P2H.10 **LANDFALLING TROPICAL CYCLONES IN THE EASTERN PACIFIC. PART II: WRF SIMULATIONS OF JOHN AND PAUL (2006)**

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1. INTRODUCTION

Three tropical cyclones that developed during the 2006 season over the eastern Pacific ocean, made landfall in northwestern Mexico. John affected Baja California and Lane and Paul brought intense precipitation to the mainland. The observational characteristics of these events are described in a companion study at this conference (Farfan et al, 2008) and, here, we focus on numerical simulations performed using the Weather Research and Forecasting (WRF) model.

The genesis of John occurred in the Gulf of Tehuantepec in late August and the cyclone then moved parallel to the Mexican coast to make landfall in the Baja California peninsula. Its slow motion resulted in precipitation that exceeded the maxima observed during the last 30 years in the mountainous regions in the southern peninsula. Paul developed in late October when low and mid-level winds exhibited a significant westerly component. The storm made landfall in Sinaloa on 26 October and the interaction with the Sierra Madre Occidental also resulted in intense precipitation.

Numerical simulations with WRF are used to study the life cycle of these two hurricanes and their sensitivity to microphysics and cumulus parameterizations. Results from the simulations are compared with those from observations presented in part I.

2. DATA AND SIMULATION CHARACTERISTICS

Simulations of hurricanes John and Paul were initiated on 31 August, 2006 at 00 UTC and 22 October, 2006 at 00 UTC, respectively. Both simulations included 2 nested grids (30 and 10 km resolution) and were performed for 4 days. The Final (FNL) analyses from the Global Data Assimilation System (GDAS) provided the initial and lateral boundary conditions for simulations every six hours. The Mellor-Yamada parameterization was selected for the boundary layer processes and Monin-Obukhov describes those in the surface layer.

The Kain-Fritsch cumulus parameterization was used in the external domain and the microphysics scheme of Lin et al. (1983) was used in the inner one. New simulations using the Thompson et al. (2004) microphysics scheme in the inner domain and the simplified Arakawa-Schubert (SAS) cumulus parameterization in the outer one were performed to test sensibility. Table1 shows a description of the simulations described in this study.

Digital imagery from the Geostationary Operational Environmental Satellite-11 (GOES-11) is used to compare with cloud cover from simulations. The simulated rain rate and accumulated precipitation were compared with 3B42 TRMM 3-hourly rain rate (mm/h) at 0.25 degree resolution and with rain gauges from the Mexican network managed by the Comisión Nacional del Agua (CNA), respectively. Vorticity, wind shear, geopotential and sea surface temperature fields from simulations and FNL were also analyzed.

3. RESULTS

3.1 *Simulations JohnKL and PaulKL*

The model trajectory for JohnKL fails to make landfall in the southern tip of Baja California, predicting a more westerly course than observed (Fig. 1). In reality, on 1 September, John turned toward the north-northwest as the mid-level ridge to the north of the hurricane weakened. This large scale feature was not captured by the simulation and neither by the National Hurricane Center (NHC) official track, which presented large errors beyond 96 h in Table 2. Less than a day before

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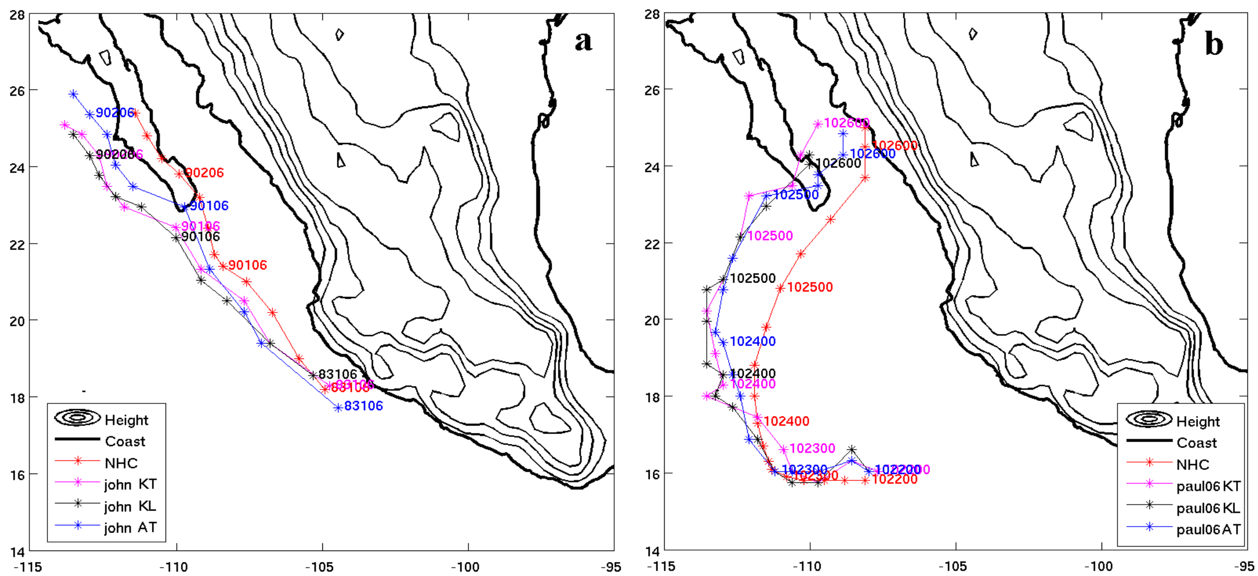

Fig. 1. Best track and simulated (WRF) positions. a) Hurricane John, 28 August-4 September 2006. b) Hurricane Paul, 21-26 October 2006.

landfall, the NHC official report and JohnKL show the TC to move near Cabo San Lucas, rather than to the northeast, where landfall occurred. Most of the forecast tracks did not predict the landfall of John, possibly due to a lack of radiosonde data in northwestern Mexico that are usually assimilated during the model initialization procedure. Paul's track was more complicated than that of John; nevertheless, PaulKL simulation was able to capture its behavior adequately (Fig. 1). Afterwards, the simulation failed due to a slower than reality northward turn of the hurricane. Errors in the trajectory of PaulKL are smaller than those in JohnKL when they are compared with the NHC official forecast errors (Table 2).

Table1. Description of simulations performed in this study for hurricane John. Similar names are used for Paul.

Name	Cumulus	Microphysic
JohnKL	Kain-Fritsch	Lin
JohnKT	Kain-Fritsch	Thompson
JohnAT	Arakawa-Schubert	Thompson

The large-scale air flow at middle levels is the main factor determining the motion of a cyclone. However, the vortex depth, its radial structure and azimuthal asymmetry can also modify the track (Wang and Holland 1996; Wang 2002; Fovell and Su 2007). This implies that a poor representation of the vortex (or the storm intensification) could cause errors in its trajectory.

Simulations do not reproduce the storm intensification observed in the NHC official report. JohnKL attains a minimum central pressure of 970 hPa, while a minimum of 950 hPa was reported by the NHC. In addition, its temporal evolution show large differences (Fig. 2a). In the case of PaulKL, no intensification was simulated (Fig. 3a). Large-scale characteristics that have a key role in the tropical cyclone (TC) intensification, such as the sea surface temperature (SST) and the vertical wind shear (VWS), are slightly different in JohnKL due to its deviation from the NHC track (Figs. 2b,c). Such differences negatively affect the TC intensification. VWS and SST values are very similar in PaulKL to those in the FNL (Fig. 3b,c) but no intensification occurred. The simulated geopotential field at 850, 700 and 200 hPa (not shown) is also similar to that in analyses (20 m error) in both simulations. This suggests that problems in reproducing the intensification of TCs could be associated to the inability to represent the smaller-scale processes that occur in the eye-core and have an important role in cyclone development. FNL analyses, do not show the reported intensification (green lines in Figs. 2a and 3a). Another important factor could be the poor representation of the surface fluxes in the region as a result of the inadequacy of the chosen parameterization.

Simulations show that John developed in a more humid environment than Paul (Fig. 4), consistent with observations. Furthermore, Paul weakened when it moved to the North due to its interaction with dry air coming from the northwest Pacific and with a region that shows larger values of VWS between 850 and 200 hPa (Fig. 2d). In the case of John, the advection of dry air is considerably smaller (Fig. 4a), which favors its intensification. Both hurricanes transport large amounts of moisture to Baja California and the northwestern coast of Mexico, contributing to increase the precipitation in the region.

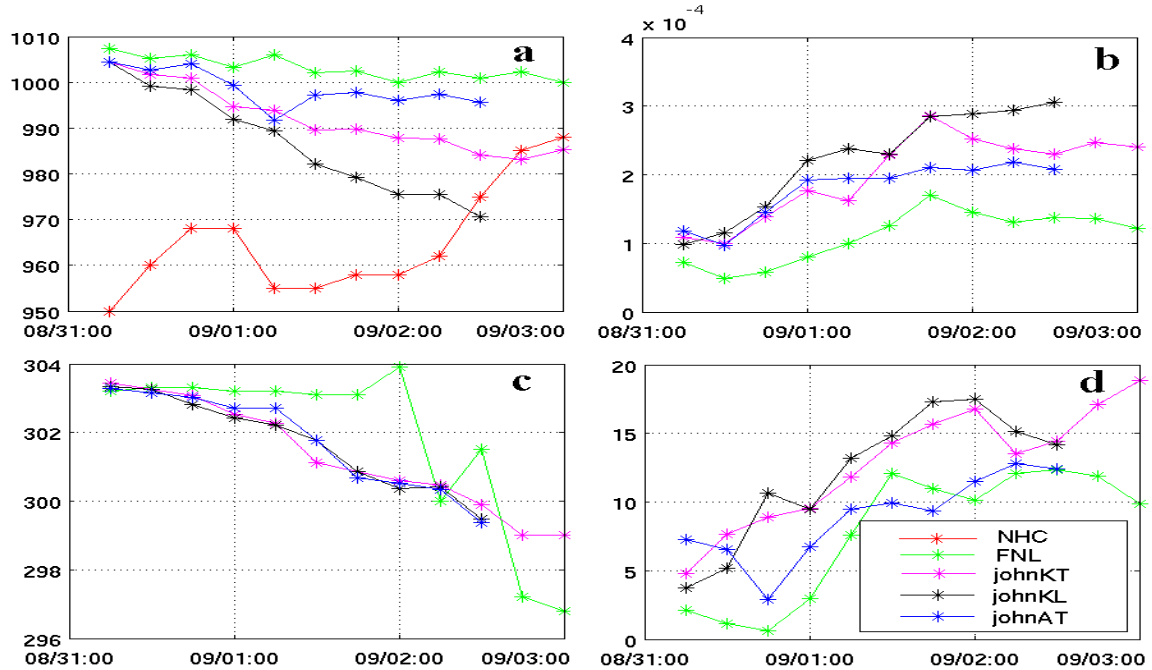

Fig. 2. Hurricane John. Temporal evolution of a) Minimum central pressure b) Mean vorticity over the storm. c) Sea surface temperature. d) Mean vertical shear (850-200mb) over the storm.

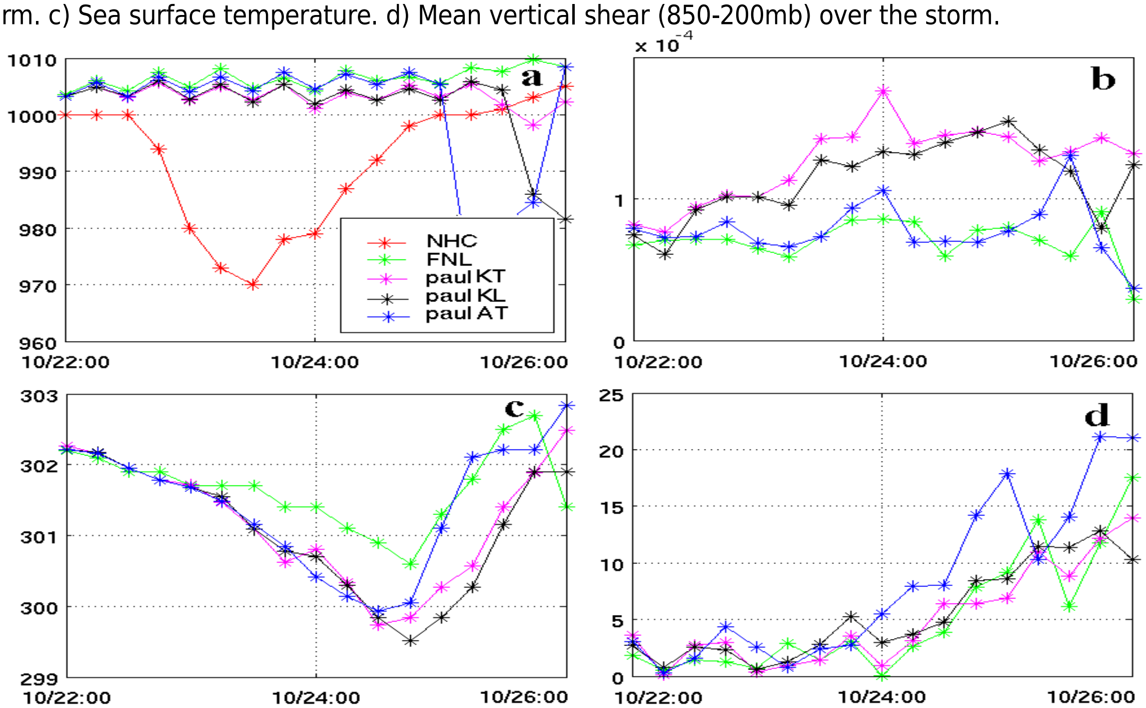

Fig. 3. Hurricane Paul. Temporal evolution of a) Minimum central pressure b) Mean vorticity over the storm. c) Sea surface temperature. d) Mean vertical shear (850-200mb) over the storm.

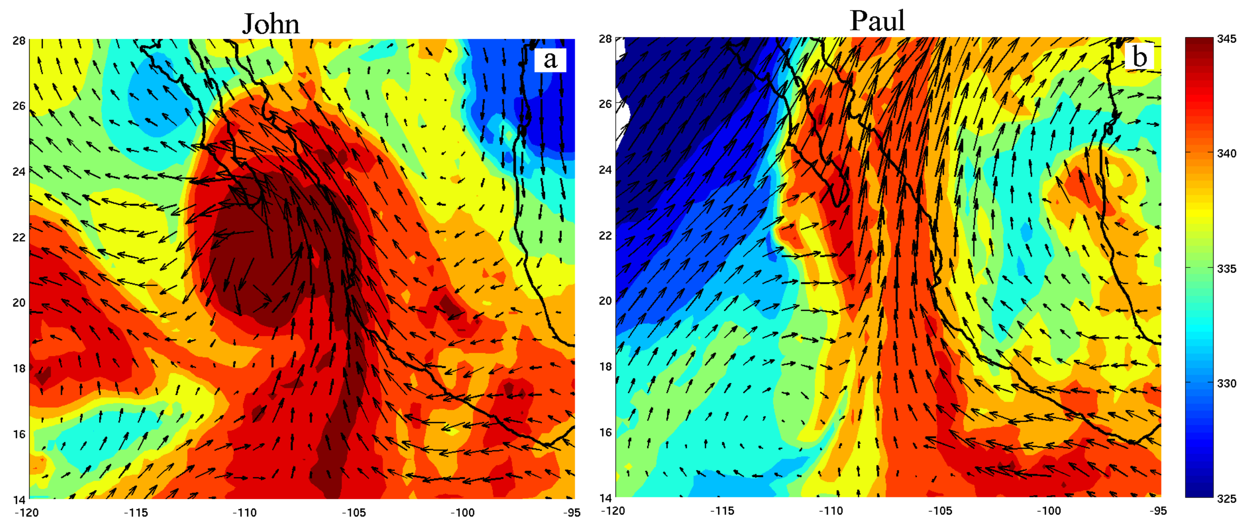

Fig. 4. Equivalent potential temperature at 500mb and wind vectors. a) Hurricane John, 1 September at 00 UTC. b) Hurricane Paul, 25 October at 00 UTC.

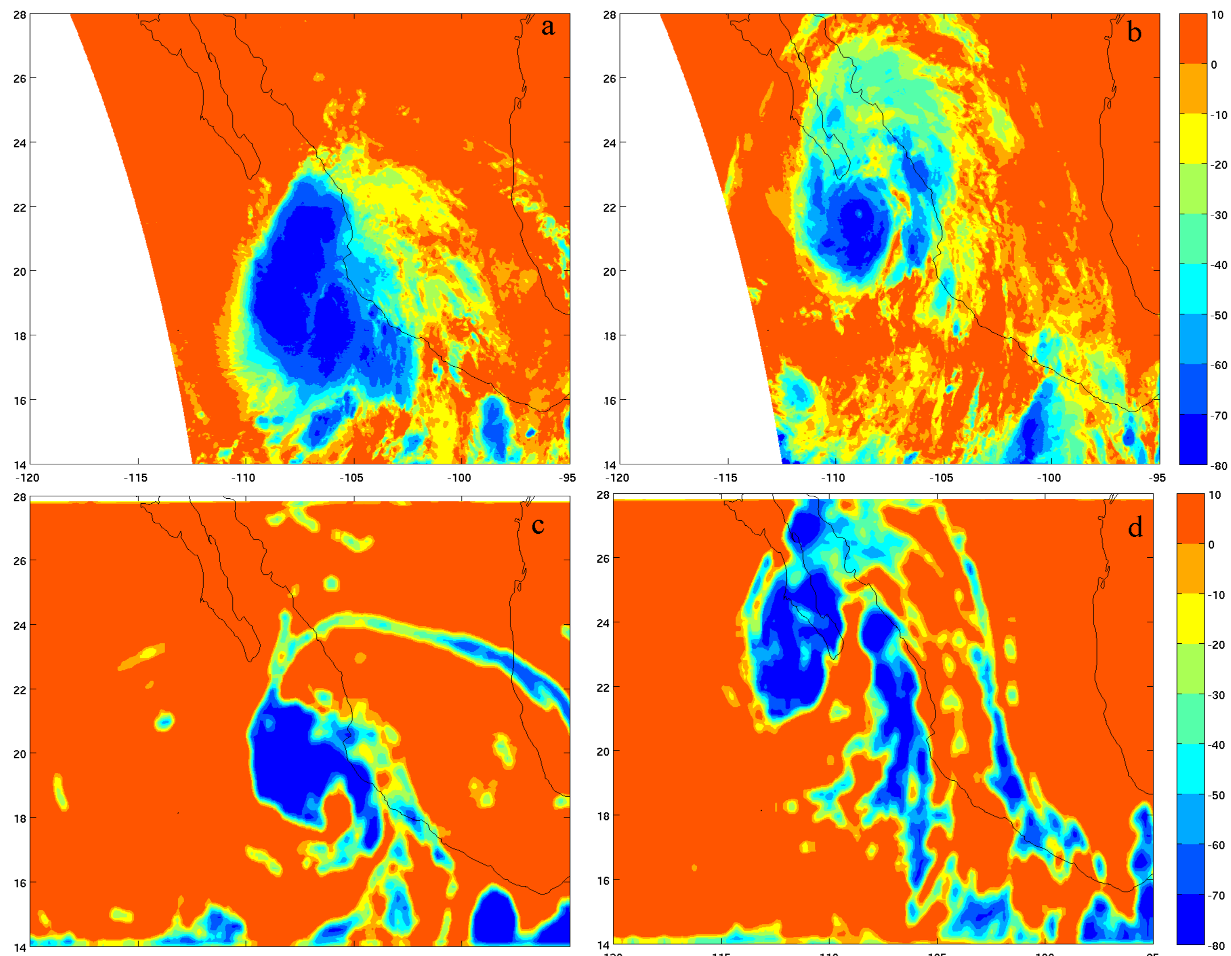

Fig. 5. Cloud cover from Hurricane John. GOES-11 for a) 31 August at 12 UTC and b) 1 September at 12 UTC. JohnKL simulation for c) 31 August at 12 UTC and d) 1 September at 12 UTC .

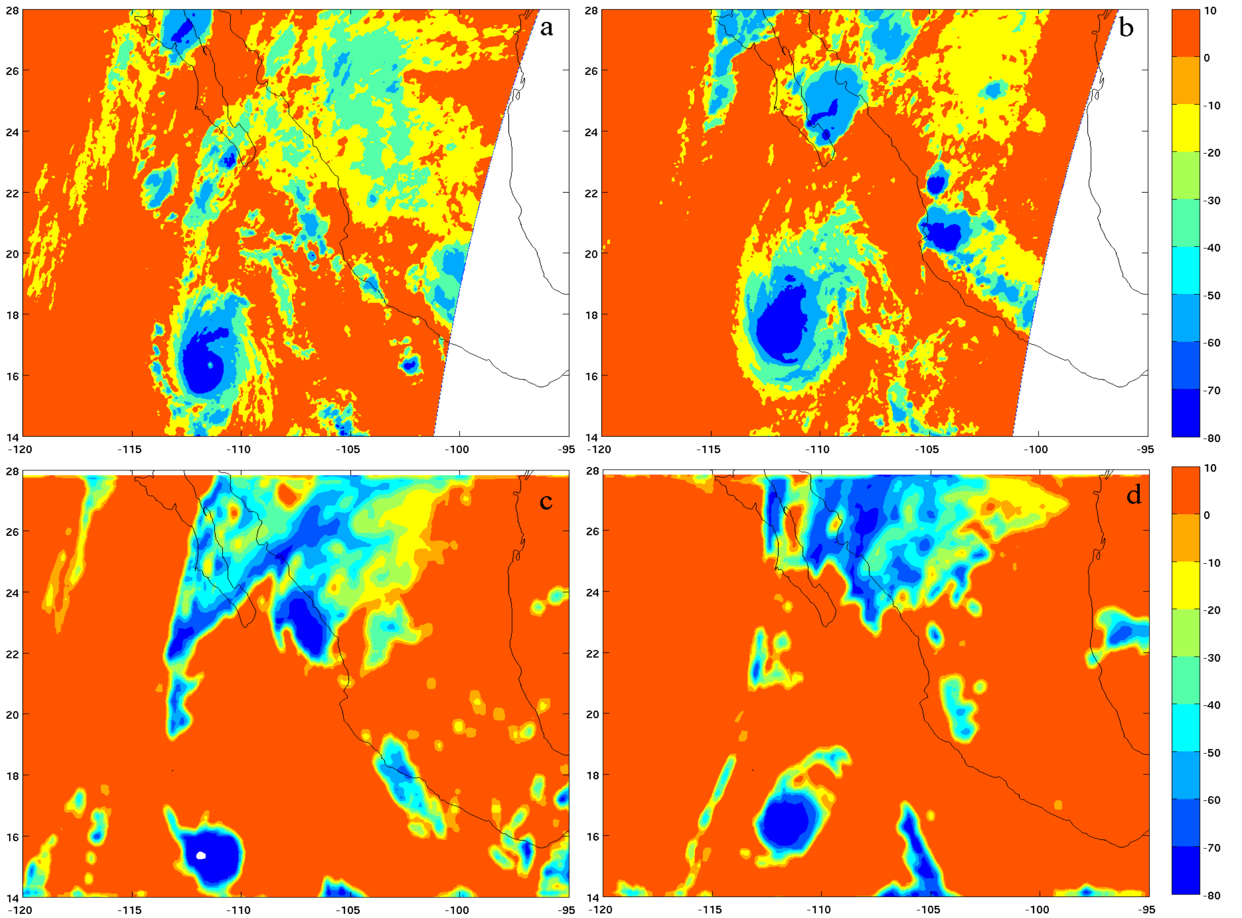

Fig. 6. Cloud cover from Hurricane Paul. GOES-11 for a) 23 October at 12 UTC and b) 24 October at 00 UTC. PaulKL simulation for c) 23 October at 12 UTC and d) 24 October at 00 UTC.

Table2. Forecast errors (n mi) for Hurricanes Paul and John.

Forecast Technique (hurricane)	Forecast Period (h)					
	12	24	36	48	72	96
WRF (PaulKL)	43.3	23.5	117.9	110	120	118.4
WRF (PaulKT)	14.15	42.5	114.1	91.3	115.2	104.8
WRF (PaulAT)	19.0	24.9	117.6	143.6	148.3	46.8
OFCL (Paul)	**38**	**71**	**96**	**144**	**201**	**231**
WRF (JohnKL)	63.8	92.7	170.27	204.38	180.9	-
WRF (JohnKT)	63.8	94.5	199.7	191.3	169.5	-
WRF (JohnAT)	80.4	77.5	199.2	214.2	209.0	-
OFCL (John)	**24**	**37**	**51**	**71**	**145**	**242**
NHC Official (2001-2005 mean)	35	60	83	103	145	192

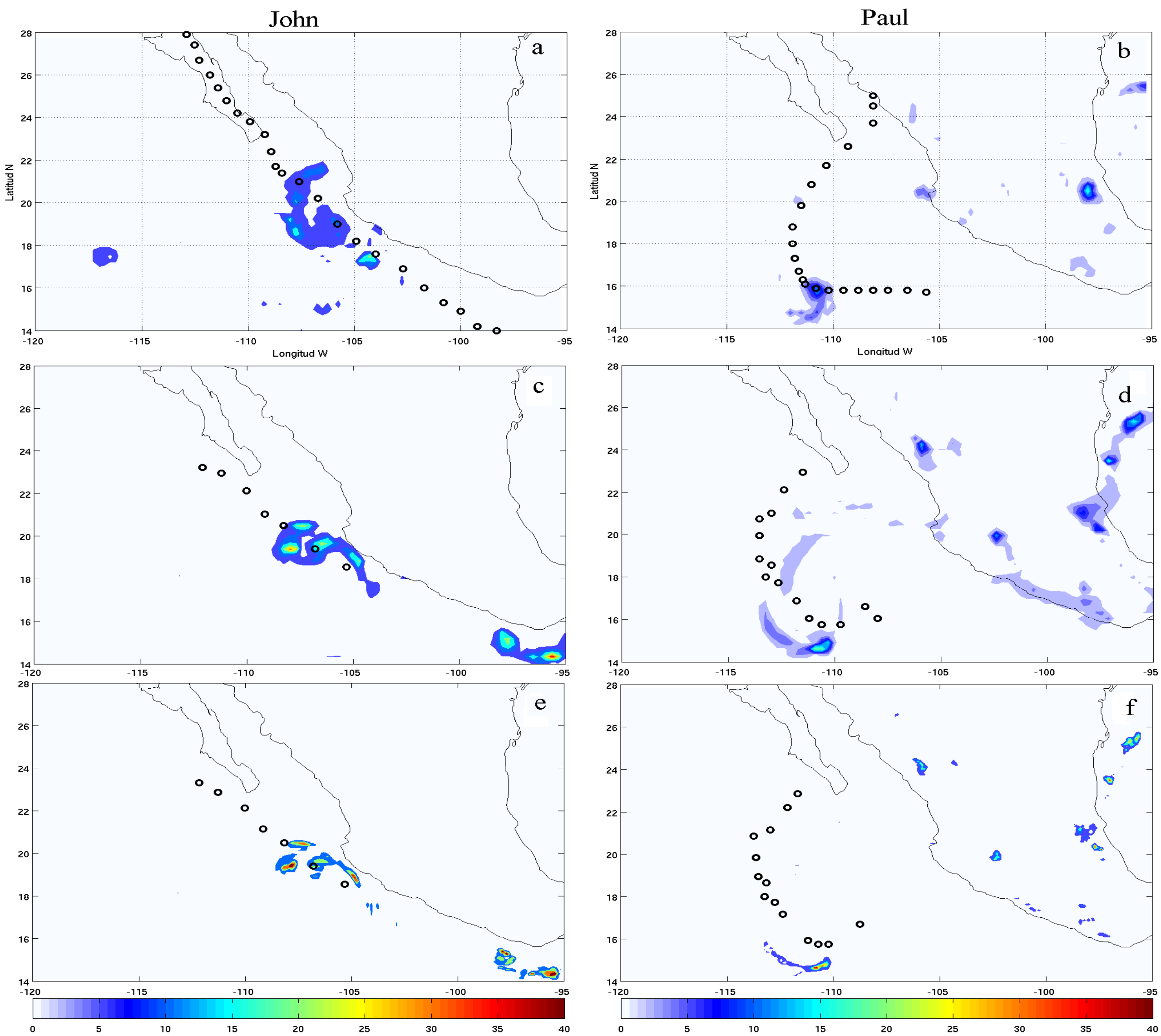

Fig.7. Rain rate (mm/h) for hurricanes John (a,c and d) and Paul (b,d and f). a,b) TRMM. External domain for simulation c) JohnKL and d) PaulKL. Inner domain for simulation f) JohnKL and g) PaulKL.

The comparison of simulations with GOES data shows a similar cloud pattern but clouds are underestimated (Figs. 5 and 6). Figs. 5a,c show the cloud top temperature from GOES and the simulation initiated on 31 August at 12 UTC, respectively. Precipitation from TRMM and results from the simulations are shown in figures 7a,c. Despite the large differences observed in the cloud cover, differences in the intensity or the area of precipitation are small. This indicates that the simulation does not reproduce very well clouds that produce little or no precipitation. In addition, the inadequate intensity forecast leads to less defined cloud patterns than in the real hurricanes. In general, the heavy rain is overestimated in simulations (Fig. 7). This overestimation is larger in the inner domain, where the microphysics scheme of Lin et al. (1983) was used. This parameterization overestimates precipitation since it produces much larger amounts of hail than observed and underestimates light rain (Smedsmo et al. 2005; Zhang et al. 2001). The accumulated precipitation comparison between simulations and meteorological stations data indicates that Loreto, Acaponeta and San Lucas show the largest values but they were underestimated in hurricane John. In the case of Paul, Pericos station showed the largest precipitation value in both the simulation and observations, and its magnitude is underestimated too. This underestimation may be related with differences in the simulated storm track.

3.2 *Sensitivity to microphysics and cumulus parameterizations (JohnKL, JohnKT and JohnAT)*

The simulations with Thompson parameterization for the inner domain, (JohnKT and JohnAT) show landfall 18 h before and farther to the west to the observed hour and position of landfalling (Fig. 1). Differences in the error track of ± 29 n mi are observed between Thompson and Lin schemes. Such a strong sensitivity to the selected microphysical parameterization was not expected. Differences in the cyclone intensification in the different simulations, though small, could produce changes in the track since the vortex characteristics and the distribution of convection around the storm center are modified.

None of the simulations, with different combinations in cumulus and microphysics schemes, reproduce adequately the intensification process. The minimum pressure from JohnKL shows the best agreement with the NHC report. JohnAT shows the least agreement with observations and it differs from JohnKL by 20 hPa at 48h of simulation.

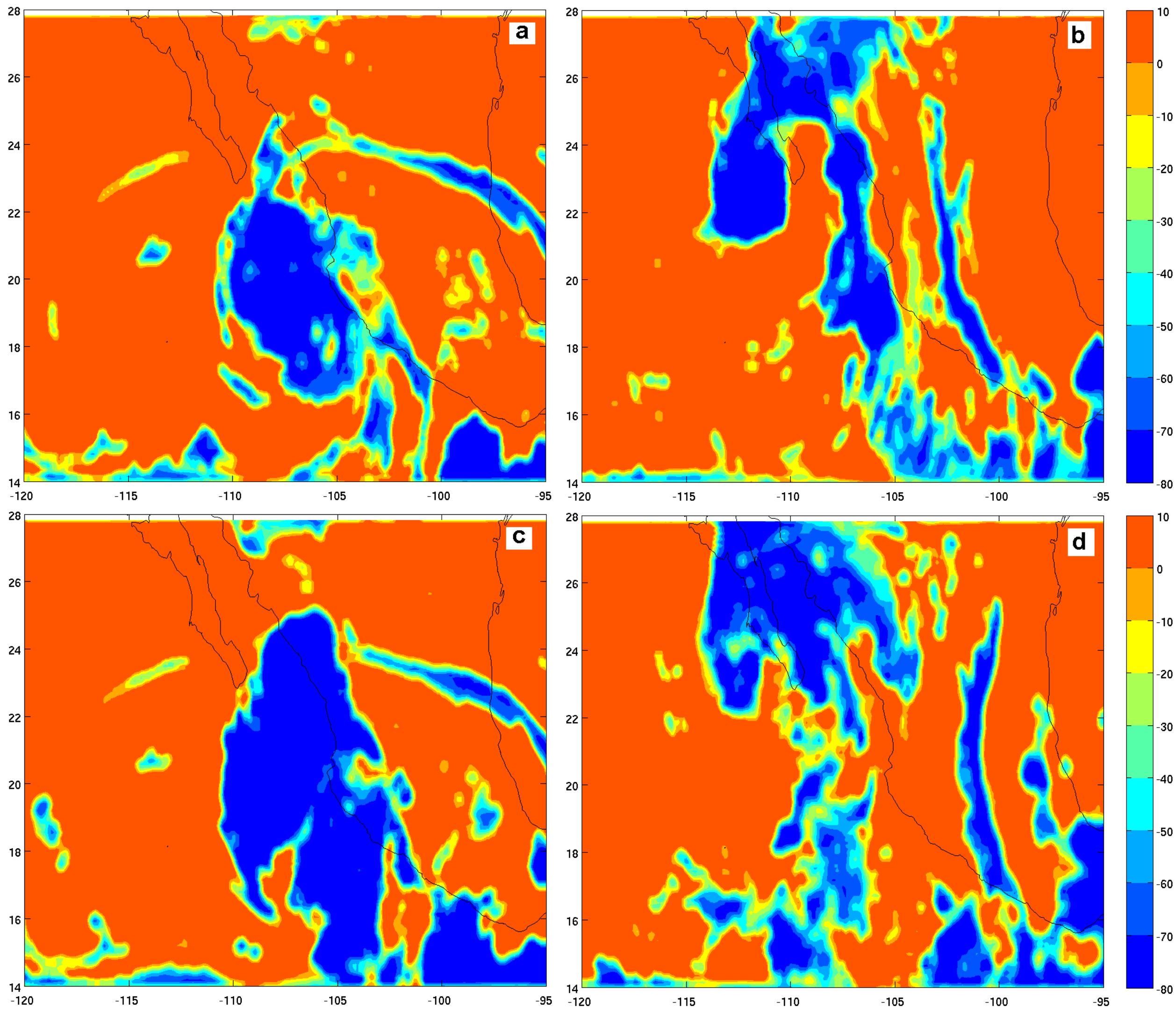

Fig. 8. Cloud cover from hurricane John. JohnKT simulation for a) 31 August at 12 UTC and b) 1 September at 12 UTC. JohnAT simulation for c) 31 August at 12 UTC and d) 1 September at 12 UTC .

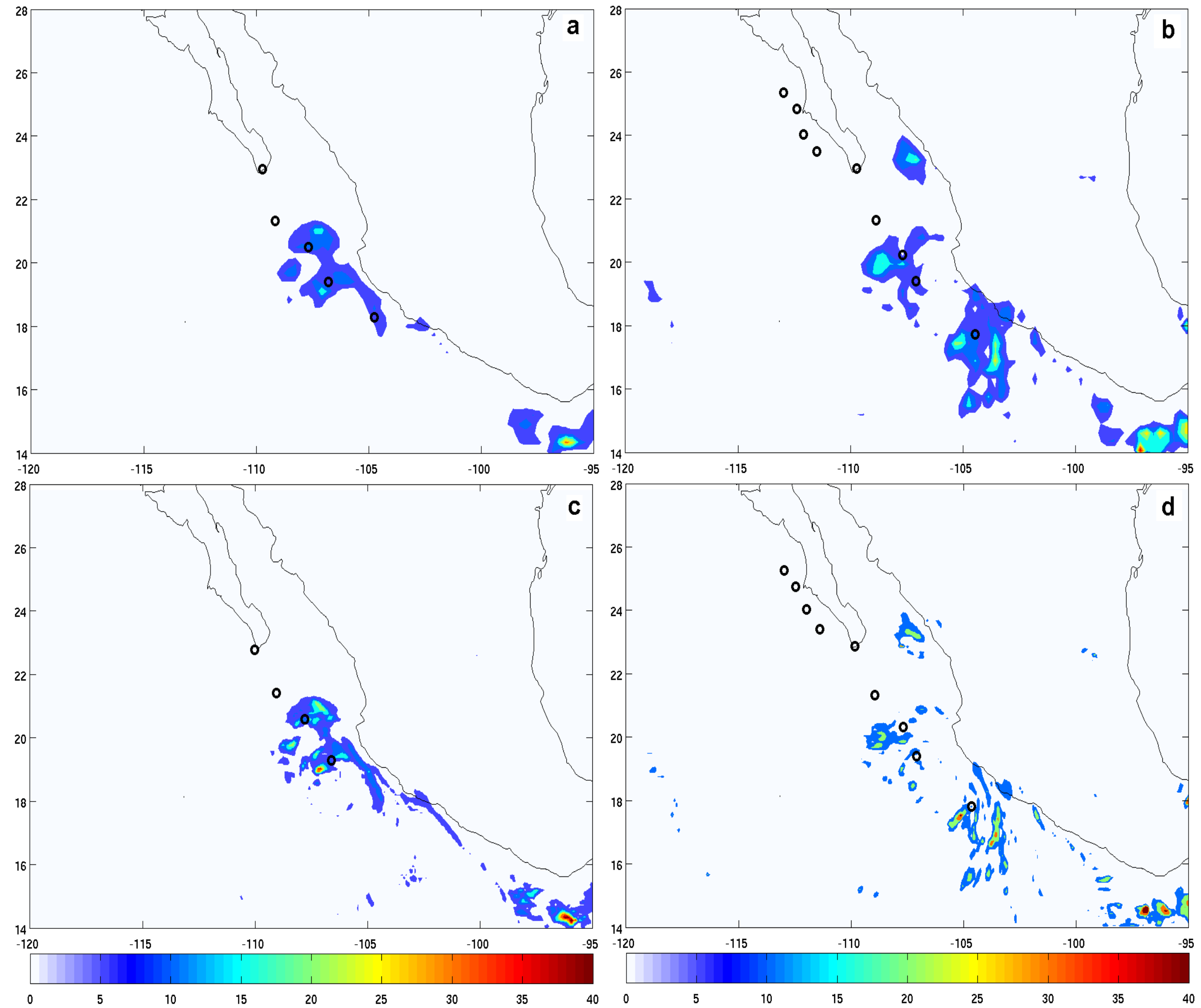

Fig. 9. Rain rate (mm/h). External domain for simulation a) JohnKT and c) JohnAT. Inner domain for simulation b) JohnKT and d) JohnAT.

Table 3. Rainfall accumulation (mm) for tropical cyclones John (31 August-3 September) and Paul (24-26 October). Station values (mm) are followed by simulation values in parentheses.

Station	JohnKL	JohnKT	JohnAT	PaulKL	PaulKT	PaulAT
Loreto	263(140)	263(140)	263(160)	57(60)	57(40)	57(80)
La Paz	83(40)	83(40)	83(60)	2(60)	2(40)	2(60)
San Lucas	129(80)	129(100)	129(80)	36(60)	36(100)	36(120)
Choix	75(40)	75(80)	75(40)	50(60)	50(60)	50(100)
Pericos	14(20)	14(20)	14(20)	224(120)	224(140)	224(200)
Mazatl'an	89(40)	89(80)	89(20)	32(100)	32(120)	32(200)
Acaponeta	98(40)	98(60)	98(40)	18(20)	18(20)	18(40)
Tepic	27(20)	27(40)	27(20)	36(40)	36(40)	36(40)

Large differences are shown in the observed cloud and precipitation distributions (Figs. 8 and 9). Results from JohnAT (Figs. 8c,d and 9b,d) do not reproduce at all the observed distributions in TRMM (Fig. 7a) and GOES (Figs. 5a,b) as JohnKL does. JohnAT overestimates much more the cloud top heights and the precipitation area than JohnKL. JohnKT shows a closer agreement with GOES cloud cover than JohnAT, although it overestimates the cloud top heights. JohnKT shows the least overestimation of precipitation intensity when compared with TRMM, and it reproduces better than the other simulations, the accumulated precipitation reported by surface stations (Table 3).

4. CONCLUSIONS

Simulations of hurricanes John and Paul, performed using the WRF model, were compared with observations. The Kain-Fritsch and the Arakawa-Schubert cumulus parameterization in the 30 km horizontal resolution domain and Thompson et al. 2004 and Lin et al. 1983 microphysics schemes in the inner domain (10 km resolution) were selected to evaluate the sensibility to different combinations in the cumulus and microphysics parameterizations.

None of the simulations reproduces accurately the cyclone intensification. Hurricane Paul does not show any intensification at all, despite presenting a good agreement with the large-scale fields from the FNL analysis. This can affect the simulated trajectory and convective organization.

Track errors in JohnKT are the smallest among simulations since the simulated translation velocity is the closest to the one from the NHC. JohnKL (JohnAT) does the best (worst) job in reproducing the observed cloud field from GOES. Simulations using the Thompson (Lin) microphysics overestimate (underestimate) the high clouds. Lin reproduces much better the low clouds while still underestimating them. Simulations with the K-F cumulus parameterization show a better agreement with the observed precipitation distribution and specifically, JohnKT, shows the best agreement with TRMM and surface station observations.

Simulations show that tropical cyclones supply large amounts of humidity to Baja California and largely contribute to the precipitation accumulation in the region with respect to the total annual average, as reported from observations in Part I.

5. REFERENCES

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