Assessment of RegCM4 simulated inter-annual variability and daily-scale statistics of temperature and precipitation over Mexico

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Abstract The skill of a regional climate model (Reg-CM4) in capturing the mean patterns, interannual variability and extreme statistics of daily-scale temperature and precipitation events over Mexico is assessed through a comparison of observations and a 27-year long simulation driven by reanalyses of observations covering the Central America CORDEX domain. The analysis also includes the simulation of tropical cyclones. It is found that RegCM4 reproduces adequately the mean spatial patterns of seasonal precipitation and temperature, along with the associated interannual variability characteristics. The main model bias is an overestimation of precipitation in mountainous regions. The 5 and 95 percentiles of daily temperature, as well as the maximum dry spell length are realistically simulated. The simulated distribution of precipitation events as well as the 95 percentile of precipitation shows a wet bias in topographically complex regions. Based on a simple detection method, the model produces realistic tropical cyclone distributions even at its relatively coarse resolution (dx = 50 km), although the number of cyclone days is underestimated over the Pacific and somewhat overestimated over the Atlantic and Caribbean basins. Overall, it is assessed that the performance of RegCM4 over Mexico is of sufficient quality to study not only mean precipitation and temperature patterns, but also higher order climate statistics.

1 Introduction

Daily scale temperature and precipitation extreme events are important due to their potential to cause life and economic losses (see, for example, Gosling et al. 2007; Poumadere et al. 2005; Brody et al. 2007), as well as damage to natural ecosystems (Easterling et al. 2000; Garrabou et al. 2009).

Central America has been identified as one of the most prominent climate change "hot spots" in the tropics (Giorgi 2006). In particular, Mexico is highly exposed and vulnerable to climate variability and tropical storms. De Alba and Andrade (2009) reported that between 1970 and 2006, about three hurricanes every 2 years reached the Mexican territory causing heavy damages and losses. For example in 2005, the Mexican Association of Insurance Institutions (AMIS) estimated that the economic losses due to hurricanes Emily, Stan and Wilma were about 2,282 million USD.

Previous studies examined different aspects of variability and extreme events over Mexico (Cavazos 1999; Cavazos and Rivas 2004). For instance, Cavazos (1999) studied the large-scale conditions associated with extreme precipitation events over Northeastern Mexico and Southeastern United States. A similar study for the city of Tijuana, Mexico, was carried out more recently (Cavazos and Rivas 2004). García-Cueto et al. (2010) investigated the duration and intensity of heat waves in the city of Mexicali (northern Mexico), and found that in 2006 there were 2.3 times more heat waves than in the decade of the 1970s. Arriaga-Ramírez and Cavazos (2010) calculated

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regional trends in annual and seasonal daily precipitation in Northwestern Mexico and Southwestern United States and found positive annual trends over the region.

Some studies assessed extreme events in climate change projections over some regions of Mexico and North America. For example, Diffenbaugh et al. (2008) found that regions of Northwestern Mexico and Southwestern United States might be highly vulnerable to climate change, mostly because of increases in variability of precipitation and temperature extremes. In fact, the impacts of climate change will be felt most strongly through changes in hydroclimatic variability and extremes rather than in mean values (IPCC 2007), particularly due to an increase in the intensity of storms together with a decrease in the frequency of rainy days (Trenberth 1999; Giorgi et al. 2011).

Both global and regional climate models (RCMs) can be used to simulate the changes in daily climate statistics in response to global warming, but their performance needs to be assessed prior to the production of climate projections. In particular, RCMs have been shown to provide reasonable representations of the tails of the daily-scale temperature and precipitation distributions in different contexts (e.g. Walker and Diffenbaugh 2009; Diffenbaugh et al. 2005). However, to date an analysis of variability and extremes in RCM simulations for Mexico has not been carried out. Therefore, in this paper we evaluate the skill of an RCM (RegCM4 described by Giorgi et al. 2012) in capturing mean patterns, variability and higher order statistics of daily-scale temperature and precipitation events over Mexico, and attempt to explain the causes of eventual mismatches between observations and simulation. We focus on interannual variability and on the annual 5 and 95 percentiles of daily temperature, 95 percentile of precipitation, frequency of occurrence of events of given intensities, maximum dry spell length and number of tropical cyclone days, quantities that are all important for impact studies. The aim of this assessment is to test the performance of RegCM4 as a tool for the study of climate variability and extremes over Mexico and their change under global warming conditions.

2 Methods

2.1 RegCM4 configuration

We use the hydrostatic, compressible, three-dimensional, regional climate model RegCM4 (Giorgi et al. 2012). This is the latest version of the modeling system originally developed by Giorgi et al. (1993a, b) and Pal et al. (2007). Several physics parameterizations are available in the model. For the present study, we

employ the best performing configuration identified by Diro et al. (2012), which includes an enhanced radiative transfer scheme (Kiehl et al. 1996, Giorgi et al. 2012), a modified version of the planetary boundary layer scheme of Holtslag et al. (1990) (see Giorgi et al. 2012), a mixed convection scheme in which the parameterization of Emanuel (1991) is used over oceans and the scheme of Grell (1993) over land and the resolvable scale precipitation scheme of Pal et al. (2000). For the representation of land surface processes the model employs the Biosphere–Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1993).

The model domain (see Fig. 1) follows the specifications of the Central America COordinated Regional climate Downscaling EXperiment (CORDEX) domain, covering a large area of Central America and adjacent ocean and land regions at a grid spacing of 50 km. This domain will be used for the first set of PHASE I CORDEX projections (Giorgi et al. 2009). The ERA Interim reanalysis is used to provide lateral boundary conditions (Dee et al. 2011) for a 27-year simulation period of 1982–2008. Diro et al. (2012) discuss a series of sensitivity experiments over this model domain for a shorter 5-year simulation period.

2.2 Precipitation, temperature and tropical storm observations

We use various datasets to evaluate the model performance. When assessing the model over the whole domain, we refer to precipitation data from the monthly datasets of the Global Precipitation Climatology Project (GPCP, Adler et al. 2003), and surface air temperature data from the University of Delaware (UDel, Legates and Willmott 1990a, b). The resolution of these datasets (GPCP and UDel) are 2.5° and 0.5°, respectively. For a more focused assessment, we analyze precipitation over seven subregions of Mexico: Baja California (BC), North-West Mexico (NW), Central-North Mexico (NM), North-East Mexico (NE), Central Mexico (CM), South Mexico (SM) and the Yucatan Peninsula (YP). Furthermore, we compare RegCM4 simulated precipitation and temperature statistics with Mexican daily observations from the CLI-COM data set (Zhu and Lettenmaier 2007; Munoz-Arriola et al. 2009), which has a 0.12° resolution. Finally, we assess simulated tropical cyclone days against observations from the HURDAT best track database of the US National Weather Service National Hurricane Center (downloaded from the US National Weather Service National Hurricane Center online site: http://www.nhc.noaa.gov/pastall.shtml). Simulated wind fields are compared with the 1.5° resolution ERA-Interim (Dee et al. 2011) dataset.

Fig. 1 The Mexico and Central-America CORDEX domain topography and coastline at a grid spacing of 50 km
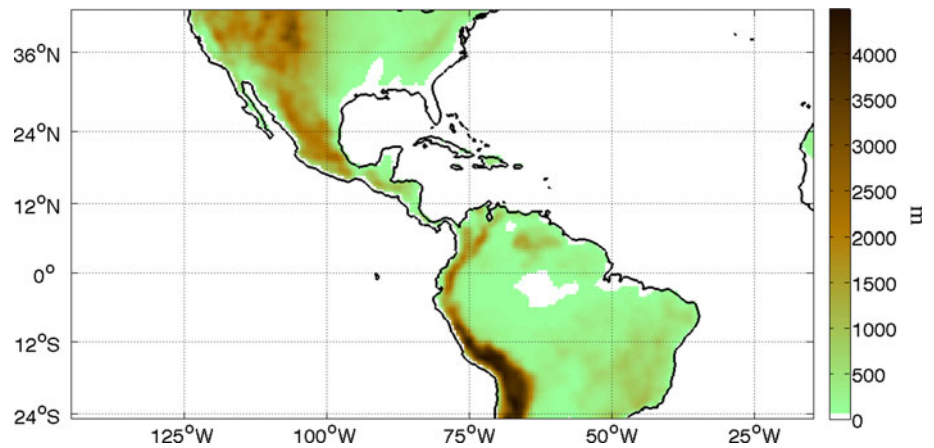
2.3 Statistical metrics of precipitation and temperature performance

Interannual variability is measured in terms of interannual standard deviation of seasonal values for temperature and interannual coefficient of variation (standard deviation divided by the mean) for precipitation. In terms of extremes, the metrics considered here (all calculated for the period 1982–2008) are: Annual 5 and 95 percentiles of daily temperature (T05 and T95), annual 95 percentile of daily precipitation (P95) (Diffenbaugh et al. 2005), and maximum dry spell length (MDSL) defined as the maximum number of consecutive days in a year with precipitation <1 mm. Finally, in order to assess the RegCM4 performance in reproducing the distribution of precipitation intensity, we compare observed and simulated frequency of events exceeding specific precipitation thresholds.

We also compare the simulated and observed spatial distribution of tropical cyclones. Several algorithms have been developed to detect cyclones from reanalysis of observations or from atmospheric models (see for example Manabe et al. 1970; Bengtsson et al. 1982; Broccoli and Manabe 1990; Haarsma et al. 1993; Bengtsson et al. 1995; Tsutsui and Kasahara 1996; Vitart et al. 1997; Walsh 1997; Vitart and Stockdale 2001, Walsh et al. 2004). These methods in general monitor when some chosen dynamical and thermodynamical variables, for example sea level pressure, vorticity, wind speed or precipitation, exceed thresholds determined from observed tropical storm characteristics. These studies have shown that models can reproduce some aspects of storm climatologies, such as geographical and temporal distributions. However, it has been reported that the intensity of simulated tropical

storms is weaker, and their spatial scale larger than observed because of low model resolution (Bengtsson et al. 1982; Vitart et al. 1997). Furthermore, threshold criteria taken from observed climatological values do not account for model biases and deficiencies. Camargo and Zebiak (2002) using their own detection algorithm demonstrated that the use of basin- and model-dependent threshold criteria improves the climatology and interannual statistics of model tropical cyclones. There is thus an element of customization in the selection of criteria for the identification of tropical storms in climate models.

Based on these considerations and on the characteristics of the simulated cyclones by RegCM4 we selected a series of variables that allowed us to identify most tropical cyclones generated in the domain. Specifically, we define a cyclone-day for a particular location as a day in which a tropical cyclone passes through a grid-point of our domain. Tropical cyclone conditions are identified when, at a given grid point, the following conditions are satisfied at least once during the day: wind speed ≥ 21 m s^{-1}, sea level pressure $\leq 1{,}005$ hPa, daily precipitation rate ≥ 15 mm day^{-1}. These days are then summed over the 27 year simulation to obtain the total number of cyclone days. The same variable thresholds are used to identify observed tropical storm data. In order to compare spatially observed and simulated tropical cyclones, we gridded the 6 hourly available observed HURDAT cyclone track information onto a 1° mesh covering the simulation domain. Following Weatherford and Gray (1988) the inner core of a cyclone extends from the center of the cyclone for a 111 km radius, so that, once we identify the center of the cyclone at a given grid point we consider the 8 surrounding 1-degree grid points to be part of the cyclone core. Although this
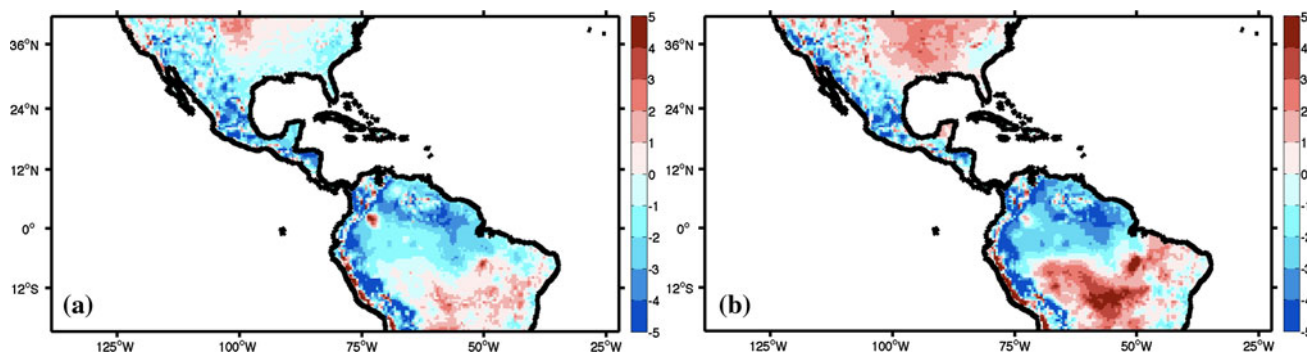
Fig. 2 Mean seasonal temperature biases of RegCM4 with respect to UDEL observations (RegCM4 simulation minus the observations) for **a** DJF and **b** JJA. The *colorbar* units are °C

procedure does not employ a formal cyclone detection and tracking algorithm, extensive visual tests showed that it is a simple way to identify most tropical depressions generated in the domain (see Sect. 3.5).

3 Results and discussion

3.1 Seasonal precipitation and temperature means over the Central-America CORDEX domain for the 1982–2008 period

Figure 2 shows for the entire domain the RegCM4 December, January and February (DJF) and June, July and August (JJA) temperature bias (defined as the difference of simulated minus observed value) compared with UDEL observations, while Fig. 3 shows the comparison of the observed and simulated seasonal mean precipitation and low level wind. Warm biases are found over regions of South America in DJF and over the central plains and the Yucatan peninsula in JJA, with the largest bias occurring over South America and in the Great Plains of the Unites States in JJA. Conversely, a cold bias is found over Northwestern Mexico and the Southwestern USA as well as the northern regions of South America, with largest the biases occurring along the main mountain ranges of the domain in both seasons, also likely because of a valley warm bias in the observations (see Fig. 2).

The RegCM4 simulation captures adequately the patterns of seasonal precipitation over the Central America region (see Fig. 3). In DJF, a slight northeastward shift of the simulated Inter-Tropical Convergence Zone (ITCZ) over the eastern Pacific Ocean (see Fig. 3e, f) generates a wet bias over the western Mexican and Central-American coasts and a dry bias over the western South American coast (Fig. 3). In addition, an atypical northward wind is observed over northern South America (compared to the ERA-Interim reanalysis), causing a wet bias in this region and a dry bias over most of Brazil (Fig. 3e). For JJA, the northward excursion of the ITCZ is not well resolved by RegCM4, and thus we find a negative bias of precipitation in the Tropical North-eastern Pacific Ocean west of the Mexican coast. This may be associated with an anticyclonic circulation anomaly formed over this region (Fig. 3f), which moves the area of convergence further south than observed. In the case of the Atlantic Ocean north of Brazil, a northward wind anomaly may be partially causing a wet bias over this region.

Focusing on Mexico, Figs. 4 and 5 show the mean observed and simulated temperature and precipitation during winter (DJF) and summer (JJA) along with their corresponding biases compared to the CLICOM dataset. The spatial pattern of the temperature is generally well reproduced by the model, except for a tendency towards a cold bias in mountainous regions (as may be seen also in Fig. 2). As mentioned previously, although this is partially related to the model precipitation bias (see Fig. 5), a contribution to this cold temperature bias is given by the smoothed model topography and the likely prevalence of valley observing stations. In general, Fig. 4e, f show that RegCM4 tends to underestimate temperature over most of Mexico with the exception of the two peninsulas (BC and YP) during the summer.

Concerning precipitation, the model shows a prevailing tendency to overestimate rainfall (compared with the CLICOM data) over the mountainous areas particularly during the summer, except for the NW, YP and BC regions (as also seen in Fig. 6) although much of the broad regional topographically induced spatial detail is captured. As was the case for temperature, we note that this bias may be
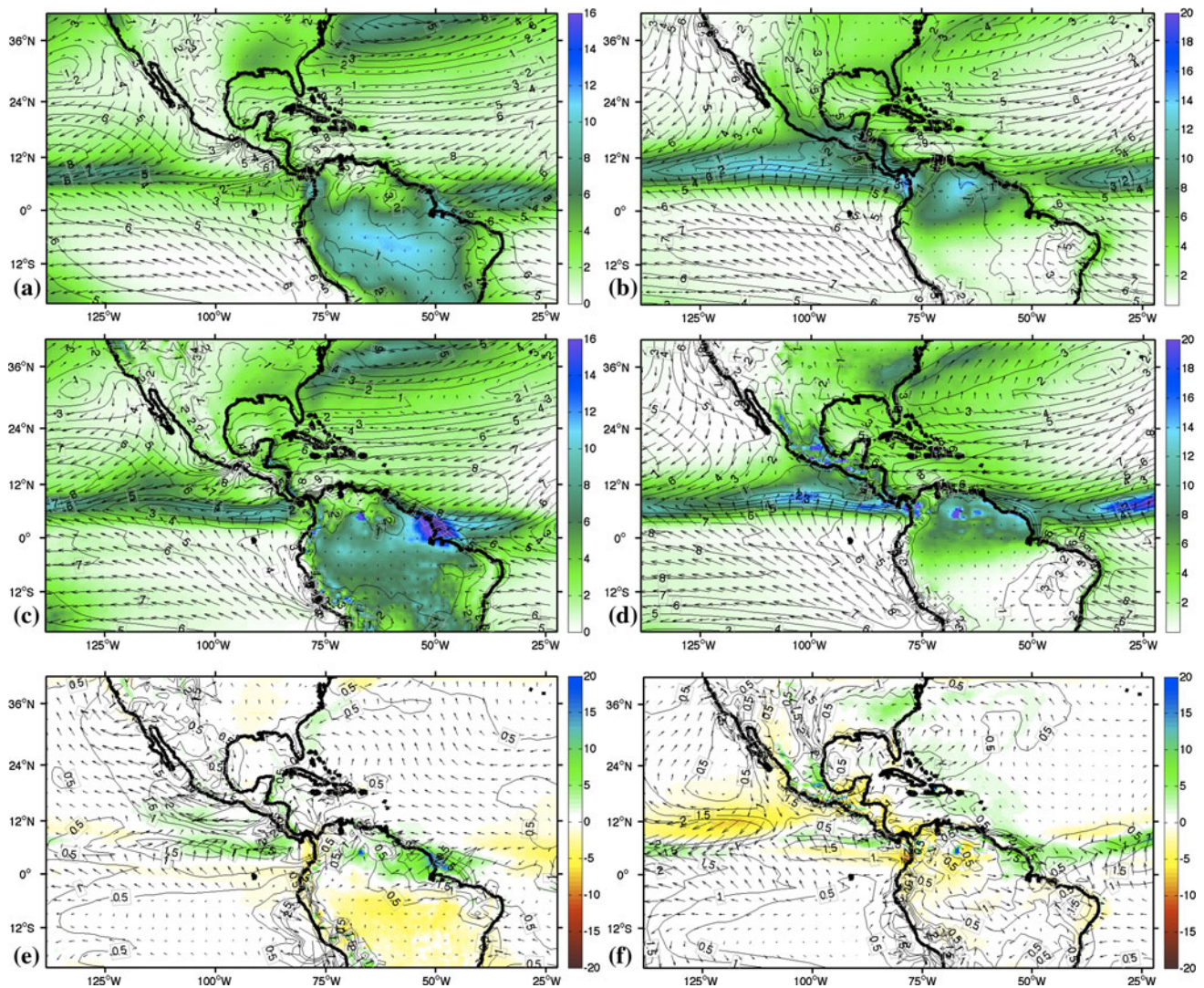
Fig. 3 a Seasonal average of daily precipitation from GPCP (*color-bar*) and mean wind circulation (*arrows*) from ERA-Interim reanalysis and **c** the corresponding RegCM4 simulation for the DJF season. **b**, **d** same as **a**, **c** but for the JJA season. **e**, **f** wind circulation and precipitation biases between observations and RegCM4 (showed as simulation minus observations) for DJF and JJA, respectively. Precipitation units are mm day^{-1}, wind contour's labels indicate the wind arrows speed in m s^{-1}

somewhat enhanced by the relative lack of high elevation observing sites. In addition, the CLICOM observations do not include any under-catch gauge correction that in winter and over mountain areas can be relatively large (Adam and Lettenmaier 2003).

For a more quantitative precipitation assessment, in Fig. 6 we show the annual cycle of observed (GPCP, CLICOM), ERA-Interim reanalysis and RegCM4 simulated precipitation for all sub-regions of Mexico (see Fig. 5). We find that RegCM4 is able to capture the annual cycle of precipitation over all regions, including regions of single and double rainy seasons separated by a summer dry period. Precipitation amounts are however overestimated over the SM, NE and CM regions and underestimated over the BC, NW and YP regions, while they are well reproduced over the NM region. We also note the good agreement between the CLICOM, GPCP and ERA-Interim datasets, although ERA-Interim gives the lowest precipitation amounts especially during the summer over the NW, CM and YP regions.

The underestimation of precipitation over Baja California (BC) during winter (see Fig. 5) may be related to the circulation biases, since the simulation shows a northward anomalous wind circulation (see Fig. 3) that may inhibit
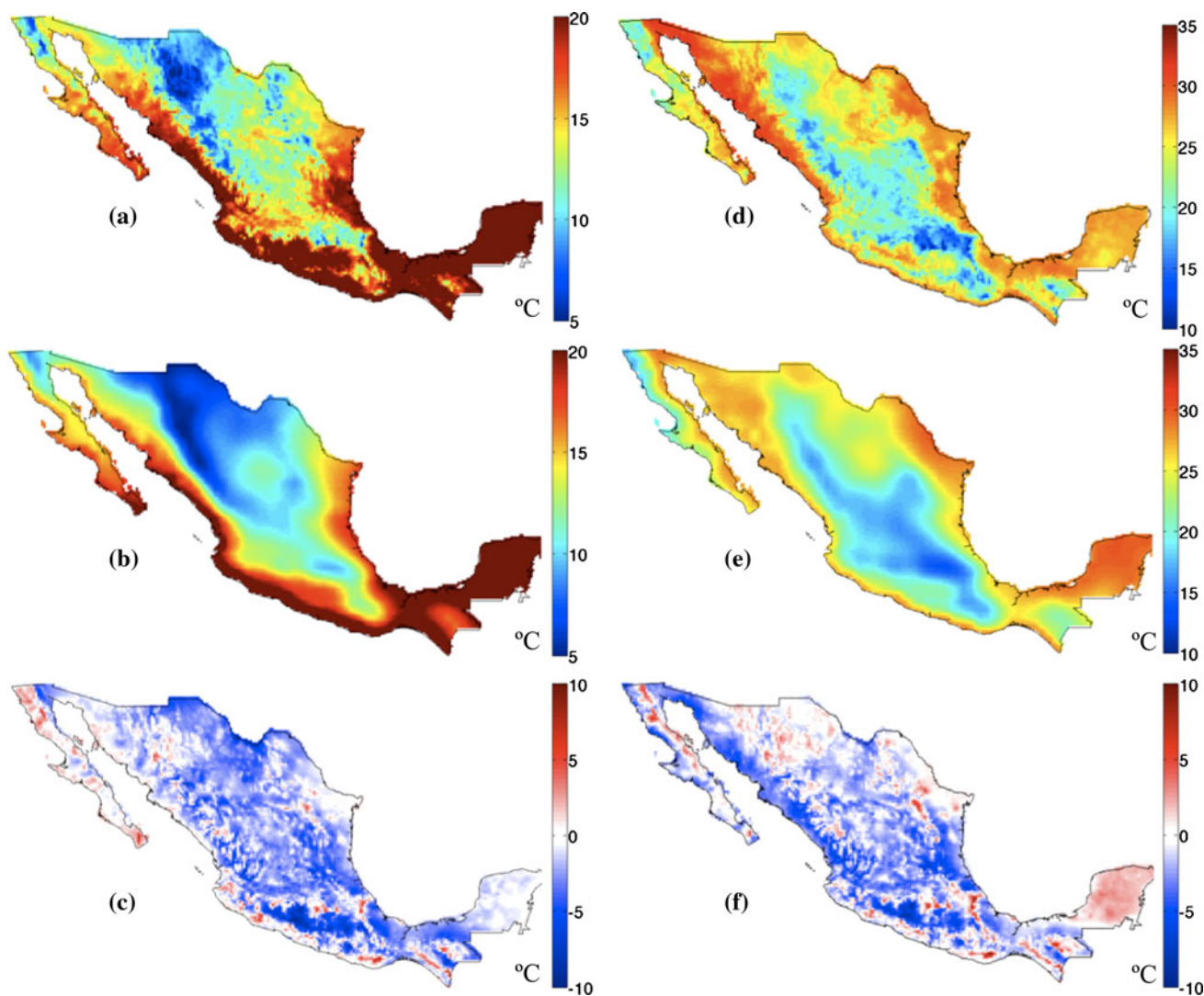
Fig. 4 **a** Seasonal DJF average of daily mean temperatures from the CLICOM dataset and **b** from the RegCM4 simulation. **d**, **e** same as **a**, **b** but for the JJA season. **c**, **f** temperature biases between CLICOM observations and RegCM4 for DJF and JJA respectively

advection of cold and moist masses over the BC. Conversely, the precipitation underestimation over the NW region may be due to the weakened land-sea thermal contrast in the simulation during the rainy season, which in turn may induce a weakening of the North American Monsoon (Turrent and Cavazos 2009). Figure 4 shows a cold bias in JJA that may cause a weakening of the thermal low that forces the advection of moist air from the Pacific Ocean. The overestimation of precipitation over the mountainous areas of the NE, CM and SM regions is likely tied to the land surface and convection schemes used. For example, Diro et al. (2012) show that the use of BATS tends to produce relatively high precipitation amounts and

that the simulation of precipitation over mountainous Central America is generally sensitive to the land and ocean flux surface physics schemes used in the model.

3.2 Interannual variability

In Figs. 7 and 8, we compare RegCM4 and CLICOM interannual variability metrics for temperature and precipitation, respectively. Note that the temperature standard deviations are calculated after detrending the data in order to remove the effect of long-term trends (e.g. due to global warming) during the simulation period. Figure 7 shows pronounced fine scale variations of the temperature variability, possibly indicating
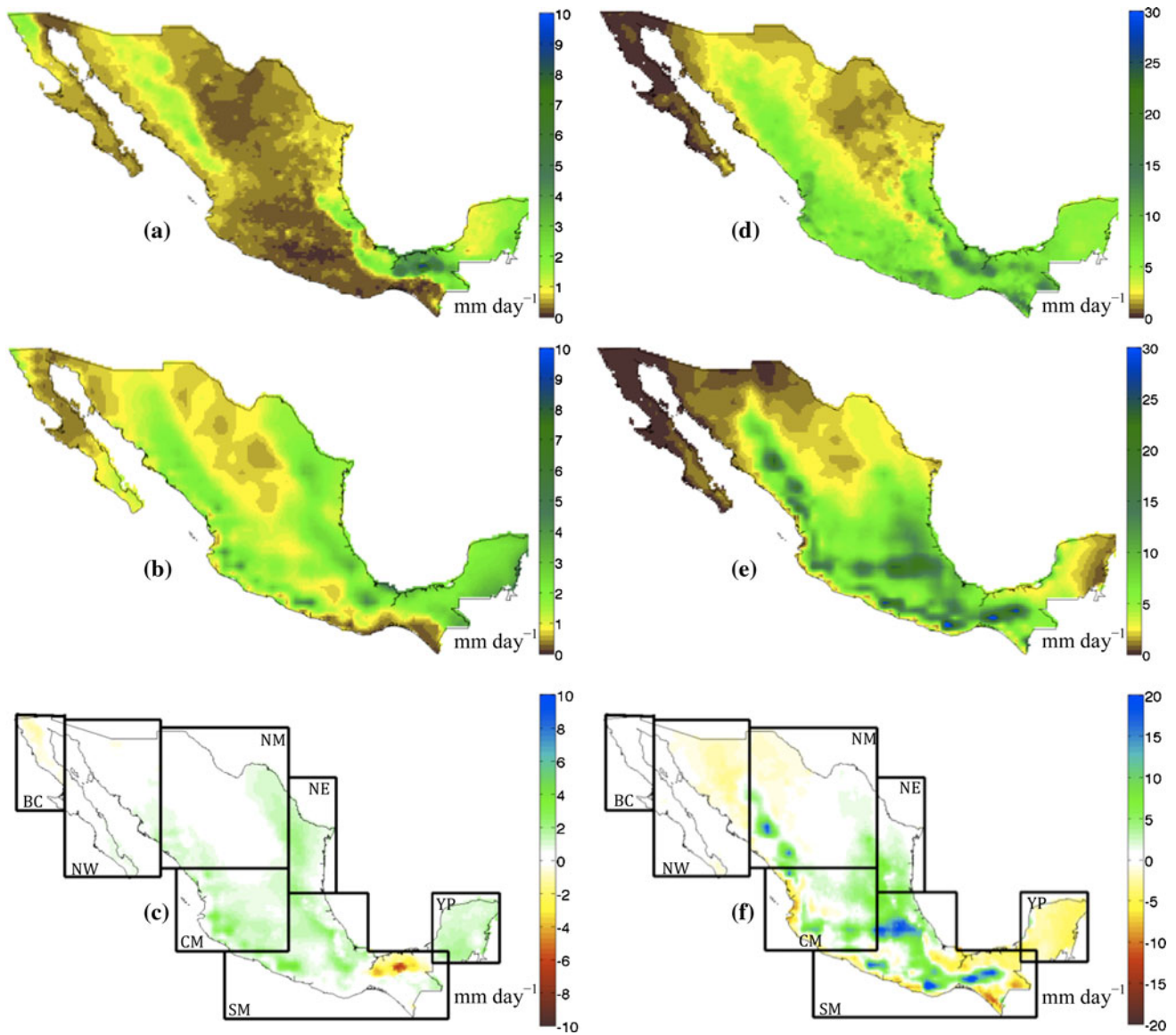
Fig. 5 a Observations of daily precipitation from the CLICOM dataset and **b** the corresponding RegCM4 simulation for the DJF season. **d**, **e** same as **a**, **b** but for the JJA season. **c**, **f** precipitation biases between CLICOM observations and RegCM4 for DJF and JJA, respectively. Enclosed on boxes are the sub-regions of Mexico in which the precipitation is analyzed: Baja California (BC), North-West Mexico (NW), Central-North Mexico (NM), North-East Mexico (NE), Central Mexico (CM), South Mexico (SM) and the Yucatan Peninsula (YP)

strong local effects, or alternatively problems in the dataset, given that usually temperature anomalies do not show such type of fine scale structure (Giorgi 2002). This is especially the case in Northeast Mexico and some mountainous regions, where the variability is much larger than in surrounding areas. On a broad scale, however, a reasonable agreement is found between the model and data. Similarly, for precipitation the CLICOM data show much finer spatial detail of variability than the model, but the broad regional patterns with higher variability in the north and lower in Central and Southern Mexico is captured.

Figures 9 and 10 compare RegCM4, ERA-Interim and CLICOM annual anomalies of temperature and precipitation averaged over the seven regions of Fig. 5. Also reported in this figure and summarized on Table 1 are the temporal correlations between the RegCM4 (or ERA-
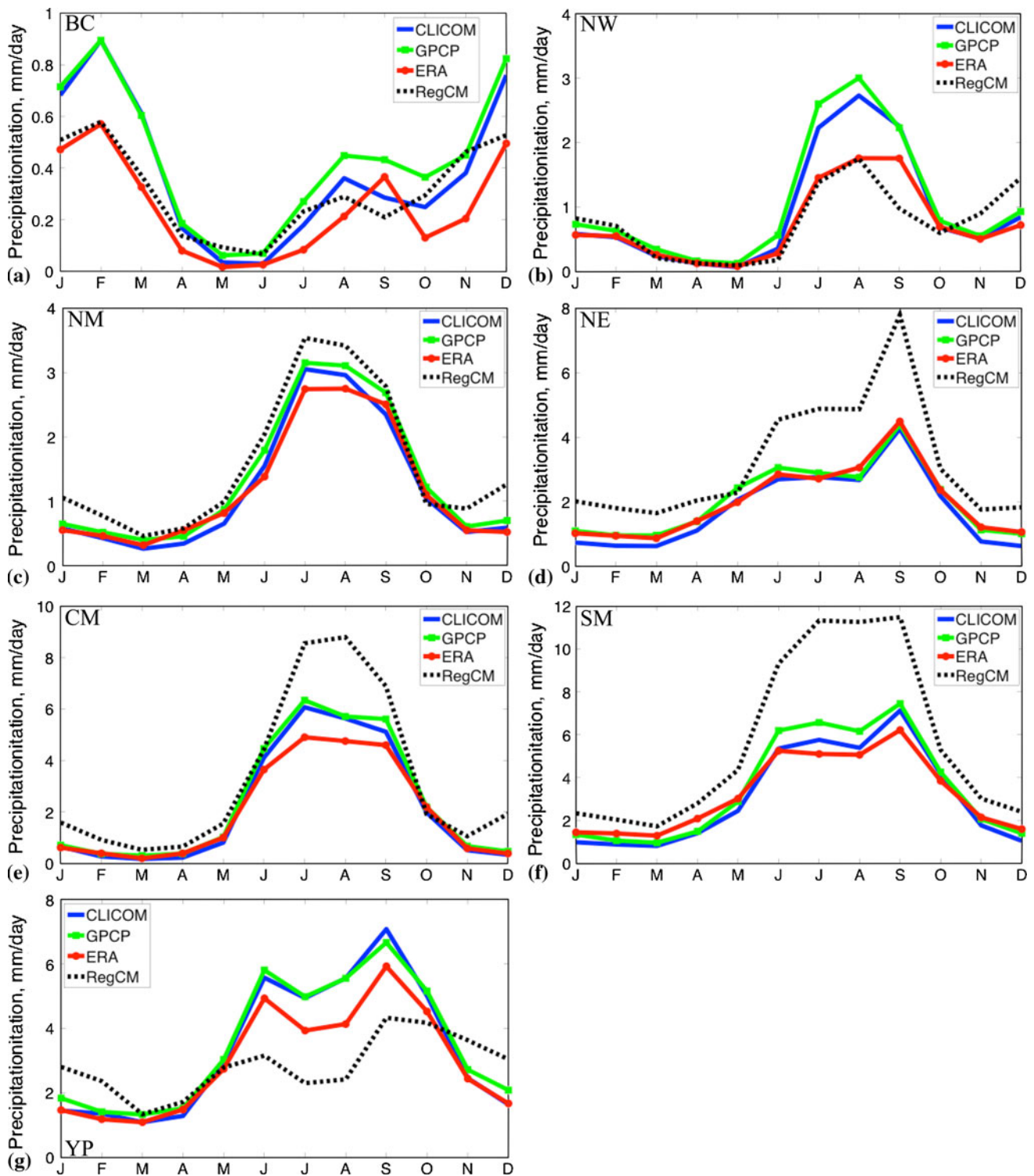
Fig. 6 Annual cycle of observed precipitation from GPCP (*green solid line with squares*) and CLICOM (*blue solid line*) datasets, ERA-Interim (*red solid line with dots*) and RegCM4 simulated precipitation (*dashed black line*) for BC (**a**), NW (**b**), NM (**c**), NE (**d**), CM (**e**), SM (**f**) and YP (**g**) regions for the 1982–2008 period
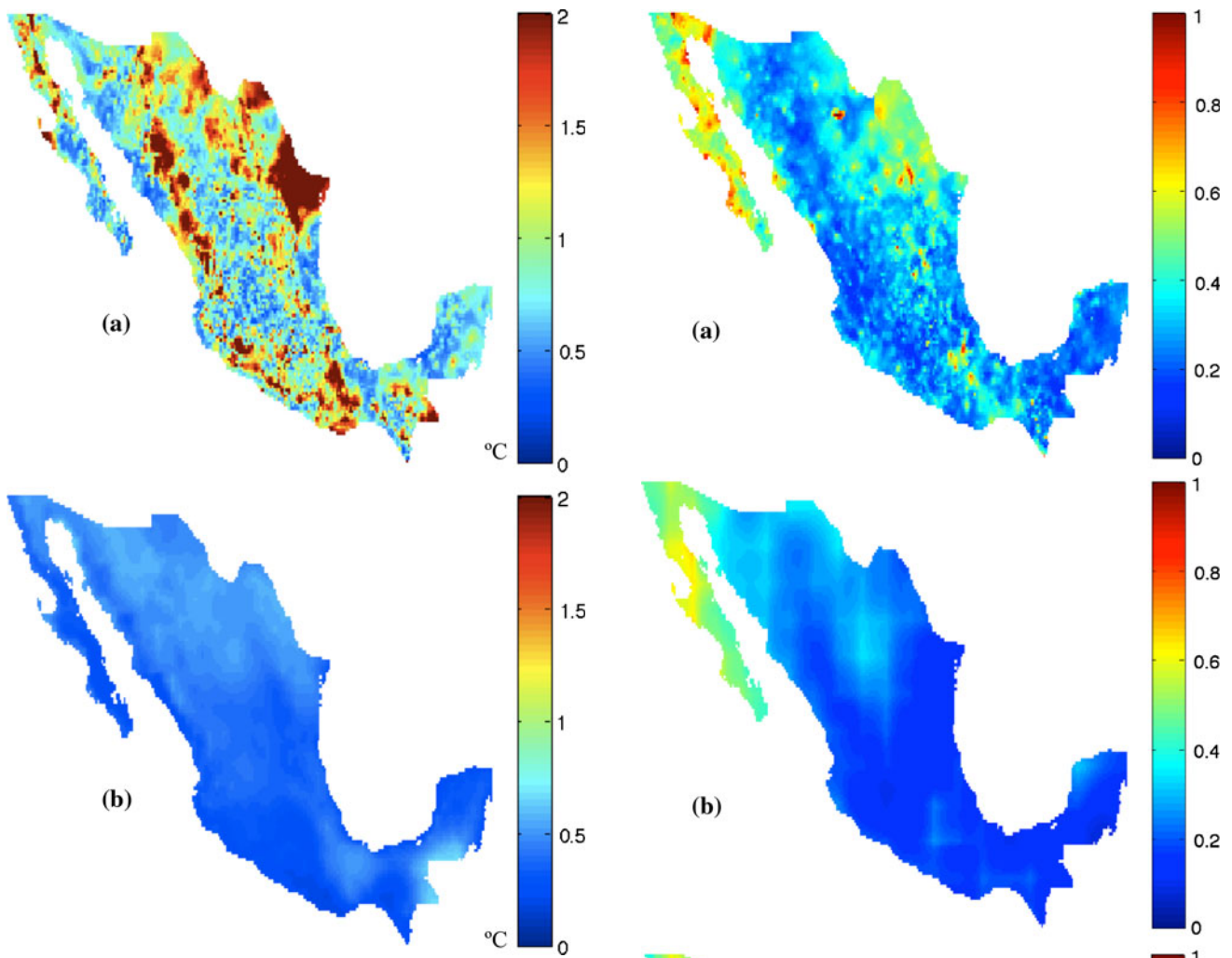
Fig. 7 Standard deviations of the mean annual temperatures from the de-trended CLICOM dataset (**a**) and the RegCM4 simulation (**b**) for the 1982–2008 period

Interim) anomalies and the CLICOM anomalies and the interannual variability metrics for each dataset. For temperature (see Fig. 9) we find that the CLICOM observations show substantial warming trends over a number of regions, particularly in central and northern Mexico (NW, CM, BC). RegCM4 and ERA-Interim capture these positive trends in temperature, although they appear to be somewhat underestimated compared with the trends observed in CLICOM (except over CM). Overall, the RegCM4 shows a better agreement with the CLICOM data than the ERA-Interim, both in terms of yearly anomaly correlations and interannual standard deviation. In particular, ERA-Interim shows systematically lower standard
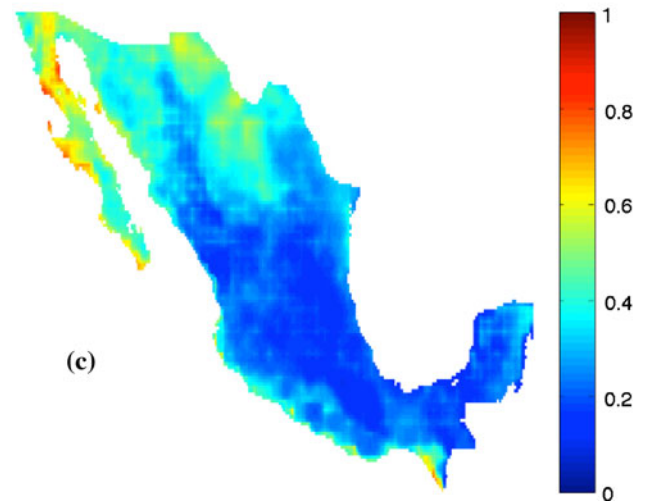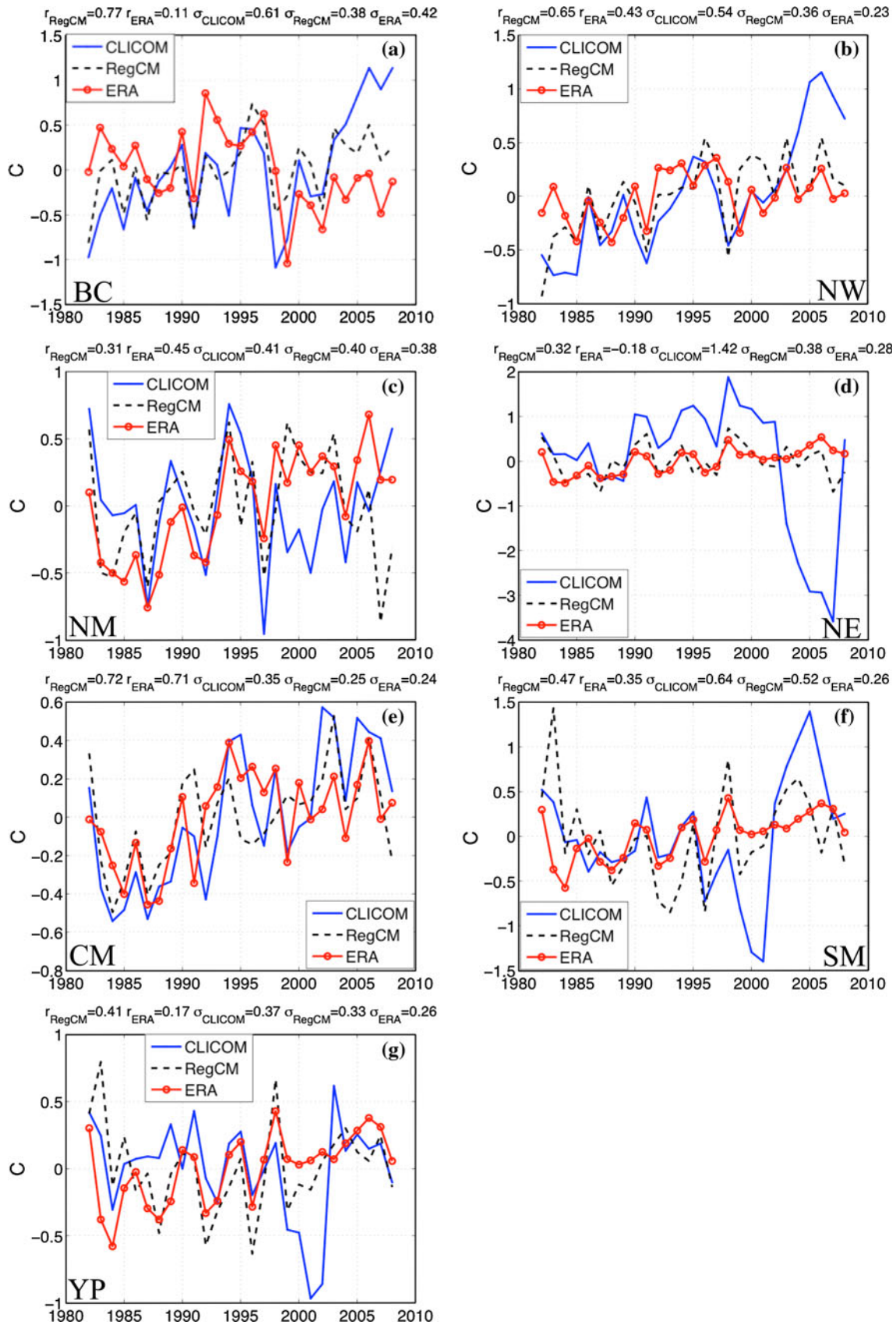

Fig. 8 Standard deviations of the annual precipitation from the CLICOM dataset (**a**), the ERA Interim reanalysis (**b**) and the RegCM4 simulation (**c**) for the 1982–2008 period

deviations than both CLICOM and RegCM4. We finally
note that over the regions SM and NE the CLICOM data
exhibit a very anomalous behavior in the latest part of the
record, perhaps an indication of problems in this portion of
the data (see also the large standard deviation values over
these areas in Fig. 7).

We find a different behavior in the northern versus the
central and southern Mexican regions for precipitation
variability (see Fig. 10). In the northern regions (BC, NM,
and NW) the model and ERA-Interim reproduce well the
CLICOM data in terms of both variability metric and
correlation. By contrast the correlations are low and the
interannual variability somewhat underestimated in the
other regions, where however the anomalous year 2003
heavily affects the CLICOM variability value (see
Table 1). Overall, if we do not consider the large variations
occurred in the recent record over some regions, the model
generally reproduces the observed interannual variability.

3.3 Daily precipitation intensity, P95 and MDSL over Mexico

Figure 11 shows the observed and simulated number of
daily events with precipitation intensity within given
thresholds divided by the total number of daily precipita-
tion events (normalized frequency of events). The CLI-
COM observations frequency is calculated with respect to
the total number of observed precipitation events (the sum
of the events from all the rainfall classes). Similarly, the
frequency of simulated events is calculated with respect to
the total number of simulated events for the 1982–2008
period. For the seven sub-regions of Mexico, RegCM4
captures reasonably well the frequency distribution for
each of the precipitation intensity classes, with only a small
overestimation of light precipitation events. In fact, we
found that the regions characterized by a wet bias in the
annual precipitation cycle (NE, CM and SM) (Fig. 5) also
exhibit an overestimation of the frequency of events with
precipitation <10 mm, indicating that in general the over-
estimation of the precipitation derives from low intensity
events.

The model reproduces the main spatial features of the
27-year average MDSL over Mexico for the total period
analyzed here (Fig. 12), showing an east–west gradient
with maximum MDSL (>120 days) in the dry West coast
and minimum (~20 days) over Eastern and Southern
Mexico. The overestimation of the MDSL over the YP and
NW mountainous regions is reflected in the annual cycle
for the regions discussed above (see Fig. 5). Similarly, the
underestimation of MDSL over SM and NE is consistent
with the overestimation of precipitation and frequency of
events with <10 mm/day over these regions. The spatial
pattern of average P95 for the 1982–2008 period (see
Fig. 13) is well reproduced by RegCM4, with the greatest
overestimation of P95 over the mountains and a slight
overestimation in the NE, CM and SM regions. The NM
and BC regions show the best model performance for this
metric.

3.4 T95 and T05 over Mexico

The RegCM4 simulation captures the T95 observed pat-
tern showing maxima values greater than 42 °C in
Northwestern Mexico and minimum values over the trans-
Mexican volcanic belt (see Fig. 14). The simulation shows
a warm bias (>3 °C) over the Baja California mountains
and over the Yucatan peninsula, while a cold bias is found
over the northwestern coasts. The RegCM4 model does
not capture the T95 fine scale patterns in regions of
complex terrain (Fig. 14) but this can be expected in view
of the relatively coarse resolution of the model. Never-
theless, in general RegCM4 reproduces reasonably well
the mean T95 pattern.

Similarly, the spatial pattern of T05 in RegCM4 is
similar to that in CLICOM (see Fig. 14) with the coldest
mean T05 values occurring in the northwestern mountains.
The warmest T05 values (>15 °C) are consistent in CLI-
COM and RegCM4 and occur over the southern and
southeastern states. The warm T05 bias in RegCM4 is
partly due to its relatively coarse resolution over complex
mountain areas, but it can also be affected by a north-
westward wind anomaly during DJF in the Pacific Ocean,
west of the Mexican coast (see Fig. 3), whereby cold air
masses crossing Mexico from the northwest may not be
adequately reproduced in the simulation.

3.5 Number of tropical cyclone days

As mentioned in Sect. 2, for the identification of tropical
storms, we did not use a formal storm-tracking detection
algorithm but a simpler ad hoc method based on mean sea
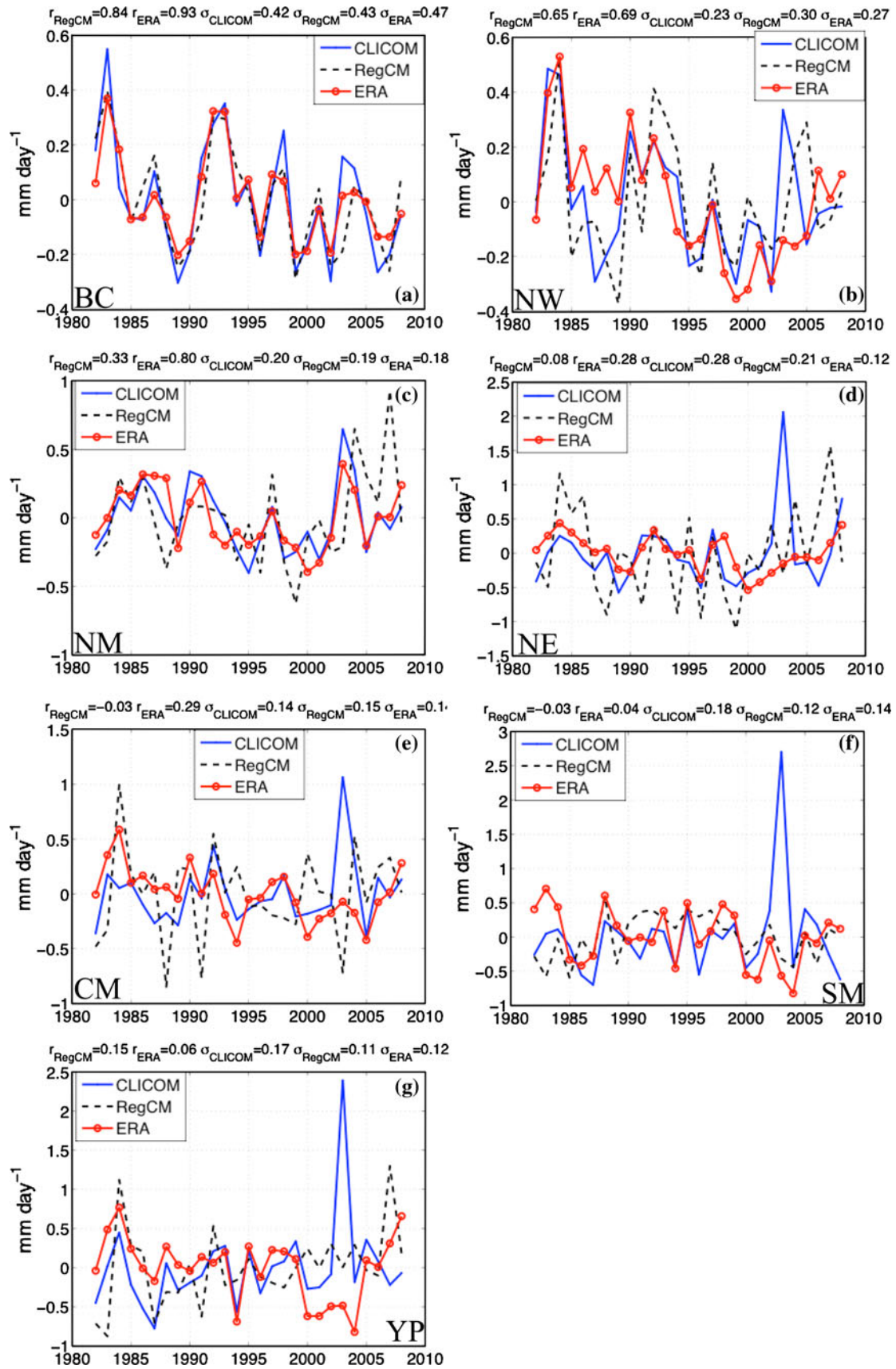
◄ **Fig. 10** Annual precipitation anomalies calculated from the CLI-COM observations (*blue solid line*), RegCM4 simulation (*black dashed line*) and from the ERA Interim reanalysis (*red line with circles*) over the BC (**a**), NW (**b**), NM (**c**), NE (**d**), CM (**e**), SM (**f**) and YP (**g**) regions. Anomalies are with respect to the 1982–2008 climatology

level pressure, precipitation and wind thresholds. Figure 15 illustrates a specific case of simulated cyclones occurring in both the equatorial Atlantic and Pacific basins as an example of how this method identifies storms. This shows that the model is able to capture intense closed tropical cyclonic systems without considering weak systems or systems of more extratropical structure.

The spatial distributions of the number of tropical cyclone days (NCD) in the 1982–2008 period based on this detection method in the model and observations are shown in Fig. 16. Overall, the model reproduces the observed patterns, with maxima in the western equatorial Atlantic and Gulf of Mexico as well as the eastern equatorial Pacific off the coasts of western Mexico. In the meridional direction, both RegCM4 and observations indicate that tropical cyclone days only occur north of 9°N in both the Atlantic and Pacific oceans. In the zonal direction RegCM4 shows the occurrence of some cyclone days east of 25°W, which are not found in the observations. Furthermore, RegCM4 does not produce cyclone days west of the meridian 128°W, where some cyclones are found in the observations.

Concerning the cyclone concentration, RegCM4 captures the area of large NCD density in the Equatorial Eastern Pacific, with a maximum of around 250 hurricane days within all the 1982–2008 period, but this area is smaller in RegCM4 than observed, indicating an underestimate of cyclone days. We analyzed two possible sources

of this bias: surface wind circulation and vertical wind shear. Regarding the former, during summer the simulation shows an atypical atmospheric anticyclone at low levels compared with the ERA-Interim reanalysis, which may be causing humidity divergence and inhibiting cyclogenesis. The RegCM4 underestimation of the NCD in the Equatorial Pacific Ocean is also reflected in the dry bias over this region (see Fig. 3).

Concerning the vertical wind shear, the underestimation of the NCD over the Pacific may be due to a somewhat stronger than observed wind shear between 200 and 850 hPa compared to ERA-Interim (Fig. 17). In fact, it has been reported that tropical cyclones are highly dependent on vertical wind shear, with cyclogenesis decreasing for vertical wind shear ≥ 12 m s^{-1} (Corbosiero and Molinari 2002; Gray 1968; Hanley et al. 2001).

On the other hand, over the Atlantic Ocean RegCM4 appears to produce more cyclone days than observed, which may be related to a weaker vertical wind shear over the Atlantic Ocean in the simulation (Fig. 17). It is worth to notice that the overestimation of the NCD in the Intra-American Seas and the Gulf of Mexico seems to generate more land-falling tropical cyclones over the Yucatan peninsula and Eastern Mexico. We should mention that mismatches between observations and simulation may be due to differing numbers or duration of events, but our analysis cannot separate these two factors.

Some uncertainties in the comparison of simulated and observed cyclones are obviously due to our detection method. We experimented with different pressure, precipitation and wind threshold criteria and even though the calculated NCD varied, the general conclusions deriving from Figs. 16 and 17 were not substantially modified.

Table 1 The second and third columns show the correlation (r) of CLICOM observations with ERA-Interim (ERA) and RegCM4 simulation for temperature (T) and precipitation (P) over each of the seven analyzed sub-regions shown in Fig. 5

Region	r(RegCM, CLICOM)		r (ERA, CLICOM)		σ CLICOM		σ ERA		σ RegCM	
	T	P	T	P	T	P	T	P	T	P
BC	0.77	0.84	0.11	0.93	0.61	0.42	0.42	0.47	0.38	0.43
NW	0.65	0.65	0.43	0.69	0.54	0.23	0.23	0.27	0.36	0.30
NM	0.31	0.33	0.45	0.80	0.41	0.20	0.38	0.18	0.40	0.19
NE	0.32	0.08	−0.18	0.28	1.42	0.28	0.28	0.12	0.38	0.21
CM	0.72	−0.03	0.71	0.29	0.35	0.14	0.24	0.14	0.25	0.15
SM	0.47	−0.03	0.35	0.04	0.64	0.18	0.26	0.14	0.52	0.12
YP	0.41	0.15	0.17	0.06	0.37	0.17	0.26	0.12	0.33	0.11

Columns four, five and six show the precipitation (mm day^{-1}) and temperature (°C) standard deviations (σ) for CLICOM, ERA-Interim and RegCM4
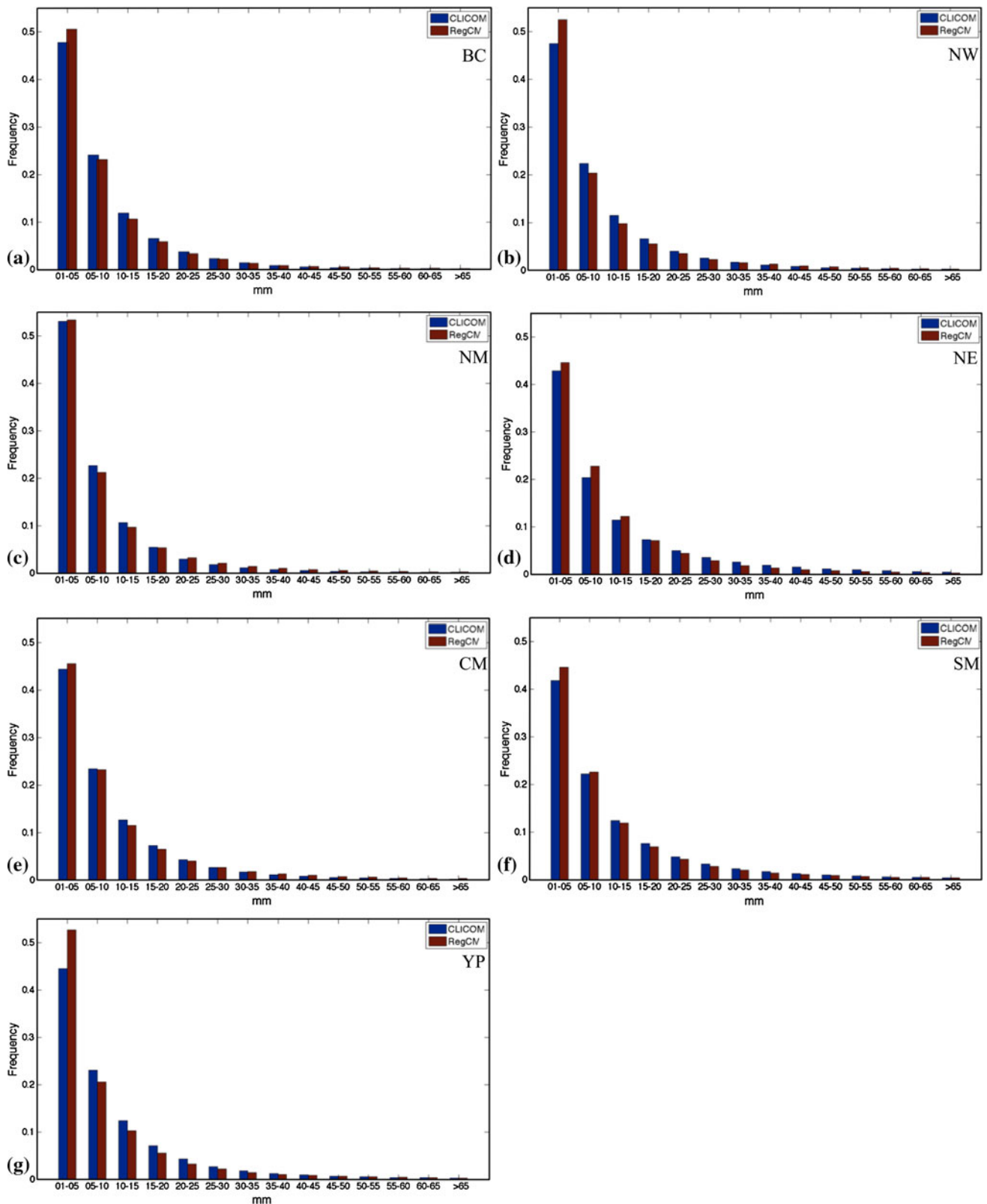
Fig. 11 Normalized observed and simulated distribution of daily precipitation according to different precipitation thresholds for BC (**a**), NW (**b**), NM (**c**), NE (**d**), CM (**e**), SM (**f**) and YP (**g**) regions. Frequency based on the total number of days with precipitation for the 1982–2008 period
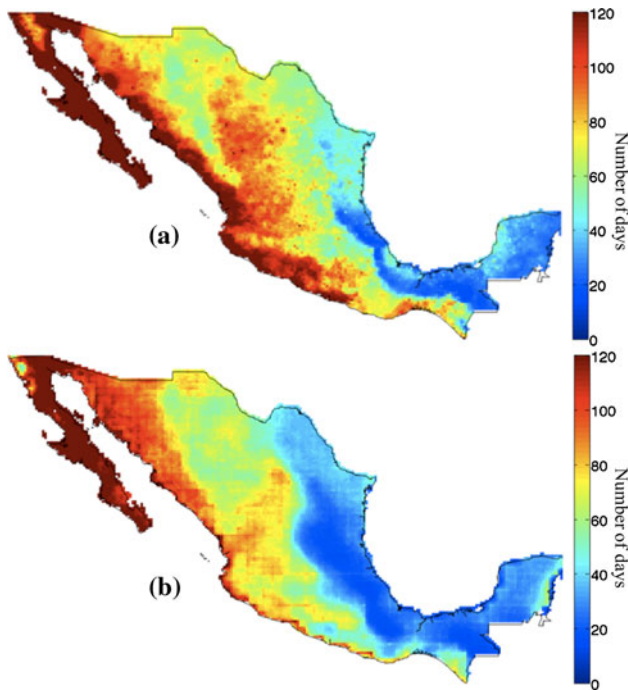
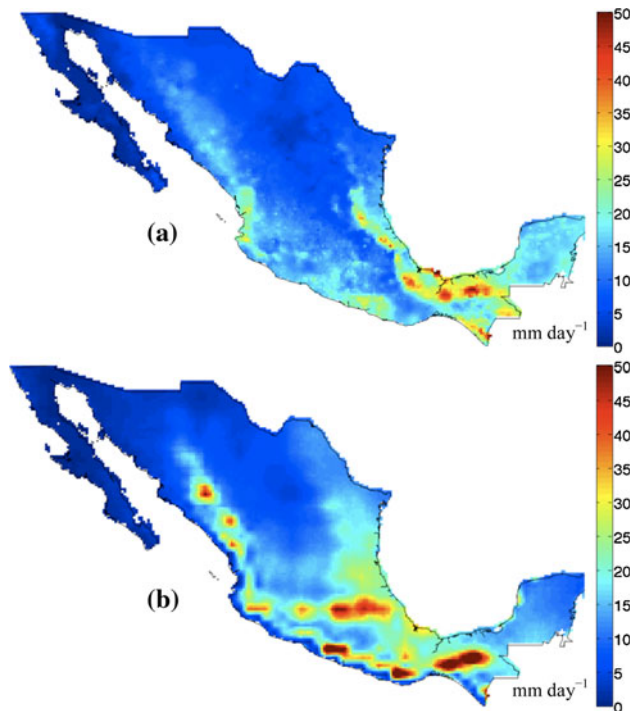**Fig. 12** Average of the maximum dry spell length (MDSL) 1982–2008, **a** observed and **b** simulated

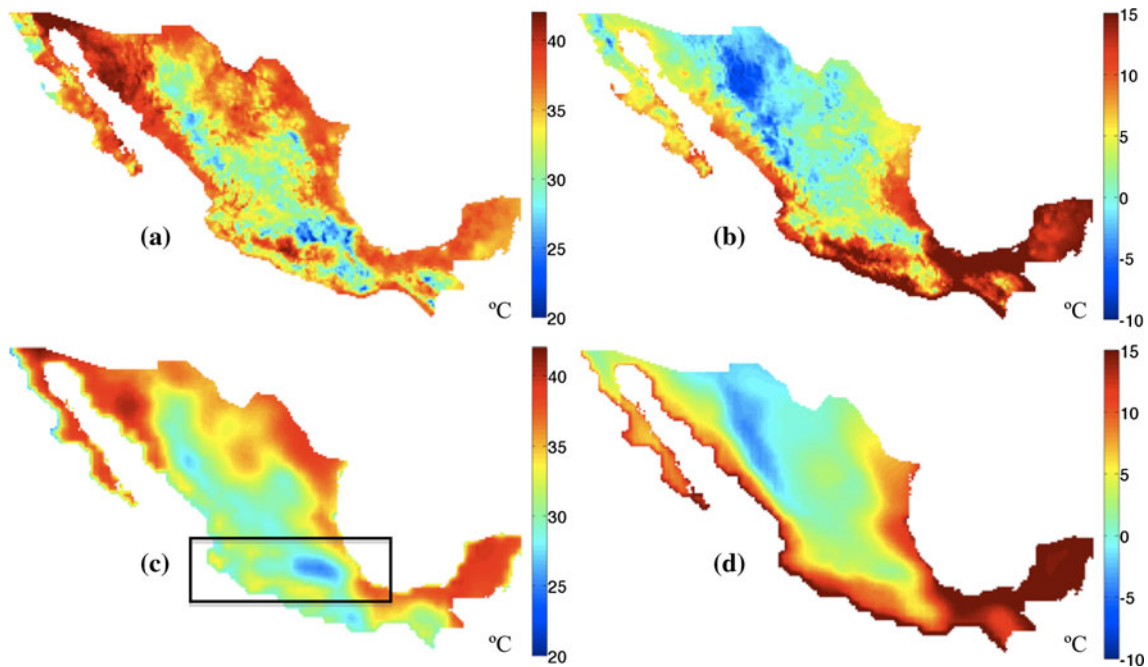**Fig. 13 a** Observed 1982–2008 average of annual P95 and **b** the corresponding RegCM4 simulation

Fig. 14 a Observed average of annual T95 and **b** T05 from CLICOM dataset. **c**, **d** same as **a**, **b** but for the RegCM4 simulation. The *rectangle* in **c** encloses the Trans-Mexican volcanic belt
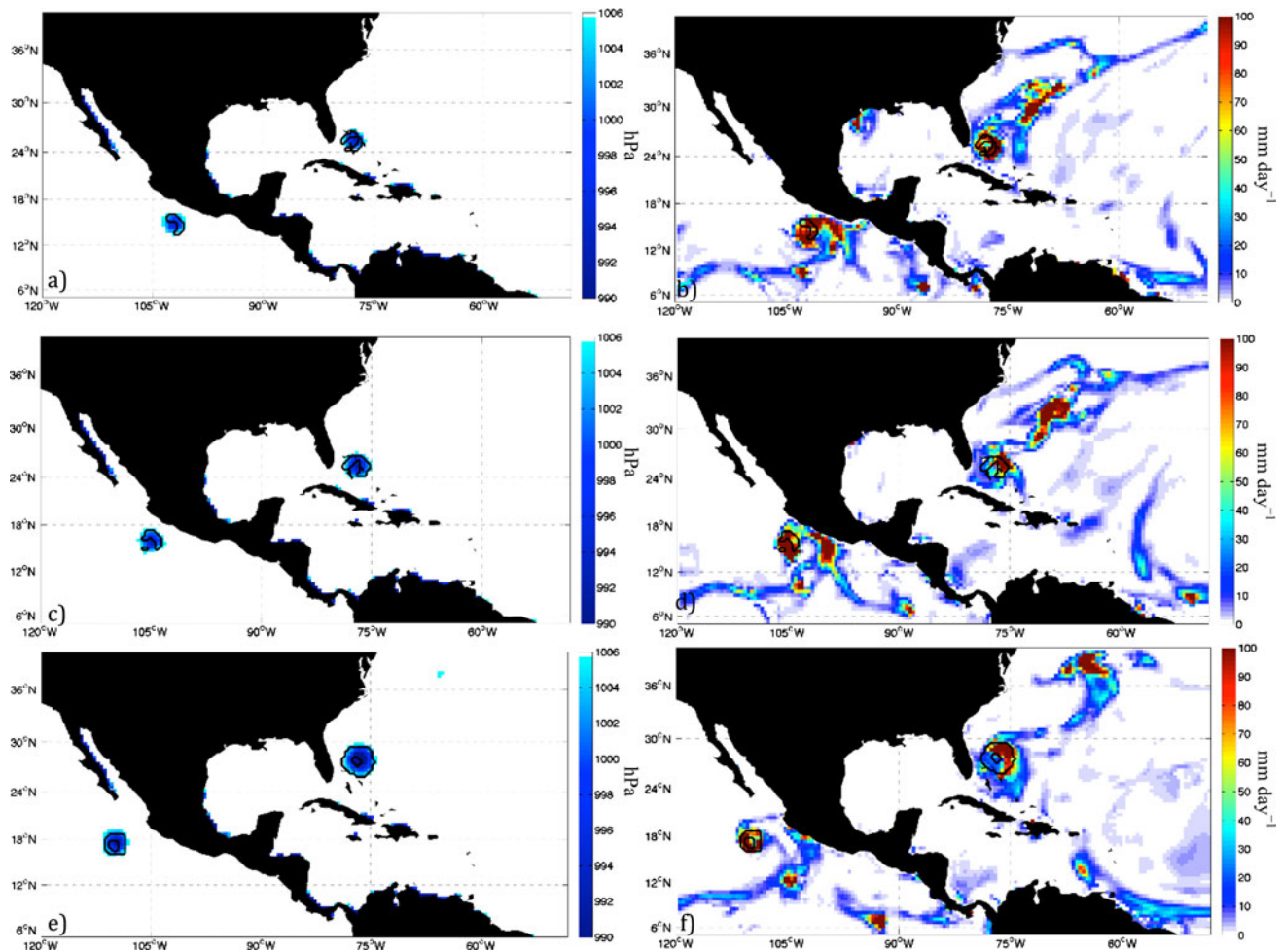
Fig. 15 Simulated tropical cyclones obtained with the following criteria: wind speed at 10 m $\geq$ 21 m s^{-1}, sea level pressure $\leq$1005 hPa, precipitation rate >15 mm day^{-1} and temperature at 2 m > 25 °C. **a, c** and **e** show the pressure field on August 25th, 26th and 27th, respectively. Contoured with *black solid lines* are the areas considered to have a tropical cyclone using these criteria. **b, d, f** show the corresponding precipitation field for the same dates as the pressure plots

4 Conclusions

We evaluated the skill of the regional climate model RegCM4 in reproducing different statistics of the climate of Central America and more specifically Mexico, as a preliminary step before using this model for climate change projections over this region. The model was run using the Central America CORDEX domain specifications and lateral boundary conditions from ERA-Interim reanalysis for the period 1982–2008. We analyzed both climate means and higher order statistics relevant to impacts over the region, such as interannual variability and extremes. Furthermore, we analyzed the model performance in simulating statistics of tropical cyclones.

The model generally reproduced the spatial patterns of mean temperature and precipitation, as well as their interannual variability and extremes. The main deficiencies of the model were found over mountainous terrain, where precipitation was overestimated mainly due to the high frequency of low-precipitation events. The biases are related to anomalies in the reproduction of circulation patterns, such as shifts in the ITCZ position with its consequent effect on humidity advection, along with possible shortcomings in the parameterization of convection over high mountains. Uncertainties in observations associated with sparse station density as well as lack of under-catch gauge correction most likely add uncertainty in the evaluation of the model.

On the other hand, the RegCM4 reproduced well the phase of the mean annual cycle of precipitation for all the sub-regions of Mexico, capturing in particular the midsummer drought over SM and YP regions. The model was also successful in reproducing the observed characteristics of interannual variability, particularly in the northern

Fig. 16 Number of tropical cyclone days (NCD) for the 1982–2008 period. **a** Observed from HURDAT and **b** from RegCM4 simulation
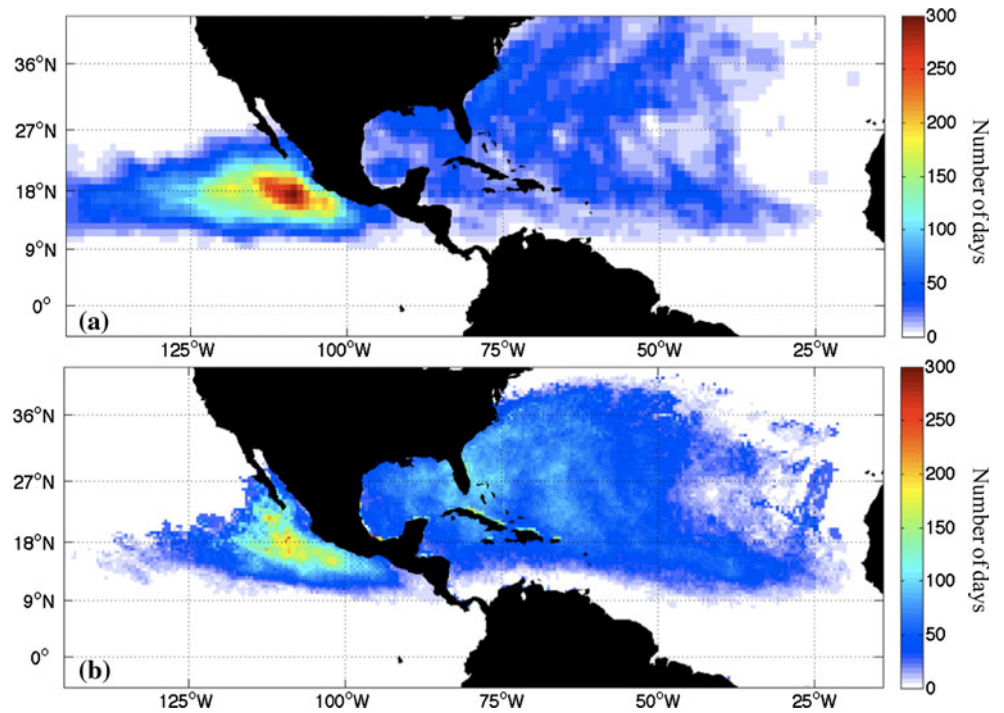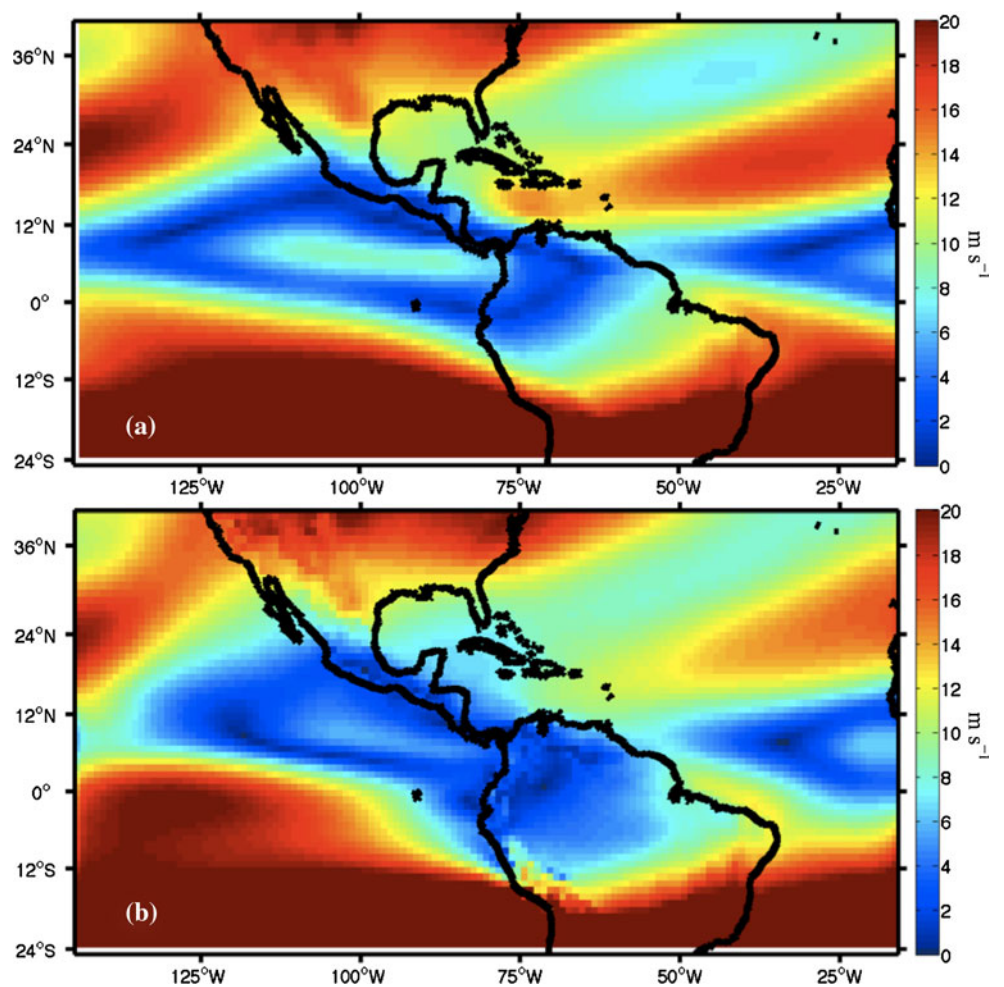

Fig. 17 Average of vertical wind shear between 200 and 850 hPa from June to November for **a** ERA-Interim reanalysis and **b** for RegCM4 simulation in the 1982–2008 period

regions of Mexico. The spatial patterns of extreme statistics such as P95, T05 and T95 and MDSL were also captured. Although local biases were found, the comparison of observed and simulated precipitation intensity distribution showed a good agreement, with the exception of an over-estimation of light precipitation events. The latter is a common problem in climate models related to the relatively coarse model resolution.

Concerning the occurrence of tropical cyclones, despite the relatively coarse model resolution and the simplicity of our detection method, we found that consistently with observations the model did generate realistic regions of tropical cyclone occurrence. The cyclone density was however underestimated in the Equatorial Pacific and overestimated in the Atlantic and Caribbean regions. Nevertheless, despite these biases, the model showed an encouraging performance in simulating tropical cyclones, which calls for detailed examination of this topic with improved detection and tracking algorithms.

Our analyses show that, in terms of climatological means as well as higher order statistics, RegCM4 is capable of providing realistic representations of Mexico and Central America climate. Therefore, in upcoming contributions, we shall apply this model to a series of climate-change projections over this region as part of the CORDEX program.

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