## Abstract

In this chapter, we performed a climatological study of the tropical cyclone (TC) precipitation in the satellite observations and the reanalysis from the ECMWF and NCEP/NCAR centers over the North Atlantic (NATL) basin. Using the recently developed best track IBTrACS (Kruket al. 2009; Knapp et al. 2009) we derived the mean daily TCs rainfall within $10^6 \times 10^6$ box around the center of the TCs, the fraction of TCs rainfall to total rainfall and the TCs precipitation efficiency (TCPE). These variables were used to assess the ability of the reanalysis to represent the impact of TCs in altering the total rainfall over the North Atlantic basin.
Chapter 4
Tropical Cyclones Rainfall in the Observations, Reanalysis and ARPEGE Simulations in the North Atlantic Basin

Anne S. Daloz, F. Chauvin, and F. Roux

In this chapter, we performed a climatological study of the tropical cyclone (TC) precipitation in the satellite observations and the reanalysis from the ECMWF and NCEP/NCAR centers over the North Atlantic (NATL) basin. Using the recently developed best track IBTrACS (Kruk et al. 2009; Knapp et al. 2009) we derived the mean daily TCs rainfall within $10^\circ \times 10^\circ$ box around the center of the TCs, the fraction of TCs rainfall to total rainfall and the TCs precipitation efficiency (TCPE). These variables were used to assess the ability of the reanalysis to represent the impact of TCs in altering the total rainfall over the North Atlantic basin. The main results show that:

- The maximum of cyclonic precipitation is located in the Caribbean Sea and the Gulf of Mexico, for the observation and the reanalysis.
- TCs contribute to a maximum of precipitation (between 15° and 25°N) over the Southern Gulf of Mexico, the Caribbean Sea and the West Atlantic Ocean for the observation and the reanalysis.
- The most efficient TCs are located in the Gulf of Mexico, the Caribbean Sea and the West Atlantic Ocean for the observation and the reanalysis.

We used a high resolution (0.5°) stretched atmospheric global climate model (GCM) ARPEGE to simulate the present and future TCs rainfall. The tracking of TCs was realized with the method of Chauvin et al. (2006). With the present integration, we assessed the ability of ARPEGE in simulating the TCs rainfall and the fraction and the efficiency of TCs rainfall. Future simulation has also been produced to study the possible evolution of those variables. The main results for the present and future simulations over the North Atlantic basin indicate that:

A.S. Daloz and F. Chauvin
CNRM, 42 av. G. Coriolis, 31057 Toulouse Cedex 1, France
e-mail: anne-sophie.daloz@cnrm.meteo.fr; fabrice.chauvin@meteo.fr

F. Roux
OMP, 22 av. E. Belin, 31400 Toulouse, France
e-mail: frank.roux@aero.obs-mip.fr

J.B. Elsner et al. (eds.), Hurricanes and Climate Change: Volume 2,
A.S. Daloz et al.

- ARPEGE detects the maxima obtained by the observations and the reanalysis for the TCs rainfall and the fraction. However, it overestimates them.
- ARPEGE obtains sparser results than the observations and the reanalysis for the efficiency of TCs, but detects the maxima over the West and East NATL Ocean.
- ARPEGE presents a sensitivity to the time period, consistent with the real variation of TCs activity.
- The difference between the future and present integration shows a decreasing contribution of the TCs rainfall and an increasing efficiency of TCs.

1 Introduction

Tropical cyclones (TCs) have a great impact on the environment. Rodgers and Adler (2001) showed in the NATL basin, that precipitation associated to TCs represents a small but significant amount of the total annual rainfall. Flooding produced by the TCs rainfall can be quite destructive; they are currently the leading cause of hurricane-related fatalities in the United States (Fitzpatrick 2006). Coastal communities devastated by strong hurricanes usually take years to recover. Inland flooding associated with TCs accounted for a majority (57%) of the 600 US deaths due to hurricanes between 1970 and 1999 (Rappaport 2000).

In the North Atlantic basin, the official hurricane season begins June 1 and ends November 30, although activity has been observed outside this time frame. Due to the changes of genesis location during the hurricane season (Neumann et al. 1999), the genesis patterns in the Atlantic and the Gulf of Mexico can be divided in tree categories (Fitzpatrick 2006): early season (June 1–July 15), mid-season (July 16–September 20), and late season (September 21–November 30). In the early-season, storms mostly occur in the Western Caribbean Sea and the Gulf of Mexico. Midseason storms originate in the main basin of the tropical Atlantic Ocean even if genesis still occur in the Gulf of Mexico, but not in the majority of cases, and is virtually nonexistent in the Caribbean Sea. The mid-summer genesis lull in the Caribbean Sea is possibly due to local enhancement of trade winds mixing the ocean in the area (Inoue et al. 2008) or because conditions favorable for dynamic instability only occur in the early and late season (Molinari et al. 1997). Genesis in the tropical Atlantic Ocean peaks in the midseason. Water temperatures are warm enough to immediately impact tropical waves propagating off the African continent. The late season witnesses a quick decline in the main basin of the tropical Atlantic Ocean. However the Gulf of Mexico experiences a more gradual decline and the Caribbean Sea a revival of storm formation.

According to the Fourth Intergovernmental Panel on Climate Change (IPCC 2007), it is difficult to distinguish any man-induced long-term trend of the cyclonic activity and scenarios for a warmer climate do not converge on any trend in the intensity or number of TCs. Most recent studies assessing the associated precipitation to TCs in the NATL basin indicate that an increase may be induced by a warmer climate (Lau et al. 2008). However, questions remain concerning the ability of the
TCs rainfall observed and simulated in the NATL basin.

Rodgers and Adler (1999) first estimated monthly TC rainfall using Special Sensor Microwave Imager (SSM/I) satellite data in the Western North Pacific (WNP) Ocean. They indicated that about 7% of the rainfall to the entire domain of the WNP from June to November is due to TCs and also that TCs rainfall contribute to a maximum of 40% off the lower Baja California. They also studied the impact of El Niño on the TCs rainfall, and they noticed that in general, TCs rainfall is enhanced during El Niño years. Dedicated to the WNP basin, Ren et al. (2006) studied the TCs rainfall using stations observations in China. They showed that in most of the southeastern regions, TCs rainfall accounts for more than 20–40% of the total annual precipitation. They suggested that China has experienced decreasing TCs rainfall influence over the past 48 years, presenting downwards trends of the TCs rainfall volume, the annual frequency of torrential events and the contribution of TCs rainfall. Wu et al. (2007) confirmed the decreasing influence of the TCs rainfall using station observations in the Hainan Islands. In the WNP basin, Kubota (2009) investigated the effects of TCs on seasonal and interannual rainfall variability by using rainfall data in stations. They showed that, in some regions, TC rainfall exceed 60% of the total rainfall. They also found that the interannual variability of the TC rainfall is primarily modulated by El Niño-Southern Oscillation (ENSO). Hasegawa and Emori (2005) used a relatively high resolution (1.1°) atmospheric GCM to simulate TCs rainfall within the WNP basin under present day and doubled CO₂ climates. They found an increase in mean TCs rainfall over Japan with doubling CO₂ despite an accompanying decrease in the frequency and intensity of TCs. In the NATL basin, Rodgers and Adler (2001) showed that the contribution was around 4% for the entire basin, but regionally could reach 30% in the northeast of Puerto Rico, 15°W, 55°W and off the west coast of Africa. During warm El Niño events TCs rainfall is inhibited. Larson (2004) used gridded daily rainfall analysis based on rain gauge observations and found that landfalling TCs contribute up to 15–20% of rainfall along the US Gulf and Mexican coast on average. Moreover they noted that tropical cyclone activity was modulated on both seasonal and intraseasonal time scales by the Arctic Oscillation (AO) and El Niño. During La Niña conditions with AO positive conditions, the atmospheric circulation is more conducive to activity in the main development region. Shepherd et al. (2007) studied the contribution of tropical cyclones to extreme rainfall in four mini-basins near coastal southeastern United States using satellite precipitation dataset (TRMM). They noticed that major hurricanes produce the most extreme rainfall days, but tropical depression/storm days contribute most significantly to cumulative seasonal rainfall (8–17%) and are thus more critical to assess trends. Lau et al. (2008) conducted a study with GPCP and TRMM rainfall data on the relationship between TCs and extreme rain events in the NATL and WNP basins. Results show that climatologically, TCs contribute to 8% of rain events and 17% of total rain amount in NATL, compared to 9% of rain events and 21% of rain amount in WNP. In the NATL basin, there is a positive trend in the contribution of TCs to extreme events. The last result is confirmed by Knight and Davis (2009)
for the Southeastern United States where they studied the contribution of tropical cyclones to extreme rainfall with surface observation station. They attributed this increase to the storm wetness (precipitation per storm), the storm frequency and storm duration driven by natural decadal oscillations or by large-scale warming of the environment. Based on the TRMM database, Jiang and Zipser (2009) studied the global, seasonal and interannual variations of the monthly TCs rainfall in the six basins of tropical cyclogenesis. For the NATL basin they found that, TCs contribute 8–9%, with a maximum contribution in September and more generally during La Niña years.

The next question that should be addressed is the manner in which reanalysis and GCMs simulate the influence of the TCs to the total North Atlantic rainfall. In a first part, we focus on the study of the TCs rainfall from the satellite observation and the reanalysis. The mean daily North Atlantic TCs rainfall is determined using the recently developed best track, IBTrACS. We also established two quantitative metrics for the cyclonic rainfall associated with tropical systems; the mean precipitation distribution of the TCs and the precipitation efficiency of the TCs. The second section is dedicated to the analysis of high resolution present and future (0.5°) stretched grid experiment using the tracking method presented in Chauvin et al. (2006). The final section provides conclusion and discussions.

2 Observation and Reanalysis

2.1 Datasets and Tracking Methodology

2.1.1 Datasets

Satellite Observations

- TRMM

  The Tropical Rainfall Measurement Mission (TRMM) (daily; 3B-42; 0.25° by 0.25° grid) is used to generate daily gridded precipitation data (Huffman et al. 2007). TRMM rainfall estimates are produced in four stages: (1) the microwave estimates precipitation are calibrated and combined, (2) infrared precipitation estimates are created using the calibrated microwave precipitation, (3) the microwave and IR estimates are combined, and (4) rescaling to monthly data is applied.

- GPCP

  The Global Precipitation Climatology Project (GPCP) (daily; 1DD; 1° grid by 1° grid) daily precipitation is produced at the NASA Goddard Space Flight Center. They used the geo-synchronous-satellite operators to collect histograms of geo-IR brightness temperature that allowed the estimation of the precipitation. To complete
TCs rainfall observed and simulated in the NATL basin. The global coverage, they estimated the precipitation outside of the geo-IR coverage using sounding data from low-earth polar satellites. The different methods employed for the construction of this dataset are detailed in Huffman et al. (2001).

**Reanalysis**

**ECMWF (European Centre for Medium-range Weather Forecasts) – Reanalysis**

- ERA-40

  A 44-year integration (1958–2001) ERA-40 product (daily, 1.12° by 1.12° grid) has been developed by the ECMWF. This dataset is obtained through a global spectral model with T159L60 truncation. ERA data are freely distributed to the scientific community, but after being downgraded to a lower resolution corresponding to a T95 truncation (2.5° resolution). Analysis involves comprehensive use of satellite data, starting 1972 and later including Cloud Motion Winds will be used from 1979 onwards. More details can be found in Uppala et al. (2005).

- ERA-Interim

  The ERA-Interim (daily, 1.5° by 1.5° grid) archive is more extensive than that for ERA-40. The number of pressure levels is increased from ERA-40’s 23 to 37 levels, main advances are done in the data assimilation and the sets of observations acquired for ERA-40 are supplemented by data for later years from ECMWF’s operational archive. Several of the problems experienced in ERA-40 have been significantly reduced in ERA-Interim such as the too-strong tropical oceanic precipitation beginning in the 1990s (Uppala et al. 2008).

**NCEP (National Center for Environmental Prediction / NCAR (National Center for Atmospheric Research – Reanalysis**

- NCEP-1

  This data archive is issued by NCEP/NCAR center, covering the period from 1948 to present. NCEP-1 reanalysis (daily; 2.5° by 2.5° grid) was provided by a global spectral model with T62 truncation and 28 vertical levels (T62L28; Kalnay et al., 1996).

- NCEP-2

  NCEP-2 (daily; 1.875° by 1.875° grid) is an improved version of the NCEP Reanalysis I model that fixes errors and updates parameterizations of physical processes. For a detailed explanation of the improvements see Kanamitsu et al. (2002).

**2.1.2 Tracking Methodology**

The NOAA National Climatic Data Center (NCDC) created a new global tropical cyclone 6-hourly best track dataset. The International Best Track Archive for
Climate Stewardship, IBTrACS is a global best track compilation dataset which contains information on all documented tropical cyclones which have been compiled and archived by many agencies from around the world. The methods used to combine the disparate datasets into a centralized repository of global TC best track data are detailed in Kruk et al. (2009) and Knapp et al. (2009).

2.2 TCs Rainfall

To assemble the mean daily TCs rainfall data, observations and reanalysis of TCs rain rates are used. Only the rain rates that are observed within a $10^5 \times 10^5$ box around the center of TCs are sampled. This TC rain-rate sampling area is chosen to encompass the majority of the rainfall that is contributed by TCs. The radius of a TC, defined by the location and area of threshold speed, varies widely (radii between 100 and 1,100 km have been observed) and is not necessarily proportional to TC intensity. Most of the time, the precipitation shield is found to be asymmetric, but for an objective procedure we supposed that the TCs rainfall were symmetric around the center. The radius of 5° around the center has already been tested by Englehart and Douglas (2001) who showed that the distance between the center of a TC and an outer edge of its cloud shield is between 550 and 600 km for 90% of the cases. Larson (2004) also did some sensitivity tests between 2.5° and 7.5° radius and found that radii smaller than 5° necessarily exclude much of the TCs-rainfall. Centers of the sampled tropical cyclones for the time of the observations and the reanalyses comes from IBTrACS data.

The precipitation associated with TCs is seen in Fig. 1 for TRMM (left panel) and GPCP (right panel) for 1998 to 2006, in the NATL ocean. Figure 1 shows that a TCs rainfall maximum is located in the Caribbean Sea and in the South-eastern part of the Gulf of Mexico, for both datasets. TRMM shows higher values (310 mm/year) in comparison with GPCP (240 mm/year). We can see that in the Honduras Bay, GPCP clearly underestimates the local maxima detected by TRMM. TRMM and GPCP also detect three rainfall maxima in the center of the Atlantic Ocean. They

Fig. 1 A plan view showing the TRMM (a) and the GPCP interpolated on the TRMM grid (b) North Atlantic TCs rainfall (mm/year) averaged over the time period 1998–2006
4 TCs rainfall observed and simulated in the NATL basin.

Fig. 2 A plan view showing the ERA-40 (a), ERA-Interim (b), NCEP-1 (c) and NCEP-2 (d) North Atlantic tropical cyclones precipitation (mm/year) averaged over the time period 1989–2001

are located around the latitude 18°N; on the French Antilles (64°W), at the longitudes 55°W and 46°W; attaining values between 160 and 220 mm/year. The highest values of TCs rainfall are obtained by TRMM. Differences in range of value between TRMM and GPCP must partly be due to the higher spatial resolution of the TRMM experiment.

Figure 2 presents the TCs rainfall calculated in the reanalysis from the ECMWF and NCEP/NCAR centres in the NATL Ocean. On the top left panel, we find ERA-40 and on the top right panel ERA-Interim for 1989–2001. A comparison of these two figures shows that ERA-40 TCs rainfall is globally higher than ERA-Interim, especially in the Caribbean Sea and the center of the NATL basin. A reason for this difference is explained in (Uppala et al. 2008). ERA-40 has a problem in term of humidity from the 1990s. Strong discrepancies have been detected over the oceanic domains, where values are more likely influenced by the physics of the atmospheric model and the method used for the extrapolation of unmonitored locations. Few values of RH850 are lower than 0%, but numerous are higher than 100%. The maxima encountered in Fig. 1 for the satellite observations, in the Caribbean Sea, the Gulf of Mexico and the French Antilles are also detected by ERAs datasets, but with a lower range of value, around 150 mm/year for ERA-40 (Fig. 2a) and 175 mm/year for ERA-Interim (Fig. 2b). Theses differences in range of value must partly be due to the change of time period between Figs. 1 and 2 from 1998–2006 to 1989–2001 respectively. However, it still remains an underestimate of TCs rainfall from the reanalysis. The lower resolution could also impact local maxima in the center of the NATL Ocean (18°N, 55°W) obtained by TRMM and GPCP (Fig. 1) because
they are not detected by the ECMWF reanalysis. Except the eastern maxima (Fig. 1, 18°N, 46°W) not detected by TRMM, GPCP and ERAs datasets which comes from the time period from 2002 to 2006. Figure 2 also shows the TCs rainfall calculated in two datasets of the NCAR/NCEP center in the NATL Ocean. Bottom left panel shows NCEP-1 and the bottom right panel NCEP-2 for 1989–2001. The maximum encountered in Figs. 1 and 2a, b on the Caribbean Sea, the Gulf of Mexico and the French Antilles are also detected by the NCEP datasets. NCEP-1 obtains a lower range of value in comparison with TRMM and GPCP, around 175 mm/year (Fig. 2c) and NCEP-2 (Fig. 2d) attains values in between the satellite observations with 270 mm/year. Both NCEP datasets miss the local maxima situated at 18°N, 55°W. It should also be noticed that a maximum appears for NCEP-1 and especially NCEP-2 in the Bay in front of Panama and Costa Rica that is not detected by ERAs reanalysis, it could be an artifact of the NCEP’s reanalysis.

Uppala et al. (2008) allows us to identify ERA interim as the more reliable dataset in comparison with ERA-40. The results from the Figs. 1 and 2 pointed out NCEP-2 with regard to NCEP-1. NCEP-2 is even closer than ERA-Interim to the results obtained by our reference TRMM in terms of amplitude and localization of TCs precipitation maxima. The differences between ERA-Interim and NCEP-2 come partly from the way of assimilating the satellite observations. NCEP-2 directly assimilates the rain rates from the instruments on the satellite TRMM, the TRMM Microwave Imager (TMI) and the Special Sensor Microwave Imager (SSM/I). On the other hand, ERA-interim only uses the data from the SSM/I instruments and they do not assimilate the rain rate but the humidity profiles obtained with the variance.

Figure 3 presents the TCs rainfall of ERA-Interim (Fig. 3a) and NCEP-2 (Fig. 3b) on the common time period from 1998 to 2006. Figure 3 confirms the good agreement between TRMM and NCEP-2 in amplitude and localization of the maxima of TCs rainfall. The amplitudes of the maxima from NCEP-2 in the North of the Caribbean Sea and the French Antilles islands is nearly the same as those obtained by TRMM (Fig. 1a). However, we should also notice that the maximum in the South of the Caribbean Sea detected by NCEP-2 and discussed in the precedent section seems to be an artifact of this dataset as we are now on the same time period, and

![Fig. 3](image-url) A plan view showing the ERA-Interim (a) and NCEP-2 (b) North Atlantic tropical cyclones precipitation (mm/year) averaged over the time period 1998–2006
TCs rainfall observed and simulated in the NATL basin.

Table 1  TCs rainfall averaged over the four regions defined in Fig. 4 for the satellite observations TRMM and GPCP, and the reanalysis ERAI and NCEP2

<table>
<thead>
<tr>
<th>TCs rainfall (mm/year)</th>
<th>NW-NATL</th>
<th>NE-NATL</th>
<th>SW-NATL</th>
<th>SE-NATL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM</td>
<td>68.43</td>
<td>18.73</td>
<td>81.53</td>
<td>55.17</td>
</tr>
<tr>
<td>GPCP</td>
<td>40.51</td>
<td>11.76</td>
<td>49.02</td>
<td>39.85</td>
</tr>
<tr>
<td>ERAI</td>
<td>54.99</td>
<td>15.90</td>
<td>85.79</td>
<td>53.90</td>
</tr>
<tr>
<td>NCEP2</td>
<td>89.79</td>
<td>16.81</td>
<td>128.24</td>
<td>62.67</td>
</tr>
</tbody>
</table>

Fig. 4  A plan view showing the map of the NATL basin with four boxes presenting the areas of studies: NW-NATL, NE-NATL, SW-NATL and SE-NATL

this maximum is not appearing in TRMM. In order to obtain a more objective vision of the performance of GPCP, ERA-interim and NCEP-2 in comparison with TRMM, we derived the mean TCs rainfall in different regions of the NATL basin presented in Table 1. The NATL basin has been divided in four areas as presented in Fig. 4. The coordinates of the regions are

- NW (North-Western) – NATL = 96–56°W and 22–30°N
- NE (North-Eastern) – NATL = 55–15°W and 22–30°N
- SW (South-Western) – NATL = 96–56°W and 5–21°N
- SE (South-Eastern) – NATL = 55–15°W and 5–21°N

Table 1 allows us to see that for the TCs rainfall in average, ERA-Interim seems to be closer to TRMM than GPCP and NCEP-2 in the four areas of study. The bias encountered for NCEP-2 in the Caribbean Sea is visible in the Table 1 as the value of TCs rainfall in the SW-NATL zone is the highest for NCEP-2. With Figs. 1 and 3, we noticed that in term of amplitude of maxima NCEP-2 offers the closest results to TRMM, but the Table 1 showed that in term of average, ERA-Interim seems to be closer.

As we have seen with the study of the Figs. 1 to 3, GPCP, ERA-Interim and NCEP-2 underestimate, miss or create some of the TCs rainfall maxima when comparing with TRMM. We hypothesized that these biases could be related to the higher spatial resolution of TRMM. The lower resolution of GPCP and the reanalysis datasets could have an effect on the winds and on the representativeness of the
different categories of TCs. Figure 5 presents the TCs rainfall associated with systems from Tropical Storms (TSs) to Category 2 of TCs for the satellite observations TRMM (Fig. 5a), GPCP (Fig. 5b), the reanalysis ERA-Interim (Fig. 5c) and NCEP-2 (Fig. 5d) for the time period 1998–2006 on the NATL basin. TRMM (Fig. 5a) shows the same maximum encountered in Fig. 1a, on the Caribbean Sea and local maximum in the center of the NATL basin (55°W and 46°W) but they attain lower values and are less spread. GPCP (Fig. 5b) presents the same maximum with an underestimate in comparison with TRMM, which is coherent with the results of Fig. 1b for the total TCs rainfall. ERA-Interim misses all the maximum obtained by TRMM and overestimates the TCs rainfall in the Honduras Bay. NCEP-2 (Fig. 5d) overestimates the maximum on the North of the Caribbean Sea and does not show those in the center of the NATL basin. NCEP-2 presents a maximum in the South of the Caribbean Sea assumed as an artifact, as it is present neither in TRMM, nor in GPCP. NCEP-2 also represents fairly well the maximum in the Main Development Region (MDR) except that it is located too West.

Figure 6 presents the precipitation from intense TCs (Category 3 to 5) for TRMM (Fig. 6a), GPCP (Fig. 6b), ERA-Interim (Fig. 6c) and NCEP-2 (Fig. 6d) from 1998 to 2006 in the NATL basin. TRMM presents a maximum of precipitation for intense TCs in the North of the Caribbean Sea with the maximum cumulated value equal to what is obtained at the same place for weak TCs (TS to Category 2). GPCP, ERA-Interim and NCEP-2 find the same maxima with nearly the same rain rate as TRMM for NCEP-2, but GPCP and ERA-Interim present an underestimate. The maxima on
4 TCs rainfall observed and simulated in the NATL basin.

Fig. 6 A plan view showing the TRMM (a), GPCP (b), ERAI (c) and NCEP-2 (d) North Atlantic tropical cyclones precipitation (mm/year) averaged over the time period 1998–2006 for the systems from Category 3 to 5 on the Saffir–Simpson scale

the center of the NATL basin are nearly the same for GPCP in comparison with TRMM, however NCEP-2 and ERA-Interim missed it, except the one on the French Antilles.

Figures 1 to 6 present the tropical cyclonic precipitation in satellite observation and reanalysis. They suggest that the tropical cyclone rainfall maxima are concentrated in the subtropical latitudes from the middle NATL basin, toward the Gulf of Mexico. No TC rainfall is found off the west coast of Spain and Africa and equatorward of 5°N latitude. The regional area with the greatest tropical cyclone rainfall occurs in the Caribbean Sea and the Gulf of Mexico. Many weak and intense TCs are born and intensify in this region. Local maximum are also found in the center of the NATL Ocean. For example around the French Antilles, which is a region where many TCs recurve and momentarily intensify. We also noticed that the values of the maxima of TCs rainfall are higher for the satellite observations in comparison with the reanalysis; this is especially true for TRMM. The dissimilarities between the datasets are partly due to a difference of spatial resolution which create discrepancies in the representation of weak and intense TCs.

2.3 Fraction of TCs Rainfall

The fraction of TCs rainfall is defined as the ratio of tropical cyclone rainfall to total rainfall multiplied by one hundred. Figure 7 presents the geographical distribution of the percentage of rainfall contribution by TCs over the NATL basin for 1998–2006 for the satellite observations TRMM (Fig. 7a) and GPCP (Fig. 7b), ERA-Interim
Fig. 7 Fraction of TCs rainfall (%) in the NATL basin for 1998–2006 for: TRMM (a), the GPCP interpolated on the TRMM grid (b), ERA-Interim (c) and NCEP-2 (d). In the eastern NATL Ocean (12–20°N; 56–30°W), there is a broad region where the contribution of TCs rainfall is high for TRMM (Fig. 7a), GPCP (Fig. 7b), ERA-Interim (Fig. 7c) and NCEP-2 (Fig. 7d). The satellite observations obtain values between 30% and 40%, the reanalysis between 20% and 25%. This result shows that the area where contribution of TCs rainfall is the highest (eastern NATL) is not necessarily the region of highest TCs rainfall rates (cf. Fig. 1, western NATL). In the western NATL Ocean, the contribution of TCs rainfall is not negligible as it reaches around 30% for TRMM, 20% for GPCP and NCEP-2, and 10% for ERA-Interim. The fraction is lower as others mechanisms such Mesoscale Convective Systems (MCSs, Houze, 1988) contribute to the total rainfall. It should also be noticed that a large area (green in the figures) for the four datasets presents no negligible values of fraction, as it attains values around 10% of the total rainfall.

Table 2 presents the averaged fraction of TCs rainfall for the observations and the reanalysis on the four areas of study defined in Section 2.2. In average for the four regions, all the datasets underestimate the fraction of TCs rainfall from TRMM. The closer results on the four regions are obtained by NCEP-2 in comparison with TRMM even if it is underestimated; GPCP and ERA-Interim are both under NCEP-2. These results put in evidence the good results of NCEP-2 in terms of maximum and average for the fraction of TCs rainfall, that is maybe due to the way of assimilating the precipitation. Table 2 also shows that GPCP and the two reanalysis datasets obtain a too low contribution of TCs rainfall to total rainfall.
TCs rainfall observed and simulated in the NATL basin.

### Table 2
Fraction of TCs rainfall (%) averaged over the four regions defined in Fig. 4 for the satellite observations TRMM and GPCP, and the reanalysis ERAI and NCEP-2.

<table>
<thead>
<tr>
<th>Fraction (%)</th>
<th>NW-NATL</th>
<th>NE-NATL</th>
<th>SW-NATL</th>
<th>SE-NATL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM</td>
<td>7.5</td>
<td>3.48</td>
<td>8.47</td>
<td>10.11</td>
</tr>
<tr>
<td>GPCP</td>
<td>4.83</td>
<td>2.17</td>
<td>5.64</td>
<td>7.38</td>
</tr>
<tr>
<td>ERAI</td>
<td>5.07</td>
<td>2.04</td>
<td>5.81</td>
<td>6.60</td>
</tr>
<tr>
<td>NCEP2</td>
<td>6.71</td>
<td>2.13</td>
<td>6.88</td>
<td>7.75</td>
</tr>
</tbody>
</table>

### 2.4 Tropical Cyclonic Precipitation Efficiency – TCPE

We defined the TCs precipitation efficiency (TCPE) as the mean precipitation per day of TCs. TCPE is equal to the precipitation associated with TCs, divided by the number of days of TCs activity over each grid point in a $10^\circ \times 10^\circ$ box of precipitation. The unit of this variable is mm/TC day. Figure 8 presents the TCPE over the NATL basin averaged over the time period 1998–2006 for TRMM (Fig. 8a), GPCP (Fig. 8b), ERA-Interim (Fig. 8c) and NCEP-2 (Fig. 8d). A maximum over the Southern Gulf of Mexico and the Caribbean Sea is detected by TRMM (30 mm/TC day), GPCP (35 mm/TC day) and NCEP-2 (30 mm/TC day). TRMM also detects a maximum of TCPE in front of the West African coast (20 mm/TC day). In this area GPCP (30 mm/TC day) and NCEP-2 (36 mm/TC day) also find a maximum but they overestimate it, as it is higher and further spread. Globally, GPCP is overestimating the TCPE. NCEP-2 has a maximum in the South of the Caribbean Sea, but as we have seen with the TCs rainfall Figs. 1a and 3b, it is an artifact of the reanalysis. In the Western NATL basin, all the datasets obtain a maximum off the West African coast, but NCEP-2 (Fig. 8d) overestimates it.

Table 3 presents the TCPE for the four regions of the NATL basin described in Section 2.2 for the satellite observations and the reanalysis for the time period 1998–2006. ERA-Interim is closer to TRMM but still underestimates the Northern region and overestimates the Southern region. These results show a better agreement between ERA-Interim and TRMM than from GPCP and NCEP-2 with TRMM for the average of TCPE.

The results obtained in Figs. 1 to 8 show that in the Gulf of Mexico and the Caribbean Sea, we have a maximum of tropical cyclonic precipitation (Fig. 1 to 6) certainly due to the high efficiency of the TCs in this region (Fig. 8). However the contribution of TCs rainfall to total rainfall is not the highest in the western NATL basin (Fig. 7), even if it is not negligible as it varies between 10% and 25%. Nevertheless in this area other mechanisms are highly contributing to the total rainfall. It should be noticed that, the regions where the fraction is over 10% and the TCPE is over 10 mm/TC day are inhabited area such as the South of Florida, Cuba and the French Antilles. In the eastern part of the NATL basin, we do not find such high values of TCs rainfall (Fig. 1 to 6) and TCPE (Fig. 8) but the fraction is really elevated (Fig. 7) due to the type of precipitation in this area. The rainfall in this region
Fig. 8 Tropical cyclonic precipitation efficiency (TCPE, mm/TC day) in the NATL basin for 1998–2006 for: TRMM (a), the GPCP interpolated on the TRMM grid (b), ERA-Interim (c) and NCEP-2 (d).

Table 3 TCPE averaged over the four regions defined in Fig. 4 for the satellite observations TRMM and GPCP, and the reanalysis ERAI and NCEP2.

<table>
<thead>
<tr>
<th></th>
<th>NW-NATL</th>
<th>NE-NATL</th>
<th>SW-NATL</th>
<th>SE-NATL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM</td>
<td>6.16</td>
<td>12.16</td>
<td>5.2</td>
<td>8.4</td>
</tr>
<tr>
<td>GPCP</td>
<td>2.32</td>
<td>5.76</td>
<td>1.88</td>
<td>2.08</td>
</tr>
<tr>
<td>ERAI</td>
<td>7.48</td>
<td>4.00</td>
<td>8.4</td>
<td>12.28</td>
</tr>
<tr>
<td>NCEP2</td>
<td>5.60</td>
<td>9.52</td>
<td>6.04</td>
<td>7.52</td>
</tr>
</tbody>
</table>

comes in majority from the tracks of the just born TCs from the West African continent. The fraction and the TCPE have allowed us to indicate the areas where TCs are the most dangerous in term of precipitation and through the possible spot of floods. These two variables have also permitted us to test the different datasets of satellite observations and reanalysis. This characterictic can also be used to test the capability of the models to represent the tropical cyclonic precipitation.

3 Global Climate Model ARPEGE

3.1 Model Description and Tracking Methodology

3.1.1 Model Description and Experiment Design

The ARPEGE-Climate model originates from the ARPEGE/IFS (Integrated Forecast System) numerical weather prediction model developed jointly by
4 TCs rainfall observed and simulated in the NATL basin.

Meteo-France and ECMWF. It is a spectral atmospheric model with a hybrid pressure vertical coordinate. Since the first release of the ARPEGE-Climate model (Deque et al. 1994), many developments have been included, both dynamical and physical. Here we use the third generation ARPEGE-Climat model (Deque 1999). The main difference compared to former versions is the use of a time-level semi-Lagrangian numerical integration scheme with a 30 min time-step. The physical package includes the turbulence-scheme of Louis et al. (1981), the statistical cloud scheme of Ricard and Royer (1993) and the mass-flux convective scheme with Kuo-type closure of Bougeault (1985). The radiative scheme is derived from Morcrette (1990) and is activated every 3 hours. More details about the physics of the model can be found in Geleyn et al. (1995).

A rotated-stretched twentieth–twenty-first century experiment was performed using the ARP-EGE-Climat GCM (Courtier and Geleyn 1988), to represent Atlantic hurricane activity. The grid stretching technique permits distortion of the initial globally uniform grid in such a way that a maximum concentration of grid points will cover the region of interest at the expense of antipode. Once the region of interest is chosen, the grid is rotated so as to bring the pole over the center of the domain. This method has been used and validated for a long time in operational meteorological forecast (Courtier et al. 1991) and in climate modeling studies (Deque and Piedelievre 1995; Lorant and Royer 2001; Moutaoui et al. 2002). It has also been validated by Chauvin et al. (2006) for the ARPEGE integrations used in this paper. In addition, they showed that, for a spatial resolution high enough, ARPEGE is able to represent TCs structures. The stretching coefficient is 2.5 in our simulations, and the pole of the grid is located 60°W, 20°N in the Western Atlantic. Simulations for present and future climates are 30 years long with year-to-year variation of SSTs, reproducing the interannual variability of 1960–1989 observed patterns. The equivalent resolution is of approximately 50 km over the Atlantic basin and decreases linearly when going far away from the pole to reach approximately 310 km at the opposite. Another experiment was performed in the stretched configuration for the twenty-first century scenario. For the future climate, an anomaly was added to the 1960–1989 climatology. SST anomaly was taken from a Hadley Centre coupled simulation and following a SRES-A2 IPCC scenario for the GHGs (Johns et al. 2001) for 2070–2099.

3.1.2 Tracking Methodology

In order to track the tropical storms, Chauvin et al. (2006) used and updated the method developed at Mto-France by Ayrault and Joly (2000) to track mid-latitude lows for the Atlantic tropical cyclones. For the construction of the tracks, criteria from Bengtsson et al. (1995) have been introduced and the following criteria were retained:

- Mean sea level pressure (MSLP) is a local minimum (considered therefore as the center of the system)
- 850 hPa vorticity > VT (a vorticity threshold)
Anomalies are defined as the difference between the system and its environment. For each criterion, a threshold is fixed and a grid point, at a given time step, must meet all conditions to be selected for a track. Choice of the thresholds was made subjectively, partly in agreement with literature and partly to compare favourably with the real world. The threshold combinations adopted, for this case, are the followings:

\[ VT = 14.10^{-5} \text{ 1/s}, \quad WT = 15 \text{ m/s} \quad \text{and} \quad TT = 3^\circ \text{K} \]

The entire description of the tracking method is given in Chauvin et al. (2006).

### 3.2 Present Integration

#### 3.2.1 TCs Rainfall

Figure 9 presents the tropical cyclonic precipitation in the NATL basin in the present integration of ARPEGE for the three decades: 1960–1969 (Fig. 9a), 1970–1979 (Fig. 9b) and 1980–1989 (Fig. 9c). The first decade (Fig. 9a) presents a maximum of TCs rainfall in the Caribbean Sea (850 mm/year) and from the South of the Gulf of Mexico (500 mm/year) to the eastern Florida peninsula. We also have some traces of...

---

**Fig. 9** TCs rainfall (mm/year) in the NATL basin in the present ARPEGE integration for the time periods: 1960–1969 (a), 1970–1979 (b) and 1980–1989 (c)
4 TCs rainfall observed and simulated in the NATL basin. tracks in the center of the NATL basin coming from the West African coast, but the signal is really lower (100 mm/year). The second decade (Fig. 9b) presents the same position of maximum but with a lower range of value than the first decade except for the south of the Gulf of Mexico. The maximum on the Caribbean Sea attains 600 mm/year, the eastern Florida 250 mm/year. The trace of TCs from the West African coast is less visible in this decade. For the last decade, the maximum on the Caribbean Sea obtains values between the two other decades (~700 mm/year). In the Gulf of Mexico, the TCs rainfall give the same range of value as the two other decades. The TCs rainfall in the eastern Florida and the center of the NATL basin, as the second decade, are lower than the first decade. The results from Fig. 9 put in evidence the sensitivity of the simulated TCs rainfall to the period of study. The amplitude of the maxima in all the areas vary in function of the time period, except the Gulf of Mexico. We could also notice that the decades where ARPEGE simulates a lower activity are the real time period known for lower TCs rainfall. If we compare the results of ARPEGE, to those obtains by TRMM in Fig. 1, taking account that it is not the same period of study, we can still see that ARPEGE is highly overestimating the TCs rainfall. However the bias of the TCs rainfall of ARPEGE must also be due to the errors in the tracking of the TCs. We surely have too many tracks on the west side of the NATL basin and not enough in the east side explaining why we have so low precipitation in the center of the NATL basin.

3.2.2 Fraction of TCs Rainfall

Figure 10 presents the fraction of TCs rainfall simulated by ARPEGE in the North Atlantic Basin for the three decades: 1960–1969 (Fig. 10a), 1970–1979 (Fig. 10b) and 1980–1989 (Fig. 10c). The first decade (Fig. 10a) presents maxima over the Gulf of Mexico, the Caribbean Sea with equivalent values (~25%) and close to the West African coast with a higher amplitude (60%). The next decades (Fig. 10b, c) show nearly the same results for the Gulf of Mexico and the Caribbean Sea. However the maxima on the West African coast nearly disappears in the second decade (1970–1979) and comes back in 1980–1989. When comparing the results of the simulation with those of TRMM, we can see that the maximum in the west of the NATL basin is broader and northern for ARPEGE. The difference on the localization can come from the sensitivity to the time period. On the eastern part of the NATL basin ARPEGE finds a maximum on two decades which is, in the satellite observation, more in the center of the ocean and broader. This maximum is highly overestimated by the model. Like in the TCs rainfall, we can assume that some of the differences between the model and the observation come from the tracking in the simulations.

3.2.3 Tropical Cyclonic Precipitation Efficiency – TCPE

Figure 11 presents the TCPE simulated by ARPEGE in the North Atlantic Basin for the three decades: 1960–1969 (Fig. 11a), 1970–1979 (Fig. 11b) and 1980–1989 (Fig. 11c). In the three panels, we nearly obtain the same amplitude (25–40 mm/TC
Fig. 10 Fraction (%) in the NATL basin in a present ARPEGE integration for the time periods: 1960–1969 (a), 1970–1979 (b) and 1980–1989 (c).

Fig. 11 TCPE (mm/TC day) in the NATL basin in a present ARPEGE integration for the time periods: 1960–1969 (a), 1970–1979 (b) and 1980–1989 (c).
TCs rainfall observed and simulated in the NATL basin. (day) in the Gulf of Mexico and the Caribbean Sea. We can also notice the trace of efficient TCs in the New Orleans and Guatemala coast, regions vulnerable to TCs. For the TCPE, the sensitivity to the time period is visible especially off the West African coast. The amplitude is nearly the same in the center and the east of the NATL basin and is really close to what obtained TRMM in Fig. 1.

### 3.3 Future Integration

#### 3.3.1 Fraction of TCs Rainfall

Figure 12 presents the fraction of TCs rainfall from the future integration (2060–2089) minus the present integration (1960–1989) over the NATL basin. The blue values indicate a decrease of fraction of TCs rainfall and the red, an increase. This figure shows that for this configuration of ARPEGE, the contribution of TCs rainfall is decreasing in the future in comparison with the present. But as the fraction is a ratio this decrease means a decrease of TCs rainfall or an increase in total rainfall.

#### 3.3.2 Tropical Cyclonic Precipitation Efficiency – TCPE

Figure 13 presents the TCPE from the future integration (2060–2089) minus the present integration (1960–1989) over the NATL basin. The blue values indicate a decrease of TCPE and the red, an increase. It seems that the efficiency is slightly increasing in the future, in comparison with the present, as the red value indicate a positive difference between the two integrations.

![Fig. 12](image.png)

**Fig. 12** Difference in fraction of TCs rainfall (%) between the future (2060–2089) and present (1960–1989) ARPEGE integration in the NATL basin
4 Conclusion and Discussions

The impacts of the TCs rainfall on geographical variability of the total rainfall over
the NATL basin is investigated in a first part, in daily satellite observations and
reanalysis. We studied TRMM and GPCP for the satellite observations, ERA-40,
ERA-Interim, NCEP-1 and NCEP-2 for the reanalysis. The patterns of TRMM TCs
rainfall are similar to GPCP features, but GPCP presents an underestimate in am-
plitude and misses some local maxima in the center of the NATL basin surely due
to the lower spatial resolution of the latter. Then, we studied the ability of GPCP
and the reanalysis to represent the tropical cyclonic precipitation in comparison with
TRMM. It may be surprising to study the TCs rainfall from the reanalysis as we said
before that the spatial resolution seems to be important for the TCs rainfall. However
the time period covered by the reanalysis is not offered by the satellite observations
and for the study of climate integrations, we need a longer time period, that is why
we tried to validate the reanalysis. In this aim, we used a variety of metrics such as
the fraction of TCs rainfall and the TCPE. We noticed the improvement with the new
versions of the reanalysis from ECMWF and NCEP/NCAR centers (ERA-Interim
and NCEP-2). We especially note the good representation of the TCs rainfall for
NCEP-2 in comparison with TRMM, that is surely due to the way that NCEP-2 as-
similates the precipitation. The maximum of cyclonic precipitation is located in the
Caribbean Sea and the Gulf of Mexico, for the observation and the reanalysis. GPCP
and ERA-Interim underestimate the TCs rainfall in comparison with TRMM due to
an underestimate of intense TCs. TCs contribute to a maximum of precipitation (be-
tween 15° and 25°N) over the Southern Gulf of Mexico, the Caribbean Sea and the
West Atlantic Ocean for the observation and the reanalysis. The most efficient TCs
are located in the Gulf of Mexico, the Caribbean Sea and the West Atlantic Ocean
for the observations and the reanalysis.
4 TCs rainfall observed and simulated in the NATL basin.

In a second part, we studied the ability of ARPEGE to simulate the TCs rainfall in present simulation. ARPEGE is able to detect the maxima of TCs rainfall, fraction of TCs rainfall and TCs efficiency obtained in the observation and reanalysis however it overestimates them in term of amplitude. The decomposition of the 30 years of integrations in decades has permitted to show the sensitivity of the model to the time period. It is interesting to notice that the two last decades present lower TCs rainfall which is consistent with the real TCs activity. This study has also allowed to see the problems in the localization of the tracks. The tracking produces too much TCs in the western NATL basin and not enough off the West African coast. Finally, we run a future simulation to see the possible evolution of the fraction of TCs rainfall and the TCPE. The difference between the future and present simulations shows an decreasing contribution of TCs rainfall to total rainfall and an increasing efficiency of TCs.

References


Morcrette J (1990) Impact of changes to the radiation transfer parameterizations plus cloud optical properties in the ecmwf model. Mon Weather Rev 118:520–534

Morcrette J (1990) Impact of changes to the radiation transfer parameterizations plus cloud optical properties in the ecmwf model. Mon Weather Rev 118:520–534


TCs rainfall observed and simulated in the NATL basin.


AUTHOR QUERIES

AQ1. Please provide Full name for Author F. Chauvin and F. Roux.
AQ2. Please provide abstract and Keywords if appropriate
AQ3. Please specify corresponding author.
AQ4. Please check the closing brackets.
AQ5. Please provide place of proceedings for Courtier et al. (1991) and Geleyn et al. 1995.
AQ6. Please provide publisher name and location details for Houze Raj (1988).
AQ7. For IPCC 2007, please provide name for the last editor. Only initials are given.
AQ8. Please provide the location of the “National Climatic Data Center” in Neumann et al (1999).