Sensitivity of Numerical Simulations of Hurricane Joaquin (2015) to Cumulus Parameterization Schemes: Implications for Processes Controlling a Hairpin Turn in the Track

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Abstract

Hurricane Joaquin, a notable hurricane that occurred over the Atlantic Ocean in 2015, is studied with an emphasis on its unique hairpin turn that occurred between 2100 UTC 1 October and 0600 UTC 2 October 2015. A series of mesoscale high-resolution numerical simulations are performed with an advanced research version of the Weather Research and Forecasting (WRF) model. The sensitivity of numerical simulations to different cumulus, boundary layer, and microphysical parameterization schemes is examined to investigate the most relevant processes influencing the track evolution of Hurricane Joaquin. It was found that the numerical simulation of Hurricane Joaquin's track is highly sensitive to the choice of cumulus scheme. Large-scale environmental conditions and hurricane inner-core structures are diagnosed. The results indicated that middle- to upper-level steering flows are crucial in influencing Joaquin's track. Further investigation of the large-scale environment (middle- and upper-level trough, blocking high, thermal distribution, etc.) shows that middle-level blocking high plays an important role in Joaquin's movement. The structure of the hurricane core region, including the vertical extent of diabatic heating, vertical velocity, and relative humidity, could also play an important role. Specifically, the asymmetry and local absolute vorticity tendency over the inner-core region and its vicinity have a strong implication for Joaquin's hairpin turn.

Keywords cumulus parameterization; hurricane; track forecasting; WRF model

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1. Introduction

Accurate prediction of tropical cyclone (TC) track and intensity is a challenging problem in numerical weather prediction. Owing to higher-quality observations and better physical representation in regional models, TC track forecasts have been greatly improved

during the past several decades (Rogers et al. 2013; Gall et al. 2013). According to the US National Hurricane Center forecast verification of early models for the period from 1994 to 2015, there has been a downward trend in model forecast error. The 48 h track errors for different global and regional models in 2015 ranged between 50 and 150 nautical miles (approximately 100–300 km). However, despite the remarkable research progress that has been made in recent years on the fine-scale inner-core structure of TCs and the interaction between TCs and oceans (e.g., Chan and Kepert 2010), there has been less

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improvement in forecasts of TC intensity than for TC track (Burton et al. 2010; Duan et al. 2012). Moreover, despite the improvements in hurricane track forecasting, TC tracks can still pose a significant forecasting challenge. Notable examples include real-time forecasts of Hurricane Sandy (2012) and Hurricane Joaquin (2015) over the Atlantic Ocean.

Specifically, the prediction of Hurricane Joaquin's clockwise hairpin turn from 2100 UTC 1 October 2015 to 0600 UTC 2 October 2015 presents a forecasting challenge during real-time prediction, as tracks of several numerical models differ from each other. In particular, during the real-time forecast of Hurricane Joaquin in 2015, several operational models forecasted Joaquin's landfall over the East Coast of the United States, whereas other models correctly forecasted the recurve of Joaquin over the Atlantic Ocean (Berg 2016). Therefore, the track forecast of Joaquin has become an interesting research question.

Several factors could contribute to inaccurate TC track forecasts: uncertainties in physical representations in numerical weather prediction (NWP) models, the dearth of observations, and the lack of understanding of the processes that control TC tracks (Rogers et al. 2006). Specifically, one of the greatest challenges in hurricane numerical prediction is the ability of numerical models to accurately depict the large-scale environmental flow of the atmosphere that is largely responsible for steering TCs (e.g., Marchok 2014; Wang and Wu 2004). Another is the accurate representation of the structure of the hurricane vortex (e.g., Zhang et al. 2011; Pu et al. 2009). In this study, we investigate the factors controlling the hairpin turn of Hurricane Joaquin (2015) from both large-scale environmental flow and vortex inner-core perspectives. A series of mesoscale numerical simulations at a convection-permitting scale (~ 3 km horizontal resolution) are performed. Through the sensitivity of numerical simulations to various physical processes and initial conditions, we aim to obtain some insights into the key processes controlling Joaquin's track and its hairpin turn, thus enhancing our understanding of TC track recurves and their forecasting.

Section 2 describes the Weather Research and Forecasting (WRF) model and experimental setup. Section 3 summarizes the numerical simulation results and their evaluation. Section 4 further diagnoses the numerical simulation results, with a discussion of the processes that control Joaquin's track recurve. Section 5 provides a summary and some concluding remarks.

2. WRF model, experimental design, and brief description of physical schemes

2.1 WRF model and setup

An advanced research version of the Weather Research and Forecasting model (WRF-ARW, version 3.7) is used to conduct numerical simulations of Hurricane Joaquin. A detailed description of WRF-ARW can be found in the paper by Skamarock et al. (2008). A two-way interactive, three-level nested grid technique is employed. Figure 1 shows the location of model domains, and Table 1 lists the specifications for these domains. All three domains are fixed with 27 km, 9 km, and 3 km horizontal grid spacing, respectively. The model vertical structure comprises 62 levels, with the top set at 50 hPa. The National Centers for Environmental Prediction's (NCEP) Global Forecast System final analysis data (GFS-ANL) at $0.5^\circ \times 0.5^\circ$ horizontal resolution is selected in this study for initial and boundary conditions after initial sensitivity tests comparing the simulations using the GFS-ANL and the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses, respectively. Different lead times have also been tested, and 1200 UTC 30

Fig. 1. The location of WRF nested domains.

Table 1. Summary of model domain specifications.

Domain	Dimensions (x, y, z)	Grid size (km)	Time step (s)
D01	$227 \times 188 \times 62$	27	90
D02	$355 \times 355 \times 62$	9	30
D03	$613 \times 589 \times 62$	3	10

(1200 UTC 30 Sep 2015)

September 2015 has been chosen as the forecast initial time since it leads to the best simulation results among all the tests. All numerical simulations are conducted for five-day integrations from 1200 UTC 30 September 2015 to 1200 UTC 5 October 2015 to include the period of Joaquin's hairpin turn.

2.2 Sensitivity experiments

The WRF model has multiple options for each type of physical parameterization. These available options facilitate the study of the sensitivity of numerical simulations of Hurricane Joaquin to various physical processes in addition to initial conditions and different lead times. The sensitivity experiments help us not only to identify a good simulation among many experiments but also to understand the processes associated with hurricane evolution (e.g., Li and Pu 2008; Bassill 2014). In this study, a series of sensitivity experiments are performed with the WRF-ARW model using three different cumulus schemes, three microphysics (MP) schemes, and two planetary boundary layer (PBL) schemes that were popular in previous hurricane simulations (e.g., Zhu and Zhang 2006; Li and Pu 2008; Nolan et al. 2009; Tao et al. 2011; Li and Pu 2014; Liu et al. 2017). The PBL and MP schemes are applied to all three domains, whereas the cumulus schemes are applied only to the 9 km and 27 km grid spacing domains. Although there is a limit to the use of cumulus schemes at high resolutions (e.g., less than 10 km grid spacing), in previous studies, it was indicated that TC track and intensity appear to be highly sensitive to the choice of cumulus parameterization (e.g., Nicholas 2003; Li and Pu 2009; Pattanayak et al. 2012; Biswas et al. 2014).

A summary of all sensitivity experiments is provided

in Table 2. Among the physical parameterization schemes used in the sensitivity studies are three widely used cumulus schemes: the Kain–Fritsch (KF; Kain 2004; Kain and Fritsch 1993), Betts–Miller–Janjic (BMJ; Janjic 2001), and Old Simplified Arakawa–Schubert (OSAS; Pan and Wu 1995) schemes. Two PBL schemes, that is, the Yonsei University (YSU; Hong and Dudhia 2003) and the Mellor and Yamada (1982) by Janjic (MYJ; Janjic 1994), are used. Three MP schemes are used: the WRF Single-Moment 6-Class Microphysics Scheme (WSM6; Hong and Lim 2006), the New Thompson Scheme (Thompson et al. 2004), and the Ferrier Scheme (Ferrier 1994). A detailed description of these physical schemes can be found in the research by Skamarock et al. (2008).

3. Simulation results and overall evaluation

Simulation results show that, during the simulation period (from 1200 UTC 30 September 2015 to 1200 UTC 5 October 2015), track simulations were quite sensitive to the cumulus scheme, especially during Joaquin's unique recurve, whereas sensitivity to the MP and boundary layer schemes was not significant (Fig. 2).

Specifically, track errors range from 50 to 200 km for simulations with both the YSU and the MYJ boundary layer schemes (Fig. 3a). Simulation with the WSM6 microphysical scheme leads to a better forecast (with the errors ranging from 50 to 200 km) than simulations with the Ferrier and New Thompson Schemes (with errors ranging from 50 to 350 km) (Fig. 3b). For the experiments with different cumulus schemes, the simulation with KF correctly simulates the hairpin turn (Fig. 3c), whereas the simulations with BMJ and OSAS fail to capture it. Before the 36 h integration,

Table 2. Configurations of sensitivity experiments.

Sensitivity Experiments	Cumulus	Microphysics	Boundary Layer	Initial/Boundary conditions
1 Cumulus	Kain-Fritsch (KF)/BMJ/ Old Simplified Arakawa- Schubert (OSAS)	WSM6	YSU	GFS-ANL
2 Microphysics	Kain-Fritsch (KF)	WSM6/Ferrier (FERRIER)/ New Thompson (NEW THOMPSON)	YSU	GFS-ANL
3 Boundary Layer	Kain-Fritsch (KF)	WSM6	YSU-sfclay_physics =1 MYJ-sfclay_physics =2	GFS-ANL
4 Initial and boundary conditions	Kain-Fritsch (KF)	WSM6	YSU	GFS-ANL

Fig. 2. Comparison of WRF simulated tracks and the best track during the 120 h integration (6 h interval) initialized at 1200 UTC 30 September 2015. Sensitivity of WRF simulations to (a) cumulus, (b) PBL, and (c) MP schemes.

Fig. 3. Time series of track errors (km) from different experiments initialized at 1200 UTC 30 September 2015 for sensitivity experiments with (a) cumulus, (b) PBL, and (c) MP schemes during the 120 h integration.

all simulations with the three cumulus schemes show a similar track forecast with errors of around 50 km. Major track differences occur after the hairpin turn. At the 120 h integration, the track error of the simulation with the KF scheme remains within 200 km, whereas it extends far beyond 1000 km for simulations with both the BMJ and the OSAS schemes.

For the intensity simulations, none of the WRF simulations produce a minimum sea-level pressure (MSLP) and maximum surface wind (MSW) that match the best-track data. Rather, the trend of intensity changes is simulated by all experiments except for the simulation using the OSAS cumulus scheme, which

Fig. 4. Time series of MSLP (top) and MSW (bottom) of Hurricane Joaquin for simulations with the KF (red), BMJ (blue), and OSAS (green) cumulus schemes during the 120 h integration, initialized at 1200 UTC 30 September 2015.

produces a much weaker hurricane. This indicates that intensity forecasts are also not sensitive to PBL and MP schemes but are more sensitive to cumulus schemes (Figs. 2–4).

Since the focus of this paper is on Joaquin's track, the following discussion emphasizes the factors that influence the track forecasts. In addition, among all the different experiments, the most significant sensitivities are found in the experiments with the three cumulus parameterization schemes. Therefore, the following diagnosis will also highlight the three experiments with different cumulus schemes.

4. Possible factors controlling Joaquin's track

As shown in Fig. 3, large differences among the various experiments are seen, beginning before and during Joaquin's hairpin turn. In previous studies, it was indicated that TC tracks are guided primarily by the surrounding large-scale environment and a combination of local and environmental factors (Rodwell and Hoskins 2001; Miyasaka and Nakamura 2005; Nigam and Chan 2009; Colbert and Soden 2012; Chen et al. 2013; Li and Pu 2014). Specifically, TC

tracks are determined by the large-scale steering flow and its interaction with storm dynamics (Colbert and Soden 2012). Even small deviations in TC tracks can be a direct result of large-scale steering flow regimes. Wu et al. (2013) stated that sudden track changes can also be a result of low-frequency and synoptic-scale (environmental) flows.

In order to investigate the possible factors controlling Joaquin's track, especially its hairpin turn, diagnoses are conducted using simulation results from three experiments with the KF, BMJ, and OSAS cumulus schemes (referred to as KF, BMJ, and OSAS hereinafter). Specifically, parameters affecting the large-scale environment such as steering vectors, the large-scale wind field, and geopotential height fields are considered. The thermal structure parameters of the hurricane vortex such as diabatic heating, vertical velocity and moisture flux, and absolute vorticity tendency (AVT) led by different cumulus schemes are also analyzed.

4.1 Large-scale steering flow

According to Elsberry (1987), TC tracks can be explained mainly by their environmental steering. We calculated the total environmental steering vectors by averaging winds within Domain 2 outside of a radius of 600 km from the simulated storm center and between 850 and 200 hPa vertically for all three experiments during the 0–60 h integration period (Fig. 5a). Among the three experiments, total steering vectors show little variations until 42 h, when they start to diverge. KF contains the greatest northeasterly component after the 42 h integration, indicating that the steering vectors for this simulation guide the storm from the southwest toward the northeast during this period. Notwithstanding, not much information can be gathered regarding Joaquin's sharp hairpin turn by simply looking at total steering vectors because of the lack of directional vector variation and the weak vector speeds represented by KF during and several hours after the hairpin turn. Therefore, we also calculated the same environmental steering vectors, but for lower (1000–800 hPa), middle (750–500 hPa), and upper (400–200 hPa) vertical levels during the 0–60 h simulations for different experiments. Figure 5b reveals that the steering flow direction has the greatest variance in the middle and upper levels, starting around the 30 h integration. Steering vectors in the upper levels for KF consistently contain a larger southerly component than do BMJ and OSAS until the 54 h integration. Upper-level steering vectors for KF attain a more westerly component around the 39 h

Fig. 5. Time series of the total steering vectors (a) and steering vectors by level (b) for simulations with the KF, BMJ, and OSAS schemes for the 60 h integration initialized at 1200 UTC 30 September 2015 calculated within Domain 2.

integration, during which the magnitude of these vectors decreases through the 51 h integration. Importantly, this shift of upper-level steering vectors toward the west is consistent with the hairpin turn in KF and occurs later than the hairpin turn in the best-track data. Meanwhile, the upper-level steering flow does not attain a northerly or easterly component in KF until the 54 h integration, and it is also very weak (near 0 m s^{-1}). The middle-level steering vectors indicate weak ($< 3 \text{ m s}^{-1}$) northeasterly flow in KF during the 27–39 h integration, becoming larger in that direction ($\geq 3 \text{ m s}^{-1}$) during the 42 h integration and increasing in speed to $\geq 6 \text{ m s}^{-1}$ by the 60 h integration. The vectors also become more easterly through the 60 h integration and remain more east-northeasterly than either BMJ or OSAS during the 27–60 h integration. The period during which KF simulates Joaquin's hairpin turn is, again, the 39–42 h integration. Therefore, the middle-level steering vectors in KF best correspond to Joaquin's hairpin turn and continuous move

toward the northeast.

4.2 Associated large-scale conditions

Why are there different steering flows in these experiments? It seems that complex large-scale weather patterns, including areas of high pressure aloft over the northern Atlantic Ocean, an area of high pressure near the surface nosing southward over the western Atlantic, a middle- to upper-level trough over the eastern United States, and remnants of Tropical Storm Ida in the Atlantic, are all present and could all potentially explain the large uncertainty of the steering flow. To obtain an insight into this question, detailed diagnoses of these variables are conducted. For the geopotential height fields, all three experiments are similar in the lower and outflow levels (not shown), but different in the middle levels (500 hPa), as shown in Fig. 6. The high-pressure region, approximately 500–700 km southwest of Joaquin, is stronger in KF than in BMJ or OSAS during the 33–42 h integration, whereas it greatly weakens in all three experiments during this period.

In addition, a middle- to upper-level trough over the eastern United States is present in all three simulations (Fig. 6). Because of the stronger blocking high to the southwest and the trough, as well as the stronger intensity of the storm (see discussion in Section 4.3), the storm in KF is separated from the trough during the 33–39 h integration. Meanwhile, the vortex of Hurricane Joaquin is relatively weaker and more connected to the trough in BMJ and OSAS, leading the storm to move northeast toward the continental US. At the 42 h integration, along with the disappearance of the high pressure to the southwest, the storm in KF finally moves to the trough (also indicated by the 5840 m geopotential height contour) and is steered by it.

Furthermore, over the high-pressure region to the southwest of Joaquin during the 36 h integration, wind speeds are light and northerly at 500 hPa in all experiments (Fig. 7). At the 42 h integration, however, winds generally decrease even more as this region of high pressure southwest of the storm diminishes, and directional flow becomes more indiscernible, especially in BMJ and OSAS. Meanwhile, the wind speed over the eastern portion of the trough over the US East Coast is different in the three experiments with the greatest wind speed values during the 36–42 h integration occurring within BMJ. Specifically, the wind speed associated with the trough is strong in KF but weak in OSAS and BMJ. One can argue that the wind in this portion of the trough seems to have a little influence on steering Hurricane Joaquin; otherwise, the strong

Fig. 6. 500 hPa geopotential heights (unit: m) and flow vectors for simulations with the KF (top), BMJ (middle), and OSAS (bottom) schemes at the 36 h and 42 h integrations at 1200 UTC 30 September 2015 calculated within Domain 2.

Fig. 7. Wind speed (unit: m s^{-1}) at 500 hPa for simulations with the KF (top), BMJ (middle), and OSAS (bottom) schemes at the 36 h and 42 h integrations initialized at 1200 UTC 30 September 2015 calculated within Domain 2.

trough in KF would steer the storm closer to the US East Coast. It is noteworthy that since the trough over the East Coast lies just outside Hurricane Joaquin and the vortex is separated from the trough (Fig. 6), the blocking high at 500 hPa should play a more important role than that of the middle- to upper-level trough in controlling Joaquin's track in KF.

Overall, the simulated large-scale environment is different in the three simulations, mainly because of the formation of the region of high pressure over the southwest portion of the domain in KF. As stated previously, the existence of the blocking high in KF is the result of this strong high-pressure region. This region noses northwestward and connects with the area of high pressure along the east of the US East Coast to block the storm in KF from moving toward and being steered by the trough.

Different height/pressure fields could be associated as a result of varying heat distribution. As can be seen from the temperature fields at different pressure levels during the 33–42 h forecasts, the temperature is much greater in KF than in BMJ or OSAS in the lower to middle levels south of Hurricane Joaquin. For instance, lower-level 700 hPa temperatures over nearly the entire region to the southwest of Joaquin are greater than 283 K in KF (Fig. 8), whereas only a few regions show temperatures greater than 283 K in OSAS and BMJ. OSAS and BMJ contain colder temperatures at 700 hPa (Fig. 8) compared to KF in Joaquin's environment, especially south and west of the simulated Joaquin, corresponding well to the pressure and wind distribution as stated above. Specifically, the warmer lower- to middle-level temperatures in KF produce a stronger high-pressure region around 500 hPa and thus a stronger blocking high that prevents more westerly drift as in the simulations with BMJ and OSAS. Thus, the simulation with KF is found to resolve a far more accurate track.

4.3 TC structure

Besides the environmental steering flow, the TC structure could also play a role in its track and intensity evolution (Wang and Wu 2004). Chan (1984) conceptualized TC motion (or steering) and indicated that a TC moves toward an area of maximum increase in absolute vorticity, whereas the local AVT is dominated by the horizontal advection of absolute vorticity. Following this concept, we focus on low levels (e.g., 850 hPa) of AVT where the vortex is more clearly structured to examine whether these values provide information about the potential track of Joaquin, specifically when its northwestward movement begins

(namely, the beginning of its hairpin turn). Figure 9 shows the AVT values in different simulations. In KF, maximum AVT values exist along the southern periphery of the storm center at 36–39 h (Fig. 9a), indicating that Joaquin will likely continue moving southward where the AVT is greater. By 39–42 h (Fig. 9b), the maximum is located along the northern periphery of the storm, indicating that the storm will likely shift to the north. Compared with the best track, the simulation with KF predicts Joaquin's hairpin turn during the 39–42 h integration. Meanwhile, for BMJ, the maximum AVT at 30–33 h (Fig. 9c) is located along the southern (and western) portion of the storm center, which indicates the possible continuation of the southward movement. By 33–36 h (Fig. 9d), there are large values of positive AVT located west of the storm center, indicating that the storm might start shifting to the west. Indeed, the storm in BMJ makes its turn to the west during the 33–36 h integration. For OSAS, the AVT values are relatively neutral around the storm center, considering that the maximum value areas of AVT are in the northwest and southeast quadrants, with very small values of AVT in the northeast and southwest quadrants (Fig. 9e). By 36–39 h (Fig. 9f), there is a clear area of positive AVT west/northwest of the storm center (albeit with weaker values than in the previous 3 h interval), indicating that the storm will likely begin shifting to the west. Correspondingly, the storm in OSAS makes its turn to the west during the 33–39 h integration. Thus, in both BMJ and OSAS, the simulated storm does not make a sharp hairpin turn back to the north and east as in KF. Rather, it continues to move west and then northwest toward the eastern US coast.

The above analysis clearly shows that the AVT structure has implications for the hairpin turn of Joaquin. It also proves that the hurricane inner-core structure could also play a significant role in Joaquin's track. Meanwhile, there is a noticeable discrepancy in the intensity simulation among the three experiments. Specifically, as shown in Fig. 4, the intensity evolution is similar in KF and BMJ, whereas OSAS is much weaker. The 33–36 h simulation marks the period not only when the track diverges but also when the MSW in OSAS suddenly weakens. To investigate why the OSAS storm is far weaker than the KF and BMJ storms and also to gain further insights into the different tracks from these simulations, the characteristics of the hurricane inner core are investigated.

The wind field around the eye of Joaquin is first diagnosed. Hovmöller plots (Fig. 10) of south–north (S–N) and west–east (W–E) wind speed cross sections

Fig. 8. Temperature at 700 hPa for simulations with KF (top), as well as temperature differences at 700 hPa between BMJ (middle) and OSAS (bottom) and KF (KF minus BMJ/OSAS), respectively, at 36 h and 42 h integrations initialized at 1200 UTC 30 September 15 calculated within Domain 2.

Fig. 9. AVT values ($10^{-5} \text{ s}^{-1} (3 \text{ h})^{-1}$) at 850 hPa for simulations with the (a) KF scheme at the 36–39 h integration, (b) KF scheme at 39–42 h integration, (c) BMJ scheme at 30–33 h integration, (d) BMJ scheme at 33–36 h integration, (e) OSAS scheme at 33–36 h integration, and (f) OSAS scheme at 36–39 h integration initialized at 1200 UTC 30 September 2015. The black dots indicate the TC center, and the black arrows indicate the storm motion at that time.

centered at the storm center are illustrated. The locations of the storm centers, marked by the eye where wind speeds are near zero, are similar up to the 33 h integration for all three experiments. After this time, the movements diverge; the storms in BMJ and OSAS

stop moving southward, and their westward speeds are faster than in KF. At the 60 h integration, the storm center in BMJ is about 0.5 degrees north and 1.0 degree west of the center in KF. The storm center in OSAS is closer to KF, less than 0.5 degrees north

Fig. 10. 0–60 h time evolution of 850 hPa wind speed (unit: m s^{-1}) across the storm center from S–N (upper) and W–E (lower). Left column: KF scheme; middle column: BMJ scheme; right column: OSAS scheme. The horizontal red lines indicate the 33 h integration, and the red vertical lines denote the final latitudes and longitudes at the 60 h integration initialized at 1200 UTC 30 September 2015.

and about 0.5 degrees west of the storm center in KF. It should be noted that the wind field around the eye in OSAS is far weaker than that in KF or BMJ, corresponding to the weaker intensity of the simulated hurricane in OSAS.

To examine the possible reasons for the strengthening or weakening storm wind field (inflow/outflow) among the three experiments at 2100 UTC 1 October (33 h) and 0000 UTC 2 October (36 h), Fig. 11 illustrates a cross section of perturbation temperature (temperature anomalies) from 1000 hPa to 100 hPa, along with storm relative flow vectors, calculated out to a horizontal distance of 500 km from the storm center. These anomalies are a departure from the average temperature field within the domain. KF and BMJ indicate warm-core temperature anomalies in the

middle and upper levels on 1 October, with a 10°C temperature perturbation extending from ~ 750 hPa up to ~ 300 hPa, extending radially out to about 20 km from the storm center. Three hours later (0000 UTC 2 October), the warm core becomes slightly broader as it reaches out radially to near 30 km. There is also strong outflow at 200 hPa and above to release exhaust from the storm, indicating a strong and potentially intensifying storm. However, the OSAS temperature anomalies are far different from those in the other two experiments (Fig. 11). The temperature anomalies within the inner core of OSAS reach 10°C , but the vertical extent is small (~ 550 hPa to ~ 390 hPa on 1 October). By 0000 UTC 2 October, the upper-level temperature anomaly dissipates rapidly with values of $\sim 5^{\circ}\text{C}$ remaining. Instead, the temperature anomaly

Fig. 11. Perturbation temperature (temperature anomalies) (unit: °C) and storm relative flows for simulations with the KF (top), BMJ (middle), and OSAS (bottom) schemes at 2100 UTC 1 October 2015 and 0000 UTC 2 October 2015 for simulations initialized at 1200 UTC 30 September 2015.

sinks considerably toward the surface, with 10°C anomalies extending from ~900 hPa to 650 hPa. Also, storm relative flow vectors during this time are pointed toward the surface within this warm core (inner

20 km of the storm) with small updrafts within the next 40 km from the warm core. These features are a glaring indication of a rapidly weakening storm since the upper-level anomaly is lowering and updrafts look

Fig. 12. Time series of 0–60 h simulations of temperature anomalies (unit: °C, top) at the storm center and azimuthal wind speed (unit: m s^{-1} , bottom) around the radius of maximum wind for the simulations with the KF (left), BMJ (middle), and OSAS (right) schemes, respectively.

to be too weak to transport large relative humidity values that would allow for latent heat of condensation release.

Figure 12 further confirms that the evolution of the temperature anomaly and wind structure correlates well. For KF and BMJ, when the upper-level temperature anomaly begins to intensify at the 18 h integration, the MSW also begins to increase. The same occurs for OSAS at the 24 h integration. Another common feature in the three experiments is that when

the temperature anomaly is significantly greater in the lower or middle levels, a corresponding region of low wind speed exists. This can be seen at around the 12 h integration in KF and at the 15 h integration in OSAS. In addition, storms in all experiments intensify after the warm-core height increases. Hence, the evolution of TC intensity can be attributed to the core region temperature structure, especially with upper-level temperature anomalies. According to Zhang and Zhu (2012) and Li and Pu (2014), the stronger upper-level

warming results in a greater surface pressure drop.

Furthermore, the core region thermal structure is significantly different in the simulation with the OSAS scheme compared with the other two schemes. First, the upper-level temperature anomaly intensifies more slowly in the simulation with the OSAS scheme. Second, before the storm in the OSAS simulation makes the hairpin turn at the 33 h integration, the core region temperature anomaly suddenly decreases in the lower to middle levels. Finally, after the recurve of the OSAS storm at the 36 h simulation, the warm-core height of the OSAS storm significantly lowers and suddenly stops intensifying. Meanwhile, the temperature anomaly and azimuthal wind speed in the other schemes continue to increase. The first difference can explain the relatively low MSLP in OSAS at the 18–33 h integration through the assumption that TC intensity is positively related to the upper-level temperature anomaly. The second and third differences are related to the sudden decrease in MSW at the 36 h simulation. The reason for the sudden weakening of MSW in the OSAS during 2100 UTC 1 October to 0000 UTC 2 October 2015 (33–36 h integration) is further investigated by examining the difference in diabatic heating.

Diabatic heating can be estimated as the apparent heat source Q (Yanai et al. 1973):

$$Q = \frac{T}{\theta} \left(\frac{\partial \theta}{\partial t} + u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} + \omega \frac{\partial \theta}{\partial p} \right), \quad (1)$$

where θ is the potential temperature and T is the temperature. The diabatic heating is calculated along with the WRF model integration. Figure 13 compares the calculated diabatic heating averaged over the hurricane core region (the area within a 300 km radius of the storm center) for KF, BMJ, and OSAS at 2100 UTC 1 October (Fig. 13a) and 0000 UTC 2 October (Fig. 13b). During the earlier time, OSAS shows a greater amount of diabatic cooling near the storm center in the lower levels and much weaker heating in the middle levels compared to the other two experiments, especially at 750 hPa and 500 hPa. This low-level diabatic cooling and weak middle-level heating might explain the sudden weakening of MSW in the cold-core region in the lower to middle levels. After the recurve of the storm in OSAS at 0000 UTC 2 October 2015, diabatic heating in the core region differs mainly between 850 hPa and 600 hPa and from 500 hPa to 200 hPa where the heating in OSAS is much weaker than in KF and BMJ within these levels (Fig. 13b).

Fig. 13. Averaged diabatic heating (unit: $K (3 h)^{-1}$) profile over the area within 300 km of the storm center for simulations with the KF (red), BMJ (blue), and OSAS (green) schemes valid at (a) 2100 UTC 1 October 2015 and (b) 0000 UTC 2 October 2015.

Vertical motion and relative humidity are further analyzed to gain insights into the diabatic heating distribution and storm-core thermal structures among the different experiments. Figure 14 shows a cross section of vertical velocities and relative humidity fields from 1000 hPa to 100 hPa within a radial distance of 500 km from the storm center during 2100 UTC 1 October to 0000 UTC 2 October (33–36 h integration). In KF, large positive vertical velocities (strong updrafts) exit just outside the storm center at 2100 UTC 1 October. Also, the 80 % RH contour extends up to 300 hPa, and the 90 % RH contour extends up to ~ 450 hPa. By 0000 UTC 2 October, vertical velocities are still positive and large, and the 80 % RH contour still extends to ~ 300 hPa. The 90 % RH contour lowers to ~ 700 hPa. Still, KF exhibits a strong storm with warm, moist air being lifted into its inner-core region during this time, indicating a good convective environment near the storm center. Meanwhile, in OSAS, vertical velocities at 0000 UTC 1 October (33 h integration) are weak near the storm center and

Fig. 14. Vertical velocity (unit: cm s^{-1}) and relative humidity (unit: %) valid at 2100 UTC 1 October 2015 (left column) and 0000 UTC 2 October 2015 (right column) for simulations with the KF (top), BMJ (middle), and OSAS (bottom) cumulus schemes, initialized at 0000 UTC 30 September 2015.

do not transport moist air to the upper levels to the extent that the KF scheme does. The 80 % RH contour reaches ~ 300 hPa, and the 90 % RH contour extends to only ~ 600 hPa. By 0000 UTC 2 October, a strong downdraft exists with vertical velocity values of near -10 cm s^{-1} found from the lower to the upper levels

(950 hPa to 300 hPa) and weak updrafts ($\sim 6 \text{ cm s}^{-1}$) between 20 and 40 km outside the inner core (Fig. 14). Furthermore, the 90 % RH contour is even lower, at ~ 850 hPa compared to ~ 600 hPa just three hours earlier. At no point during this period are there strong updrafts transporting moist air upward within the

inner core within the OSAS scheme. This analysis shows that the storm in OSAS is weak and continues to weaken, which is consistent with its large drop in MSW at this time. It also indicates why the KF scheme produces a far stronger storm that is closer to the best-track data.

5. Summary and concluding remarks

In this study, the high-resolution WRF-ARW model was used to perform sensitivity experiments to investigate the processes associated with the sharp hairpin turn of Hurricane Joaquin (2015) over the Atlantic Ocean during 2100 UTC 1 October to 0000 UTC 2 October 2015. Numerical simulations of Joaquin's track are not sensitive to either the PBL or MP parameterizations. The selection of different cumulus schemes does, however, significantly impact both track and intensity forecasts. The KF cumulus scheme, along with the WSM6 and YSU schemes, initializes at a more mature stage of the TC (1200 UTC 30 September 15), leading to the best-track simulation. Specifically, the simulation with KF produces a track that follows a far more similar path to the best-track data over the entire course of the storm, especially in later integrations after recurvature.

Total steering vectors were calculated but did not provide a clear indication of why the storm track varies among the experiments with different cumulus schemes. When steering vectors are examined at different levels, the variability of the steering vectors among the different experiments is found in the middle and upper levels, including the outflow region of the TC. This variability begins at the 33 h integration when the simulations with BMJ and OSAS produce upper-level steering vectors with a more westerly component compared to KF. The reason for the difference in steering is found to be due to how the different schemes resolve the environmental geopotential height, pressure field, and wind field.

Analysis of geopotential height at 500 hPa shows that the simulation with KF reproduces a stronger "blocking high" to the south of the TC that noses around Joaquin to its west and connects with another blocking ridge off the East Coast of the United States. Unlike in the simulations with the BMJ and OSAS schemes, where the simulated high pressure is far weaker, the storm in the simulation with the KF scheme is not able to connect with the trough over eastern US and instead is forced to interact with a trough over the central Atlantic Ocean. This forces the storm to turn sharply to the northeast, where it simulates a track very similar to that of the best-track

data. Further analysis of the different geopotential height fields shows that the 700 hPa temperatures to the southwest of the simulated TC are greater in the simulation with KF than in the other two simulations. This warmer lower- to middle-level region produces a stronger high-pressure region around 500 hPa and thus a stronger blocking high that prevents more westerly drift as in the simulations with BMJ and OSAS. Thus, the simulation with KF is found to resolve the heat distribution the best and ultimately produces a far more accurate track.

Moreover, local AVT provides a good representation of the environment concerning where Hurricane Joaquin is likely to move. The inner-core wind and temperature fields are then diagnosed to examine the cause of the significant differences in the vorticity fields and also the intensity of the storms. It is found that the simulations with KF and BMJ simulate large warm anomalies in the upper levels after the 21 h integrations, respectively, corresponding to an intensification of the hurricane. In addition, an examination of the diabatic heating within the inner core of the storm indicates that the difference in the inner-core diabatic heating in the upper levels between KF (and BMJ) and OSAS helps explain why the KF scheme outperforms the OSAS scheme in simulating maximum wind speeds and MSLP that are more congruent with best-track data.

In addition, the azimuthally averaged vertical velocity and relative humidity fields are analyzed. We found that, in the KF scheme, the stronger convection corresponding to large positive vertical velocities and vertical moisture transport led to a stronger warm core in the eye compared to the OSAS scheme. This corresponds well with why KF (and BMJ) outperforms OSAS in terms of MSW and MSLP and why KF is an overall favored cumulus scheme in this study regarding its accurate simulation of both track and intensity. Due to the different thermal and dynamic structures, the resulting differences in AVTs eventually lead to the different movements of the simulated Joaquin in the three simulations.

Future work will include more case studies of TCs with unique tracks so that a complete comparison of cumulus schemes and the quality of track forecasts can be made. Also, further detailed investigations into the factors that influence hurricane track and intensity forecasts will be conducted.

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References

- Bassill, N. P., 2014: Accuracy of early GFS and ECMWF Sandy (2012) track forecast: Evidence for a dependence on cumulus parameterization. *Geophys. Res. Lett.*, **41**, 3274–3281.
- Berg, R. J., 2016: Hurricane Joaquin (AL112015). *National Hurricane Center Tropical Cyclone Report*. 36 pp. [Available at http://www.nhc.noaa.gov/data/tcr/AL112015_Joaquin.pdf.]
- Biswas, M. K., L. Bernardet, and J. Dudhia, 2014: Sensitivity of hurricane forecasts to cumulus parameterizations in the HWRF model. *Geophys. Res. Lett.*, **41**, 9113–9119.
- Burton, A., L. Bernardet, J. L. Beven II, G. Faure, D. Herndon, J. Knaff, Y. S. Li, J. Mayers, F. Radjab, C. Sampson, and A. Waqaicelua, 2010: Tropical cyclone structure and intensity change: Operational guidance. *Seventh International Workshop on Tropical Cyclones (IUTC-VII)*, La Reunion, France, WMO/CAS/WWW, 1.5.1–1.5.33.
- Chan, J. C. L., 1984: An observational study of the physical processes responsible for tropical cyclone motion. *J. Atmos. Sci.*, **41**, 1036–1048.
- Chan, J. C. L., and J. D. Kepert, 2010: *Global Perspectives on Tropical Cyclones: From Science to Mitigation*. World Scientific Series on Asia-Pacific Weather and Climate, vol.4, World Scientific, 444 pp.
- Chen, G., H. Yu, Q. Cao, and Z. Zeng, 2013: The performance of global models in TC track forecasting over the western North Pacific from 2010 to 2012. *Trop. Cyclone Res. Rev.*, **2**, 149–158.
- Colbert, A. J., and B. J. Soden, 2012: Climatological variations in North Atlantic tropical cyclone tracks. *J. Climate*, **25**, 657–673.
- Duan, Y., L. Chen, Y. Xu, and C. Qian, 2012: The status and suggestions of the improvement in the typhoon observation, forecasting and warning systems in China. *Eng. Sci.*, **14**, 4–9 (in Chinese).
- Elsberry, R. L., 1995: Tropical cyclone motion. *Global Perspectives on Tropical Cyclones*. Tropical Cyclone Programme, Report No. TCP-38, World Meteorological Organization Technical Document WMO/TD-No.693, 106–178.
- Ferrier, B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci.*, **51**, 249–280.
- Gall, R., J. Franklin, F. Marks, E. N. Rappaport, and F. Toepfer, 2013: The Hurricane Forecast Improvement Project. *Bull. Amer. Meteor. Soc.*, **94**, 329–343.
- Hong, S.-Y., and J. Dudhia, 2003: Testing of a new nonlocal boundary layer vertical diffusion scheme in numerical weather prediction applications. Preprints, *20th Conference on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc., 17.3. [Available at <http://ams.confex.com/ams/pdfpapers/72744.pdf>.]
- Hong, S.-Y., and J.-O. J. Lim, 2006: The WRF Single-Moment 6-class Microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, **42**, 129–151.
- Janjić, Z. I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945.
- Janjić, Z. I., 2001: Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP meso model. NCEP Office Note 437, 61 pp. [Available at <https://www.emc.ncep.noaa.gov/officenotes/newer-notes/on437.pdf>.]
- Kain, J. S., 2004: The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181.
- Kain, J. S., and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models*. Meteor. Monogr., Vol.24, Amer. Meteor. Soc., 165–170.
- Li, X., and Z. Pu, 2008: Sensitivity of numerical simulation of early rapid intensification of Hurricane Emily (2005) to cloud microphysical and planetary boundary layer parameterizations. *Mon. Wea. Rev.*, **136**, 4819–4838.
- Li, X., and Z. Pu, 2009: Sensitivity of numerical simulations of the early rapid intensification of Hurricane Emily to cumulus parameterization schemes in different model horizontal resolutions. *J. Meteor. Soc. Japan*, **87**, 403–421.
- Li, Z., and Z. Pu, 2014: Numerical simulations of the genesis of Typhoon Nuri (2008): Sensitivity to initial conditions and implications for the roles of intense convection and moisture conditions. *Wea. Forecasting*, **29**, 1402–1424.
- Liu, J., F. Zhang, and Z. Pu, 2017: Numerical simulations of the rapid intensification of Hurricane Katrina (2005): Sensitivity to boundary layer parameterization schemes. *Adv. Atmos. Sci.*, **34**, 482–496.
- Marchok, T., 2014: *Operational Hurricane Track and Intensity Forecasting*. Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration. <https://www.gfdl.noaa.gov/operational-hurricane-forecasting/>
- Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20**, 851–875.

- Miyasaka, T., and H. Nakamura, 2005: Structure and formation mechanisms of the Northern Hemisphere summertime subtropical highs. *J. Climate*, **18**, 5046–5065.
- Nigam, S., and S. C. Chan, 2009: On the summertime strengthening of the Northern Hemisphere Pacific sea level pressure anticyclone. *J. Climate*, **22**, 1147–1192.
- Nolan, D. S., D. P. Stern, and J. A. Zhang, 2009: Evaluation of planetary boundary layer parameterizations in tropical cyclones by comparison of in situ observations and high-resolution simulations of Hurricane Isabel (2003). Part II: Inner-core boundary layer and eyewall structure. *Mon. Wea. Rev.*, **137**, 3675–3698.
- Pan, H.-L., and W.-S. Wu, 1995: *Implementing a mass flux convection parameterization package for the NMC mediumrange forecast model*. Office Note 409, U.S. Department of Commerce National Oceanic and Atmospheric Administration, National Weather Service, National Meteorological Center, 43 pp.
- Pattanayak, S., U. C. Mohanty, and K. K. Osuri, 2012: Impact of parameterization of physical processes on simulation of track and intensity of Tropical Cyclone Nargis (2008) with WRF-NMM Model. *Sci. World J.*, **2012**, 671437, doi:10.1100/2012/671437.
- Pu, Z., X. Li, and E. J. Zipser, 2009: Diagnosis of the initial and forecast errors in the numerical simulation of rapid intensification of Hurricane Emily (2005). *Wea. Forecasting*, **24**, 1236–1251.
- Rodwell, M. J., and B. J. Hoskins, 2001: Subtropical anticyclones and summer monsoons. *J. Climate*, **14**, 3192–3211.
- Rogers, R., S. Aberson, M. Black, P. Black, J. Cione, P. Dodge, J. Dunion, J. Gamache, J. Kaplan, M. Powell, N. Shay, N. Surgi, and E. Uhlhorn, 2006: The intensity forecasting experiment: A NOAA multiyear field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc.*, **87**, 1523–1537.
- Rogers, R., S. Aberson, A. Aksoy, B. Annane, M. Black, J. Cione, N. Dorst, J. Dunion, J. Gamache, S. Goldenberg, S. Gopalakrishnan, J. Kaplan, B. Klotz, S. Lorsolo, F. Marks, S. Murillo, M. Powell, P. Reasor, K. Sellwood, E. Uhlhorn, T. Vukicevic, J. Zhang, and X. Zhang, 2013: NOAA'S hurricane intensity forecasting experiment: A progress report. *Bull. Amer. Meteor. Soc.*, **94**, 859–882.
- Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, and J. G. Powers, 2008: *A description of the Advanced Research WRF Version 3*. NCAR Tech. Note NCAR/TN-475+STR, 113 pp.
- Tao, W.-K., J. J. Shi, S. S. Chen, S. Lang, P.-L. Lin, S.-Y. Hong, C. Peters-Lidard, and A. Hou, 2011: The impact of microphysical schemes on hurricane intensity and track. *Asia-Pacific J. Atmos. Sci.*, **47**, 1–16.
- Thompson, G., R. M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev.*, **132**, 519–542.
- Wang, Y., and C.-C. Wu, 2004: Current understanding of tropical cyclone structure and intensity changes—A review. *Meteorol. Atmos. Phys.*, **87**, 257–278.
- Witcraft, N. C., Y.-L. Lin, and Y.-H. Kuo, 2003: Sensitivity of tropical cyclone track, intensity, and orographic precipitation to cumulus and microphysical parameterizations. *10th Conference on Mesoscale Processes*, 9.3.
- Wu, L., Z. Ni, J. Duan, and H. Zong, 2013: Sudden tropical cyclone track changes over the western North Pacific: A composite study. *Mon. Wea. Rev.*, **141**, 2597–2610.
- Yanai, M., S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.
- Zhang, D.-L., and L. Zhu, 2012: Roles of upper-level processes in tropical cyclogenesis. *Geophys. Res. Lett.*, **39**, L17804, doi:10.1029/2012GL053140.
- Zhang, F., Y. Weng, J. F. Gamache, and F. D. Marks, 2011: Performance of convection-permitting hurricane initialization and prediction during 2008–2010 with ensemble data assimilation of inner-core airborne Doppler radar observations. *Geophys. Res. Lett.*, **38**, L15810, doi:10.1029/2011GL048469.
- Zhu, T., and D.-L. Zhang, 2006: Numerical simulation of Hurricane Bonnie (1998). Part II: Sensitivity to varying cloud microphysical processes. *J. Atmos. Sci.*, **63**, 109–126.