NUMERICAL WEATHER PREDICTION AND TROPICAL CYCLONE TRACK FORECASTING IN THE CARIBBEAN USING MM5. CASE STUDIES OF HURRICANES DEAN (2007), OMAR (2008) AND PALOMA (2008).

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1. Introduction

During the hurricane season (July-November), the islands of the Caribbean archipelago are regularly threatened by tropical cyclones passing in their vicinity. The resulting damages on property and life depend partially upon the accuracy of the meteorological forecasts related to the hurricane trajectories. Although, in the last decades, important progress has been made concerning the estimation of the hurricane trajectories at large scales, the prediction of the damages at island scales remains still problematic. This is mainly due to the fact that the characteristic dimension of most Caribbean islands (~80 km) is comparable to the error associated to the 24 hours hurricane trajectory forecasts. Additional investigations in order to improve the trajectory forecast quality at island scales seem therefore to be necessary.

Since 1998, the two versions (2 and 3) of the fifth-generation Mesoscale Modeling System MM5, developed by the Pennsylvania State University and the National Center for Atmospheric Research, have been installed successively at the Cuban Institute of Meteorology (INSMET) and have been adapted to represent the regional conditions of Cuba and adjacent seas (Mitrani and Pérez, 1999; Mitrani et al., 2003; Mitrani and González, 2005; Mitrani et al., 2006). More recently, the Advanced Regional Prediction System (ARPS) developed at the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma was run in Guadeloupe (UAG) for both experimental regional weather prediction and hurricane track forecasting at scales comparable with the island scale. Consequently, the Regional authority of Guadeloupe, the "Université des Antilles et de la Guyane" (UAG) and the Instituto de Meteorologia (INSMET, Cuba) developed a collaborative project (PREVIOS, 2009, http://www.previos.fr) financed by European Community funds. The aim of this project was to create a framework consisting of meteorological mesoscale models, statistical means and vulnerability models for the prediction of hurricane paths, hurricane intensities and potential damages at the scale of the small Caribbean islands.

This paper presents and discusses the hurricane track forecasts obtained, in the context of this framework, with the mesoscale model MM5 for three hurricanes that affected some of the Caribbean islands in 2007 (Dean) and 2008 (Omar and Paloma).

2. Methods and data Sets

The 3.7 version of MM5 is a limited area mesoscale model. The primitive equation system is solved in finite differences with sigma vertical coordinates. The structure of the model, its different variants and the possibilities of physical process parameterizations are explained in detail by Grell et al. (1994) and in the user guide (PSU/NCAR, 2000). For the present work, the non hydrostatical approximation was used.

The initial and boundary conditions were extracted from the appropriate GFS outputs (Global Forecast System, http:/nomads.ncdc.noaa.gov/data.php) and the following meteorological variables were used : air temperature, wind speed components, relative humidity, sea level pressure, and geopotential height from the surface and levels of 1000, 850, 700, 500, 400,300, 200, 150 and 100 hPa. The sea surface temperature was calculated by using the air temperature profile and was conserved constant during the forecast period. Topography and land-use data were taken from USGS EROS Data Center's data base (http://edcftp.cr:usgs.gov), with a maximum resolution of 30s.

The following physical parameterization schemes were chosen for the simulations:

- Blackadar, for the planetary boundary layer,
- Grell, for cumulus convection,
- Radiative transfer, including cloudiness effect,
- Shallow convection,
- Precipitation, including ice phase,
- Horizontal diffusion,
- Macro-scale condensation.

The track forecast evaluation was made by using the best track data published by the National Hurricane Center (NHC). Some comparisons between the MM5 output fields and real meteorological fields were made using the reanalysis maps (http://www.nomads.ncdc.noaa.gov/ncep-data/, NCEP/DOE), reanalysis -2 and CDAS-NCEP/NCAR reanalysis. The geopotential fields from the 200, 700 and 850 hPa levels, and the vorticity field from the 500 hPa level were selected, since they are considered as representative of the main thermodynamical characteristics of the atmospheric circulation in the hurricane environment (Merrill, 1988, 1993; Mitrani and González, 2005).

The numerical experiments were conducted on two alternative platforms:

- An HP multiprocessor system using the open MP platform for shared memory. The computation time needed for a 72 h simulation was roughly 3 h.
- A cluster system, using 32 Power PC processors of 64 bits. The computation time needed for a 72 h simulation was roughly 30 mn.

A set of GrADS scripts (http://www.iges.org/grads) was developed to produce graphic outputs of the evolution of the meteorological fields after every 3 hours of simulation.

For Dean-2007, three domains (Figure 1) were chosen with central coordinates located respectively on 14.7^0 N, 52.86^0 W (D1), on 14.35^{0}N, 53.26^0 W (D2) and on 15.89^{0}N, 61.59^0 W (D3). The grid spacings were respectively 60 km, 20 km and 6.6 km. For Omar-2008 and Paloma-2008 (Figure 2), two domains (D1 and D2), extending from Central America to the Lesser Antilles (Figure 2), both centered by (20°N, 80°W), were defined with respective grid spacings of 81 km and 27 km.

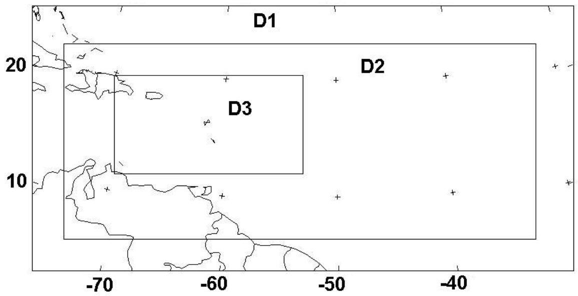


Figure 1. Nested domains, used with MM5 for Dean, 2007.

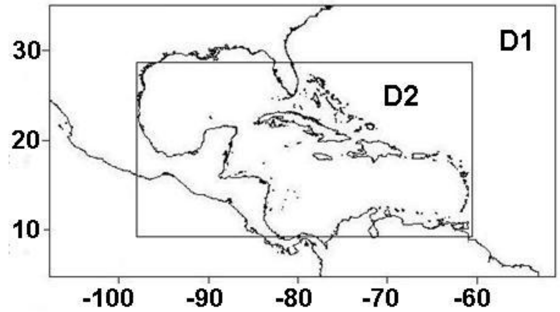


Figure 2. Nested domains, used with MM5 for Omar and Paloma, 2008.

3. Results and discussion

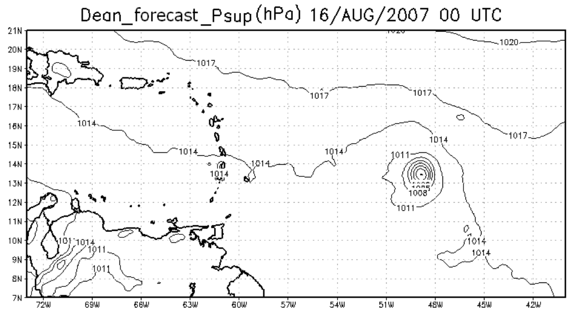
According to the general opinion of operational forecasters, two of the three examined cases (Omar, Paloma) presented particularities making forecasts difficult. For homogeneity reasons, only the results for the D2 domains (20 and 27 km grid spacing) are considered here.

3.1. Dean (2007)

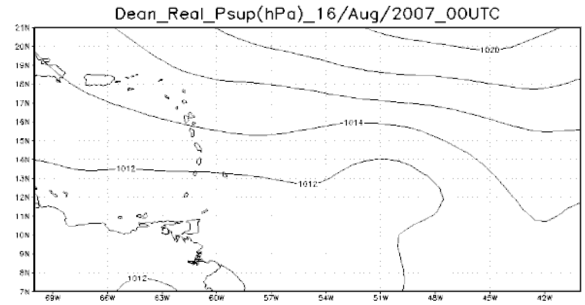
As described by Franklin (2008), Dean originated from a tropical wave that crossed the western coast of Africa on 11 August 2007. It became a hurricane on August 16, about 15 km east of Barbados. Dean entered the Caribbean Sea on August 17, its center passing between Martinique and St. Lucia roughly at 09:30 UTC. Then, it began to strengthen rapidly in the eastern Caribbean Sea, increasing from category 1 to category 5 in 24 h on August 18. During this period of rapid deepening, Dean's forward motion continued with the same heading, passing roughly 300 km south of Puerto Rico, 140 km south of Haiti and 36 km south of Jamaica. On August 21, the center made landfall in Yucatan as a category 5 hurricane, crossed the peninsula to enter the Gulf of Mexico and made landfall at 16:30 UTC that day roughly 160 km northeast of Veracruz, as a category 2 hurricane.

Three experiments were made. The most important forecast term for this analysis was from August 15 (00:00 UTC) to August 17 (12:00 UTC).

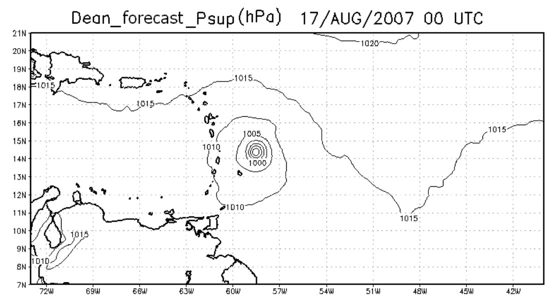
Dean moved, as from August 14, to the south of a deep-layer ridge of high pressure for the next seven days. This circulation was well forecast by the model all the time. The good agreement between the model and reanalysis configuration of the sea level pressure fields may be seen in Figs. 3(A-F).



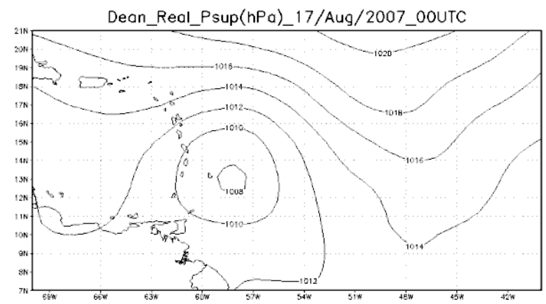
A)



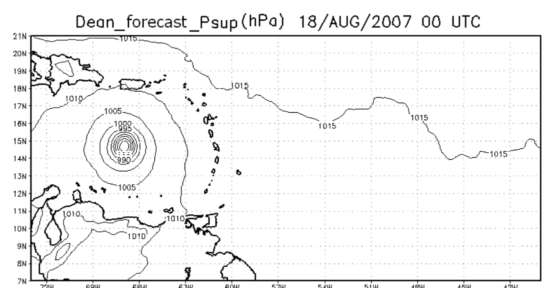
B)



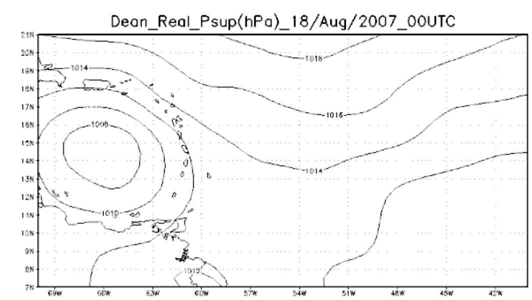
C)



D)



E)



F)

Figure 3 (A-F). Sea level pressure field from MM5 outputs for 24h (A), 48h (C) and 72h (E) forecasts with initial conditions on 15/08/2007 (00:00 UTC), along the way of hurricane Dean, compared to the corresponding NCEP reanalysis (B, D, F).

An interesting detail was observed on August 16, when the upper-level outflow became more pronounced and Dean reached an intensity of $41 m.s^{-1}$ at 12:00 UTC. Another situation of deepening, however more intense, was observed from August 17 (12:00 UTC) to August 18 (12:00 UTC), when the upper-level outflow increased in all quadrants and Dean began to strengthen rapidly in the eastern Caribbean Sea. The corresponding 850, 700 and 200 hPa geopotential fields are shown in Figs. 4(A-F), 5(A-F) and 6(A-F).

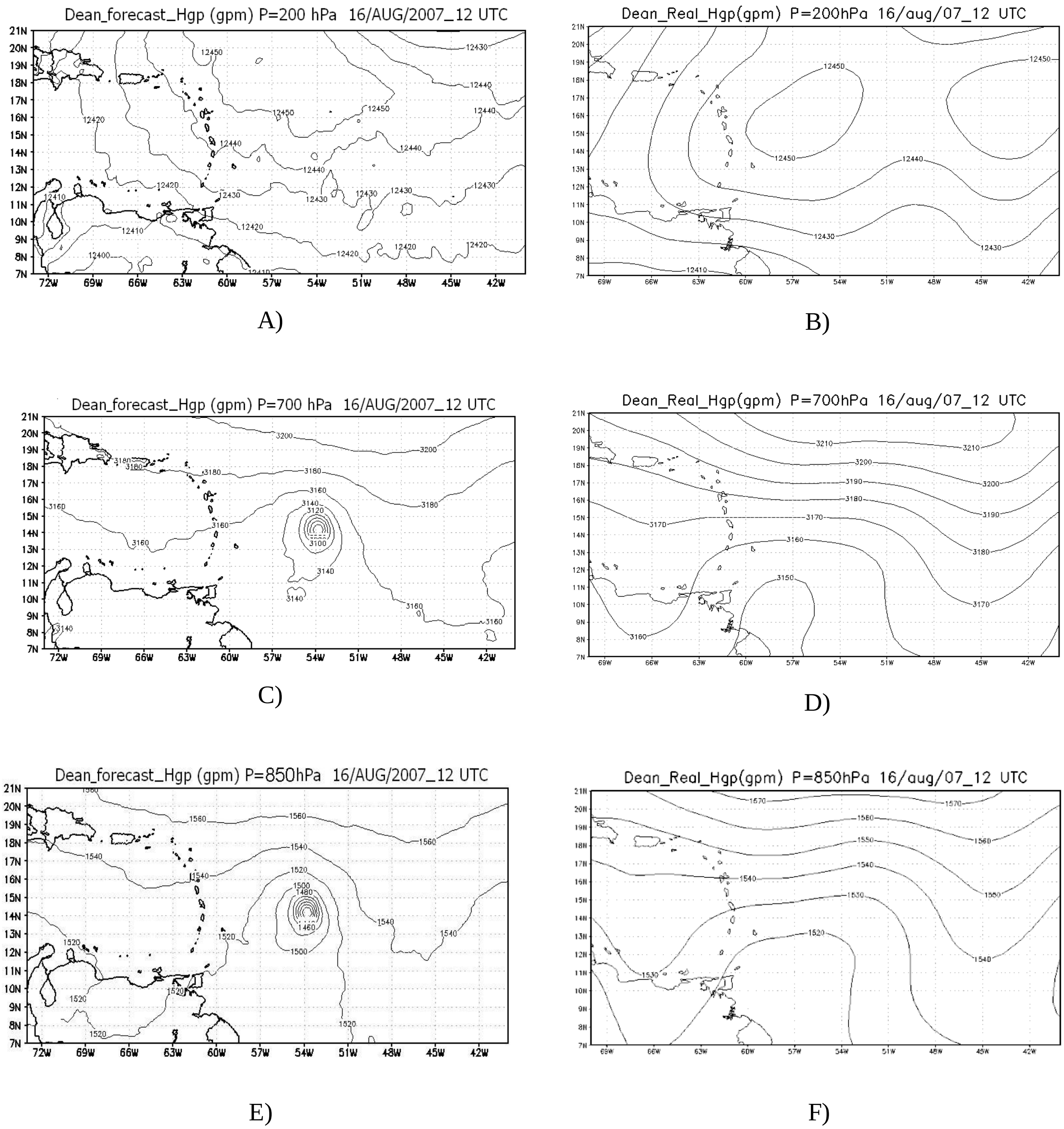


Figure 4 (A-F). As Dean strengthens, MM5 geopotential field output at 200hPa (A), 700hPa (C) and 850hPa (E) and corresponding NCEP reanalysis (B, D, F) on 16/08/07 at 12:00 UTC (36h forecast), with initial conditions corresponding to 15/08/00 (00:00 UTC).

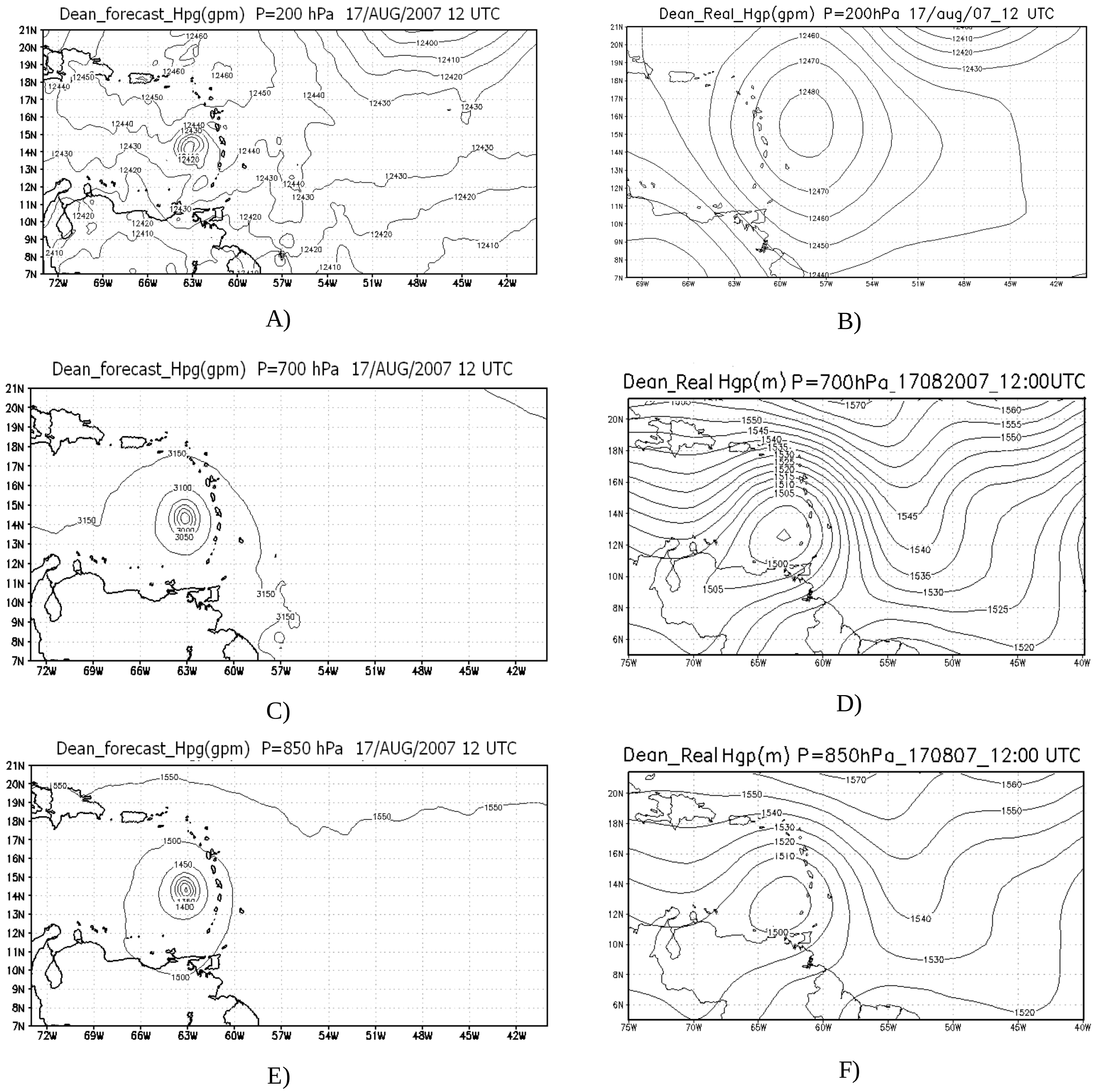
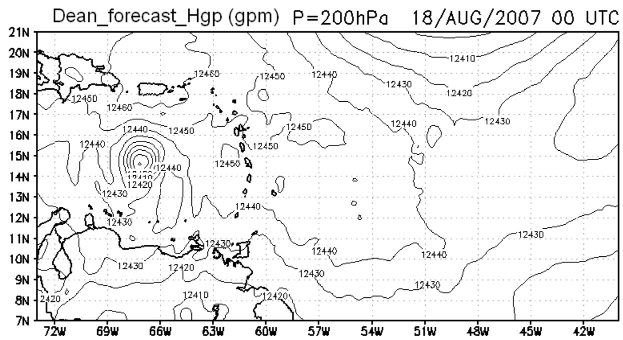
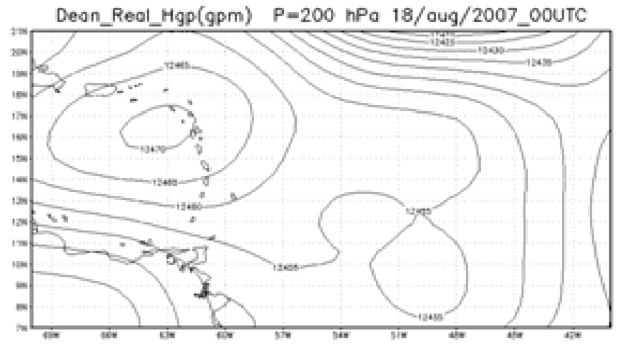


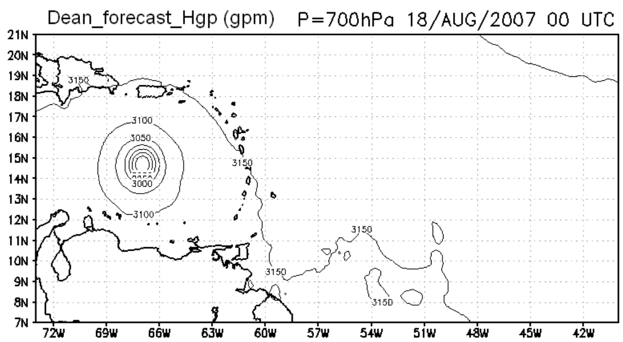
Figure 5 (A-F). As in Figure 4 (A-F) on17/08/07 at 12:00 UTC (60h forecast).



A)



B)



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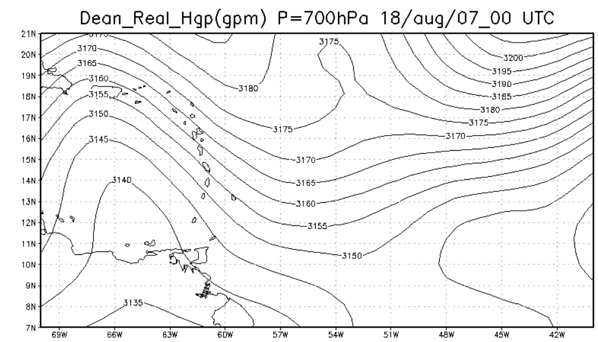

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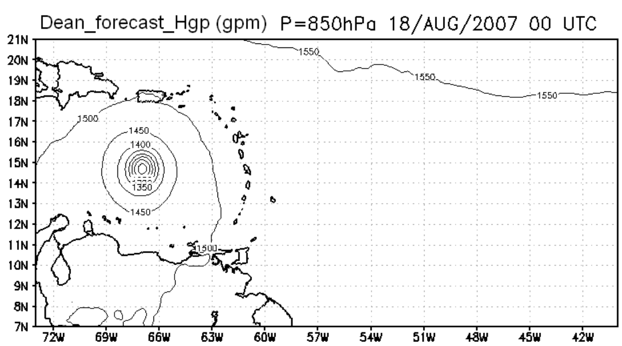

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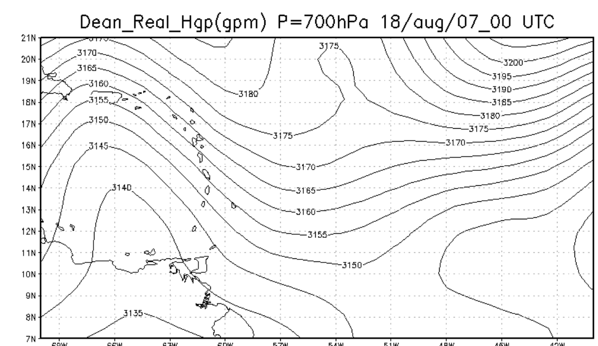


F)

Figure 6 (A-F). As in Figure 4 (A-F) on 18/08/07 at 00:00 UTC (72h forecast).

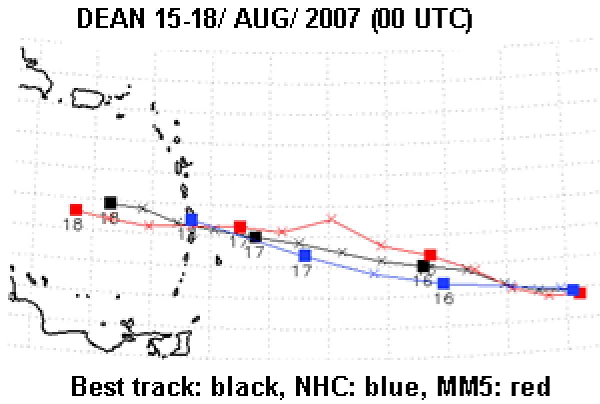


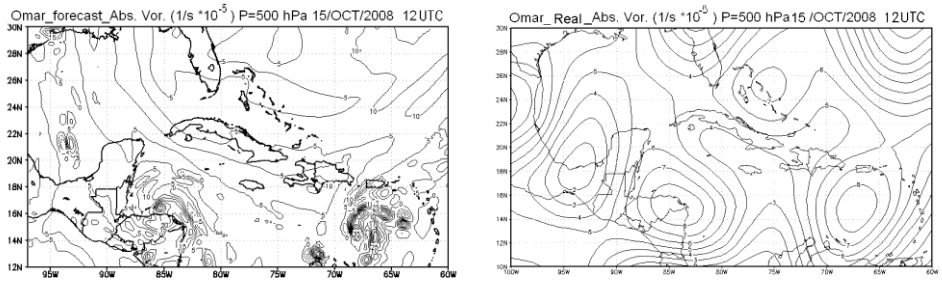
Figure 7. Dean´s MM5 track forecast compared to NHC forecasts and corresponding best track.

As a result of the correct representation of the meteorological fields, the track forecast for hurricane Dean was very close to the NHC best track and satisfactory. An example is shown in Figure 7.

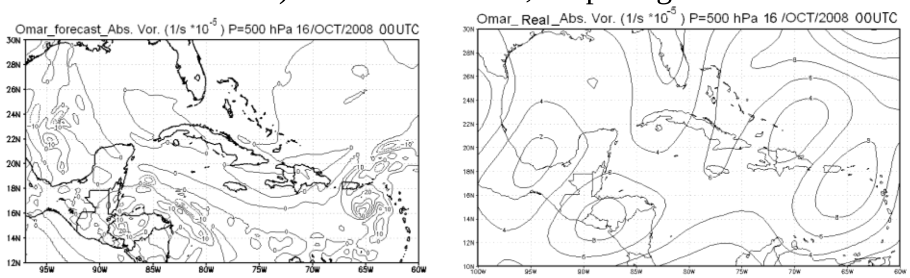
3.2. Omar (2008)

Following the NHC description (Beven and Landsea, 2009), tropical cyclone Omar originated from an easterly wave which formed near the coast of west Africa on September 30. The wave moved westward, developed to a powerful convective system and became a tropical depression around 0600 UTC on October 13 in the central Caribbean Sea. Omar intensified slowly, turning counter-clockwise on October 14, and this motion continued early the next day. Later, on October 15, the cyclone began moving toward the Northeast under the influence of a deep tropospheric trough at the Northwest and a mid- to low-level ridge to its East. This trough accelerated Omar Northeastward. Omar's intensity increased from 65 km/h at 00:00 UTC on October 14 to 130 km/h on October 15 and to 212 km/h at 06:00 UTC on October 16, 115 n.mi. North of Bonaire (Netherlands Antilles). Afterwards, it rapidly decreased in intensity and lost its warm core in upper levels on October 17. After a brief re-intensification, the cyclone weakened to a tropical storm around 00:00 UTC on October 18 and to a remnant low 12 h later.

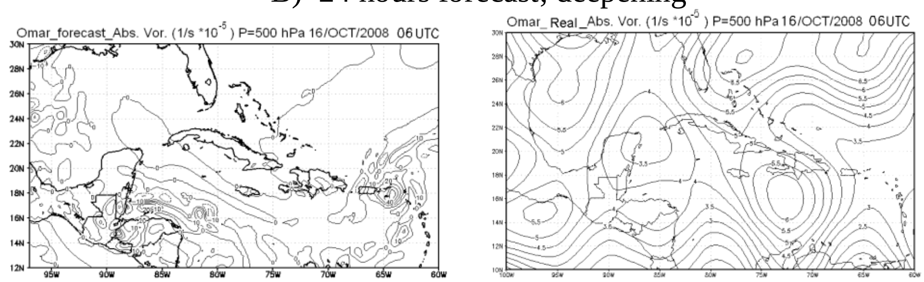
The numerical experiment was made from October 15 (00:00 UTC) to October 18 (00:00 UTC). The hurricane motion for the first 24h forecast was correctly represented in the MM5 forecast fields at surface, mid and low levels. The deepening and weakening periods between October 15 and 17 were also satisfactorily represented on the vorticity forecast fields (Figs. 8(A-C)), but the period of acceleration was not well described by the model. Thus, the track forecast was less accurate after the first 30 hours of simulation. This may be attributed to the shortage of primary meteorological information in the area and the limitations of the diabatical process representations in the model.



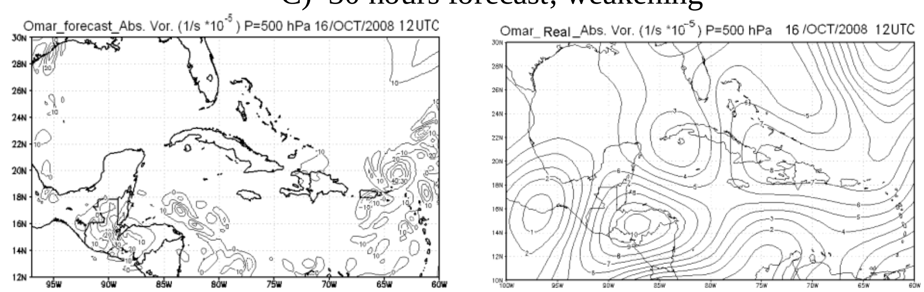
A) 12 hours forecast; deepening.



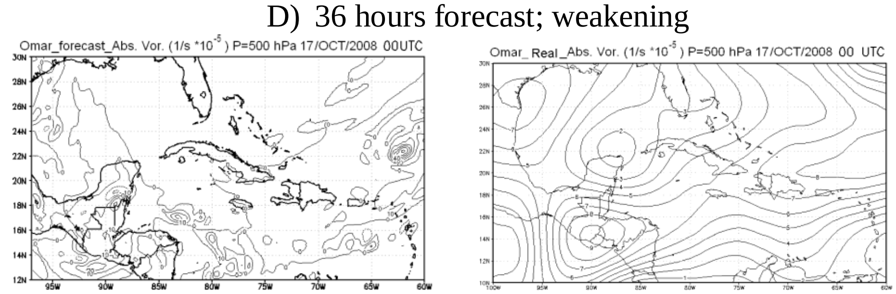
B) 24 hours forecast; deepening



C) 30 hours forecast; weakening



D) 36 hours forecast; weakening



E) 48 hours forecast; weakening

Figure 8 (A-E). Absolute vorticity MM5 output fields (left) from 15/10/08 (12:00 UTC) to 17/10/08 (00:00 UTC), with initial conditions on 15/10/08 (00:00 UTC) compared to corresponding reanalysis fields (right), on the path of hurricane Omar.

Figure 9 shows Omar's track forecast from MM5 and NHC compared to the best track. Note the similarity between the MM5 and NHC forecasts.

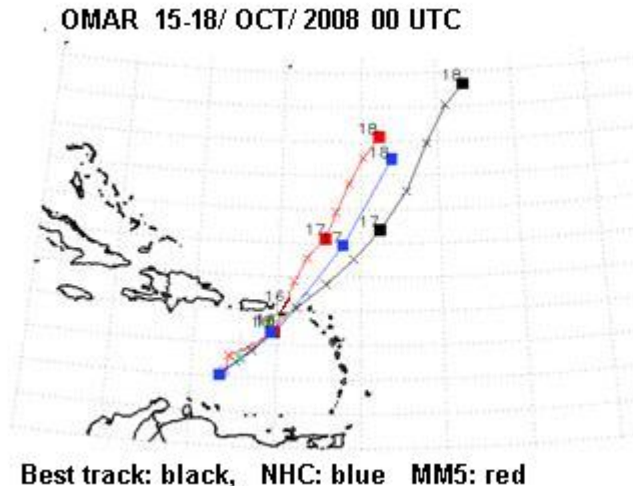
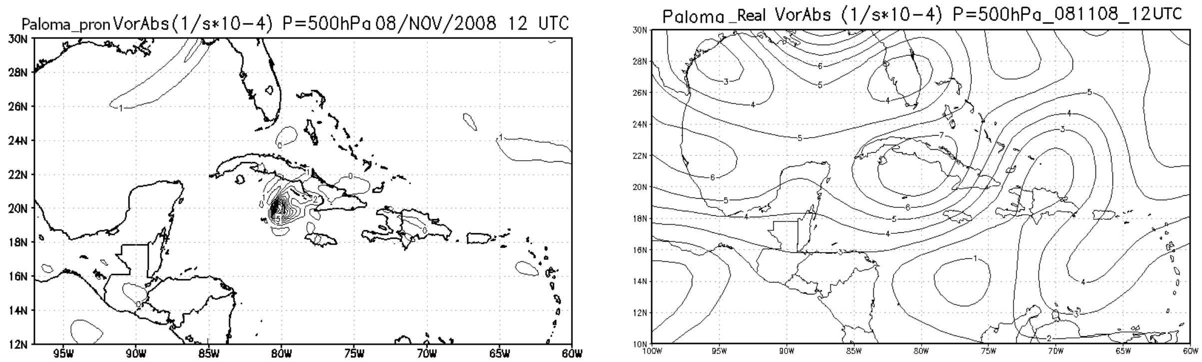


Figure 9. Omar´s track from MM5 and NHC forecasts, compared to the NHC best track.

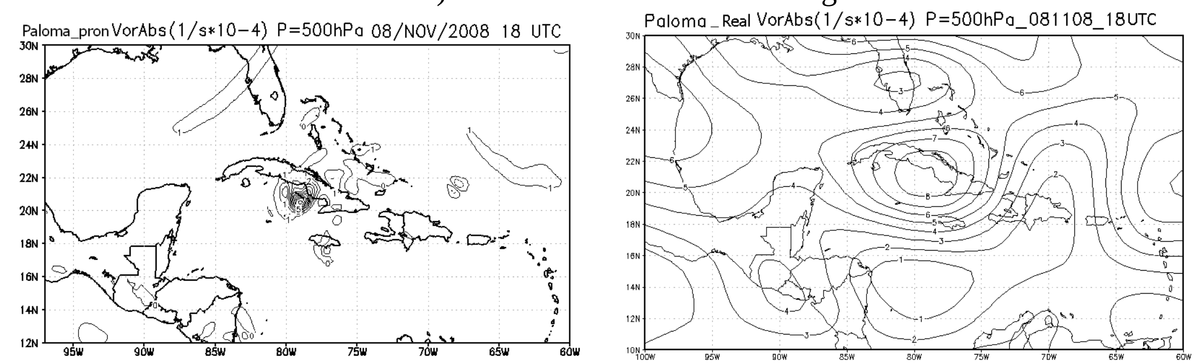
3.3. Paloma (2008)

It originated from an area of disturbed weather that developed in the southwestern Caribbean Sea on November 1, developing into a tropical depression at 18:00 UTC on November 5, about 213 km Southeast of the Nicaragua/Honduras border, on the Southwestern edge of a mid- to upper-level ridge centered over the eastern Caribbean, resulting in an initial motion toward the northwest (Brennan, 2009). Favorable oceanic conditions allowed the depression to steadily intensify, to become a tropical storm around 06:00 UTC on November 6 roughly 111 km east of the Nicaragua/Honduras border. Paloma then turned toward the North and reached hurricane status around 00:00 UTC on November 7, about 287 km South-southwest of Grand Cayman. A rapid process of intensification began, and it became a major hurricane around 00:00 UTC on November 8. As the hurricane approached Cuba, the strong upper-level Southwesterly winds advected the mid- and upper-level portions of Paloma's circulation rapidly to the Northeast. After weakening to category 2, its center made landfall around 01:00 UTC on November 9 near Santa Cruz del Sur, Camagüey, Cuba, with maximum sustained winds of 157 km/h. A short time after landfall, its vertical structure began to decouple due to continued strong vertical wind shear and interaction with the landmass of Cuba. It became a tropical storm around 06:00 UTC on November 9 and a tropical depression by 18:00 UTC on the same day. By 00:00 UTC on November 10, no deep convection was present near the circulation of Paloma and it degraded into a remnant low.

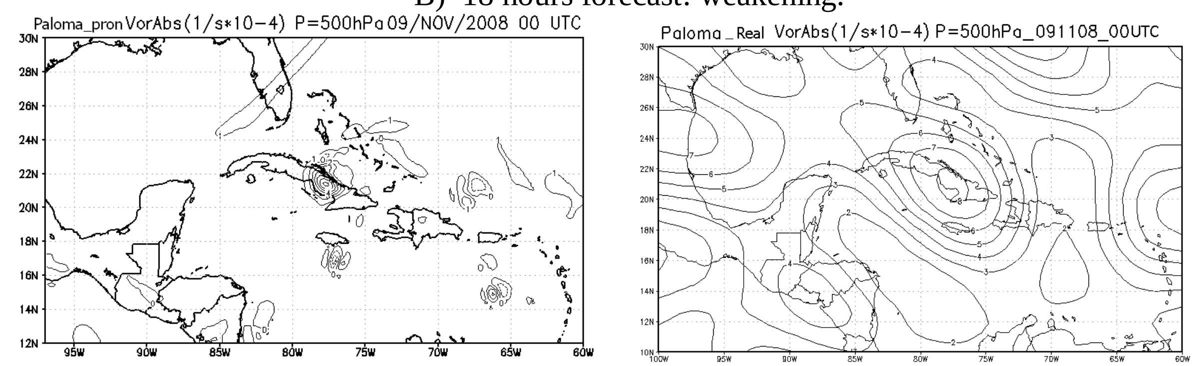
For the Paloma case, an experiment was made from November 8 (00:00 UTC) to November 11 (00:00 UTC). The very well defined initial conditions helped to obtain a high quality forecast for the first 36h. The weakening period before the landfall on Cuban Territory, was well represented on the 500-hPa vorticity field (Fig. 10 (A-D)) and also the corresponding circulation in the geopotential fields from the low to upper levels (Fig. 11 (A-D)). However, the subsequent weakening and dissipation over land, due to the concurrence of the unfavorable atmospheric conditions and the air-ground surface interaction, were not well represented by the model. It is possible that this situation is a consequence, as in Omar's



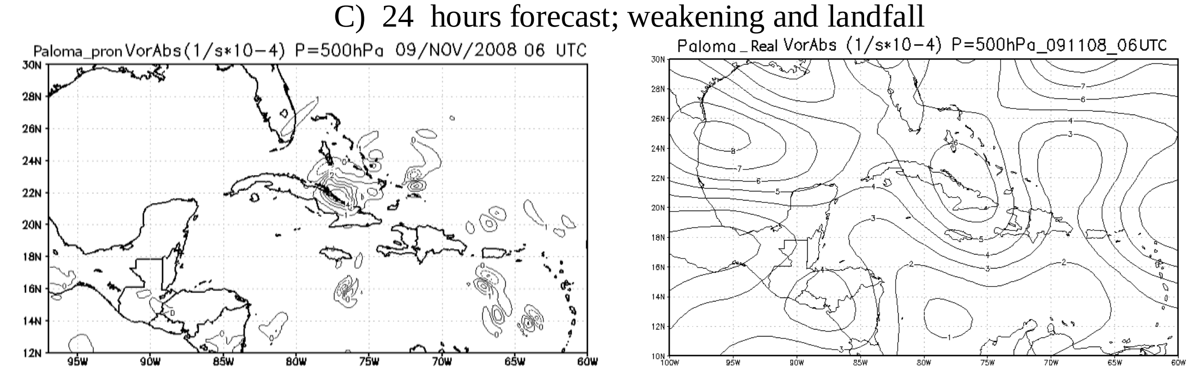
A) 12 hours forecast: weakening.



B) 18 hours forecast: weakening.

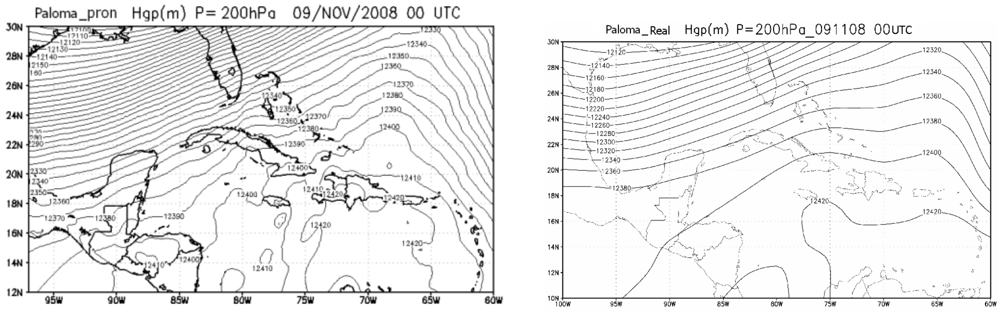


C) 24 hours forecast; weakening and landfall

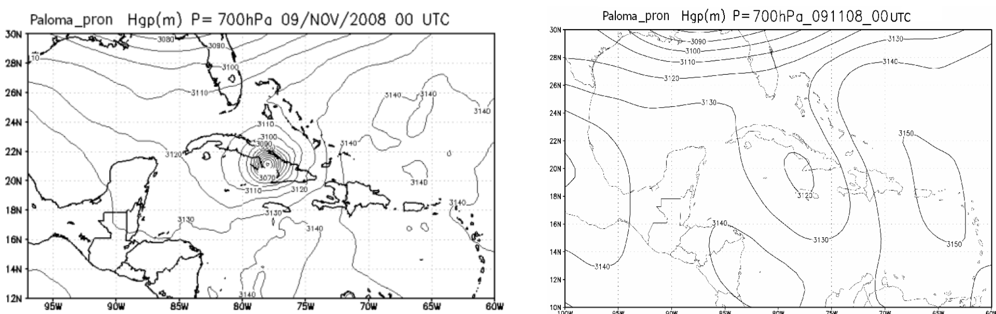


D) 30 hours forecast; over land

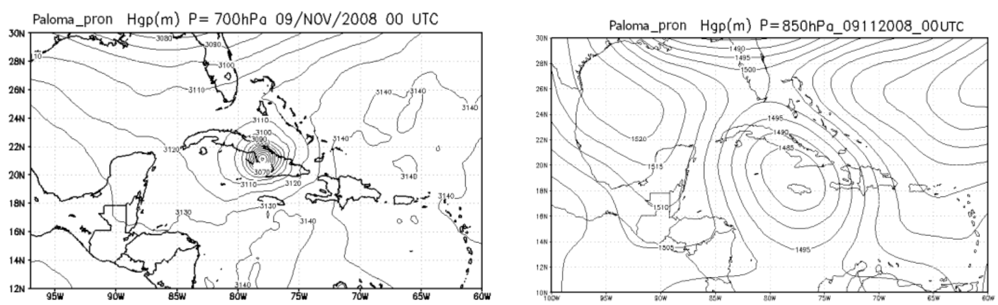
Figure 10 (A-D). As Paloma weakened and made landfall, MM5V3 absolute vorticity field outputs (left) for 12h to 30h forecasts (with initial conditions on 8/11/2008 (00:00 UTC)) and corresponding reanalysis (right).



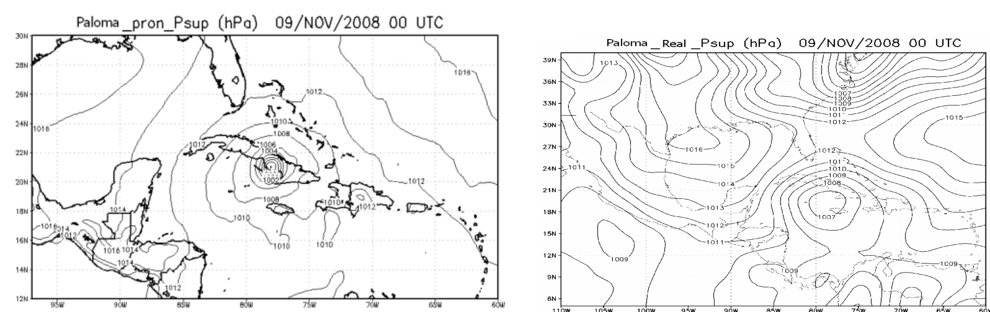
A) Level 200 hPa



B) Level 700 hPa



C) Level 850 hPa



D) Sea level pressure

Figure 11 (A-D). Geopotential height and sea level pressure field of MM5 outputs (left) and reanalysis (right), as hurricane Paloma weakened before landfall on Cuba on 9/11/2008 00:00 UTC), with initial conditions on 08/11/2008 (00:00 UTC).

case, of the limitations of the diabatical process representations, especially the boundary layer parameterization.

As a final result, the track forecast was satisfactory only for the first 30h (Figure 12).

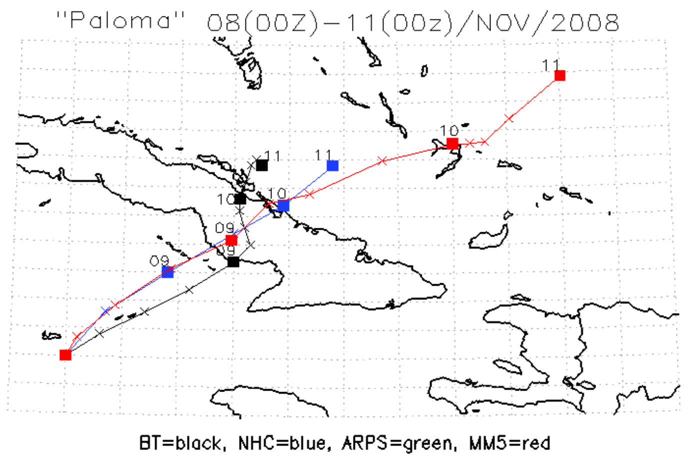


Figure 12: Paloma´s track from MM5V3 and NHC forecasts, in comparison with the NHC best track.

3. 4. Summary

Table 1 summarizes the evaluation of the MM5 track forecast for the three case studies compared to the NHC best track. The mean error (km) for each forecast term is given as well as the MM5 and NHC forecast error average (4 years).

	Term ⇒	12 hours	24 hours	36 hours	48 hours	72 hours
Hurricanes	Data Base					
"Dean"	15,16,17/08/2007 00 UTC	49(3)	81(3)	140 (3)	143 (3)	217.68(2)
"Omar"	15/10/2008 00 UTC	63 (1)	9(1)	217(1)	382(1)	706.02 (1)
"Paloma"	08/11/2008	60 (1)	43(1)	147 (1)	447(1)	457.8(1)
MM5 Average	2004-2008	54 (20)	59 (20)	157 (19)	251 (19)	340.63 (11)
NHC Average	2003-2007	51.68	88.46	124.94	161.42	234.38

Table 1. Track forecast error (km) from MM5 and NHC results. The case quantities are in brackets.

From the table and graphics, it may be seen that the MM5 errors, up to the 36h term, are almost of the same order as the NHC errors. These results are attributed to the correct domain localization and the suitable selection of the parameterization methods, allowing the reproduction of most meteorological situations.

In the cases of Omar and Paloma, the interaction between domains was also investigated, using one and two way nesting. The results are shown in Table 2.

Time range (h)/ Errors (km)	12	24	36	48	72
Initial Date: 15/10/2010 at 00 UTC					
Omar 1 way MM5 forecast	55.31	19.12	190.13	355.67	721.21
Omar 2 ways MM5 forecast	53.68	19.44	194.49	372.85	716.70
NHC forecast for hurricane Omar	40.07	22.23	144.48	274.49	716.21
NHC average for hurricane Omar	63.84	127.68	173.28	252.32	425.60
Initial Date: 08/11/2010 at 00 UTC					
Paloma 1 way MM5 forecast	47.8	65.37	80.24	321.74	575.52
Paloma 2 ways MM5 forecast	60.52	39.47	142.57	401.53	457.83
NHC forecast for hurricane Paloma	204.32	278.06	186.3	49.7	129.61
NHC average for hurricane Paloma	47.12	88.16	121.6	159.6	259.92
NHC average (2003-2007)	51.68	88.46	124.94	161.42	234.38

Table 2. Comparison between one-way and two-way nesting MM5 results for hurricanes Omar and Paloma.

Neither one-way nor two-way nesting seem to be clearly superior in performance, even if the results are slightly different.

5. Conclusion

1. MM5 showed good skill on hurricane track forecast, for time lapses up to 48 hours, for the areas of Cuba and the Lesser Antilles. The track forecast errors were close to the NHC forecast errors, especially for time laps terms less than 24 hours. Thus, the model is well adapted for local hurricane-related events forecast, such as intense rainfall and strong winds.

2. The use of nested domains led to satisfactory results on hurricane track prediction. However, results were satisfactory with a 20km (Dean) or 27km (Omar and Paloma) grid spacing and a higher space resolution did not improve them. Nevertheless, the high resolution can contribute improving the accuracy of the local weather forecasts.

3. The sensitivity to the use of one-way or two-way nesting was investigated. Neither of them proved to be clearly superior in performance, even if the results were slightly different.

4. The model limitations arise when an abrupt weakening occurs, as in the case of Paloma (48 h forecast term, with initial conditions on 8 November 2008, at 00:00 UTC).

5. The best results were achieved when the hurricane circulation was well organized and it was captured by the East mean flow, at the periphery of a high pressure center, as in the case of Dean.

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