423 In regions AND (Fig. 10g) and PAT (Fig. 10i), the coupled as well as the atmosphere-only models, although in
424 phase, are wetter than the ensemble throughout the year. This pattern was identified in seasonal fields (Figs. 2
425 and 3), in view of the fact that these areas are in the southern part of the Andes where all simulations
426 overestimate the rain. In these two regions, the monthly rainfall is small and there is not much difference
427 between rainfall throughout the year in the ensemble, while the models simulate an annual cycle with greater
428 amplitude, implying higher simulation errors. In the AND subdomain (Figure 10g), almost all of which is
429 located over the Andes, the amplitude of the annual precipitation cycle for the ensemble is small (≈ 1.0 mm day⁻¹).
430 With the increase of the horizontal resolution the simulated rain intensity increases and therefore the bias as
431 well, which is greater in NUGEM (+67%) and NUGAM (+58%) than in HiGEM (+32%) and HiGAM (+27%)
432 with the HadGEM and HadGEM providing intermediate values. In this region the correlation for the annual
433 cycle is low (less than 0.4) in most simulations, except in HadGEM and HadGAM (Fig. 11h). In the higher
434 resolution models (NUGEM and NUGAM) the increase in RMSE (Fig. 10h) may indicate, besides the larger wet
435 bias, a bigger difference between the simulated and observed maxima and minima. In PAT (Fig. 10i), rain in the
436 ensemble increases in the months of May and June, which is not properly represented in all simulations. Among
437 the coupled models, only NUGEM presents heavier rain in May, while HadGEM and HiGEM simulate only a
438 maximum in June. Among the atmosphere-only models, the peaks observed in May-June are not simulated
439 correctly, and only NUGAM simulates maximum rainfall between April and June. With increased resolution the
440 simulations in PAT have an annual rainfall cycle closer to the ensemble, both in coupled and in atmosphere-only
441 models (Fig. 10i). The correlation for the annual cycle is high in the PAT region (~ 0.8) and in all simulations
442 the amplitude of the annual cycle is slightly lower than in the ensemble (Fig. 10j). Furthermore, the diagram
443 shows that all simulations have standard deviation values close to the ensemble and small RMSE (Fig. 10j).

444 The annual cycles of temperature for the subdomains and their Taylor diagrams are shown in Figure 11. Among
445 the regions analyzed, the smallest range of temperature in the ensemble occurs in AMZ (Fig. 11a), where the

446 temperature remains close to 25°C, with an increase of at most 1°C beginning in August. In AMZ, comparison
447 with observations shows great discrepancies in the maximum and the minimum values, with differences of up to
448 1°C. In this region, both coupled as well as atmosphere-only models simulate the semi-annual cycle, with two
449 periods of maximum temperature - from September to November and from January to February. This feature
450 does not occur in the annual cycle of precipitation as discussed above. Among the coupled and atmosphere-only
451 models, except for the months from June to July, the models with resolutions of 135 and 90 km have the smallest
452 systematic errors in relation to the ensemble. In this region the increased horizontal resolution increases the bias
453 of the coupled and atmospheric simulations, ie -0.3°C (+0.8°C) in HadGEM (HadGAM) to +1.5°C (+1.3°C) in
454 NUGEM (NUGAM). The three atmospheric simulations and NUGEM have high correlations (between 0.8 and
455 0.9) for the annual cycle in temperature, while HadGEM and HiGEM had a slightly lower correlation (~0.7). The
456 larger amplitude of the annual temperature cycle in the simulations implies higher standard deviations and
457 RMSE in the AMZ region (Fig. 11b). The poor performance of lower resolution horizontal models in
458 representing the annual temperature cycle indicates that the increased resolution is not the only factor to reduce
459 the temperature simulation errors in the AMZ.

460 The annual temperature cycle in the ensemble for the NDE region (Figure 11b) locates the warmest period in the
461 months from September to March and the coldest from May to August. The coupled and atmosphere-only
462 models correctly represent these periods. In the NDE, the temperature bias of the atmosphere-only models is
463 lower from January to September, while from October to December it is lower in the coupled models. Increased
464 horizontal resolution reduces the cold bias in the coupled simulations from -1.7°C in HiGEM to -0.3°C in
465 NUGEM. In atmosphere-only simulations the bias for annual temperature remains practically constant with
466 increasing resolution (0.2°C and 0.1°C respectively in HadGAM and NUGAM). Figure 11b shows that, except
467 for NUGEM, the simulations show high temporal correlation to the annual temperature cycle (~0.95), but
468 simulate a larger amplitude of the annual cycle than observed.

469 In regions SESA, AND, and PAT the annual cycle of temperature in the ensemble indicates the cold season from
470 June to September and the warm season from December to March (Fig. 11e, g, i). The coupled and atmosphere-
471 only models are in phase with the observations in these three regions. The amplitude in the simulations is similar
472 to that of the ensemble in DNA and PAT, but in SESA it is larger in all simulations, reflected in higher RMS and
473 standard deviations (Figs. 11f, h, j). All simulations correctly represent the length of the seasons in these regions,
474 with the largest systematic errors occurring in the cold period. The correct simulation of phase involves high

475 correlation values for the annual cycle (above 0.95) and standard deviation close to that of the ensemble (Fig.
476 11). The similarity of the RMS in these regions in all simulations illustrates the correctness of the phase
477 adjustment presented by the models in these regions. In the coupled simulations, increasing the resolution
478 reduces the mean annual temperature bias to very small values (lower than $\pm 0.3^{\circ}\text{C}$), but this positive impact of
479 horizontal resolution does not occur in the atmosphere-only simulations.

480 Increased horizontal resolution in the HadGEM family of models does not particularly impact the representation
481 of the annual cycle of temperature in the SA subdomains analyzed. This indicates that for the reduction of
482 systematic temperature errors in this family of models, just a refinement of the grid is not sufficient, indicating
483 that other physical parameterizations still require adjustments in their configuration. But it is noteworthy that the
484 errors for the average annual temperature are small, always less than $\pm 1.5^{\circ}\text{C}$ in all evaluated regions.

485 **4. Conclusions**

486 Evaluation of seasonal climatology shows that the coupled and atmosphere-only models of HadGEM family
487 realistically represent the main climate-generating mechanisms over South America (the SACZ, ITCZ,
488 subtropical Atlantic and Pacific highs, and transient systems in subtropical-extratropical latitudes). In general,
489 coupled models simulate the north-south movement, the intensity of and position of the longitudinal band of rain
490 over the equatorial Atlantic of the ITCZ more closely to that observed in both TRMM and the ensemble, than do
491 the atmosphere-only models. In these models, increased horizontal resolution contributes toward the reduction of
492 the wet bias in the region of the ITCZ increasing the agreement with the observations on the localization of the
493 rainfall maximum in the Atlantic ITCZ and reducing errors in its north-south displacement. In addition, in the
494 coupled models the patterns of location and strength of the SACZ and the Pacific and the Atlantic subtropical
495 highs are closer to those observed than in atmosphere-only models.

496 Comparing the seasonal errors in precipitation and temperature, it is noted that the simulations with greater
497 systematic temperature errors on the continent also show, especially in the area of the ITCZ, larger errors in the
498 precipitation; that is, the coupled simulations with more intense rainfall are cooler than the atmospheric
499 simulations. This indicates a positive feedback between higher rainfall rate and more cloud cover, and
500 consequently, reduction in the amount of incident radiation, implying a colder troposphere.

501 In general, the coupled simulation with highest atmospheric resolution (60 km) has systematic errors smaller
502 than the atmospheric simulation for the seasonal precipitation, temperature and circulation fields. In this case, the

503 increase in resolution associated with the ocean-atmosphere coupling, which includes daily variability of SST,
504 provides more realistic simulations of atmospheric patterns observed in South America and the tropical sector of
505 adjacent oceans.

506 In most of the subdomains analyzed, both coupled and global atmosphere-only models simulate the phase of the
507 annual cycle (dry/rainy and cold/warm seasons) similar to what is observed. Over the Amazon region the
508 highlight, especially in coupled models, is the better performance of higher resolution simulations in
509 representing the annual rain cycle, thus showing the importance and the positive impact of increased horizontal
510 resolution for precipitation in the continental tropical sector of SA.

511 The impact of increased horizontal resolution of HadGEM family models on the phase and amplitude of the
512 annual cycle of precipitation and temperature does not present a common pattern in all subdomains. For
513 temperature, the errors of coupled and atmosphere-only models analyzed are small over SA - smaller than those
514 reported in other global atmosphere-only models of high horizontal resolution by Blazquez and Nuñez (2012).
515 This indicates that the increase in horizontal resolution is an important associated factor, but the physical
516 parameterizations in the models are also relevant for realistic simulation of the phenomena described in this
517 paper.

518 Based on the present results, it can be concluded that for the regions analyzed, the HadGEM family models
519 simulate satisfactorily the observed climatology of both precipitation and temperature, and that errors still
520 present are mainly in magnitude for these variables and can be considered small in comparison to errors found in
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