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

Article

Accepted Version

Published version at: http://dx.doi.org/10.1007/s00382-016-3271-8
To link to this article DOI: http://dx.doi.org/10.1007/s00382-016-3271-8

Publisher: Springer

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 Rocha[1], Tércio Ambrizzi[1], Pier Luigi Vidale[3] and Marie-Estelle Demory[3]

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

ABSTRACT

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

Keywords: South America, coupled, atmospheric, resolution

1. Introduction

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

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

Proceeding from the AR4 (IPCC, Solomon et al. 2007) and from the errors shown in the climate models of CMIP3, climate models have been improved, and their resolutions refined as shown in the IPCC AR5 report (IPCC, 2013). Here the IPCC showed that the ability of these models to simulate surface temperatures had increased in many, but not all, aspects with respect to the AR4. For the mean annual rainfall in the AR5, models also showed an improvement compared to those of the AR4, with an increase in global spatial correlation between simulations and observations. However, on a regional scale, precipitation continues to present large errors, and evaluation of this scale remains difficult due to observational uncertainties (Hegerl et al. 2015).

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

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

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

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

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

2. Materials and Methods

2.1. Model

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

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

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

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

As with the other components, the formulation for the sea ice also follows that used in HadGEM. However, the values of some parameters and the introduction of subschemes for space and time for the ice dynamics were changed. Rather than existing as a separate sub-model, part of the ice is treated within the ocean model, and a small part is resolved by the atmospheric model. The ocean model addresses the dynamics, redistribution mechanics, and thermodynamics of the sea ice, while the atmospheric model calculates the ice-air fluxes and the temperature of the ice surface using the time step of the atmosphere to allow the representation of the diurnal cycle of the ice. Mean fields are then transferred to the ocean model at each coupling time step (once a day). Further details on the sea ice component of HadGEM can be obtained in McLaren et al. (2006).

2.2. Simulations

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

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

2.3. Data

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

3. Results

3.1. Seasonal climatology: Precipitation and air temperature

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

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

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

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

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

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

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

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

As mentioned, in winter there is also a strong correlation between the spatial patterns of simulated rain and observed dataset (ensemble and TRMM). However, the rain rate is overestimated in some regions, especially the western edge of mountainous regions such as the south of Chile. This is a common feature of many models that block the flow from the west and force upward motion with consequent intense precipitation, i.e., incorrectly simulating the circulation and precipitation patterns associated with elevated topographies (Stern and Miyakoda 1995; Cavalcanti et al. 2002). In addition, owing to the small number of direct observations (stations) as well as the poor quality of estimates via satellite in the Andean region, the validation of rain becomes difficult in this area. From the observational point of view, the analysis of rain in extratropical mountainous regions needs to be improved, so that models can be correctly evaluated. Comparison of Figures 2 and 3 indicates that the increase in horizontal resolution in coupled models (HiGEM and NUGEM) helps to reduce the excessive rainfall simulated by HadGEM over the mountainous Andes region (from 25^0 to 10^0S, especially in summer).

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

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

The spatial distribution of temperature in summer (Fig. 4) and winter (Fig. 5) over the oceans in the atmospheric and coupled simulations is similar to that of the ensemble, while over the continent the differences between the simulations and the ensemble are larger. The models simulate a warmer and colder atmosphere, respectively, over north-central and south-central SA. In the atmosphere-only models, systematic errors are smaller than in the coupled models in northern and in southeast-central parts of SA. Over the oceans atmospheric simulations are slightly warmer than the ensemble, including the region of the ITCZ in the Northern Hemisphere. The better performance of the atmosphere-only models in representing the air temperature is consistent with the fact that these are forced with the observed SST, which acts as a direct regulator for the simulation of temperature.

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

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

Blazquez and Nuñez (2012) showed that in the summer, fall, and spring the high-resolution global atmospheric model of the Japanese Meteorological Agency (JMA/MRI), underestimates the temperature by up to 4°C in eastern Argentina, western Uruguay, southern Chile and tropical latitudes. In comparison, the errors both in the coupled and the atmospheric simulations analyzed here are much smaller (bias of less than +0.5°C in these regions) than those obtained in Blazquez and Nuñez (2012). The JMA/MRI model used a grid spacing of 20 km (TL959), i.e., higher than the horizontal resolution of the models discussed here, and even so it presents significant errors in the simulation of seasonal temperature. This indicates that in addition to increasing the resolution of climate models, the physical parameterizations of these models are also of great importance in reducing simulation errors over SA.

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

3.2 Seasonal climatology: Circulation at low and upper levels

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

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

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

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

ERAIN shows in Figure 9 the circulation at 200 hPa over SA, where the two characteristic systems that are prominent during the summer are the Bolivian High (AB - centered at ~22°S-60°W) and the trough over northeastern Brazil (CN - axis at ~20°W). The coupled and atmosphere-only models simulate these two systems as similar to ERAIN in position and intensity. The AB is a quasi-stationary anticyclone which in ERAIN is centered at ~20°S, 70°W. Although the simulations correctly represent the position of the AB, it worth noting that this system is simulated closer to ERAIN in NUGEM than in other simulations. The small error in positioning the AB in the simulations can be explained by the realistic representation of rain in the Amazon basin since numerical studies indicate that this system would be a response to the heat source associated with convection in this basin (Lenters and Cook 1997; Gandu and Geisler 1991). The CN is also represented in the six analyzed simulations, although the coupled as well as the atmosphere-only models locate it east of its position in ERAIN. Even in summer, the models show a pattern similar to ERAIN in the simulation of the speed maximum in the westerly flow over the southeast sector of the South Atlantic Ocean (east of ~30-20°W and centered on 45°S latitude) and the weakening of the subtropical jet over the south Pacific and South America (Fig. 9). NUGEM simulates both factors of the 200 hPa flow at mid-latitudes more closely to ERAIN.

3.3. Regional climatology: annual cycle and biases

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

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

The observations show that the rainy season in NDE is concentrated in the months from January-April, with a peak in March, due to the shift to the south of the ITCZ (Fig. 10c). In the following months the rain decreases abruptly, reaching minimum values (1 mm day^{-1}) in August-September (Fig. 10c). The coupled and atmosphere-only models are in phase with the observed annual cycle of rain with correlation of greater than 0.95 (Fig. 10d), but there are some differences in intensity. Among coupled models (Fig. 10c), those with lower resolution (HadGEM and HiGEM) present the highest relative biases (47% and 37%, respectively) for the region since they are wetter (drier) than the ensemble during the rainy (dry) season. The larger amplitude of the annual rain cycle in these simulations is reflected in the larger values of the standard deviation (Fig. 10d). NUGEM remains drier than the ensemble throughout the year, and among the coupled simulations provides the lowest relative bias (-25%) and standard deviation, similar to that of the ensemble. In the NDE region, the biases of precipitation in the atmosphere-only models (13% in HadGAM, +3% in HiGAM, and 5% in NUGAM) are smaller than in the the coupled models. The best performance of atmosphere-only models in simulating the annual cycle of precipitation in the NDE is directly related to incorrect positioning of the ITCZ over northern SA in HadGEM and HiGEM (see Figures 3c-d). The increase of the horizontal resolution in the coupled models lessens the overestimation of rainfall in NDE while correctly positioning the ITCZ (see Fig. 3e).

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

In the analysis (ensemble), the rainy and dry seasons occur from June to August and from October to April, respectively, in the SESA region (Fig. 10e). This pattern is correctly simulated by coupled and atmosphere-only models, although they overestimate the rainfall rate throughout most of the year. In this region only the coupled model with lowest resolution (HadGEM) remains drier than the observation ensemble from January to April. For annual rainfall, the relative biases in SESA range from +20% in HiGEM and HiGAM to values close to zero in HadGEM and HiGAM, in other words, values always less than 0.85 mm day^{-1}. In this region increasing the resolution increases the rainfall rate and the relative bias. However, in all simulations the biases are much lower than previously reported for other global models (Seth et al. 2010; Blazquez and Nuñez 2012) and regional models (da Rocha et al. 2014) in a similar area. Compared to Custodio et al. (2012), the version assessed here (1.1) does not change the representation of the annual cycle of precipitation in the SESA. In addition, these results represent an improvement compared to the nine coupled models of the CMIP3 project (Seth et al. 2010) and some of the CMPI5 models, which that underestimate the spring rainfall by 50% (da Rocha et al. 2014).

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

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

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

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

In regions SESA, AND, and PAT the annual cycle of temperature in the ensemble indicates the cold season from June to September and the warm season from December to March (Fig. 11e, g, i). The coupled and atmosphere-only models are in phase with the observations in these three regions. The amplitude in the simulations is similar to that of the ensemble in DNA and PAT, but in SESA it is larger in all simulations, reflected in higher RMS and standard deviations (Figs. 11f, h, j). All simulations correctly represent the length of the seasons in these regions, with the largest systematic errors occurring in the cold period. The correct simulation of phase involves high correlation values for the annual cycle (above 0.95) and standard deviation close to that of the ensemble (Fig. 11). The similarity of the RMS in these regions in all simulations illustrates the correctness of the phase adjustment presented by the models in these regions. In the coupled simulations, increasing the resolution reduces the mean annual temperature bias to very small values (lower than ± 0.3°C), but this positive impact of horizontal resolution does not occur in the atmosphere-only simulations.

Increased horizontal resolution in the HadGEM family of models does not particularly impact the representation of the annual cycle of temperature in the SA subdomains analyzed. This indicates that for the reduction of systematic temperature errors in this family of models, just a refinement of the grid is not sufficient, indicating that other physical parameterizations still require adjustments in their configuration. But it is noteworthy that the errors for the average annual temperature are small, always less than ±1.5°C in all evaluated regions.

4. Conclusions

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

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

In general, the coupled simulation with highest atmospheric resolution (60 km) has systematic errors smaller than the atmospheric simulation for the seasonal precipitation, temperature and circulation fields. In this case, the increase in resolution associated with the ocean-atmosphere coupling, which includes daily variability of SST, provides more realistic simulations of atmospheric patterns observed in South America and the tropical sector of adjacent oceans.

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

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

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

5. Acknowledgements

This research was supported by a collaboration between the University of Reading and the Met Office. The models described were developed from the Met Office Hadley Centre HadGEM1 model by the U.K. High-Resolution Modelling (HiGEM) Project and the U.K.– Japan Climate Collaboration (UJCC). HiGEM was supported by a NERC High Resolution Climate Modelling Grant (R8/H12/123). UJCC was supported by the Foreign and Commonwealth Office Global Opportunities Fund, and this work was jointly funded by NERC and the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). Model integrations were performed using the Japanese Earth Simulator supercomputer, supported by JAMSTEC. The authors thank the British Atmospheric Data Centre [BADC] for providing the GCM simulations. Thanks are also due to NCEP, CMAP, GPCP, CPC, ERAIN and TRMM for providing data sets available in the public domain. This research was partially funded by FAPESP (13/50521-7) linked to the GoAmazon Project. This work was supported by CNPq and CAPES-PROEX, as well.

6. References

Ambrizzi T, Hoskins BJ, Hsu HH (1995) Rossby wave propagation and teleconnection patterns in the austral winter. J. Atmos. Sci., v.52, p. 3661-3672

Biasutti M, Sobel AH, Kushnir Y (2006) AGCM Precipitation Biases in the Tropical Atlantic. J. Climate, v.19, 935–958

Blázquez J, Nuñez MN (2012) Performance of a high resolution global model over southern South America. Journal of Climate, v.33, n.4, p.904-919

Bombardi RJ, Carvalho LMV (2009) IPCC global coupled model simulations of the South America monsoon system. Climate Dynamics 33, 893-916. Online publication date: 1-Dec-2009

Brankovic C, Molteni F (1997) Sensitivity of the ECMWF model northern winter climate to model formulation. Climate Dynamics, 13, 75-101, DOI: 10.1007/s003820050154

Carvalho LMV, Jones C, Liebmann B (2002) Extreme precipitation events in southeastern South America and large-scale convective patterns in the South Atlantic convergence zone. Journal of Climate, v. 15, p. 2377-2394

Carvalho LMV, Jones C, Liebmann B (2004) The South Atlantic Convergence Zone: persistence, intensity, form, extreme precipitation and relationships with intraseasonal activity. Journal of. Climate, v. 17, p. 88-108

Cavalcanti IFA, Marengo JA, Satyamurty P, Nobre CA et al (2002) Global Climatological Features in a Simulation Using the CPTEC–COLA AGCM. J. Climate, v.15, 2965–2988

Cavalcanti IFA, Ferreira NJ, Silva MGAJ da, Dias MAF da S (2009) Tempo e Clima no Brasil. [S.l.]: Oficina de Textos

Chen M, Shi W, Xie P, Silva VBS, Kousky VE, Higgins RW, Janowiak JE (2008) Assessing objective techniques for gauge-based analyses of global daily precipitation. Journal of Geophysical Research, 113, D04110, doi:10.1029/2007JD009132

Collins JM, Chaves RR, Marques VS (2009) Temperature variability over South America. J. Climate, 22, 5854–5869. doi: http://dx.doi.org/10.1175/2009JCLI2551.1

Cox P, Betts R, Bunton C, Essery R, Rowntree PR and Smith J (1999) The impact of new land-surface physics on the GCM simulation and climate sensitivity. Climate Dynamics, 15: 183-203

Custodio MS, da Rocha RP, Vidale PL (2012) Analysis of precipitation climatology simulated by high resolution coupled global models over the South America. Hydrological Research Letters 6, 92–97, doi: 10.3178/HRL.6.92

da Rocha RP, Reboita MS, Dutra LMM, Llopart MP, Coppola E (2014) Interannual variability associated with ENSO: present and future climate projections of RegCM4 for South America-CORDEX domain. Climatic Change, v. 125, p.95-109

Dee DP, Uppalaa SM, Simmonsa AJ, Berrisforda P et al. (2011) The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quart. J. R. Meteorol. Soc., 137, 553-597. DOI: 10.1002/qj.828

Diedhiou AS, Machado LAT, Laurent H (2010) Mean Kinematic Characteristics of Synoptic Easterly Disturbances over the Atlantic. Advances in Atmospheric Sciences, v. 27, n. 3, p. 1-17

Gan MA, Kousky VE (1986) Vórtices ciclônicos da alta troposfera no oceano Atlântico Sul. Revista Brasileira de Meteorologia, 1, 19-28

Gan MA, Rao BV (1991) Surface ciclogenesis over South America. Monthly Weather Review, 119, 293-302, doi: 10.1175/1520-0493(1991)119<1293:SCOSA>2.0.CO;2

Gandu AD, Silva Dias PL (1998) Impact of tropical heat sources oh the South America tropospheric upper circulation and subsidence. Journal of Geophysical Research, 103, 6001-6015, doi:10.1029/97JD03114

Gandu AW, Geisler JE (1991) A Primitive Equations Model Study of the Effect of Topography on the Summer Circulation Over Tropical South America. J. Atmos. Sci., 48, 1822-1835

Gates WL, James SB, Curt C, Clyde GD et al. (1999) An overview of the results of the Atmospheric Model Intercomparison Project (AMIP I). Bull. Amer. Meteor. Soc., 80, 29–55

Gomes HB, Ambrizzi T, Herdies DL, Hodges K, da Silva BFP (2015) “Easterly Wave Disturbances over Northeast Brazil: An Observational Analysis,” Advances in Meteorology, vol. 2015, Article ID 176238, 20 pages. doi:10.1155/2015/176238

Grimm AM, Silva Dias PL (1995) Analysis of tropical-extratropical interactions with influence functions of a barotropic model. Journal of Atmospheric Sciences, v.52, p. 3538-3555

Gutman GJ, Schwerdtfeger W (1965) The role of latent and sensible heat for the development of a high pressure system over the subtropical Andes, in Summer. Jg. Heft, V.18, n.3

Hegerl GC, Black E, Richard PA, Ingram WJ et al. (2015) Challenges in quantifying changes in the global water cycle. Bulletin of the American Meteorological Society, in press, doi:10.1175/BAMS-D-13-00212.1

Hurrel JW, Hack JJ, Boville BA, Willianson DL, Kiehl JT (1998) The dynamical simulation of the NCAR Community Climate Model Version 3 (CCM3). J. Climate, 11, 1207–1236

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324

Johns TC, Durman CF, Banks HT, Roberts MJ et al. (2006) The new Hadley Centre climate model (HadGEM1): evaluation of coupled simulations. J Climate, 19: pp. 1327-1353

Jung T, Gulev SK, Rudeva I, Soloviov V (2006) Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model. In: Quarterly Journal of the Royal Meteorological Society, v.132, n.619, p.1839-1857

Kayano MT (2003) Low-Level High-Frequency Models in the Tropical Atlantic and Their Relation to Precipitation in the Equatorial South America. Meteorological Atmospheric Physics, v. 83, p. 263-276

Kalnay E, Kanamitsu M, Kistler R, Collins W et al (1996) The NCEP/NCAR reanalysis project. Bull Am Meteorological Soc, 77(3):437-471

Kodama Y-M (1992) Large-scale common features of sub-tropical precipitation zones (the Baiu Frontal Zone, the SPCZ, and the SACZ). Part I: characteristics of subtropical frontal zones. J. Meteor. Soc. Japan, 70, 813-835

Kousky EV (1980) Diurnal Rainfall Variation in Northeast Brazil. Mon. Weather Rev., 108, 488-498

Lenters JD, Cook KH (1997) On the origin of the Bolivian high and related circulation features of the South American climate. J.Amos.Sci.; V.54, p.656-677

Li J-L F, Martin K, Farrara JD, Mechoso CR (2002) The impact of stratocumulus cloud radiative properties on surface heat fluxes simulated with a general circulation model, Mon. Weather Rev., 130, 1433–1441

Ma H-Y, Mechoso CR, Xue Y, Xiao H, Wu C-M, Li J-L, De Sales F (2011) Impact of land surface processes on the South American warm season climate. Climate Dynamics, 37, 187-203. DOI 10.1007/s00382-010-0813-3

Ma CC, Mechoso CR, Robertson AW (1996) Arakawa, A. Peruvian stratus clouds and the tropical Pacific circulation: A coupled ocean–atmosphere GCM study. J. Climate, 9, 1635–1645

Machado LAT, Rossow WB (1993) Structural radiative and characteristics of tropical cloud clusters. Monthly Weather Review, 121(12): 3234-3260

Mclaren AJ, Banks HT, Durman CF, Gregory JM et al (2006) Evaluation of the sea ice simulation in a new coupled atmosphere-ocean climate model (HadGEM1). J. Geophysical Research, 111, C12014, doi:10.1029/2005JC003033

Marengo JA, Cavalcanti IFA, Satyamurty P, Trosnikov I et al (2003) Assessment of regional seasonal rainfall predictability using the CPTEC/COLA atmospheric GCM. Climate Dynamics, v21, 459-475, doi 10.1007/s00382-003-0346-0

Martin GM, Ringer MA, Pope VD, Jones A, Dearden C, Hinton TJ (2006) The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part I: Model description and global climatology. J. Climate, 19, 1274–1301

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids, International Journal of Climatology, 25, 693–712, doi:10.1002/joc.1181

Mizielinski MS, Roberts MJ, Vidale PL, Schiemann R et al. (2014) High resolution global climate modelling; the UPSCALE project, a large simulation campaign. Geoscientific Model Development Discussions, 7 (1). pp. 563-591. ISSN 1991-962X doi: 10.5194/gmdd-7-563-2014

Moura AD, Hastenrath S (2004) Climate prediction for Brazils Nordeste: Performance of empirical and numerical modeling methods. Journal of Climate, v.17, n.13, p.2667-2672

Nobre P, Moura AD, Sun L (2001) Dynamical downscaling of seasonal climate prediction over Nordeste Brazil with WCHM3 and NCEP's regional spectral models at IRI. Bull. American Meteorology Society, n.82, p.2787-2796

Nobre P, Siqueira L, Almeida R, Malagutti M et al (2013) Climate simulation and change in the Brazilian Climate Model. J. Climate 26:6716–6732

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parametrizations in the Hadley Centre climate model - HadAM3. Climate Dynamics, vol 16, 123-146, doi:10.1007/s003820050009

Pope VD, Stratton RA (2002) The processes governing horizontal resolution sensitivity in a climate model. Climate Dynamics, v.19, n.3-4, p.211-236

Quartly GD, Kyte EA, Srokosz MA, Tsimplis MN (2007) An intercomparison of global oceanic precipitation climatologies. J. Geophys. Reser., 112, D10121

Reboita MS, da Rocha RP, Ambrizzi T, Caetano E (2010b) An Assessment of the latent and sensible heat flux on the simulated regional climate over Southwestern South Atlantic Ocean. Climate Dynamics, v. 34, p. 873-889, doi: 10.1007/s00382-009-0681-x

Ringer MA, Martin GM, Greeves CZ, Hinton TJ et al. (2006) The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part II: aspects of variability and regional climate. J Clim 19: pp. 1302-1326

Roberts MJ, Clayton A, Demory M.-E, Donners J et al (2009) Impact of Resolution on the Tropical Pacific Circulation in a Matrix of Coupled Models. Journal of Climate, 22 (10). pp. 2541-2556. ISSN 1520-0442 doi: 10.1175/2008JCLI2537.1

Sakamoto MS, Ambrizzi T, Poveda G (2011) Moisture Sources and Life Cycle of Convective Systems over Western Colombia. Advances in Meteorology, v. 2011, p. 11

Satyamurty P, Mattos LF, Nobre CA, Silva Dias PL (1998) Tropics - South America. In: Meteorology of the Southern Hemisphere, Ed. Kauly DJ and Vincent DG, Meteorological Monograph. American Meteorological Society, Boston, 119-139

Seo H, Jochum M, Murtugudde R, Miller AJ, Roads JO (2008) Precipitation from african easterly waves in a coupled model of the tropical atlantic. J. Climate, 21, 1417–1431. doi: http://dx.doi.org/10.1175/2007JCLI1906.1

Seth A, Rojas M, Rauscher SA (2010) CMIP3 projected changes in the annual cycle of the South American Monsoon. Climatic Change, 98:3-4, 331

Seth A, Rauscher SA, Camargo SJ, Qian J-H, Pal JS (2007) RegCM3 regional climatologies for South America using reanalysis and ECHAM global model driving fields, Clim. Dyn., 28, 461 – 480, doi:10.1007/s00382-006-0191-z

Seth A, Rojas M (2003) Simulation and sensitivity in a nested modeling system for South America. Part I: Reanalyses boundary forcing. J Clim 16:2437–2453

Shaffrey L, Stevens I, Norton W, Roberts MJ et al (2009) UK-HiGEM: The New UK High Resolution Global Environment Model. Model description and basic evaluation. Journal of Climate, v.22, 1861–1896, 2009, doi: 10.1175/2008JCLI2508.1

Silva GAM, Dutra LMM, Rocha RP, Ambrizzi T, Leiva E (2014) Preliminary Analysis on the Global Features of the NCEP CFSv2 Seasonal Hindcasts, Advances in Meteorology, vol. 2014, Article ID 695067, 21 pages. doi:10.1155/2014/695067

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Climate Change 2007: The Physical Science Basis. Cambridge University Press, 996 pp

Stern W, Miyakoda K (1995) Feasibility of seasonal forecasts inferred from multiple GCM simulations. J. Climate, 8, 1071– 1085

Strachan J, Vidale PL, Hodges K, Roberts M, Demory M-E (2013) Investigating global tropical cyclone activity with a hierarchy of AGCMs: the role of model resolution. Journal of Climate, 26 (1). pp. 133-152. ISSN 1520-0442 doi: 10.1175/JCLI-D-12-00012.1

Torres RR, Ferreira NJ (2011) Case Studies of Easterly Wave Disturbances over Northeast Brazil Using the Eta Model. Weather and Forecasting, v. 26, p. 255-235

Uvo CRB, Nobre CA (1989a) A Zona de Convergência Intertropical (ZCIT) e a precipitação no norte do Nordeste do Brasil. Parte I: A Posição da ZCIT no Atlântico Equatorial. Climanalise, Vol. 4, número 07, 34 – 40

Vera C, Silvestri G, Liebmann B, González P (2006b) Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. In: Geophysical research letters, v.33, L13707

Waliser DE, Gautier CA (1993) A satellite-derived climatology of the ITCZ. Journal of climate, v.6, p-2162-2174

Xie P, Arkin P (1996) Analysis of global monthly precipitation using gauge observation, satellite estimates and numerical model predictions. J Clim 9:840–858

Yu JY, Mechoso CR (1999) Links between annual variations of Peruvian stratocumulus clouds and of SST in the eastern equatorial Pacific. J. Climate, v.12, 3305-3318