Revista de Climatología
Vol. 16 (2016): 77-98 ISSN 1578-8768
©Copyright of the authors of the article. Reproduction and diffusion is allowed by any means, provided it is done without economical benefit and respecting its integrity

Performance of RegCM-4.3 over the Caribbean region using different configurations of the Tiedtke convective parameterization scheme

Daniel Martínez-Castro[1], Alejandro Vichot-Llano[1], Arnoldo Bezanilla-Morlot[1], Abel Centella-Artola[1], Jayaka Campbell[2] and Cecilia Viloria-Holguin[3].

[1] *Instituto de Meteorologia de la Republica de Cuba, Habana, Cuba. <alejandro.vichot@insmet.cu> <daniel.martinez@insmet.cu> <abel.centella@insmet.cu> <arnoldo.bezanilla@insmet.cu>*

[2] *Department of Physics, University of the West Indies, Mona, Kingston, Jamaica. <jayaka.campbell@outlook.com>*

[3] *Oficina Nacional de Meteorología. Sto. Domingo, R. Dominicana. <ceciliavh22@hotmail.com>*

(Received: 19-May-2016. Published: 25-Oct-2016)

Abstract

A sensitivity study about the performance of the RegCM-4.3 regional climate model, driven by ERA Interim reanalysis was conducted for a domain including the Caribbean, with horizontal resolution of 50 km from year 2000 to 2001. Sixteen configurations of the model, including variations in the parameters of the Tiedtke convective scheme were tested. The performance of the model using these configurations was compared with data and with simulations using Emanuel (EM) and Grell over land-Emanuel over sea (GE) convective parameterization schemes. Global datasets of temperature and precipitation and quality controlled data form the weather station networks of Cuba, Jamaica and the Dominican Republic were used as reference. After an analysis of the simulated precipitation fields, some of the configurations were discarded and four of them were chosen to evaluate the representation by the model of the main climatological features of the region. The chosen configurations simulate the general wind and precipitation patterns reasonably well, and at the same time, the seasonal diurnal cycles and the Caribbean low level jet, but they showed different skill in reproducing the particular features of the regional climate. For the rainy season GE shows the best performance, while EM and the default Tiedtke scheme (TI) widely overestimate precipitation in the Pacific coast of Central America, whereas for the dry season, the Tiedtke scheme underestimates precipitation, but after tuning parameters biases were reduced. TI scheme showed the best representation of the precipitation seasonal cycle, while the diurnal circle was best reproduced by the GE scheme. Temperature fields were best simulated by Tiedtke configurations, as the area with negative bias was reduced.

Key words: Regional Climate Model, convective scheme, parameterization, sensitivity study, RegCM-4.3

Resumen

Se realizó un estudio de sensibilidad sobre el rendimiento del modelo climático regional RegCM-4.3, alimentado por los reanálisis ERA Interim para un dominio que incluye el Caribe, con una resolución horizontal de 50 km, para el período del año 2000 a 2001. Se probaron dieciséis configuraciones del modelo, incluyendo variaciones del esquema de convección Tiedtke y los esquemas de Emanuel (EM) y la combinación de Grell sobre tierra-Emanuel sobre el mar (GE). Como referencia se emplearon bases de datos globales de temperatura y precipitación y los datos de las redes nacionales de estaciones meteorológicas de Cuba, Jamaica y la República Dominicana. Después de un análisis de los campos de precipitación simulados, algunas de las configuraciones se descartaron y cuatro de ellas se escogieron para evaluar la reproducción de las principales características climatológicas de la región. Las configuraciones elegidas simulan los patrones generales de viento y precipitación razonablemente bien, y al mismo tiempo, reproducen los ciclos diurnos y estacionales y el chorro de bajo nivel del Caribe, pero mostraron habilidades diferentes en la reproducción de las características particulares del clima regional. Para la temporada de lluvias GE muestra el mejor rendimiento, mientras que EM y el esquema Tiedtke predeterminado (TI) sobreestiman las precipitaciones en la costa del Pacífico de América Central, mientras que para la estación *seca, el esquema predeterminado de Tiedtke subestima la precipitación, pero al ajustar algunos parámetros se redujeron los sesgos. El esquema de Tiedtke mostró la mejor reproducción del ciclo estacional de precipitación, mientras que GE reproduce mejor el ciclo diurno. La mejor simulación del campo de temperatura se logró con las configuraciones del esquema de Tiedtke, que reducen el área con sesgo negativo.*

Palabras clave: *Modelo Climático Regional, esquema convectivo, parametrización, estudio de sensibilidad, RegCM-4.3*

1. Introduction

The Caribbean region is one on the most difficult to represent by climate models because of the complex geography, formed by thousands of islands of very different forms, sizes and orographic characteristics. The meteorological situation is also very complex; because the islands are the center of the interaction of different regional climatic systems, as subtropical anticyclones, associated with frequent wave situations in the easterly winds, and disturbances, including tropical cyclones. Continental anticyclones, cold fronts and northerly winds in the winter, also influence the region. The islands are surrounded by the warm waters of the Caribbean Sea, the Gulf of Mexico and the Atlantic Ocean, which exert a particular influence in the regional climate (Amador, 2008). In this complex terrain situation, mesoscale forcing also becomes an important factor, and particularly sea-breeze circulation (Riehl, 1979), so that the use of high resolution regional climate models, nested in reanalysis datasets or global model output becomes very important to reproduce climate features and to develop future climate projections with the needed degree of detail for local applications (Giorgi and Mearns, 1991; Aldrian *et al.*, 2004; Giorgi *et al.*, 2009).

In the last decade, some regional climate model researchers have focused their work in the Central America and Caribbean region. Martínez-Castro *et al.* (2006) presented a sensitivity study of the influence of different convective parameterization schemes in the performance of the regional climate model RegCM-3 (Pal *et al.*, 2007) for temperature and precipitation simulations. The tested schemes in that case were Grell's (Grell, 1993) using the closure conditions developed by Arakawa and Shubert (1974) and Fritsch and Chappel (1980) closure conditions and the Kuo scheme (Anthes, 1987). This paper concluded that the best performing configuration for the region was the one using the Grell scheme, with Arakawa-Schubert closure. However, this study was made for a period of only three months, corresponding to part of the rainy season. Campbell *et al.* (2011) reproduced present-time climate and analyzed climate change projections for the Caribbean region at 50 km resolution by downscaling output from the Hadley Centre global model HadAM3P, using HadRM3P (Jones *et al.*, 2004), which is the regional climate model within the 'Providing Regional Climates for Impacts Studies System (PRECIS)' for the period 2071-2100 under the A2 and B2 Special Report on Emissions scenarios (IPCC, 2007). Using the same modeling system output, Karmalkar *et al.* (2011) found a dry bias in the wet season and a wet bias in the dry season, concluding that projected warming under the A2 scenario is higher in the wet season than that in the dry season, while a large reduction in precipitation in the wet season is projected for the region.

Diro *et al.* (2012) conducted multi-annual simulations over the Central America CORDEX domain, using RegCM-4, driven by ERA-Interim reanalysis fields. The applied convective parameterizations were the Grell scheme over land areas and the Massachusetts Institute of Technology (MIT) (Emanuel, 1991) scheme over ocean, while two land surface schemes and different methods of assimilating sea surface temperature (SST) data were tested, in order to assess their performance in reproducing summer precipitation fields and other regional climatic features. The paper was focused in the analysis of the performance of the model for Mexico and Central America. It was found that RegCM-4, with the Grell-Emanuel convective scheme, the Biosphere-Atmosphere Transfer Scheme (BATS) surface scheme and direct assimilation of SST provides a good representation of the basic features of the monsoon climate of Central America, although with some systematic biases, particularly at sub-diurnal scales. Centella-Artola *et al.* (2015) investigated the sensitivity of the PRECIS regional climate model to domain size for the Caribbean region. Simulated regional rainfall patterns from experiments using three domains with horizontal resolution of 50 km were compared with ERA reanalysis and observed datasets. The authors did not find significant sensitivity of the general results of the simulations with domain size, even if the difference in size was important. Particularly, although one of the domains included the whole Tropical North Atlantic, it didn't improve the results of the simulations in relation with a much smaller domain including only the Caribbean islands and the surrounding Inter-American Seas. Vichot-Llano *et al.* (2014) studied the sensitivity of RegCM-4.3 performance for the Greater Antilles and particularly for Cuba on domain size and resolution (25 and 50 km) for three of the convective parameterizations available in the model (Grell over land-Emanuel over sea; Emanuel and Tiedtke), using the default parameters for each of them. It was found that the smaller domain with the higher resolution showed the best performance, regarding precipitation and temperature, particularly using the Grell-Emanuel or the Tiedtke convective schemes. The relatively good results shown by the Tiedtke scheme in these preliminary tests and the potential possibility to tune it by modifying its entrainment parameters, previously applied by Wang *et al.* (2007) suggest the convenience to test different configurations of this scheme to improve the performance of the RegCM model for the Caribbean region.

The objective of the present paper is to test the performance of the Tiedtke convective parameterization scheme in the regional climate model RegCM-4.3, particularly for the region of the Caribbean, with focus in the Greater Antilles, by evaluating its sensitivity to the convective parameterization scheme for a period of two years, including the seasonal variations of the tested variables. The performance of the model using the Emanuel parameterization scheme and a combination of the Emanuel scheme over sea and the Grell's scheme over land was also tested for comparison with the Tiedtke configurations. As reference, several global datasets were used in addition to the national meteorological networks of Cuba, Jamaica and the Dominican Republic. Section 2 provides a description of the model, data and numerical experiments used to investigate the RegCM-4.3 performance and a brief description of the meteorological situation in the period of the simulations. Section 3 presents the simulation results for different convective schemes and domain. Finally, Section 4 includes the summary and conclusions.

2. Model description, data and numerical experiments

2.1. Model description

The RegCM-4.3 model (Giorgi *et al.*, 2012), used in this work, is an improved version of the International Centre for Theoretical Physics (ICTP) regional climate model RegCM-4, which is based in previous versions of the model (Pal *et al.*, 2007; Giorgi and Shields, 1999; Giorgi *et al.*, 1993a,b). It is a limited area model, with finite-difference discretization and a terrain-following sigma coordinate in the vertical. It has a hydrostatic dynamic core (Grell *et al.*, 1994) on an Arakawa B horizontal grid (Arakawa and Lamb, 1977), and terrain following sigma coordinates. The model uses the radiation scheme of the NCAR CCM3 (Community Climate Model 3; Kiehl *et al.*, 1996), which calculates separately the heating and flux of solar and infrared radiation at the surface under conditions of clear and cloudy sky. The solar-component follows the Eddington approximation in which cloud radiation depends on cloud fractional cover, liquid water content and effective droplet radius. Scattering and absorption of solar radiation by atmospheric aerosols and cloud ice are also included. The radiative transfer package includes 18 spectral intervals from 0.2 to 5μm and the effects of H_2O, O_3, O_2, CO_2, H_2, CO_2, NO_2, CH_4 and CFCs.

The soil-vegetation-atmosphere interaction processes are parameterized using the BATS scheme, which is described in detail by Dickinson *et al.* (1993). BATS includes the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy and water vapor. In the present version, 20 vegetation types are available. Each grid point of the model is represented by its dominant soil class and vegetation type, including the ocean surface as one of the soil classes. In BATS, the near surface turbulent flux of moisture, heat and moment are calculated using a standard surface drag coefficient formulation based on surface-layer similarity theory. The drag coefficient depends on the atmospheric stability in the surface layer, as measured by the Richardson number, and on the surface roughness length. For BATS the roughness length over the sea is constant and equal to 0.0004 m.

The model includes also an explicit moisture-cloud scheme (Hsie *et al.*, 1984) with a prognostic equation for cloud water, including formation, advection and mixing, evaporation and auto-conversion to rain, which is interrelated with the radiation scheme. Ice water content fraction is diagnosed as a function of temperature.

2.1.1. Convective Schemes

Convective processes are extremely important for the development of deep clouds and precipitation, particularly in the tropics, but due to their sub-scale character, they must be parameterized. RegCM-4.3 includes the possibilities of several parameterization schemes. In the Grell (1993) scheme deep convective clouds are represented by an updraft and a downdraft that are undiluted and that mix with environmental air only in the base and top of the cloud. The heating and moistening profiles are derived from the latent heat release or absorption, linked with the updraft-downdraft fluxes and compensating motion. The Grell scheme convective closure assumption can be of two types. In the Arakawa-Schubert (1974) closure, a quasi-equilibrium condition is assumed between the generation of instability by grid-scale processes and the dissipation of instability by sub-grid (convective) processes. In the Fritsch-Chappell closure (Fritsch and Chappell, 1980), the available buoyant energy is dissipated during a specified convective time period. The Emanuel scheme (Emanuel, 1991) assumes inhomogeneous mixing in clouds and considers convective fluxes based on an idealized model of sub-cloud-scale updrafts and downdrafts. Convection occurs when the level of neutral buoyancy is higher than the cloud base level. Air is lifted and a fraction of the condensed moisture forms precipitation while the remaining fraction forms the cloud. The cloud is assumed to mix with the air from the environment according to a uniform spectrum of mixtures that ascend or descend to their respective levels of neutral buoyancy. The mixing entrainment and detrainment rates are functions of the vertical gradients of buoyancy in clouds.

The Tiedtke (1989) convective scheme was experimentally introduced in RegCM-4.3 (Elguindi *et al.*, 2011). This is a bulk mass flux parameterization that was initially applied in the ECMWF global model, and has subsequently been applied to other global models, as ECHAM5, REMO and WRF. This scheme considers a population of clouds, where the cloud ensemble is represented by a one-dimensional model (Tiedtke, 1989) and both updraft and downdraft are included. Updraft interacts with the environment through convective entrainment and detrainment. Deep penetrative convection and midlevel convection are produced by large scale moist convergent flow and shallow convection is maintained by the supply of moisture due to the surface evaporation. The three types of convection are controlled by independent parameters in the model, defined as entrainment rates (“entrpen”, for penetrative convection, “entremid” for midlevel convection and “entrscv”, for shallow convection).

Only one type of convection occurs in a grid box during each time step. Downdrafts occur at the level of free sinking, where in-cloud air mixes with environmental air and becomes unstable in relation to the surrounding environment. The cloud base mass flux for deep convection is obtained by assuming that the convective available potential energy (CAPE) is totally spent by the process of convection in a time controlled by a convective turnover timescale parameter, defined as a closure condition. As this parameter depends on the resolution of the model (Nordeng, 1994; Gregory *et al.*, 2000), a non-dimensional coefficient “cmtcape” is defined in RegCM-4.3 code so that $\tau = cmtcape \cdot ds$, where ds is the resolution in km.

Several parameters account for the relative influence of different physical processes. Table 1 shows a brief definition of some of them.

Table 1: Definitions of some non-dimensional parameters of the Tiedtke convective scheme (The symbolic and descriptive names follow RegCM-4 handbook)

Symbolic name	Descriptive name	Default value
entrPen	Entrainment rate for penetrative convection	10^{-4} m^{-1}
entrMid	Entrainment rate for midlevel convection	10^{-4} m^{-1}
entrScv	Entrainment rate for shallow convection	$3 \cdot 10^{-4}$ m^{-1}
Cmtcape	CAPE adjustment time scale parameter	40
cprcon (Autoconversion)	Autoconversion parameter.	10^{-4}
cTrigger	Trigger parameter for deep convection	-1.1

2.2. The data sets

The initial and boundary conditions for RegCM-4.3 were provided by the ECMWF ERA Interim reanalysis (Simmons *et al.*, 2007). The reanalysis data set has a horizontal resolution of 1.5°x1.5° latitude by longitude, with a temporal resolution of 6 hours (00:00, 06:00, 12:00, 18:00 UTC), and 37 pressure levels, from 1000 to 1 hPa. The variables used were geopotential height, air temperature, relative humidity, horizontal wind components and mean sea level pressure. This data will be briefly referred as ERA in the rest of the paper. This dataset was also used as a reference for the temperature diurnal cycle (http://apps.ecmwf.int/).

SST was obtained by interpolation of the monthly average values of the Reynolds and Smith (1994) data set. The topography and landuse data, derived from United States Geological Survey (USGS) and Global Land Cover Characterization (GLCC, Loveland *et al.*, 2000), respectively, with horizontal resolution of 10-min, were used to provide the terrain characteristics.

The monthly climatology of air temperature over the continents, except Antarctica, of the Climate Research Unit (CRU) of the University of East Anglia, version 3.10 (Mitchell and Jones, 2005; Harris *et al.*, 2014), was utilized to verify the RegCM-4.3 results. This data set has horizontal resolution of 0.5°x0.5°.

The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42 product (described by Huffman *et al.*, 2007), is available from January 1998 to the present, and was considered the most appropriate dataset for use in this study for the diurnal cycle because it is available for the tropical region at 3-hourly temporal and 0.258°x0.258° spatial resolution. The 3B43 TRMM precipitation monthly mean data set was also used as reference for comparison with monthly precipitation estimates from the model. However, other datasets have been used to corroborate the similarity of the general precipitation patterns for the region with those of TRMM.

The CPC Merged Analysis of Precipitation (CMAP), which is developed by the Climate Diagnostic Center (Xie and Arkin, 1997), was also used for special verification purposes. The CMAP analysis provides precipitation estimates over land and oceans. It should be noted that the CMAP horizontal resolution of 2.5°x2.5° longitude by latitude is too coarse to represent some of the fine scale details predicted by the model, so that the CMAP data presented are only used to evaluate the larger-scale precipitation patterns. CMAP Precipitation data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. The GPCP (Global Precipitation Climate Project; Adler *et al.*, 2003), which is a precipitation dataset containing monthly averages, based in rain-gauge and satellite data with resolution of 2.5°, has been used as a reference for the predicted annual cycle of precipitation.

Considering the relatively low density of stations of the Caribbean islands included in the CRU dataset, precipitation monthly mean data for 67 meteorological stations of Cuba, 40 of the Dominican Republic and 239 Jamaican rain-gauges were also used for evaluation, and are separately compared with the results of the model for the islands.

2.3. Numerical Experiments

The simulated period was from January 2000 to December 2001, including the last three months of 1999 as spin- up period. Table 2 shows the 16 numerical experiments that were carried out to verify the performance of the different parameterization schemes, all of them with ERA initial and boundary conditions. Emanuel scheme was applied both to oceanic and land regions of the domain. For the GE experiment, the Grell (1993) convective scheme, with the Arakawa-Shubert (1974) closure, was applied for grid points over land and Emanuel for grid points over sea. EM and GE use their default parameters in the RegCM-4.3 model. The resolution was 50 km for all the experiments. In the TI experiment, the default parameters of the Tiedtke scheme implemented in RegCM-4.3 (shown in Table 1) were used. After some preliminary experiments with more than twenty configurations of the Tiedtke scheme, 16 variants were applied in the study, with different choices for the six selected parameters. The capital letters in the names of the parameters are used as one of the letters in the acronyms of each experiment, shown in Table 2, to indicate that the particular parameter has been changed. The acronyms are formed by the letters "TI", followed by the letters corresponding to the changed parameters, and are finished by the letters "D", if the parameters have been doubled or increased, or H, if they have been halved or decreased. The second column in Table 1 indicates schematically the transformation of the variables, indicating the coefficient by which the default value was multiplied. The other columns show the actual numerical values of the parameters for each experiment.

Figure 1 shows the limits and topography of the domain, covering the Inter American Seas and its surrounding territories, including the Eastern and Western Antilles, Central America, Mexico, the southeastern USA and the northern coast of South America at a horizontal grid spacing of 50 km (120 x 256 grid points). In the vertical axis, the model considers 18 levels, using surface-following sigma coordinate with higher resolution in the boundary layer. In this set of experiments, the surface fluxes over the ocean were calculated using the Zeng scheme (Zeng *et al.*, 1998). Lateral boundaries are updated every 6 hours. For soil variables (water content at three soil layers), the initial conditions are supplied by climatological values as function of the soil characteristics and at consecutive time steps. These variables are obtained by applying the BATS scheme over continental areas. The implicit type of averaging used in the analysis of the experimental results is averaging of model output for the entire domain or some special areas, monthly, or seasonally. Spatial averaging for specific regions is also used. For validation purposes, a special study area was defined, including the Greater Antilles (SA GAN in Fig. 1).

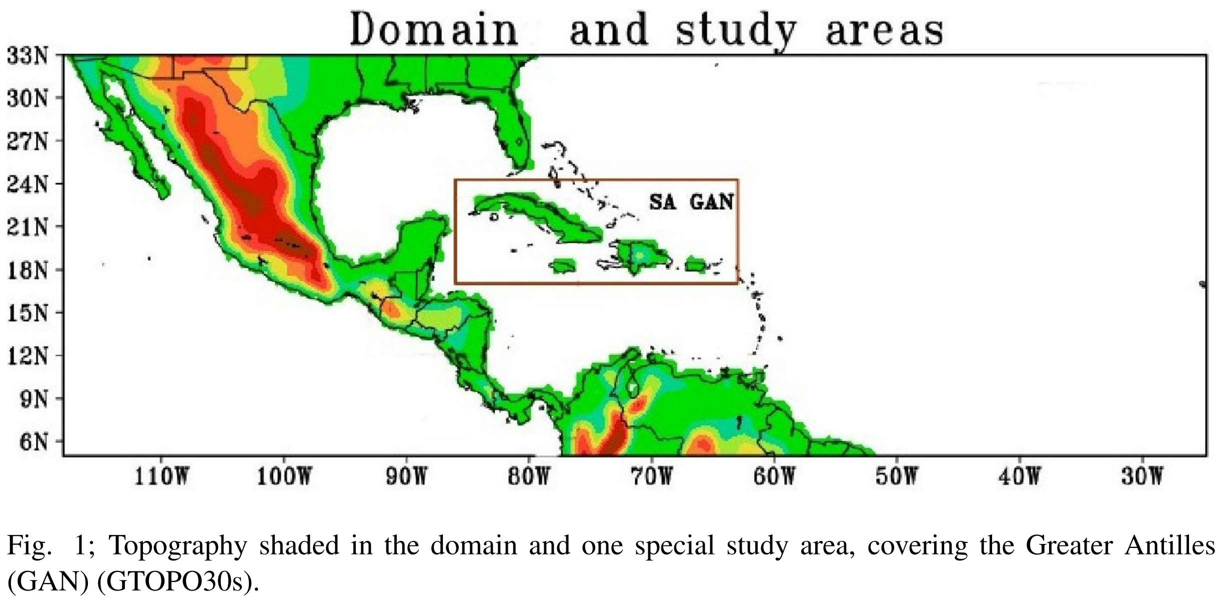

Fig. 1; Topography shaded in the domain and one special study area, covering the Greater Antilles (GAN) (GTOPO30s).

2.4. Meteorological characterization of the experimental period

Following the climatological criteria of Lecha and Paz (1994), two seasonal periods were studied, the so-called less-rainy (or dry) season (November-April), which is also the coolest period, and the rainy (or wet) season (May-October).

In the dry seasons of 2000-2001, 19 cold fronts passed through Cuba, which is slightly under-average, so that though the seasons can be considered as normal. Rainfall for these seasons was slightly above-average in Cuba. On the other hand, the rainy seasons for these two years were clearly different regarding rainfall, as 2000 was significantly under-average, while 2001 rainfall was above-average. There were also 35 tropical depressions, 30 tropical storms and 17 hurricanes, the strongest of which were Keith, Iris and Michelle, all of them category 4 in the Saffir-Simpson scale. Cuba was affected by Michelle in October, 2000.

Table 2: General design parameters of the sensitivity experiments. All the experiments used ERA Interim as boundary conditions.

Exp.	Changes in the default parameters	Entrpen (x10^{-4})	Cmtcape	Entrmid (x10^{-4})	Entrscv (x10^{-4})	Cprcon (x10^{-4})	Ctrigger
TI	—-	1	40	1	3	1	-1.1
TICMSD	[entrmid,cmtcape]*2, entrscv*6.6	1	80	2	20	1	-1.1
TICMSH	[entrmid,cmtcape]*0.5, entrscv*0.5	1	20	0.5	1.5	1	-1.1
TICPSD	[entrpen,cmtcape]*2, entrscv*6.6	2	80	1	20	1	-1.1
TICPSH	[entrpen,cmtcape]*0.5, entrscv*0.5	0.5	20	1	1.5	1	-1.1
TICD	2*cmtCape	1	80	1	3	1	-1.10
TICH	1/2*cmtCape	1	20	1	3	1	-1.10
TIPD	2*entrPen	2	40	1	3	1	-1.10
TIPH	1/2*entrPen	0.5	40	1	3	1	-1.10
TIMD	2*entrMid	1	40	2	3	1	-1.10
TIMH	1/2*entrMid	1	40	0.5	3	1	-1.10
TIAD	cprcon*2	1	40	1	3	2	-1.10
TIAH	cprcon*0.5	1	80	1	3	0.5	-1.10
TITD	trigger*2	1	80	1	3	1	-2.20
TIT0	trigger=0	1	80	1	3	1	0.00
TISD	entrscv*6.6	1	40	1	20	1	-1.10

3. Results and Discussion

3.1. Averaged estimations of precipitation and temperature

Fig. 2 shows the averaged patterns of precipitation and temperature in the domain, for the experimental period, as respectively estimated using TRMM monthly means and CRU data.

As a first step to discriminate the best performing configurations, the average precipitation patterns were obtained for all the numerical experiments for the dry and rainy seasons. For the dry season (Fig. 3) some of the configurations fail to produce precipitation in the Atlantic and Central America (TICD, TICH, TIPD, TIPH, TIMD and TIMH). These configurations also produced too little precipitation for the rainy season (Fig. 4), which was used as a criterion to preliminarily discard them. The temperature distributions (not shown) were also compared, but their difference between the configurations is much less than for the precipitation, and so, it was not used as an additional criterion.

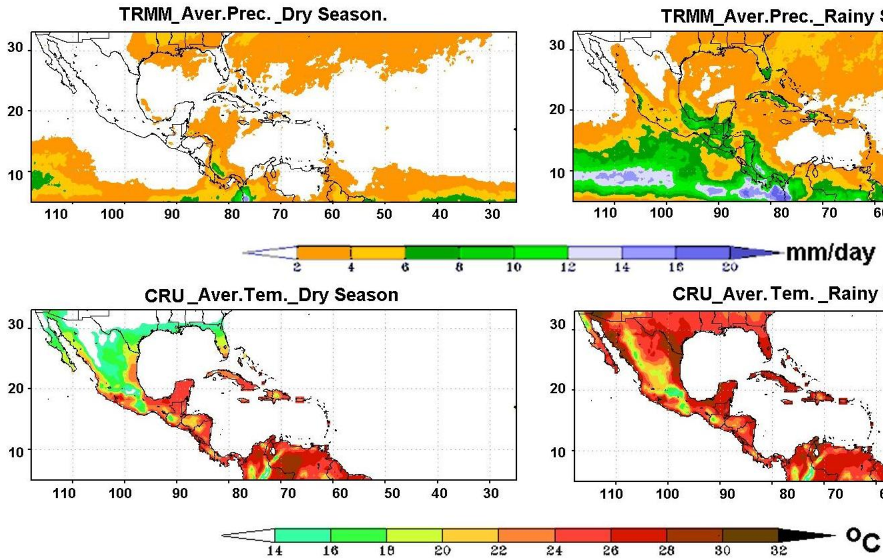

Fig. 2: Averaged monthly precipitation and monthly mean temperature for the dry and rainy seasons in the period 2000-2001, as estimated by TRMM and CRU data. The left column shows the dry season and the right column shows the wet season.

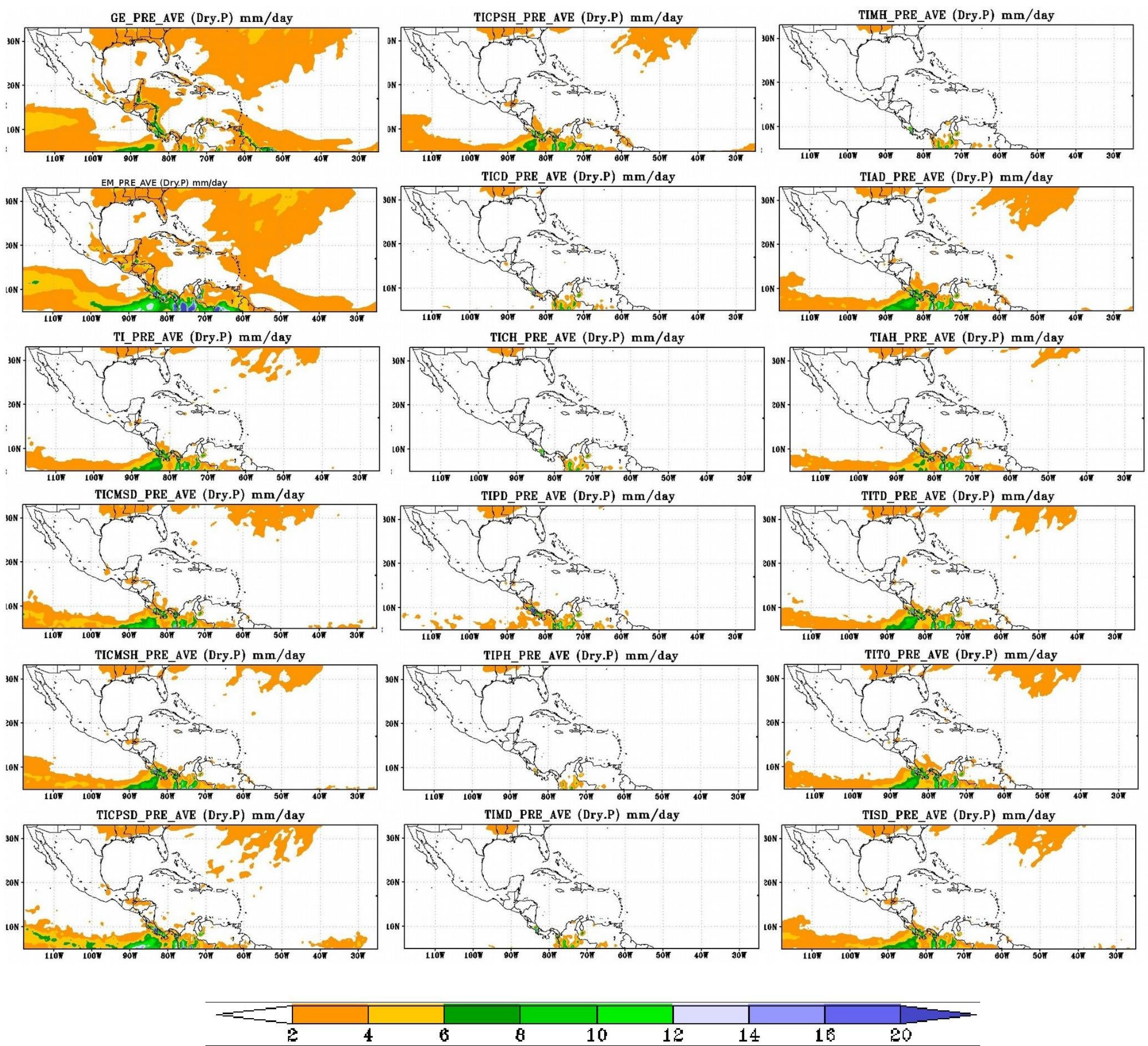

Fig. 3: Spatial distribution of the average seasonal precipitation for the dry seasons of 2000-2001 defined in table 1.

Fig. 4 shows that all the configurations of the model with the exception of GE overestimate precipitation in the Pacific coast of southern Central America in the rainy season, but the degree of overestimation depends on the configuration, so that a complementary discrimination criterion was to exclude the configurations with a greater area of very high precipitation in this region. Another important preliminary criterion was the similarity between the simulated rainfall values for the Greater Antilles and the observations. These criteria allowed discarding other configurations of the Tiedtke scheme, keeping only TICMSD, TICPSH, TIAD and TI. Configurations GE and EM were also kept for the final detailed analysis.

The comparison of simulated precipitation and temperature fields with the observations was done after applying a bilinear interpolation of the model outputs to the grid of each of the datasets considered as reference.

Average simulated temperature patterns (not shown) look very similar for all the configurations, even if a cold bias is apparent in relation with CRU data, so that no additional criterion was added to the preliminary selection of configurations attending to this parameter.

Figures 5 and 6 show the distribution of the bias of precipitation and temperature in the domain, for the 6 selected experiments, during the dry and wet seasons. EM produces a high positive bias in precipitation in the wet season, not only in Central America, but also in most of the Caribbean Sea and its islands. In the case of GE, it represents acceptably well the precipitation field for Central America and shows a small positive bias for part of the Caribbean Sea, limited to less than 3 mm/day. For the Greater Antilles the bias is very small. The TIAD, TICPSH and TICMSD configurations show a negative precipitation bias for part of the domain in the dry season which is less than 3 mm/day for most of the Caribbean and the Pacific, but it has a high positive bias for the Pacific coast of Central America and the Andes. This positive bias area in the modified configurations is less than in the default, particularly in TICPSH. The dry bias for the Greater Antilles and the Caribbean has also been reduced for this configuration.

The overestimation of precipitation in the Pacific coast of Central America is related to a problem in the estimation of the wind field by the model in the rainy season, as can be seen in Fig 7, showing the wind direction and magnitude as estimated by ERA and RegCM-4.3 for the wet season. A spurious convergence zone, along the Central America pacific coast is observed for EM and the Tiedtke scheme configurations, collocated with the unrealistic maximum in precipitation, but not for GE, which is the only scheme producing a good estimation of rainfall in this zone. EM shows the strongest convergence and also the greatest area of overestimated precipitation and the highest precipitation values. Among the Tiedtke configurations, TICPSH and TICMSD produce the less intense spurious convergence in the zone. All the configurations underestimate precipitation in the intertropical convergence zone (ITCZ), near to the southern boundary of the domain. The bias in temperature is generally negative everywhere for the dry season, except for the southern coast of the United States, where positive bias is observed, even if its area is minimal for the GE scheme. This is true also for the wet season, but in this case, the bias covers a greater area for the three experiments with the Tiedtke scheme, and a minimal area for EM.

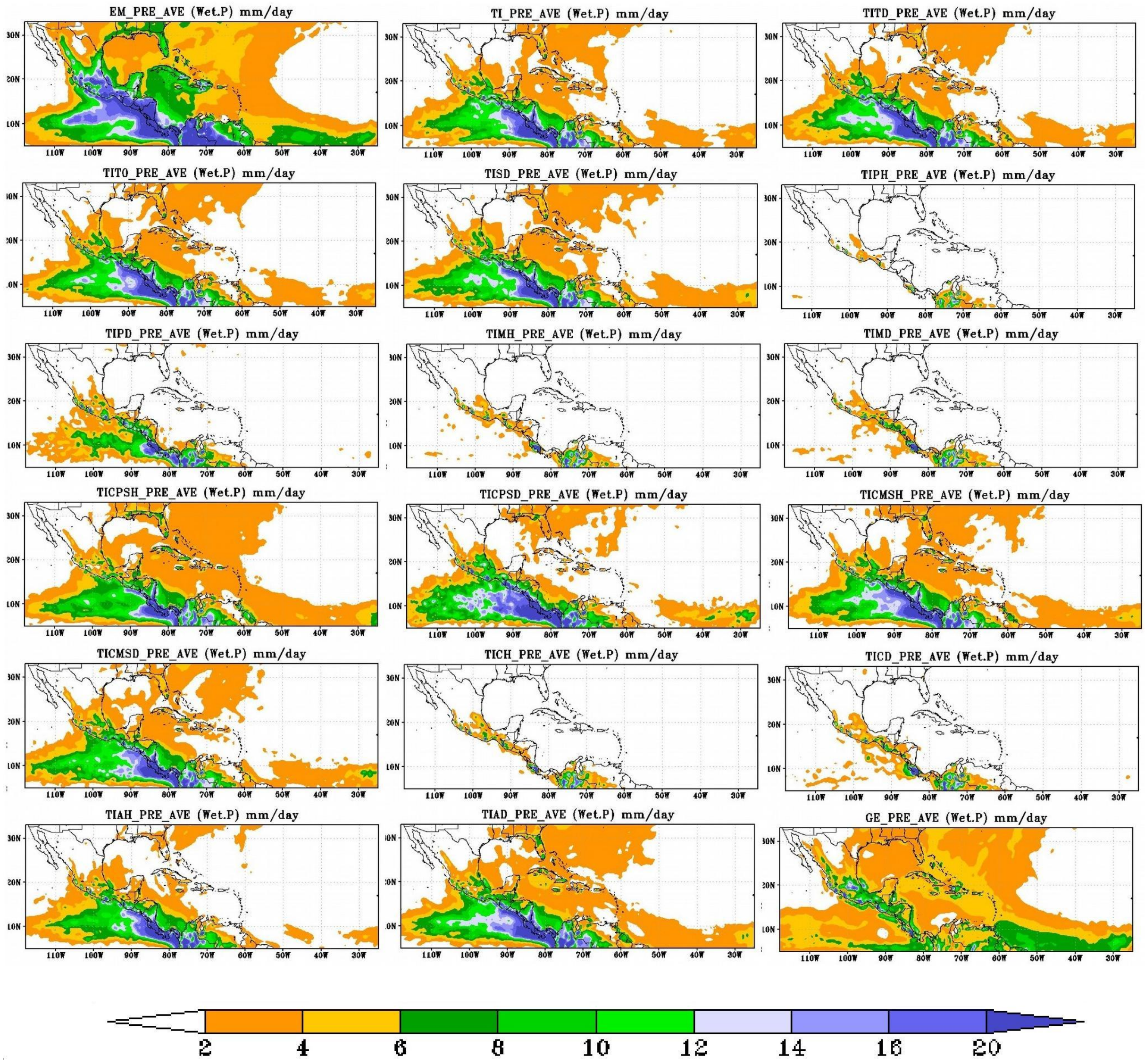

Fig. 4: Spatial distribution of the average seasonal precipitation for the rainy seasons of 2000-2001 defined in table 1.

3.2. Standard deviations and correlations of model precipitation and temperature estimations with reference datasets

To corroborate the analysis made it visually with the pattern and bias result normalized Taylor diagrams (Taylor, 2001) have been plotted (Fig. 8) to evaluate the correlation and standard deviations of precipitation and air temperature and the centered deviations of the model estimations relative to the references. The precipitation estimation for the dry season shows correlations ranging from 0.4 to almost 0.75, all significant at more than 99% level. The lowest correlations and greatest RMS deviations corresponded to EM and the rest of the configurations of the model are clustered near to the standard deviation reference line and with correlations close to 0.6-0.7. For the rainy season, the points show some dispersion along the 0.6 correlation line. EM has the highest root mean square (RMS) deviation with the reference data sets, showing that the observed bias is not a systematic error and this is another argument to discard this configuration in a projected ensemble. The least RMS deviations in precipitation correspond to GE and TICMSD.

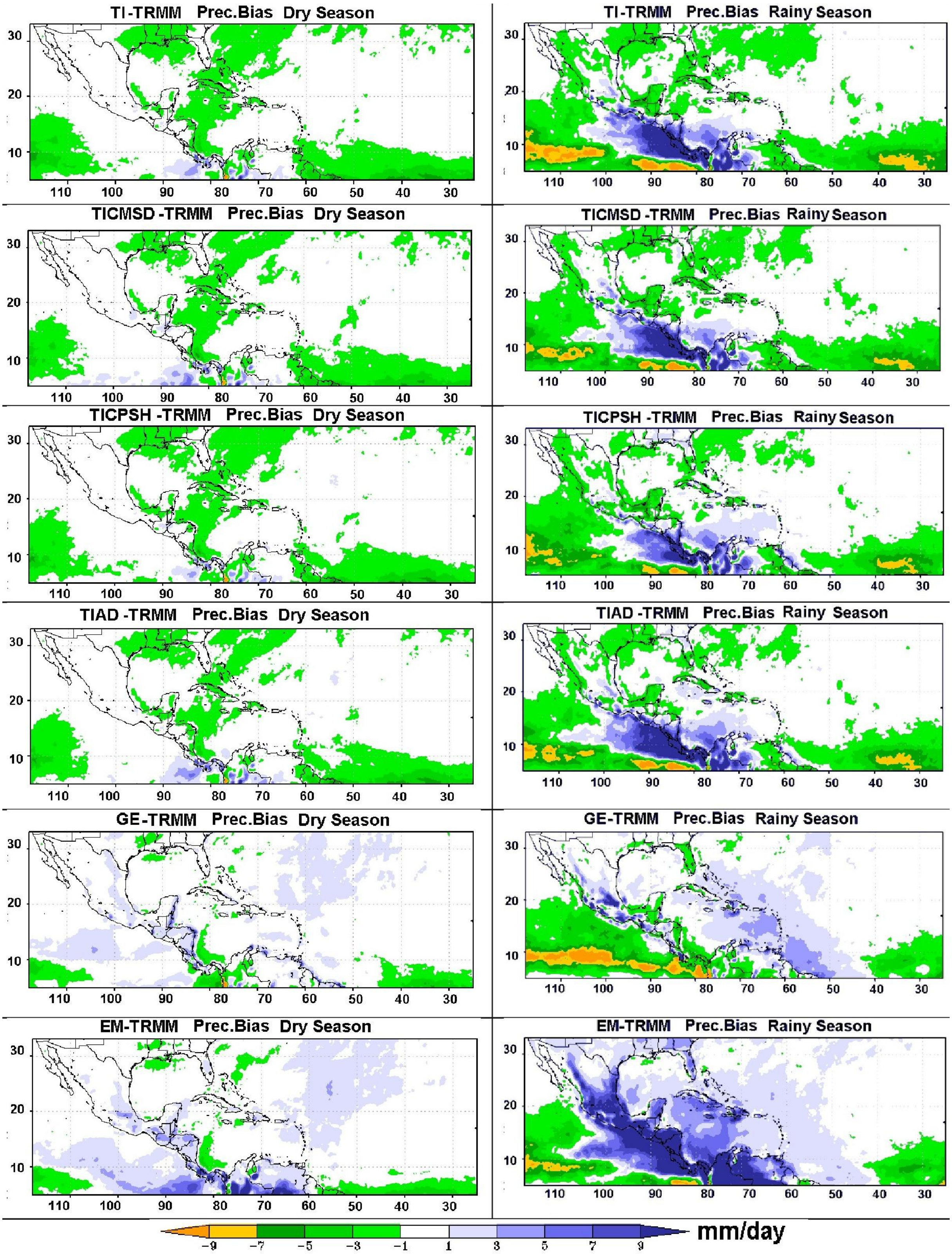

Fig. 5. Bias in the average monthly precipitation simulated by the selected RegCM-4.3 configurations for the dry (left column) and rainy (right column) seasons in the period 2000-2001, relative to the TRMM estimation.

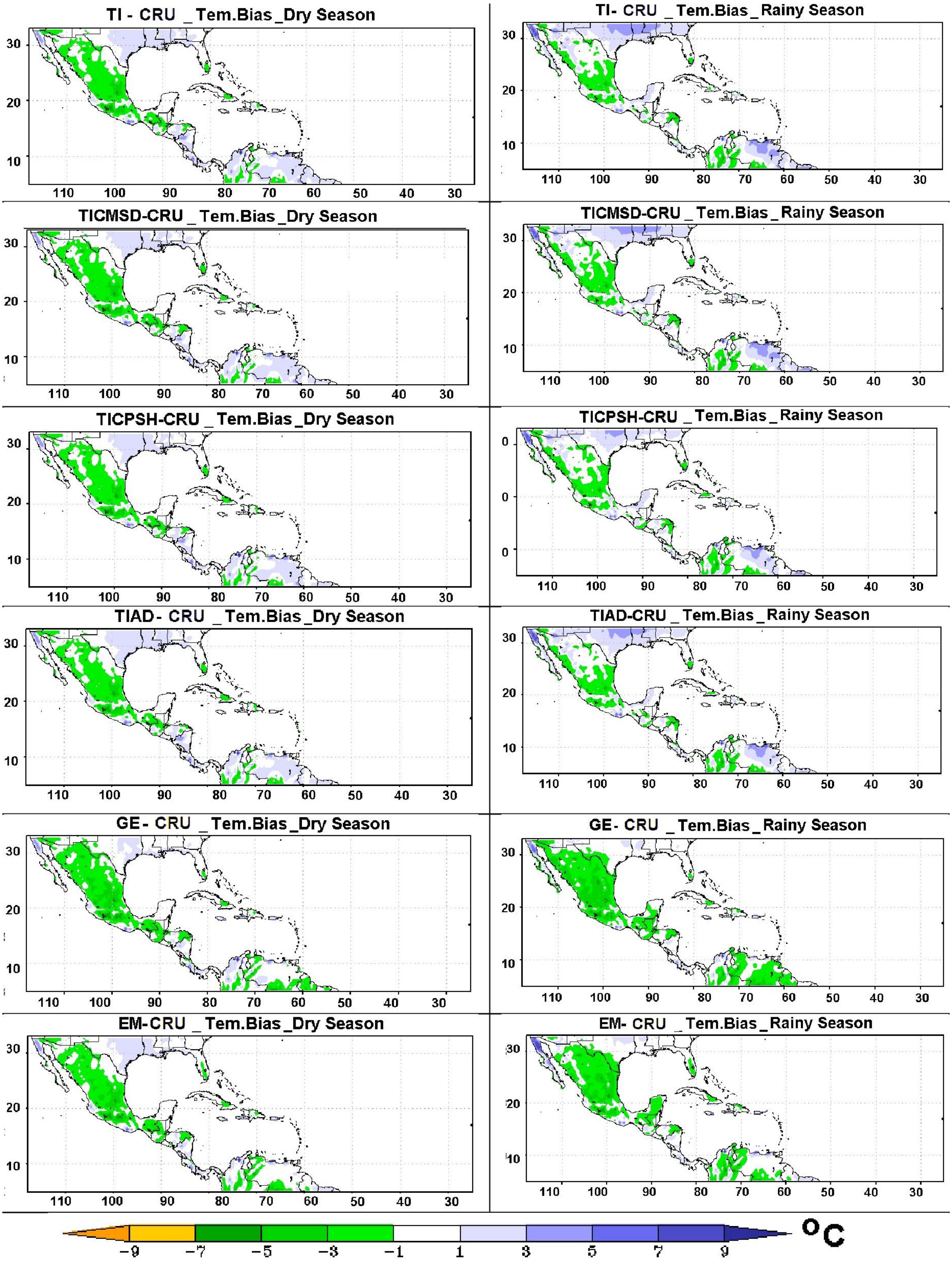

Fig. 6: Bias in the average monthly mean temperature by the selected RegCM-4.3 configurations for the dry (left column) and rainy (right column) seasons in the period 2000-2001, relative to the CRU estimation.

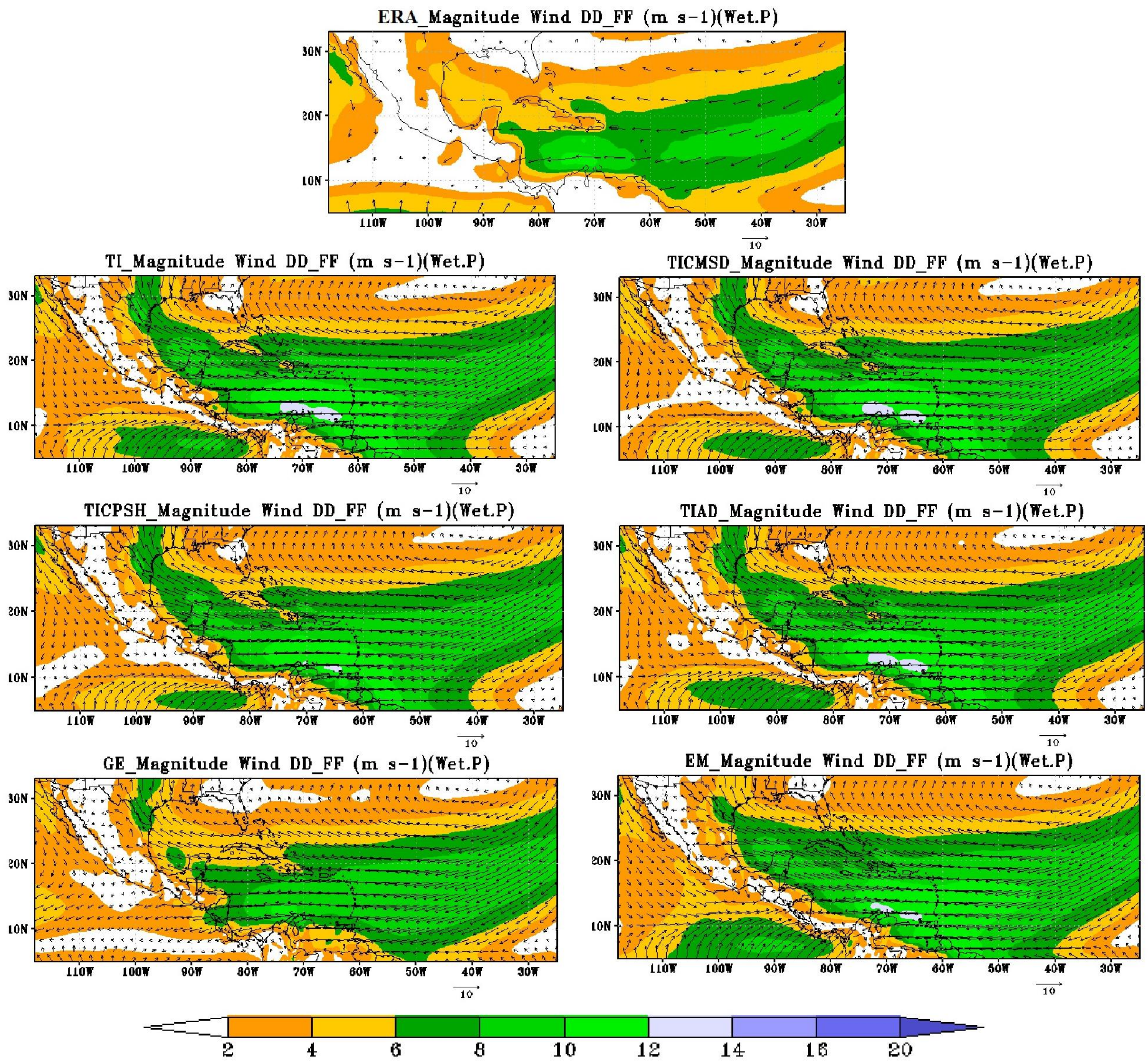

Fig. 7: Wind vector (arrows) and magnitude (shaded) for ERA and six configurations of the RegCM-4.3 model.

The temperature estimations for the dry season are practically coincident and reproduce very well the variability of the reference datasets for all the configurations of the model, showing a very high correlation of 0.95, significant at more than 99% level, very low RMS deviations and similar standard deviations, as they cluster around the reference arc. For the rainy season, the model estimations are also similar to the reference, but the RMS deviations are larger than for the dry season, and they show larger standard deviations than the reference. The correlation is good too, as it is higher than 0.8, with significance greater than 99% for most configurations.

3.3. Reproduction of climatic features of the region

Two of the most outstanding regional climatic features of the domain are the so called midsummer drought (MSD) and the Caribbean low level jet (CLLJ). The ability of the configurations of the model to reproduce these features has been explored in the present study.

3.3.1. Seasonal cycle of precipitation and midsummer drought (MSD)

For most of Central America, central and southern Mexico and the Caribbean, the annual cycle of precipitation is characterized by a rainy season extending from May to October with a relative minimum happening most frequently in July or August, though it may also happen in June. This period of relatively low precipitation and cloudiness between the two modes of the precipitation distribution is known as the midsummer drought. A thorough description of this phenomenon as well as its explanation, based on teleconnections with the fluctuations in intensity and location of the Eastern Pacific Inter-tropical convergence zone can be found in Magaña *et al.* (1999). As discussed by Karnauskas *et al.* (2013), they recently proposed an explanation of this feature of the regional climate, based on the relation of the biannual crossing of the solar declination, with increasing convective instability and rainfall in May-June and September-October, combined with the influence of remote processes as the North American monsoon, the Caribbean low-level jet (CLLJ), and the north America subtropical high (NASH). To evaluate the ability of the configurations of RegCM to reproduce this situation, a study area has been defined (Fig. 1) for the Greater Antilles. Fig. 9 shows the time series of monthly precipitation accumulates in this region for the simulation period of 2000-2001, for the configurations of RegCM, compared with the observation-based estimations of TRMM, CMAP, GPCP and CRU. Observations on monthly averaged data for the two pooled years show the expected bimodal distribution (TRMM, CMAP and GPCP), with maxima in May and September, and a minimum in June (not well defined for CRU). The midsummer minimum appears within June-July for the Tiedtke scheme configurations, but GE fails to reproduce it, while EM heavily overestimates precipitation and locates the peak correctly, but not the minimum. For separate plots for 2000 and 2001 (not shown), it becomes clear that in 2001, the minimum is observed in June, and in 2000, for the Greater Antilles, it is not very well defined in the monthly means. This shift in the occurrence of minimum precipitation with respect of the most probable occurrence in July has been reported before by Magaña *et al.* (1999, Fig. 5) in some of the years of his sample.

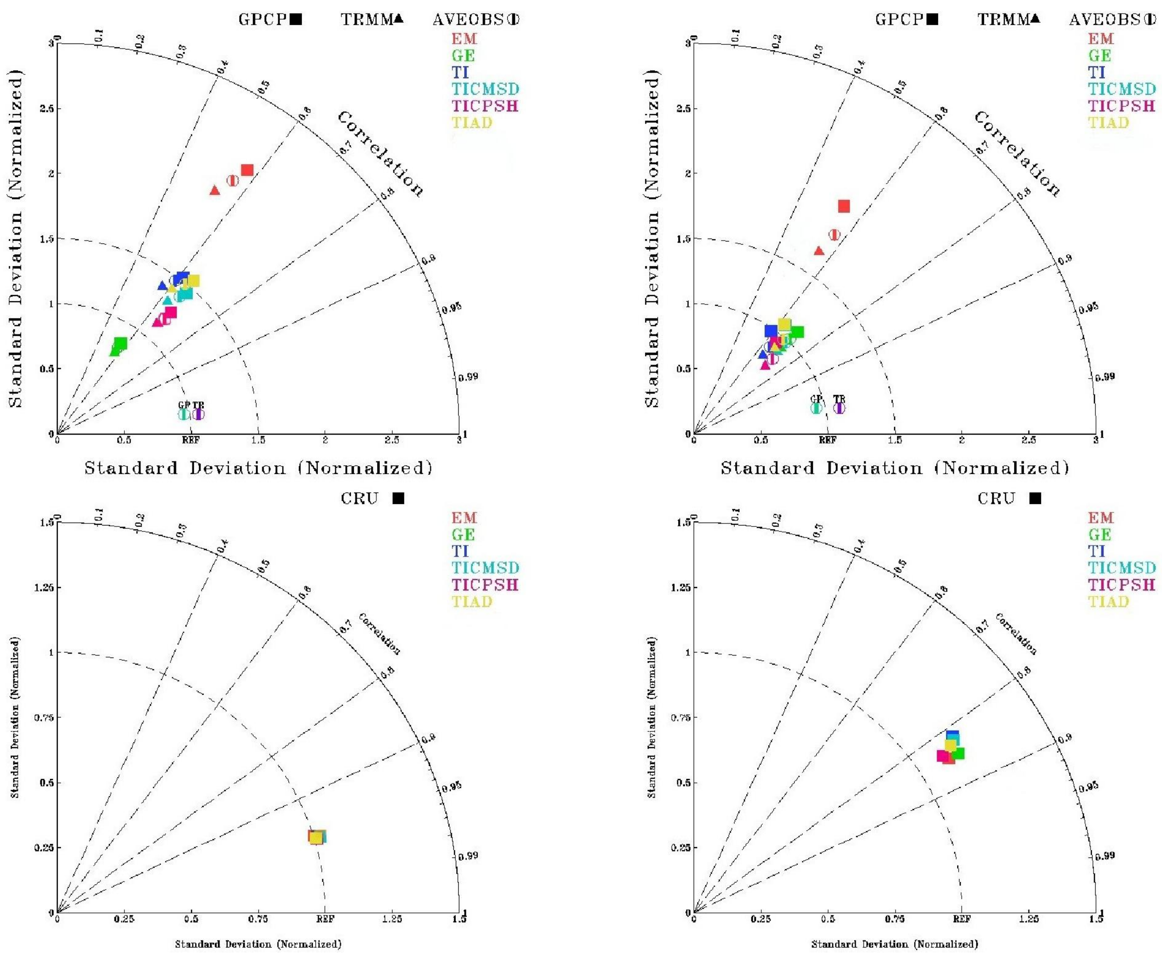

Fig. 8: Taylor diagrams of the estimations of precipitation (upper row) and temperature (lower row) for the dry (left) and rainy (right) seasons, relative to the reference data bases.

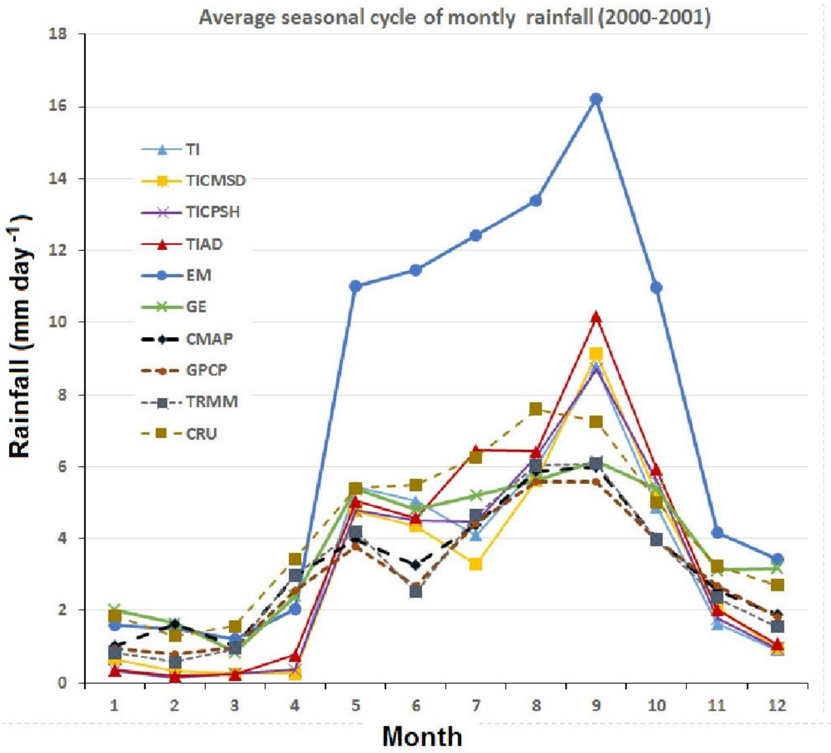

Fig. 9: Seasonal cycle of monthly rainfall for 2000-2001 for RegCM-4.3 configurations and reference data.

3.3.2. Caribbean Low Level Jet (CLLJ)

The Caribbean low-level jet is a wind speed maximum in the vertical wind profile which has been identified as a regular climatological feature in the Caribbean (Amador, 1998; Amador and Magaña, 1999). Its center is located in the region approximately defined by (70°W-80°W, 15°N) and its maximum horizontal wind speed can reach 16 m/s at the 925 hPa level. It has a semiannual cycle, with most frequent maxima in February and July, but can be found in the whole Caribbean wet season. Its summer cycle is nearly coincident with the MSD and has been considered as one of its main causes, because of the divergent flux associated with it (Magaña *et al.*, 1999; Wang, 2007; Whyte *et al.*, 2008).

To evaluate the behavior of this feature in the simulation period, the mean zonal wind field plots for the Central Caribbean were analyzed month by month. Fig. 10 shows the zonal wind field plots in the 925 hPa level for the periods of January-March and May-July of 2000-2001, obtained from ERA reanalysis, showing the occurrence of wind maxima for February and June. The summer maximum of the jet in June is coincident with the precipitation minimum of MSD, which occurrence in this month was a particular characteristic of the simulation period. Fig. 11 shows the zonal wind distribution, as reproduced in the simulation experiments for the months of January, February, June and July. The 6 configurations reproduce the average wind maxima in the correct month and approximately in the correct position, but the February and June maxima are smaller in 1-2 m/s than the ERA estimation in most simulations, but GE and EM, which reproduced the February maximum, and TICPSH, which estimated well the value of the wind maximum in June.

3.3.3. Diurnal cycle of precipitation and temperature

The diurnal cycles of temperature and precipitation are among the most important climatic features to be reproduced by a regional climate model, as they are closely related to the performance of the physical parameterizations of the model and must be mutually consistent. Martínez-Castro *et al.* 2006 found that the application of the Grell convective scheme with the Arakawa-Schubert closure allowed to reproduce the qualitative cause-effect relationship between the sea breeze convergence along the coasts of the Greater Antilles and the precipitation cycle, while Diro *et al.* (2012) obtained a good reproduction of the amplitude of the diurnal cycle with some phase shift in Central America using GE.

In the present paper, the island of Cuba has been chosen as an example to test the ability of the model to reproduce the diurnal cycles because of the availability of radar information about the frequency and displacement of convective cells during the day (Novo-Cuervo *et al.*, 2013). Fig. 12 shows the average diurnal cycle of precipitation and temperature, as obtained from the model output averages of each of the three hourly terms in the period from May 2000 to April 2001 for the selected configurations. TRMM 3B42 data are used as reference for precipitation and ERA estimates are used for surface air temperature reference. Time zone for Cuba is UTC-5. The air temperature cycles for Cuba are nearly sinusoidal and similar in form for the different convective schemes. All the configurations overpredict ERA temperature for all the times, but bias for TI and TICPSH is very small, while GE estimation of the maximum value exceeds one degree. The precipitation diurnal cycle shows a greater dependence on the convective scheme, as the Tiedtke configurations reproduce quite well the onset of convective rainfall in the afternoon while GE is the only one reproducing well the slow decrease or precipitation in the evening. For Cuba, the Tiedtke configurations reproduce the maximum at 18 UTC (13 LST), with a delay in the maximum relative to TRMM and to local radar based studies of storm evolution (Novo-Cuervo *et al.*, 2013), but GE correctly reproduces the maximum between 21 and 00 UTC (16-19 LST).

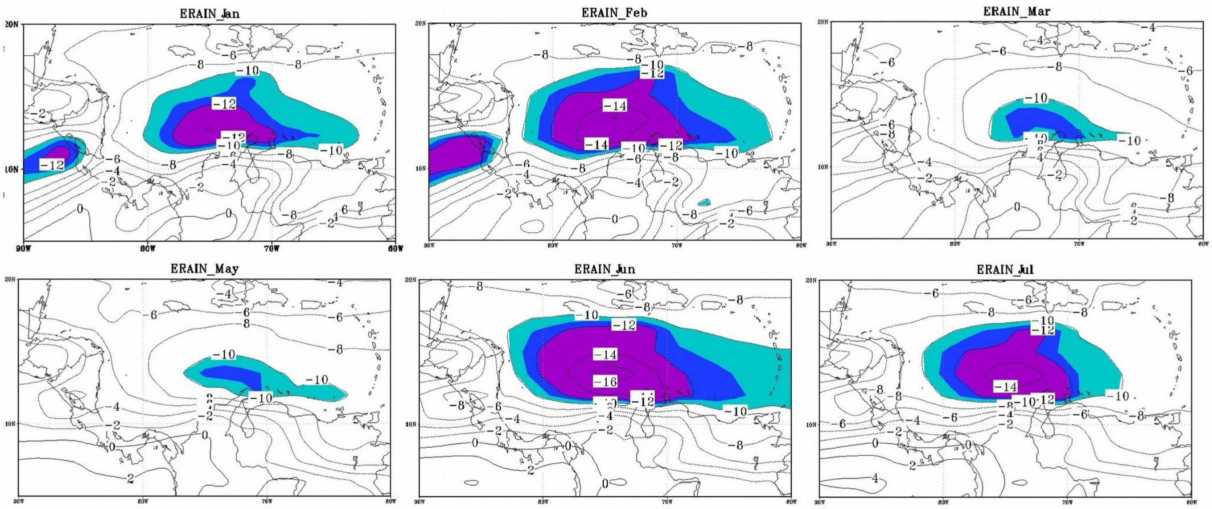

Fig. 10: Averaged zonal wind for January, February and March (upper row) and for May,June and July (lower row) for the southern Caribbean, obtained from ERA. The isotach intervals with wind speed higher than 10 m/s have been shaded.

3.4. Comparison with high resolution surface data for Cuba, Jamaica and Dominican Republic

One of the uncertainties in the evaluation of the regional climate model predictions lays in the relatively low resolution and inherent uncertainty of world data sets, commonly used for testing the performance of the models in present time conditions. One of the most solid ways to solve this problem is to include local surface data networks (LSDN) as reference in the sensitivity study. This is especially important in the case of islands, and complex orographic regions. Martínez-Castro *et al.* (2006) have compared the temperature and precipitation fields produced by RegCM-3 with data of the Cuban Surface Network (CSN) of meteorological stations for three months of the wet season in the Island. In the present paper, a similar comparison is presented, for Cuba, Dominican Republic and Jamaica, extended to the two-year simulation period, and differentiating three regions inside Cuba.

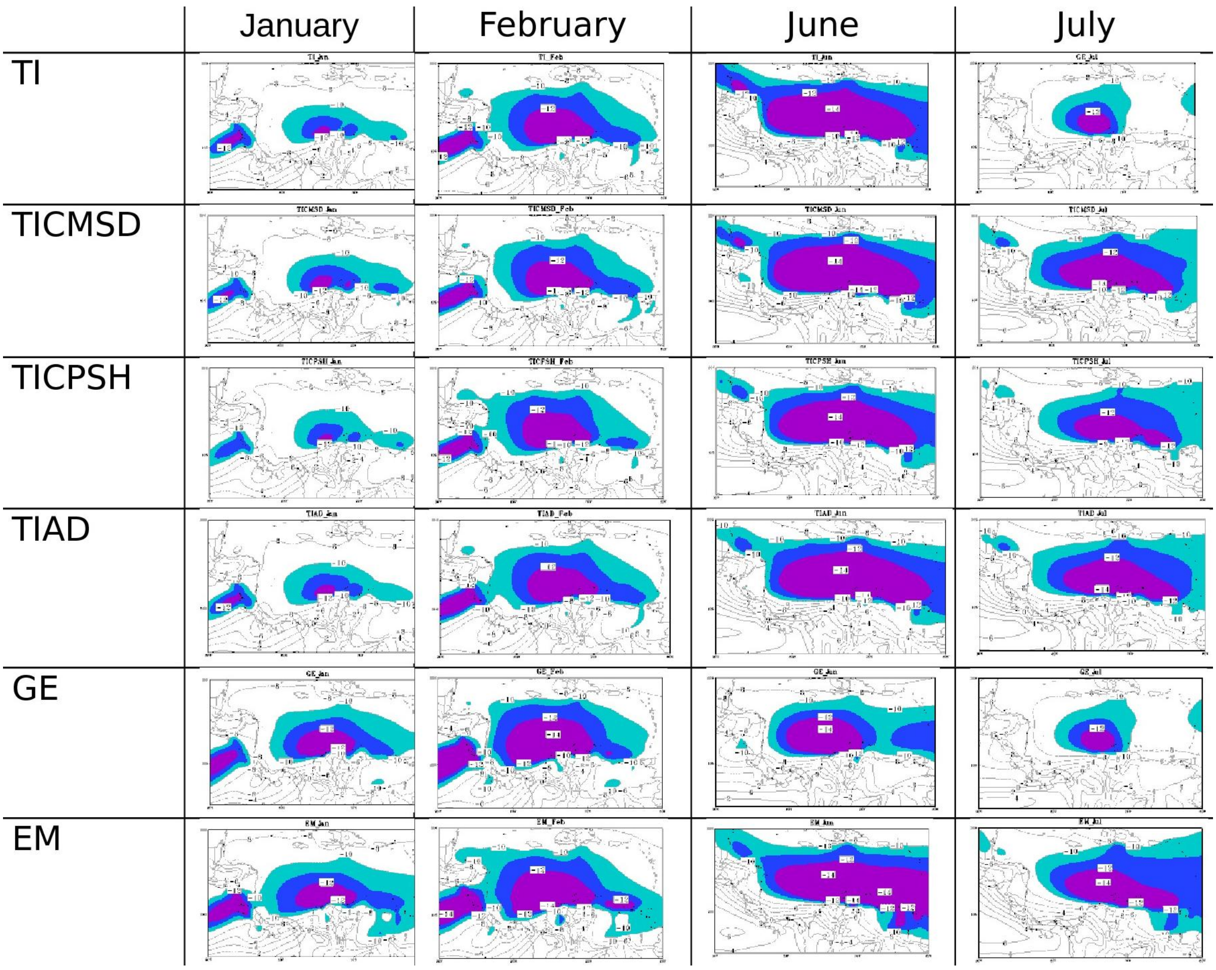

Fig. 11: Average zonal wind for January, February, June and July for the southern Caribbean, obtained from the selected configurations of the model. The isotach intervals with wind speed higher than 10 m/s have been shaded

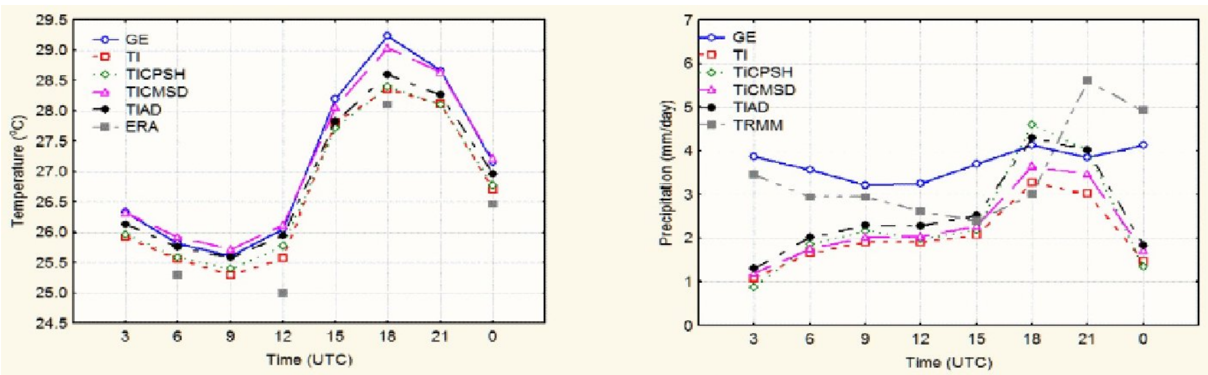

Fig. 12: Diurnal cycles of air temperature (left) and precipitation (right) over land for Cuba from the 3 hourly output from the model. Precipitation data from TRMM 3B42 product are used as a reference for precipitation and ERA Interim estimations are the reference for temperature.

Fig. 13 shows the spatial distribution of the bias of the selected configurations of the model, relative to LSDN of Cuba, Dominican Republic and Jamaica, which have been interpolated to the grid of the model. For the dry season, GE and EM produce the lower precipitation biases for most regions of the islands, but for the wet season, EM shows a high wet bias. It can be noticed that the wet bias for GE is small over the islands. For the selected configurations using the Tiedtke scheme, dry bias prevails, except TICPSH, for which the bias is low and balanced through the different regions of the three islands.

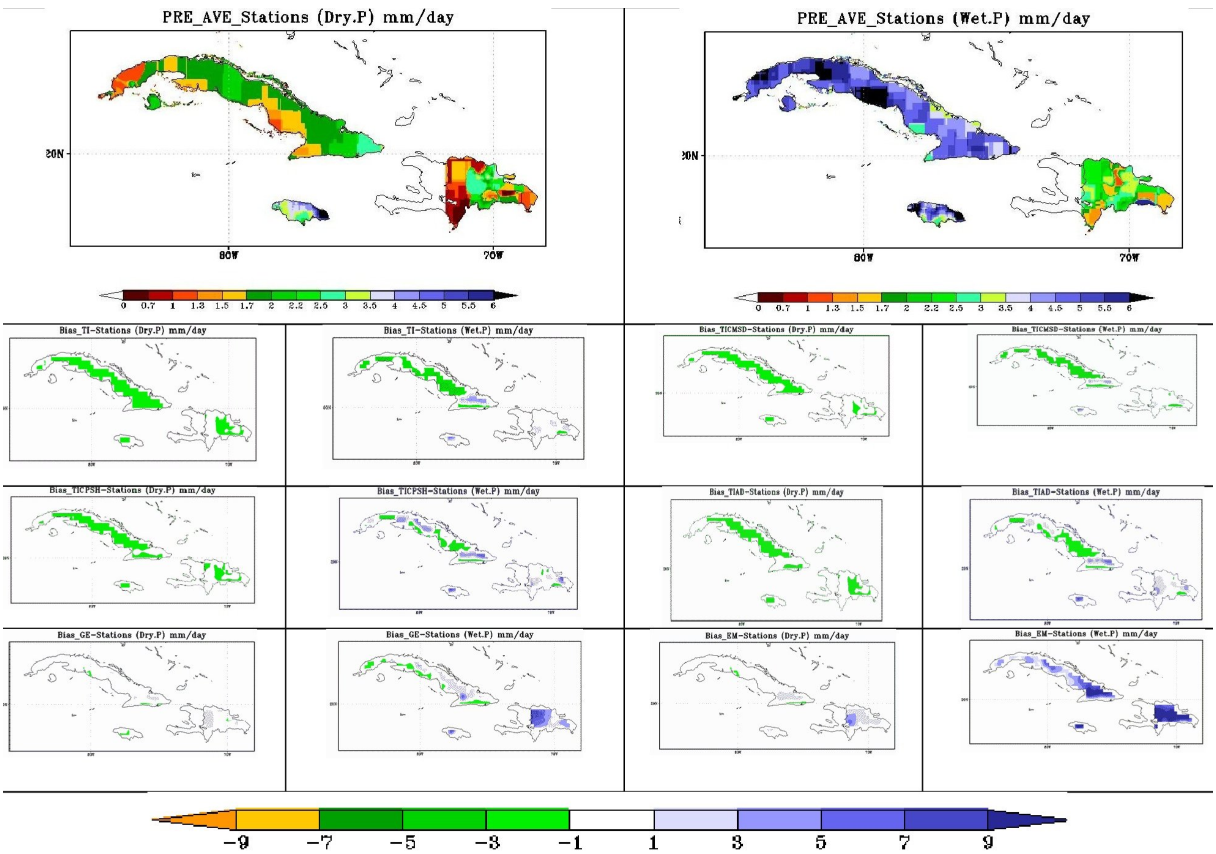

Fig. 13: Precipitation bias for the Greater Antilles, relative to the local meteorological surface networks for the selected configurations of the model. The upper row shows the average precipitation distribution for the two seasons, and the three lower rows show the estimated bias for the configurations of the model.

4. Conclusions

We have presented a sensitivity study of the performance of version 4.3 of the ICTP regional climate model RegCM-4 for a sub domain of the Central America CORDEX domain, with a horizontal resolution of 50 km, using the Tiedtke convective parameterization scheme, and the Grell-Emanuel (GE, Grell over land, Emanuel over sea) and Emanuel (EM) convective schemes. For the Tiedtke scheme, five parameters related with the closure condition, microphysical processes and entrainment rates were tuned. The main climatic features of the behavior of air temperature and precipitation in the region were tested for a simulation period of two years. A preliminary analysis of the ability of the configurations to reproduce the temperature and precipitation fields and their variability allowed us to discard 10 of the configurations as not capable to reproduce the precipitation patterns of the region for the dry and rainy seasons.

The ability of the model to reproduce the seasonal cycle of precipitation and the presence of the midsummer drought were tested for the Greater Antilles. The comparison with the reference datasets showed that the Tiedtke scheme reproduced best the cycle. The Caribbean low level jet was reproduced by all the configurations, but the maximum wind value was underestimated in 1-2 m/s by most configurations, except for GE and EM, which reproduced the February maximum, and TICMSD, which estimated well the value of the wind maximum in June. The precipitation and air temperature diurnal cycle were tested for five selected configurations for Cuba. The temperature cycle is well reproduced for Cuba by all configurations, even if the afternoon maximum is underestimated. The diurnal precipitation cycle over Cuba shows a greater dependence on the convective scheme, as the Tiedtke configurations reproduce well the abrupt onset of convective rainfall in the afternoon, but with a delay of 2-3 hours, while GE is the only one reproducing well the time of the maximum (21-00 UTC) and the slow decrease of precipitation in the evening.

A special comparison was made using the high resolution surface data of Cuba, Dominican Republic and Jamaica. For the dry season, GE and EM produce the lower precipitation biases for most regions of the islands, but for the wet season, EM shows a high wet bias. It can be noticed that the wet bias for GE is small over the islands. For the selected configurations using the Tiedtke scheme, dry bias prevails, except TICPSH, for which the bias is low and balanced through the different regions of the three islands.

It can be concluded that the performance of the selected configurations of the Tiedtke convective scheme is comparable with the previously tested Grell-Emanuel scheme, and much better that the Emanuel scheme, even if bias in precipitation persists in part of the domain. However, the reproduction of the diurnal and seasonal cycles of precipitation is good, as well as the representation of regional climatic features as the midsummer drought and the Caribbean low level jet. The authors consider this result as an encouraging argument for the use of the Tiedtke parametrization in RegCM for the Caribbean and Central America. A further step will be the analysis of simulations using the Tiedtke scheme in RegCM-4.3 with higher horizontal resolution and for a longer testing period to contribute to a parametrical ensemble for the downscaling of climate change projections and seasonal forecasting.

5. Acknowledgments

This work was funded by the Climate Change Program of the Cuban Enviroment Agency of Cuba. Finnancial support for storage capacity and travel was given by the Caribbean Community Climate Change Centre and the Abdus Salam International Centre for Theoretical Physics (ICTP), which also granted access its facilities to four of the authors through its Associateship and Federation Programs. We thank the Weather and Climate Physics Group of ICTP for providing the RegCM-4.3. Thanks also to ECMWF, for free access to the ERA Interim reanalysis and The University of East Anglia Climate Research Unit, (CRU), NASA, the Japan Aerospace Exploration Agency (JAXA), NOAA the Goddard Distributed Active Archive Center (DAAC), for available datasets.

6. References

Adler R, Huffman G, Chang A, Ferraro R *et al.* (2003): The Version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-Present). *J. Hydrometeoro.*, 4:1147-1167.

Aldrian E, Deumenil-Gates L, Jacob D, Podzun R, Gunawan D (2004): Long-term simulation of Indonesia rainfall with the MPI regional model. *Clim. Dyn.*, 22:795-814.

Amador J (1998): A climatic feature of the tropical Americas: The trade wind easterly jet. *Top. Meteor. Oceanogr.*, 5:91-102.

Amador JA and Magaña VO (1999): Dynamics of the Low Level Jet over the Caribbean Sea. Preprints 20^{th} Conference in Tropical Meteorology. 10-15 January 1999, Dallas, Texas, American Meteorological Society, 401 y 402.

Anthes RA, Hsu EY, Kuo YH (1987): Description of the Penn State/ NCAR Mesoscale Model Version 4(MM4). NCAR Tech. Note, NCAR/TN-282+STR, 66 pp.

Arakawa A, Schubert WH (1974): Interaction of a cumulus cloud ensemble with the large scale enviroment. Part I. *J. Atmos. Sci.*, 31:674-701.

Arakawa A, Lamb VR (1977): Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods in Computational Physics,* 17:173-265.

Campbell JD, Taylor MA, Stephenson TS, Watson RA, Whyte FS (2011): Future climate of the Caribbean from a regional climate model. *Int. J. Climatol.*, 31, 12. 1866-1878. DOI:10.1002/joc.2200

Centella-Artola, Taylor MA, Bezanilla-Morlot, Martinez-Castro, Campbell JD, Stephenson TS, Vichot-Llano (2015): Assessing the effect of domain size over the Caribbean region using the PRECIS regional climate model. *Clim. Dyn.*, 21 44. 1901-1918. DOI 10.1007/s00382-014-2272-8.

Dickinson RE, Henderson-Sellers A, Kennedy P (1993): Biosphere-atmosphere transfer scheme (BATS) version 1eas coupled to the NCAR community climate model. TechRep, National Center for Atmospheric Research Tech. Note NCAR. TN-387+SRT, NCAR, Boulder, CO.

Diro GT, Rauscher SA, Giorgi F, Tompkins AM (2012): Sensitivity of seasonal climate and diurnal precipitation over Central America to land and sea surface schemes in RegCM4. *Clim. Res.*, 52:31-48, doi:10.3354/cr01049.

Elguindi N, Bi X, Giorgi F, Cozzini S, Giulani G (2011): *RegCM version 4.3 User's Guide*. PWCG Abdus Salam ICTP, Trieste, 62 pp.

Emanuel K (1991): A scheme for representative cumulus convection in large scale models. *J. Atmos. Sci.*, 48:2313-2335.

Fritsch JM, Chappel CF(1980): Numerical prediction of convectively driven mesoscale pressure systems. Part I: Convective parameterization. *J. Atmos. Sci.*, 37:1722-1733.

Giorgi F, Marinucci MR, Bates GT (1993a): Development of a second generation regional climate model (RegCM2). Part I: Boundary layer and radiative transfer processes. *Mon. Wea. Rev.*, 121:2794-2813.

Giorgi F, Marinucci MR, Bates GT, De Canio G (1993b): Development of a second generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.*, 121:2814-2832.

Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla MB, Bi X, Elguindi N, Diro GT, Nair V, Giuliani G, Turuncoglu UU, Cozzini S, Guttler I, O'Brien TA, Tawfik AB, Shalaby A, Zakey AS, Steiner AL, Stordal F, Sloan LC, Brankovic C (2012): RegCM4: Model description and preliminary test over multiple CORDEX domains. *Climate Research*, 52:7-29.

Giorgi F, Jones C, Asrar G.R (2009): Addressing climate information needs at the regional level the CORDEX framework. *WMO Bulletin*, 58:175-183.

Giorgi F, Mearns LO (1991): Approaches to regional climate change simulation: a review. *Rev. Geophys.*, 29:191-221.

Giorgi F, Shields C (1999): Test of precipitation parameterizations available in the latest version of the NCAR Regional Climate Model (RegCM) over the continental United States. *J. Geophys. Res.*, 104:6353-6375.

Gregory D, Morcrette JJ, Jakob C, Beljaars CM, Stockdale T (2000): Revision of convection, radiation and cloud schemes in the ECMWF Intergrated Forecasting System. *Q.J.R. Meteorol. Soc.*, 126:1685-1710.

Grell GA (1993): Prognostic evaluation of assumptions by cumulus parameterization. *Mon. Weather Rev.*, 121:764-787.

Grell GA, Dudhia J, Stauffer DR (1994): Description of the fifth generation Penn state/NCAR mesoscale model (MM5). In: NCAR Tech. Note, NCAR/TN-398+STR, NCAR,Boulder, CO.

Harris I, Jones PD, Osborn TJ, Lister DH (2014): Update high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *Int. J. Climatology*, 34:623-642, Doi:10.1002/joc.3711

Hsei EY, Anthes RA. (1984): Simulations of Frontogenesis in a Moist Atmosphere using Alternative Parameterizations of Condensation and Precipitation. *Journal of Atm. Sciences*, 41:2701-2716.

Huffman G, Adler R, Bolvin DGG *et al.* (2007): The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol,*, 8:38-55.

IPCC (2007): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones RG, Noguer M, Hassel D, Hudson D, Wilson S, Jenkins G, Mitchell J (2004): Generating high resolution climate change scenarios using HadRM3P. Met Office Hadley Centre Report, p 40.

Karmalkar AV, Bradley RS, Diaz HF (2011): Climate change in Central America and Mexico: regional climate model validation and climate change projections. *Clim. Dyn.*, 37:605-629, DOI.10.1007/s00382-011-1099-9.

Karnauskas KB, Giannini A, Busalachi J (2013): Simple mechanism for the climatological midsummer drought along the Pacific coast of Central America. *Atmósfera*, 26:261-281.

Kiehl JT, Hack JJ, Bonan GB, Boville BA, Briegleb BP, Williamson DL, Rasch PJ (1996): Description of the NCAR Community Climate Model (CCM3). NCAR Technical Note NCAR/TN420+STR, DOI: 10.5065/D6FF3Q99

Lecha LB, Paz LB (1994): *El clima de Cuba*. Editorial Academia, 186 pp.

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu J, Yang L, Merchant JW (2000): Development of a global land cover charateristics database and IGBP Discover from 1-km AVHRR Data. *Inter. J. Remote Sensing*, 21:1303-1330.

Magaña V, Amador JA, Medina S (1999): The Midsummer Drought over Mexico and Central America. *Journal of Climate*, 12:1577-1588.

Martínez-Castro D, Porfirio da Rocha R, Bezanilla-Morlot A, Alvarez-Escudero L, Reyes JP, Silva-Vidal Y, Arrit RW (2006): Sensitivity studies of the RegCM3 simulation of summer precipitation, temperature and local wind field in the Caribbean Region. *Theor. Appl. Climatol.*, 86:5-22.

Mitchell and Jones (2005): An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatology*, 25:693-712, DOI: 10.1002/joc.1181

Nordeng TE (1994): Extended versions of the convective parameterization scheme at ECMWF and their impact on the mean and transient activity of the model in the Tropics. ECMWF. Tech. Memo. 206, 41pp.

Novo-Cuervo S, Puentes-Ledesma O, Martínez-Castro D (2013): Recursos nubosos para el incremento artificial de la lluvia por siembra de nubes en las regiones occidental y centro-oriental de Cuba. Informe final de resultado Científico, Instituto de Meteorología, Cuba, 30 pp.

Pal JS *et al.* (2007): Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. *Bull. Am. Meteorol. Soc.*, 88:1395-1409, DOI: 10.1175/BAMS-88-9-1395.

Reynolds RW, Smith TM (1994): Improved global sea surface temperature analysis using optimum interpolation. *J. Climate*, 7:929-948.

Riehl H (1979): *Climate and weather in the tropics*. Academic Press, London, 611 pp.

Simmons A, Dee D, Uppala S, Kobayashi S (2007): ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter*, 110:29-35.

Taylor KE (2001): Summarizing multiple aspects of model performance in a single diagram. *J. Geoph. Res.*, 106:7183-7192.

Tiedtke M (1989): A Comprehensive Mass Flux Scheme for Cumulus Parameterization in large-scale models. *Bulletin of the American Meteorological Society*, 117:1779-1800.

Vichot-Llano A, Martinez-Castro D, Centella-Artola A, Bezanilla-Morlot A (2014): Sensibilidad al cambio de dominio y resolución de tres configuraciones del modelo climático regional RegCM 4.3 para la región de América Central y el Caribe. *Rev. Climatología*, 14:45-62.

Wang C (2007): Variability of the Caribbean Low-Level Jet and its relations to climate. *Clim. Dyn.*, 29:411-422. DOI: 10.1007/s00382-007-0243-z

Wang Y, Zhou L, Hamilton K (2007): Effect of Convective Entrainment/Detrainment on the Simulation of the Tropical Precipitation Diurnal Cycle. *Mon. Wea. Rev.*, 135:567-585.

Whyte FS, Taylor MA, Stephenson TS, Campbell JD (2008): Features of the Caribbean low level jet. *Int. J. Climatol.*, 28:119-128. DOI:10.1002/joc.1510

Xie P, Arkin PA (1997): Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model output. *Bull. Amer. Meteor. Soc.*, 78:2539-2558.

Zeng X, Zhao M, Dickinson RE (1998): Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and DATA. *J. Climate*, 11:2628-2644.