proceedings

Type of the Paper (Abstract, Meeting Report, Preface, Proceedings, etc.)

Assessing the potential of a long-term climate forecast for Cuba using the WRF model

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Abstract: Seasonal climatic prediction studies are a matter of wide debate all over the world. Cuba, a mainly agricultural nation, should greatly benefit from the knowledge with months in advance of the precipitation regime, which would allow a proper management of water resources. In this work, a series of 6 experiments was made with mesoscale model WRF (Weather Research and Forecasting Model) that produced a 15 months forecast each of monthly cumulative precipitation starting at two dates for three years with different meteorological characteristics, one dry year (2004), one year that started dry and turned rainy (2005) and one year signaled by the occurrence of several tropical storms (2008). ERA-Interim reanalysis data were used for initial and border conditions and runs started one month before the beginnings of the rainy and the dry seasons respectively. In a general sense, the experience of using WRF indicates that it is a valid resource for seasonal forecast, since results obtained are in the same range as those reported by literature for similar cases. Several limitations were revealed by the results, such as that forecasts underestimate the monthly cumulative precipitation figures, tropical storms entering through the borders may follow courses different from the real ones inside the working domain, storms that developed inside the domain were not reproduced by WRF and differences in initial conditions led to significantly different forecasts for corresponding time steps (non linearity). It is recommended to carry on ensemble forecast experiments changing model parameterizations and initial conditions.

Keywords: Seasonal forecast,; numerical weather modeling

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Proceedings* **2021**, 65, x. https://doi.org/10.3390/xxxxx

Received: date
Accepted: date
Published: date

1. Introduction

Meteorological forecasting has been a matter of utmost importance for social development. In recent decades it has been associated to the development in computer sciences and technologies, the so called numerical forecasts yield every time more truthful simulations of the atmospheric behavior, ranging from world to mesoscale area coverage and from very short time forecasts of a few hours to projections of about one hundred years. Sub seasonal and seasonal forecasts are a matter of wide discussion all over and research is in full development given the great amount of factors involved in the performance of forecasting models, which generates uncertainties [1]. Seasonal forecast lies beyond the deterministic time lapse and can only be achieved through a probabilistic approach. The main centers offering this kind of product in the world do it based on ensembles of different sizes, where members are global models of not very high resolution that are run with different sets of initial conditions [2]. In some cases atmospheric models are coupled to oceanic models [3-5] and in other cases observed or forecasted sea surface temperature anomalies are taken into account [6-8], as they are the main forcing factor in this scale. Since the establishment of the predictability of "El Niño" event [9,10] bases were settled for the development of operational seasonal forecasts.

A mainly agricultural country as Cuba should greatly benefit from the knowledge with months in advance of the precipitation regime, however, the only precedents of seasonal forecasts so far are the work of Cárdenas [11] that established a system of monthly cumulative precipitation forecasts up to 6 months in advance, based on multiple linear regression, where the sea surface temperature was included among the predictors as a teleconnection index and an extreme temperatures and cumulative precipitation forecast service that is currently operational for the whole country and for three regions within it, with one month in advance, based on global models results offered by IRI (International Research Institute for Climate and Society) and expert criteria (http://www.insmet.cu/asp/genesis.asp?TB0=PLANTILLAS&TB1=PCLIMA&TB2=/clima/pronosticoclimatico.htm). Some effort has been addressed to carry sensibility studies with different parameterizations for variables such as precipitation, temperature and wind in the Summer season using the RegCM model for the Caribbean region [12].

If the information that global seasonal precipitation models supply for Cuba is analyzed, it results scarce and of little detail, due to the narrow and elongated shape of the island only about 11 grid points lay over the Cuban territory,. Regional models should supply in these circumstances the added value of an improved representation of local and regional climatic processes [13]. The concept of Downscaling subscribes the basic principle that regional models should not alter climatic simulations at scales that can be successfully represented at the resolutions of global models [14, 15], while features such as precipitation [16] and coastal winds [17] are found to typically improve their results with regional models. To determine how robust the added details are, systematic experimentation is needed with different regional and global climate models [18], which constitutes a further motivation for ensemble forecasting studies [19-21].

The objective of this work is, therefore, to make a preliminary assessment of the skill of WRF, as a regional model, for the seasonal precipitation forecast in Cuba through experiments carried over periods with different characteristics of their cumulative precipitation behavior.The introduction should briefly place the study in a broad context and define the purpose of the work and its significance.

For papers that report original research, you should use the titles “Materials and Methods”, “Results”, “Discussion” and “Conclusions” (optional).

2. Materials and methods

2.1 Design of experiments

The numerical model selected or the proposed experiments was WRF (Weather Research and Forecasting Model) Version 3.5.1 [22], a widely known open source numerical model. There is already a working experience in the country with this model in short and mid range forecasts.

Initial and border conditions were supplied by ERA-Interim reanalysis data (European Center for Medium-Range Weather Forecasts Re-Analysis), with a time resolution of 6 hours, approximately 75 km horizontal grid size and 60 vertical levels these data were obtained from a ground - oceanic - atmospheric coupled model with 4d variational assimilation [23-25]. Elevation and land use data were assimilated from the U. S. Geological Survey (USGS) with 30", ~900 m resolution, which are available from the WRF website: http://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html. Figure 1 shows the simulation domain used in this study. It has a spatial resolution of 25 km and covers a region between 8.03 and 34.03 North latitude and between 62.09 and 99.34 West longitude. The picture also shows the section of the domain used for evaluation, that embraces Cuba and nearby sea areas. Table 1 shows the set of main configuration options for WRF applied in the simulations.

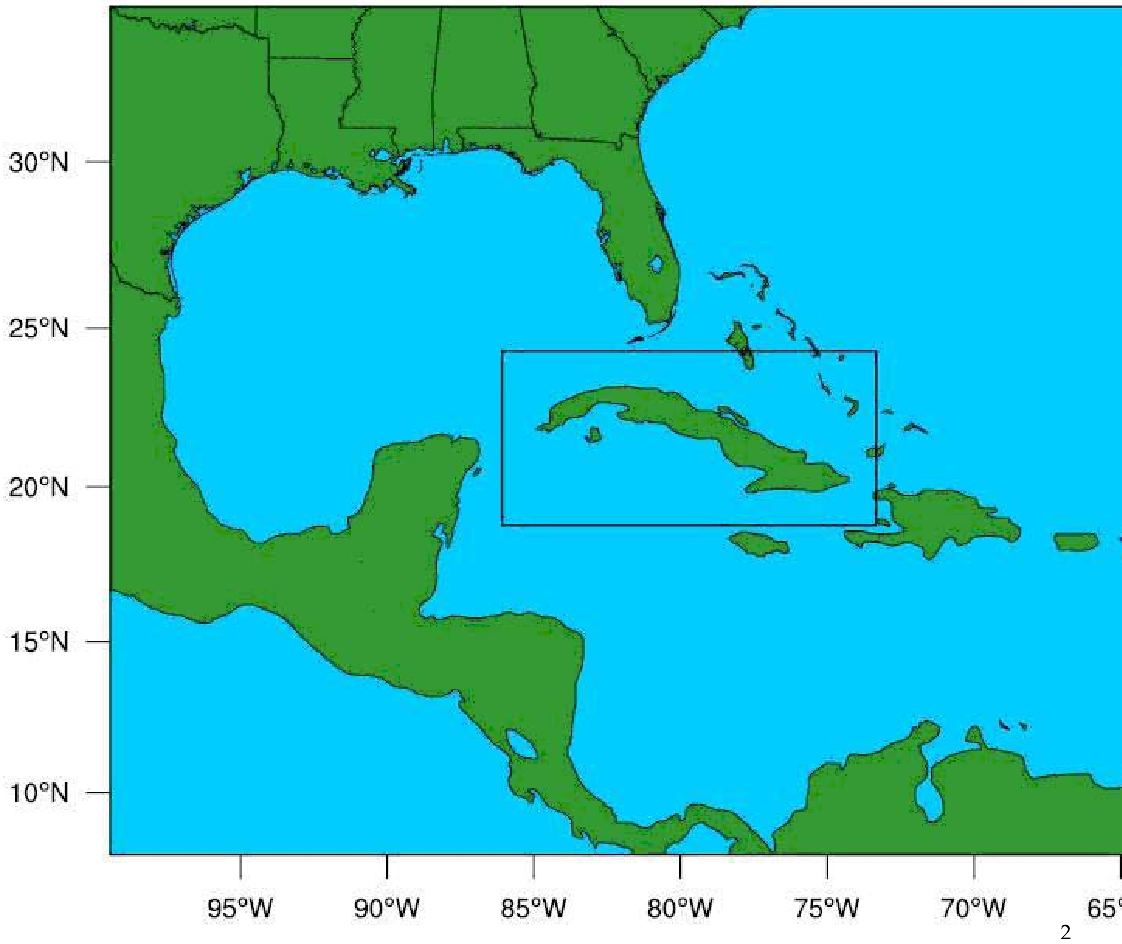


Figure 1. Representation of the runs domain. Enclosed in the rectangle is the area chosen for evaluation

Table 1. WRF runtime options applied in the experiments

Parameters	Option	Comments / references
Experiments	6	In the table they are referred to as Exp. 1 to 6.
Start Dates	Exp. 1: 1/10/2003 Exp. 2: 1/04/2004 Exp. 3: 1/10/2004 Exp. 4: 1/04/2005 Exp. 5: 1/10/2007 Exp. 6: 1/04/2008	The periods studied were chosen taking into account the availability of data, and also that different meteorological conditions would meet (dry, rainy periods, presence of tropical storms and hurricanes, etc), they were chosen also in a manner such that experiments would overlap
Simulation Times	15 months	The first month was considered as the period of model self tunning (spin up).

Ocean – Atmosphere Interaction	sst_update = 1	Sea surface temperature updates every 6 hours. Data from Era-Interim.
Boundary layer parameterization	Mellor-Yamada-Janjic	Janjic, (1994) [26]. This parameterization has obtained satisfactory results in convective forecasts [27]
Parameterization of Cumuli	Grell-Freitas	Grell and Freitas, (2013) [28]. This scheme was chosen as it's been used at the Institute of Meteorology of Cuba with favorable results [29]
Microphysics Parameterization	Lin et al.	Lin et al. (1983) [30]. It's a parameterization of relative low computational cost, which includes ice and graupel formation processes, adequate for simulations with real data
Short and long wave parameterization	Rapid Radiative transfer Model (RRTMG)	Iacono et al., (2008) [31]. These scheme represent the variability of the clouds field, not attached to the domain resolution

2.2. Real data and evaluation methodology

The TRMM (Tropical Rainfall Measuring Mission) data base and values of mean cumulative monthly precipitation from the National Network of stations of the Institute of Meteorology of Cuba (RE-INSMET) as well as those from the National Institute of Hydraulic Resources were used to evaluate the skill of the precipitation forecasts from WRF. These data correspond to the area under study as shown in Figure 1. The evaluation using the TRMM data was made in two different ways, one taking into account all grid points within the area and other taking only grid points laying over land. For the stations networks, mean values for the whole territory were calculated yielding figures that were representative of the whole country, these were compared with the mean monthly cumulative values of each network and with the mean monthly cumulative values obtained from the TRMM grid points over land. In all cases the Pearson correlation coefficient and the mean square error were used as comparison parameters.

3. Results and discussion

The comparison between the mean cumulative values for all points of the evaluation area and TRMM base values for the experiments started on October 1st is shown in Figure 2. Here it shows that the greatest discrepancies lay in the period 2004-2005, though forecasted values underestimate those from TRMM in a general manner. In the period 2003-2004 the correlation coefficient between the two curves is high, 0.97, but the spatial distribution given by the correlation between grid points reaches its maximum in the month of February with a modest value of 0.62 and the worst performing months, September and October, had negative correlations. The mean square error for all months is 52 mm. The period 2004-2005 shows a lower correlation between two curves, 0.80, and the point to point correlation reaches its maximum in March with only 0.54. The worst performance is in May and September with negative correlations. The mean square error for all months is 87 mm. There are in this period two months with remarkable differences between forecasts and TRMM that, as will be seen further on, correspond to the presence of tropical storms that generated within the model domain and were not reproduced.

The period 2007-2008 shows a correlation coefficient of 0.86 between the curves and the correlation point to point has a maximum of 0.54 in October. March and December had the worst correlations with 0.01. The average mean square error is 73 mm.

In a general sense the values obtained are in agreement with the parameters published for global forecasts at the Lead Centre for the Long Range Forecast Verification System's web page, http:// http://www.bom.gov.au/cgi-bin/climate/wmo.cgi for the main centers that make public this kind of information. Also in experiments undertaken for the area of Cuba [32] using model RegCm 4.3 [33], correlations between 0.1 and 0.6 were obtained between forecasted values and those from TRMM while forecasts also underestimated real values mainly when the Tiedtke cumulus parameterization [34] was used.

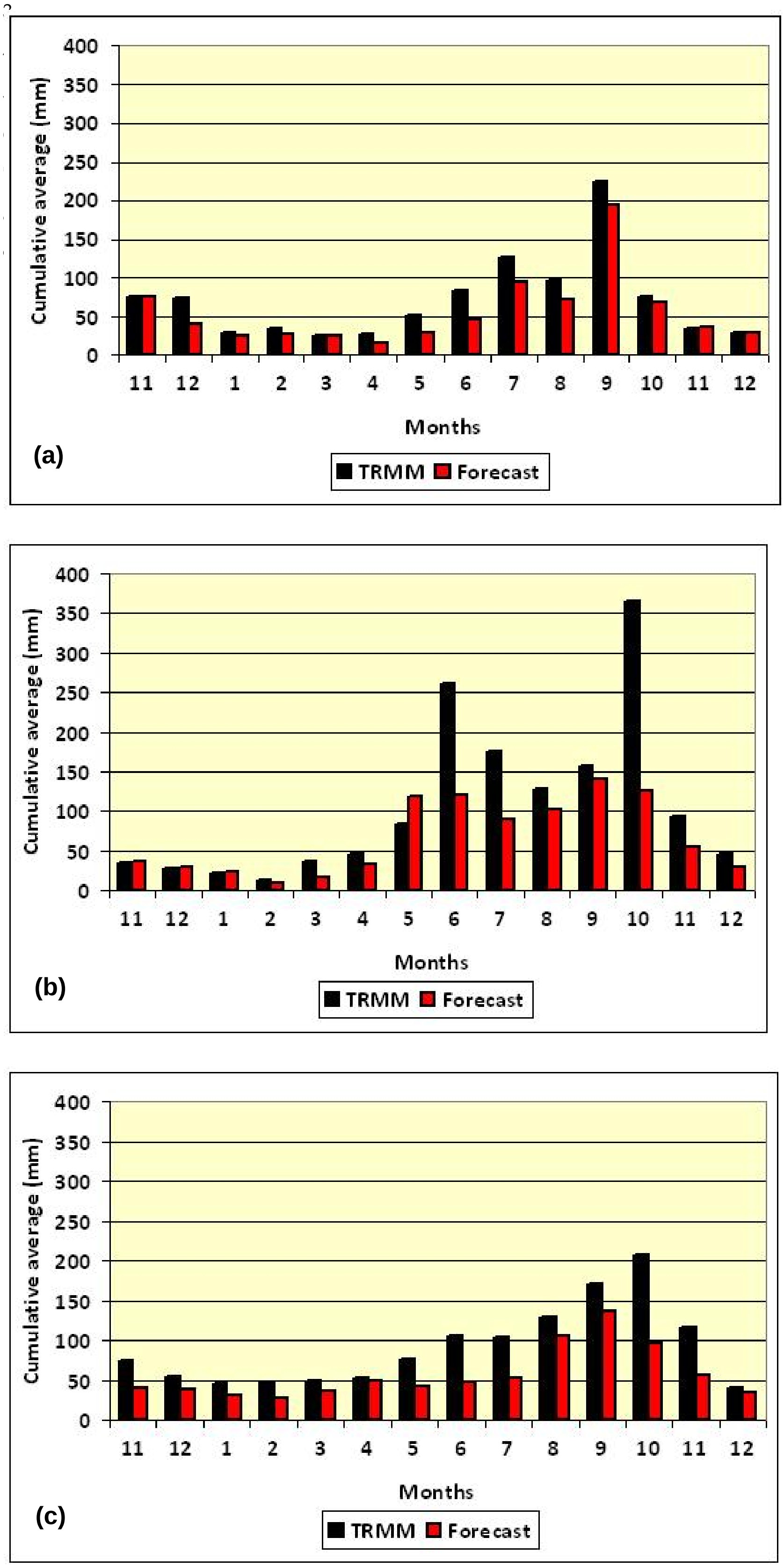
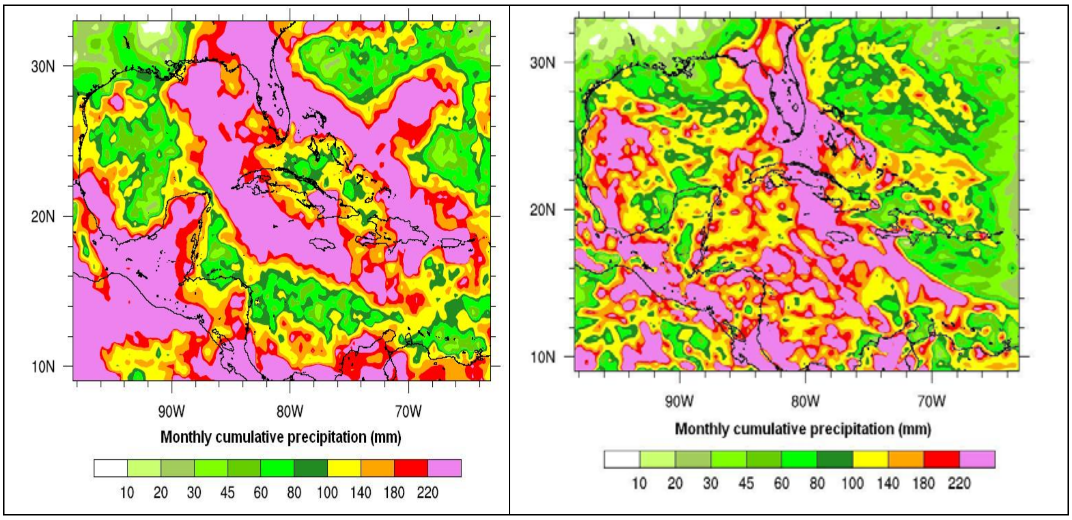

400
350
300
250
200
150
100
50
0
Cumulative average (mm)
11 12 1 2 3 4 5 6 7 8 9 10 11 12
Months
(a)
TRMM
Forecast
400
350
300
250
200
150
100
50
0
Cumulative average (mm)
11 12 1 2 3 4 5 6 7 8 9 10 11 12
Months
(b)
TRMM
Forecast
400
350
300
250
200
150
100
50
0
Cumulative average (mm)
11 12 1 2 3 4 5 6 7 8 9 10 11 12
Months
(c)
TRMM
Forecast

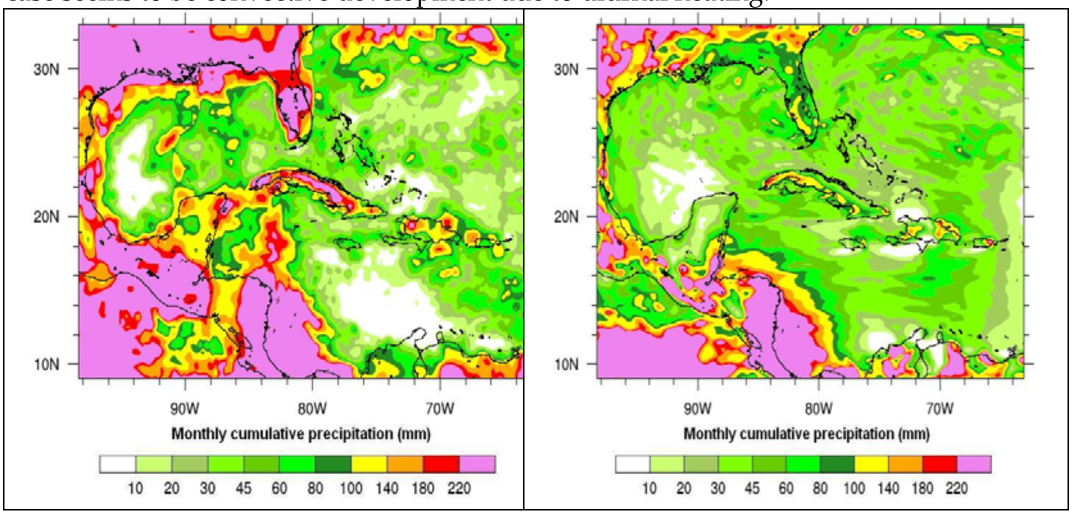
Figure 2. Monthly mean cumulative values from model forecasts and TRMM base for experiments started on October 1st. (a) corresponds to period 2003-2004, (b) to 2004-2005 and (c) to 2007-2008.

Differences in point to point correlations depend very much on the main or most frequent weather system generating precipitation for the month under evaluation, so September 2004, with a correlation of -0.02 was signaled by the presence of Hurricane Ivan. The forecast estimated the hurricane's trajectory as crossing through the center of Cuba, when it really kept a westerly course towards the strait of Yucatan. This produced forecasts of large cumulative totals at places where there weren't and viceversa, yielding, thus, this poor correlation. In Figure 3, the spatial distribution of forecasted and TRMM cumulative means over land are shown.



Figiure 3. Spatial distribution of monthly cumulative values from TRMM (left) and WRF started on October 1st 2003 (right) for September 2004.

If the same comparison is made for June 2004, where the correlation coefficient is 0.47 even with cumulative means also high, it shows (Figure 4) that forecasts explain better the spatial distribution of phenomena that generate precipitation, which in this case seems to be convective development due to diurnal heating.



FiFigure 4. Spatial distribution of monthly cumulative values from TRMM (left) and WRF started on October 1st 2003 (right) for June 2004.

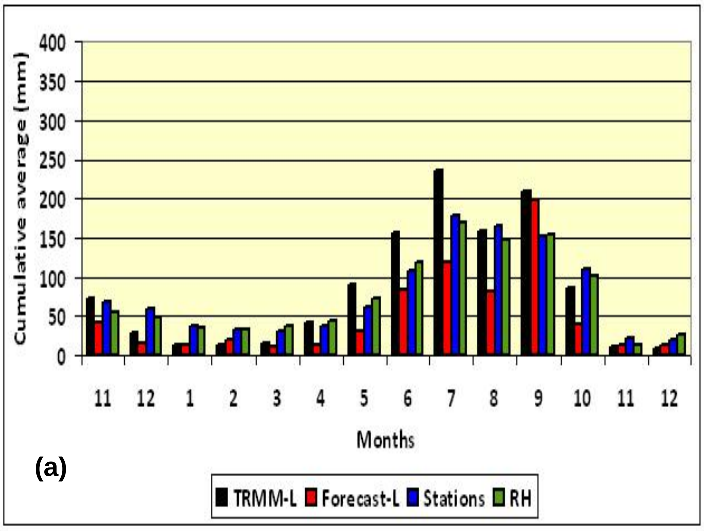
If comparisons are made now for points over land and ground networks RE-INSMET and RE-INRH are taken also into account results can be seen on Figure 5 for every period under study.

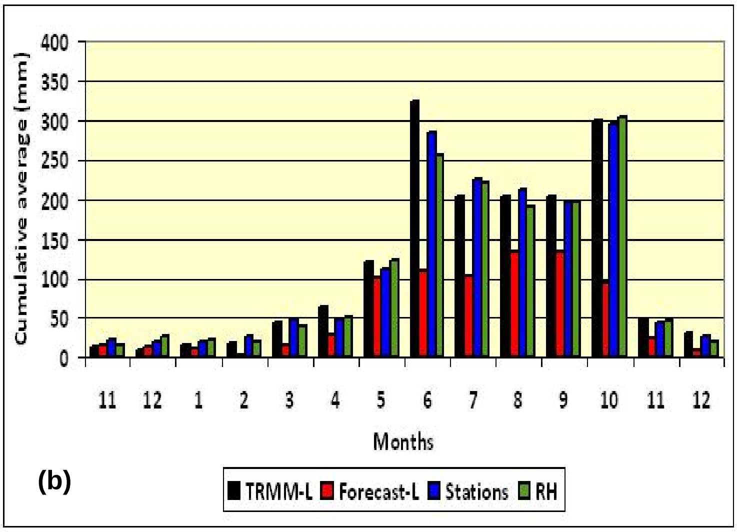
Figure 5 shows the closeness of values from both networks and, for periods 2004-2005 and 2007-2008, with data from TRMM, for the period 2003-2004 these values are somewhat different. In all cases forecasted values underestimate real ones with the highest difference occurring in the rainy season of 2004-2005.

For the period 2003-2004 the coefficient of correlation between the forecast and TRMM curves is high, 0.90, though a little lower than when the whole grid was evaluated. The spatial distribution given by the point to point correlation over the area evaluated reached its maximum in June, with 0.69 while the worst performance corresponded to November and September, with negative correlations. The mean square error for all months was 56 mm.

The period 2004-2005 shows a correlation between curves of 0.87 and the point to point correlation is maximum in March with 0.65. The worst months were January, November and December, all with negative correlations. The mean square error for all months was 78 mm.

The period 2007-2008 shows a correlation between forecasts and TRMM of 0.96, much higher than the corresponding value for the whole area. The point to point correlation is maximum for May with 0.64 and worst in December with -0.05. The mean square error was also 78 mm.





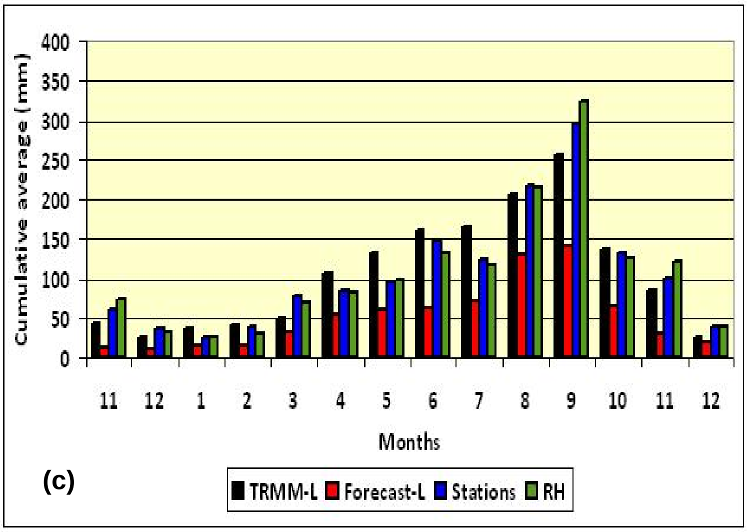


Figure 5. Monthly cumulative precipitation means from points over land for model forecasts, TRMM base, INSMET stations (RE-INSMET) and INRH stations (R-INRH), for experiments started on October 1st. (a) corresponds to period 2003-2004, (b) to 2004-2005 and (c) to 2007-2008.

If the month to month change is evaluated by assigning a positive sign when both, forecasts and TRMM change in the same direction and a negative sign when they change in opposite directions, results shown in Figure 6 are obtained. Here it shows that the worst performance occurs in the period 2007-2008, with changes for four months wrongly forecasted. The month with the poorest results was September, that failed in 2004-2005 and 2007-2008. These periods were signed by the presence of tropical storms in the area.

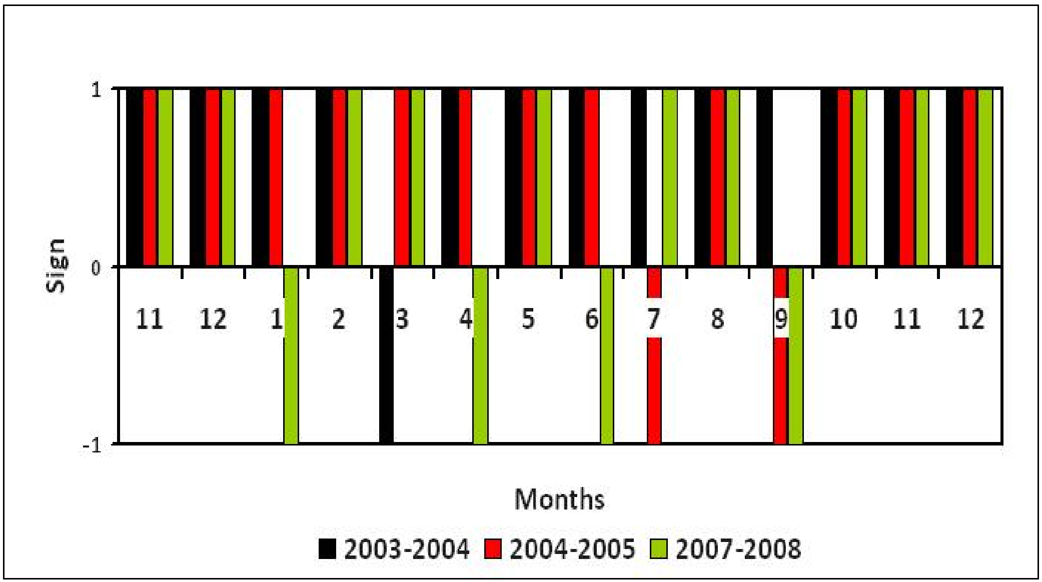


Figure 6. Evaluation of month to month change assuming a positive sign if both, model forecast and TRMM data change in the same direction and a negative if they change in opposite directions for the three periods studied.

If based on cumulative data from stations, terciles are calculated for the precipitation distribution using as baseline the period 1983-2012, results from model forecasts and station data can then be classified according to their belonging to the "lower" (first) tercile, the "normal" (second) tercile or the "higher" (third) tercile, and it is possible to evaluate how do they relate in this regard. To achieve a more general classification, percents of occurrence of "true positives" are considered as the number of cases when values from both series lay in the same tercile against the total of cases. Categories will be merged in two groups, "Normal - Low" (NL) for terciles 1 and 2 and "normal - high" (NH) for terciles 2 and 3. Results are summarized in Table 2.

Table 2. Percentages of occurrence of true positives for tercile categories "normal - low" (NL) and "normal - high" (NH) for three pairs of series: model and TRMM values for the whole grid (T-F), model and TRMM values for points over land (TL-FL) and model and station values over land (FL-S)

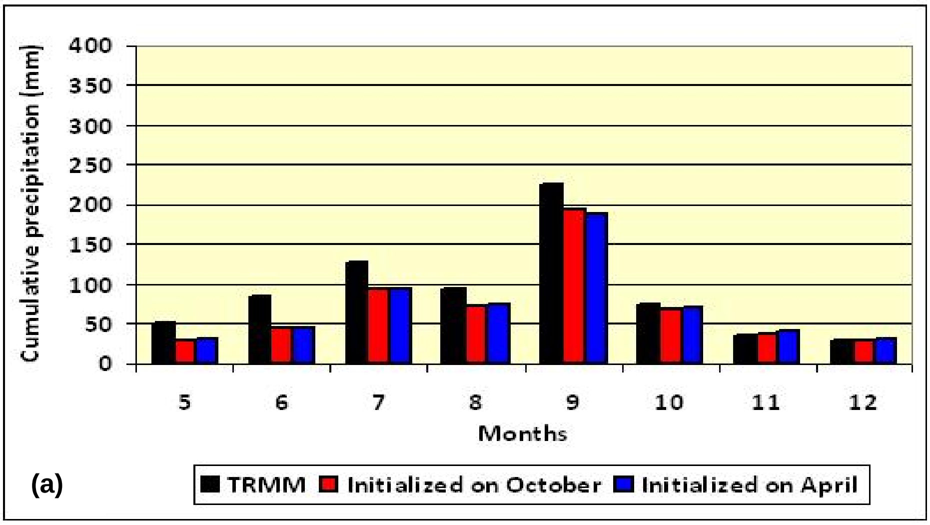
Season	Category	T-F	TL-FL	FL-S
2003-2004	NL	93	79	79
	NH	100	79	71
2004-2005	NL	93	79	79
	NH	79	86	86
2007-2008	NL	86	86	86
	NH	86	71	79
average NL		90.6	81.3	81.3
average NH		88.3	78.6	78.6

It shows in the Table above that the period with best skill was 2003-2004, which was the driest, and when only points over land are evaluated, assertiveness is generally less than when all points are considered. This might be related to the parameterizations selected for convective development, a phenomenon that's more relevant over land due to diurnal heating. It would be interesting to carry out sensibility tests with different cumulus parameterizations or even ensemble runs to consider the group skill against individual members. Even though as shown in Table 2, assertiveness percents are high, it must be taken into account that these forecasts are fed with reanalysis data, so they can be considered as "perfect forecasts".

Since experiments started on April 1st had results similar to those started on October 1st, only the period on which both experiments coincide will be analyzed here, this is, from May to December for the years 2004, 2005 and 2008.

Figure 7 shows the mean monthly cumulative values for the whole area evaluated, as given by the model forecast and by the TRMM base. The analysis reveals very little difference between forecasts started at different dates, the correlation coefficients between them is 0.99 for all the years selected, and the maximum difference is 5 mm for the year 2005. The largest point to point difference is on September 2008.

Regarding the comparison with TRMM data, cumulative values were underestimated by forecasts. The best correlation was reached on 2004 with 0.97 and the worst was on 2005 with 0.6, June and October resulted the most discordant months. The reason for this difference might be the presence of tropical organisms that even though didn't affect the country directly, their trajectories were close, and within the model's domain, for instance, on June 2005 hurricane Arlene approached the Western region of Cuba as did hurricane Wilma on October. These organisms, unlike hurricane Ivan, didn't enter the model domain through the borders but were generated by WRF as precipitation producing disturbances, however, not with the intensity of the real events (Figures 8 and 9). Other important phenomena originating within the domain area were not generated at all by the model. This suggests that if the model domain is made smaller, more cyclones could be detected as they are introduced through the borders, but this would make the borders too close to the area of interest, which could introduce spurious waves due to the integration of equations within a very limited area.



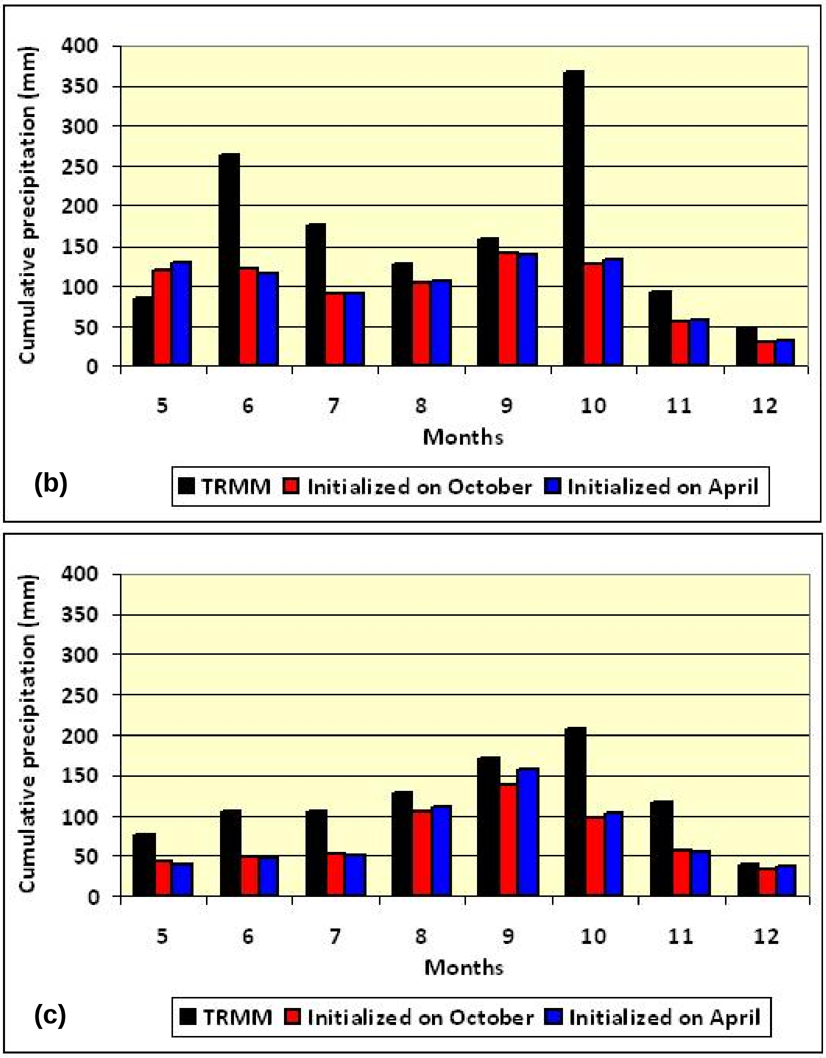


Figure 7.. Monthly cumulative precipitation means from model forecasts over the period in which both initializations coincide and TRMM data, (a) corresponds to 2004, (b) to 2005 and (c) to 2008.

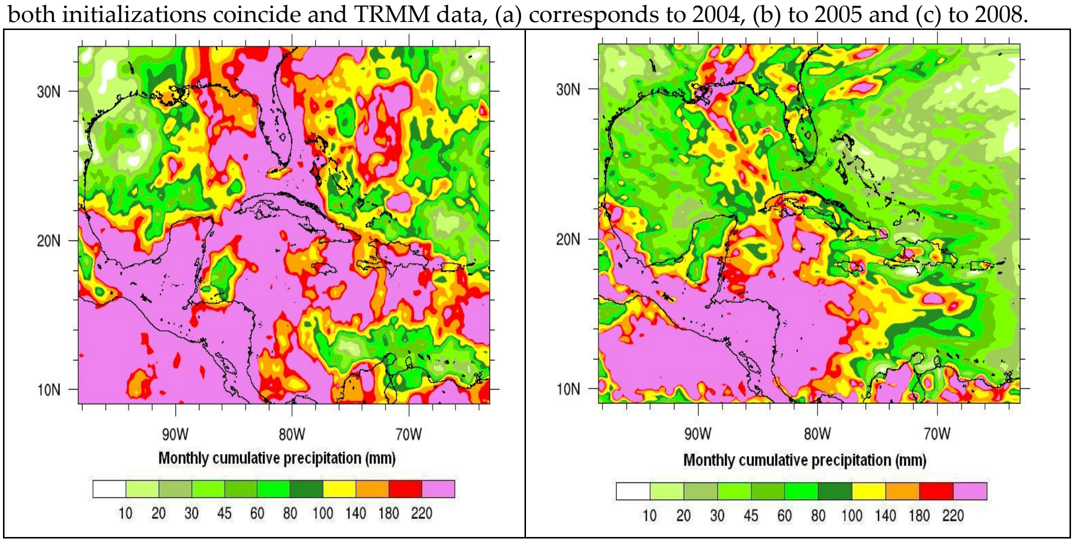


Figure 8. SpFi**Figure 8.** Spatial distribution of monthly cumulative values from TRMM (left) and WRF started on October 1st 2004 (right) for June 2005.

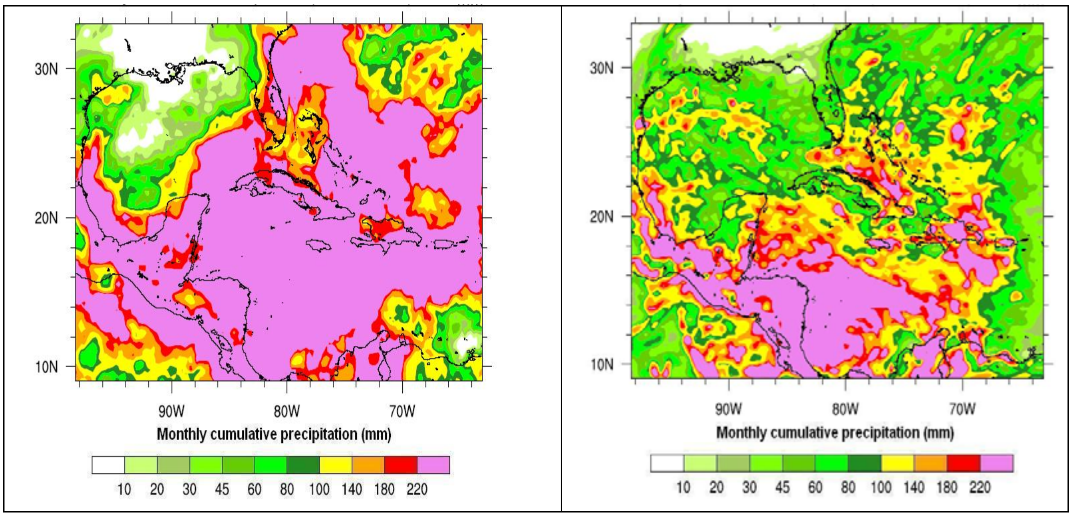


Figure 9. Spatial distribution of monthly cumulative values from TRMM (left) and WRF started on October 1st 2004 (right) for October 2005.

An improvement to consider would be the increase of the resolution of the model grid, to achieve a better representation of tropical storms and hurricanes. Also on the month of June 2005 important cumulative values showed on TRMM data over the central region of Cuba which could have been associated to the Tropical Upper Tropospheric Troff (TUTT) or other waves present at the time, this wasn't properly represented in the forecasts either.

If September 2008, which is the month with the greatest difference between mean cumulative totals forecasted by both initializations is analyzed, spatial distribution maps look quite alike (Figure 10), except near the central region of the Island of Cuba, where the run initialized on October 1st 2007 shows much lower values than those from the April 1st 2008 run. This might be related to the effect of model non linearity on long term forecasts, since the main differences occur towards the center of the domain, where the influence of border conditions supplied by reanalysis is less. Should the model be run with data from a global model, differences could be relevant over the whole domain, but mainly around the center, which is the area of most interest, hence the importance of ensembles to dampen these variations. A similar case can be noticed on May 2005 with the same effects.

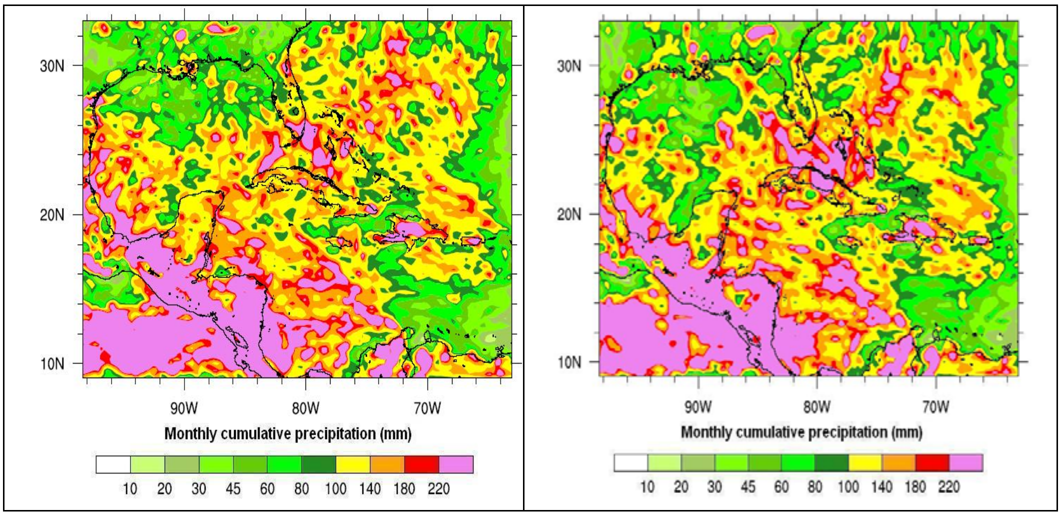


Figure 10. Spatial distribution of monthly cumulative values from WRF started on October 1st 2007 (left) and on April 1st 2008 (right) for September 2008.

When the coincidence between values from forecasts initialized at different dates is evaluated for points over land, its behavior is very similar as when all points are considered. Correlations between both forecasts range between 0.96 and 0.99, correlations with TRMM data results sometimes better and sometimes worse than when taking all points. Values were 0.87 for 2004, 0.62 for 2005 and 0.95 for 2008.

4. Conclusions and recommendations

Dynamic downscaling based on the use of WRF is a valid resource to achieve seasonal forecasts, since results obtained show a similar behavior to those from global models over large periods of time.

In all experiments carried forecasts underestimated the real values of monthly cumulative values.

Hurricanes and tropical storms had a very poor representation, given by trajectories different from the real ones when perturbations were fed from reanalysis data border conditions and the failure to reproduce vortexes when they generated within the domain.

The ability to forecast changes in the trend of monthly cumulative values had its worst period in September due precisely to the presence of tropical storms in the studied area.

The evaluation of the number of hits per tercile had its best performance over the period 2003-2004, the driest of all, generally the percents of assertiveness by terciles can be considered high, around 80%, though it must be taken into account that forecasts were fed with reanalysis data, which makes them "perfect forecasts"

Differences in initial conditions for the experiments carried out led to different forecast solutions for equal positions in time over regions distant from domain borders as a result of the non linearity of the model.

It is recommended to carry on ensemble forecast experiments changing model parameterizations and initial conditions.

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