



Impact of environmental moisture on tropical cyclone intensification

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Impact of environmental moisture on tropical cyclone intensification

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Abstract

The impacts of environmental moisture on the intensification of a tropical cyclone (TC) are investigated in the Weather Research and Forecasting (WRF) model, with a focus on the azimuthal asymmetry of the moisture impacts. A series of sensitivity experiments with varying moisture perturbations in the environment are conducted and the Marsupial Paradigm framework is employed to understand the different moisture impacts. We find that modification of environmental moisture has insignificant impacts on the storm in this case unless it leads to convective activity in the environment, which deforms the quasi-Lagrangian boundary of the storm. By facilitating convection and precipitation outside the storm, enhanced environmental moisture ahead of the northwestward-moving storm induces a dry air intrusion to the inner core and limits TC intensification. However, increased moisture in the rear quadrants favors intensification by providing more moisture to the inner core and promoting storm symmetry, with primary contributions coming from moisture increase in the boundary layer. The different impacts of environmental moisture on TC intensification are governed by the relative locations of moisture perturbations and their interactions with the storm Lagrangian structure.

1 Introduction

While the forecast of tropical cyclone (TC) tracks has been significantly improved in the past several decades, the TC intensity forecast is still a great challenge for most operational numerical weather prediction (NWP) centers (DeMaria et al., 2007). Environmental moisture has been considered as one of the important factors for TC intensity forecasting. As one of the skillful predictors, the 850 hPa relative humidity (RH) averaged between 200 and 800 km from storm center has been used routinely in the Statistical Hurricane Intensity Prediction Scheme (SHIPS) for hurricane intensity forecast in the National Hurricane Center (NHC) (Kaplan et al., 2010).

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Theoretical and modeling studies have suggested high environmental moisture may be conducive to TC intensification (e.g., Emanuel et al., 2004; Kimball, 2006). Dry air intrusion could lead to a weakening of a TC by inducing asymmetric convective activity and/or transporting low equivalent potential temperature (θ_e) air into the sub-cloud layer and storm inflow (e.g., Braun et al., 2012; Emanuel, 1989; Ge et al., 2013; Kimball, 2006; Tao and Zhang, 2014). However, some studies (e.g., Kimball, 2006; Wang, 2009; Ying and Zhang, 2012) showed that substantial moisture may also cause a negative impact on TC strength by facilitating the formation of TC rainbands, which reduces the horizontal pressure gradient of a TC. In idealized simulations, Hill and Lackmann (2009) varied RH values in the moist envelope 100 km beyond the TC core and found that larger RH results in the establishment of wider TCs with more prominent outer rainbands. However, in their study, TC intensity was nearly insensitive to environmental RH despite the variation in rainband activity.

Braun et al. (2012) showed that dry air located 270 km away from the storm center had little impact on hurricane intensity with no mean flow. Dry air intrusion into the storm vortex, however, suppressed convective activity and increased the asymmetry of convection, leading to a weakening of the storm. While a dry air envelope had no significant impact on hurricane intensity, the storm size was reduced. Vertical shear can significantly enhance the suppression effect of dry air intrusion (Tang and Emanuel, 2012; Ge et al., 2013; Tao and Zhang, 2014). By modifying the diabatic heating rate due to cloud microphysical process, Wang (2009) demonstrated that diabatic cooling in the outer spiral rainbands helped the TC remain intense and compact. Increased latent heat release in the outer spiral rainbands decreased the intensity but increased the TC size. In a sensitivity study of Typhoon Talim (2005), Ying and Zhang (2012) showed that enhanced moisture promoted convection in outer rainbands and resulted in the weakening of the storm while dry air inhibited outer rainbands and contributed to a stronger storm with smaller size. The storm was more sensitive to the moisture perturbation residing to the north than to the south due to its shorter travel time into the storm vortex.

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Composite studies using analyses datasets and satellite observations (Kaplan and DeMaria, 2003; Hendricks et al., 2010; Wu et al., 2012) have shown that rapid intensification (RI) of TCs is associated with higher environmental RH in the lower and middle troposphere than non-RI events. Using satellite observations, Shu and Wu (2009) showed that the dry Saharan air layer (SAL) can affect TC intensity in both favorable and unfavorable manners. TCs tend to intensify when dry SAL air is present in the northwest quadrant of TCs. However, TCs tend to weaken when dry air intrudes within 360 km of the TC center in the southwest and southeast quadrants. Substantial azimuthal asymmetry of RH is also found in TCs' environment based on nine years of satellite observations, with rear quadrants (relative to storm motion) being moister than front quadrants, especially during RI (Wu et al., 2012).

Most previous modeling studies prescribed moisture perturbations without specifically considering their relative location to a storm vortex (e.g., in the environment, outer rainband or inner core; front or rear quadrants), which may cause different impacts on the storm structure and intensity. In this study, we investigate the impacts of environmental moisture on TC intensity and structure using the Weather Research and Forecasting (WRF) model with artificially modified environmental moisture surrounding a storm vortex. Guided by the observational composite study by Wu et al. (2012), we focus on the azimuthally asymmetric effects of environmental moisture in the front and rear quadrants. Section 2 provides the model description and experiment design. The Marsupial Paradigm framework (Dunkerton et al., 2009) is also introduced in Sect. 2 as a tool to interpret the moisture impacts on the storm. Section 3 describes the evolution of the simulated storm in the control experiment. The results from sensitivity experiments are presented in Sect. 4. The findings from this study are summarized in Sect. 5.

2 WRF experiments and analysis framework

2.1 Model description

To examine the role of environmental moisture on TC intensification, we drive the WRF model with initial and boundary conditions from a real-case hurricane, in particular, the Hurricane Earl (2010). Hurricane Earl originated from a tropical wave west of the Cape Verde Islands on 23 August 2010. It moved westward across the Atlantic and gradually strengthened to a tropical storm. Before the RI at 00:00 UTC 29 August (Fig. 1a), a dry zone consisting of precipitable water vapor (PWV) less than 4.5 cm was located to the west of the storm, in the front quadrant relative to the storm propagation. Meanwhile, a broad moist region was observed to the south and southeast of the storm. Such a “dry front and moist rear” environmental moisture structure is typical of a rapidly intensifying hurricane as found in Wu et al. (2012). Earl underwent a RI from 06:00 UTC 29 August to 00:00 UTC 31 August. The maximum wind speed (MWSP) increased by 31 m s^{-1} while the minimum sea level pressure (MSLP) deepened by 53 hPa in 36 h.

Inspired by the rapid intensification of Hurricane Earl (2010), we initialize the Advanced Research WRF model V3.3.1 (Skamarock et al., 2008) at 00:00 UTC 29 August 2010 and run it for 48 h. Simulations are conducted with a parent grid at 9 km horizontal resolution and a vortex-following nested grid at 3 km resolution. There are 50 model levels in the vertical from the surface to 20 hPa, and the initial and boundary conditions were derived from the interim ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis (ERA-Interim) (<http://rda.ucar.edu/datasets/ds627.0/>). For all the experiments, we employ the Thompson et al. (2008) microphysical scheme, the Rapid Radiative Transfer Model for GCMs (RRTMG) shortwave and longwave schemes (Iacono et al., 2008), and the Yonsei University planetary boundary layer (PBL) scheme (Hong et al., 2006). The Kain-Fritsch cumulus scheme (Kain, 2004) is used in the parent domain while no cumulus scheme is used in the moving nested inner grids.

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rear quadrants (Fig. 1d). The Dry Rear (DR) simulation (Fig. 1e) is similar to the MR simulation but the magnitude of the RH perturbation is reduced to 30 % of the maximum RH at each level, which is drier than the CTRL. So the dry, intermediate moist and moist environments at the rear of the storm are represented by the DR, CTRL and MR experiments, respectively.

Further sensitivity experiments with moisture zones of different sizes were also tested, and the results are not qualitatively sensitive to the choice of the areal extent of the moist zone. For brevity, only MF, MFI, MR and DR are discussed in addition to the CTRL. We also perform a set of simulations in which the vertical extent of the moisture perturbations in the MR configuration is varied to examine the vertical dependence of the environmental moisture impacts.

2.3 Marsupial paradigm

The Marsupial Paradigm is a framework proposed by Dunkerton et al. (2009) to study the formation of a TC within tropical waves. Dunkerton et al. (2009) demonstrated that the critical layer of a tropical easterly wave is a region of approximately closed Lagrangian circulation (also called a “wave pouch”). The wave pouch protects the TC vortex from dry air intrusion to some extent, rendering a favorable environment for deep convection and TC formation. Owing to convergent flow, the wave pouch may have an opening that allows the influx of environmental air (see Fig. 3 in Wang et al., 2010). The Lagrangian boundary of the storm and its interaction with the ambient environment can be clearly illustrated by the streamlines in a frame of reference moving at the same speed with the wave (Fritz and Wang, 2013; Montgomery et al., 2010; Wang et al., 2009, 2012a, b). The translated streamlines in a co-moving frame, which resemble the flow trajectories, provide a Lagrangian view of the storm evolution. Although the Marsupial Paradigm framework was proposed for TC formation, we adopt the concept in this study to investigate the impacts of asymmetric environmental moisture on TC intensification and structure. In the following analysis, the modeled streamlines are

translated from the Earth-relative frame to the co-moving frame based on the estimated storm propagation speed from the automatic vortex-following algorithm in the WRF.

3 Storm evolution in the control simulation

As shown in Fig. 2, the simulated storm in the CTRL experiment (red lines) intensifies in the first 24 h. During 24–30 h, the simulated MSLP shows a slowing down of the intensification (Fig. 2a) while the MWSP (Fig. 2b) exhibits a weakening trend. The storm continues its intensification in the following 18 h. The MWSP of the simulated storm increases by 21 ms^{-1} from 6 to 48 h while the MSLP deepens by 38 hPa. The simulated intensification rate in the CTRL experiment is less than that for Hurricane Earl (2010). Since this study focuses on understanding the role of environmental moisture in TC intensification, the differences between the sensitivity experiments and the CTRL are of interest. The difference between the simulated storm in the CTRL experiment and observed Hurricane Earl is not a primary concern.

Figure 3 shows the PWV and translated streamlines of the WRF CTRL simulation in the co-moving frame. Averages over four periods (0–6, 12–18, 30–36 and 42–48 h) are displayed. At the initial time (Fig. 3a), the storm core (indicated by the relative large PWV $> 5 \text{ cm}$) is collocated with the storm Lagrangian structure (indicated by the nearly enclosed streamlines). The storm Lagrangian structure is closed to the west of the storm, where dry air is located. Thus, there is a favorable environment for the intensification of the storm, as dry air intrusion would be limited and moisture in the vortex can be preserved. The inner region of the storm continues to moisten (Fig. 3b) as the storm intensifies in the first 24 h (Fig. 2), and the dry zone to the northwest of the storm becomes even drier (Fig. 3b). On the other hand, the moist region to the south and southeast of the storm diminishes in magnitude. The storm Lagrangian structure is open to the southwest at this time. In the next 24 h (Fig. 3c and d), the storm center keeps moistening while the dry air approaches the opening of the storm Lagrangian structure to the southwest of the storm.

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storm track. In the last 24 h, the storm in the MR experiment moves less northward comparing to the storm in the CTRL experiment, along with stronger intensification in the MR. The track differences are less than 70 km between MR and CTRL for all the 48 h integration. The track differences from the CTRL experiment are insignificant in the MFI and DR experiments (not shown).

Details of the storm evolution in each sensitivity experiment are investigated in a storm-following framework in the following subsections.

4.2 MF experiment

Figure 5 shows the differences of PWV and winds between the MF and CTRL experiments. At the initialization of the simulation (Fig. 5a), a nearly saturated region with a large amount of water vapor is prescribed to the west of the storm, where it is dry in the CTRL. The prescribed moist zone is outside of the storm Lagrangian boundary. In the following 18 h, extensive precipitation (maximized between 6–12 h; not shown) develops within the prescribed moist zone in the MF experiment (Fig. 6b), which is absent in the CTRL simulation (Fig. 6a). This supplemental convective activity induces a cyclonic circulation around the prescribed moist zone in the environment of the storm, resulting in a deformation of the storm Lagrangian structure with divergence to the west of the storm center (Fig. 5b).

Consequently, both moist air from the prescribed moist zone and dry air in the environment intrude into the storm vortex from the convective-deformed portion, leading to an asymmetric moisture structure (Fig. 5b–d) and diabatic heating fields (Figs. 6b and 7). Dry environmental air has reached the storm inner core at 30–36 h (Fig. 5c). At 42–48 h forecast, a spiral band of convection with closed ring in the inner core forms in the CTRL case (Fig. 7d) while only a comma shape of convection is produced in the MF experiment (Fig. 7e) with much weaker storm intensity (Fig. 7f). In summary, convection in the environment in the MF case deforms the storm Lagrangian structure towards the dry front-side environment and facilitates the intrusion of dry air from the

north into the inner core, creating asymmetric convection in the inner core and leading to the weakening of the storm (Nolan and Grasso, 2003; Nolan et al., 2007).

4.3 MR experiment

In the MR experiment, the prescribed moist zone is located in the already relatively moist environment to the south of the storm, outside of the storm Lagrangian boundary (Fig. 8a). Similar to the MF case, the nearly saturated moist perturbation induces convective activity and precipitation (Fig. 6c) beyond the storm vortex in the first 18 h, resulting in a weaker storm compared to the CTRL case prior to 26 h (Fig. 2). Different from the MF case, the convection-induced deformation helps transport moisture to the east portions of the storm without an accompanying dry air intrusion (Fig. 8b).

Therefore, by 30–36 h (Fig. 8c), more moisture appears within the core and also on the storm's north flank, where it is also moister than in the CTRL case (Fig. 3c). This results in a more symmetric storm, with better-defined spiral rainbands than the CTRL (Fig. 9a and b). Subsequently, the MR storm starts strengthening faster than the CTRL (Figs. 2 and 9c), and by the end of the 48 h integration, the convective activity of the inner core in the MR case (Fig. 9e) shows a nearly concentric ring without the long tail of the spiral band seen in the CTRL case (Fig. 9d). In summary, the convection in the environment enhances the inflow to the storm Lagrangian structure from the moist region and facilitates the moisture transport into the storm inner core in the MR case, leading to a more symmetric storm with higher intensity.

4.4 MFI and DR experiments

The MFI and DR experiments are similar to the MF and MR cases, respectively, except that their RH perturbation magnitude at each level is reduced in the prescribed zone. In both of the MFI and DR experiments (Fig. 10), the moisture perturbations do not promote convective activity in the environment of the storm. Throughout the 48 h integration, the storms in both the MFI and DR experiments contain the Lagrangian

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structures comparable to the CTRL case. The Lagrangian structure protects the storm well from intrusion of the environmental air. The prescribed moist air in the MFI and dry air in the DR wrap around the storm without entrainment into the storm vortex during the 48 h integration. There is no significant change in storm intensity and vortex structure of the MFI and DR experiments compared to the CTRL simulation. This is broadly consistent with Braun et al. (2012) that environment moisture content does not necessarily affect the storm intensity when the perturbation magnitude is not significant.

4.5 Height dependency

Another set of experiments are conducted to identify which layer of moisture is more important to promote TC intensification in the MR experiment. In these simulations, we limit the vertical extent of the moist perturbation to 900–500, 900–300, 850–500, 500–300, 500–20, and 300–20 hPa, respectively. It is found that only the RH enhancements including the boundary layer (900–300 and 900–500 hPa cases) promote significant intensification of the storm relative to the CTRL simulation (Fig. 11). When extra moisture is provided above 850 hPa, the intensity of the storm is quite similar to the CTRL run or even slightly weaker than the CTRL case by the end of the simulations at 48 h integration, although convective activity induced by moisture perturbation is produced outside of the storm in some cases (for example, the 850–500 case). Note that saturation water vapor content in the boundary layer is significantly higher than in the middle and upper troposphere. Therefore, a small increase of RH in the boundary layer can provide much more moist static energy to fuel the storm intensification.

5 Summary and discussion

The impacts of environmental moisture on TC intensity are examined in the WRF model, with a focus on the azimuthal asymmetry of moisture impacts. The Marsupial Paradigm framework is used to understand the evolution of the storm. The intensifica-

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enhanced convective activity within the vortex, however, the direct and indirect impacts on the storm can be complex. By itself, enhanced outer rainband activity (the direct effect) may weaken the storm (Wang, 2009; Ying and Zhang, 2012). Yet, the convective activity could also deform the storm vortex, more indirectly leading to changes in the nature of the moisture inflow. Consistent with conventional understanding, a dry air intrusion into the inner core that might opportunistically cause a vortex deformation (as in the MF case) and suppress the storm, while an enhanced moisture supply into the inner core (as in the MR case) promotes intensification of the storm. The disparate responses of TC intensity to moisture perturbations in the literature may largely be a result of the different magnitudes and relative locations of moisture perturbations to the storm vortex, and thus their different ability to deform the storm vortex.

This study demonstrates that storm structure is critical for understanding environmental impacts on TCs. Previous composite data analyses have been sampled with respect to the distance from the storm center, without consideration on the storm (structure). Most modeling studies prescribed moisture perturbations, but did not pay much attention to their relative locations to the storm vortex. As shown in this study and previous papers, TCs respond differently to moisture perturbations in different locations (the inner core, the outer rainband region and the more distant environment). Thus, in order to better quantify moisture impacts on TCs, it is necessary to distinguish moisture in the outer rainband and moisture in the inner core of the storm as well as different environmental moisture distributions.

This study also explains, to some degree, the observational results by Shu and Wu (2006) that the dry SAL may have favorable or unfavorable impacts on TC intensification, depending on its position. Considering that the TCs in the North Atlantic usually have moisture inflow from the southern quadrants, when the SAL is located to the northwest of TCs, it may not affect the storm intensity, or may even indirectly favor the TC intensification by suppressing the formation of convective rainbands outside of the storm. When dry air is located to the southeast or southwest of the TCs, however, the dry air may be entrained into the storm, leading to a weakening effect. The MF

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and MR experiments suggest that the “dry front and moist rear” distribution of environmental moisture is a favorable condition for TC intensification, consistent with the observational study of Wu et al. (2012). Given that environmental moisture can have different impacts on TCs once it enters into the storm, accurate characterizations of environmental moisture are important to TC intensity forecasts.

This study shows that convection in the environment can have either favorable or unfavorable impacts on the storm intensity. Thus, a better understanding of the interaction of the storm with environmental convective activity (e.g. trough interaction with storm) is also critical to improving TC intensity forecasts.

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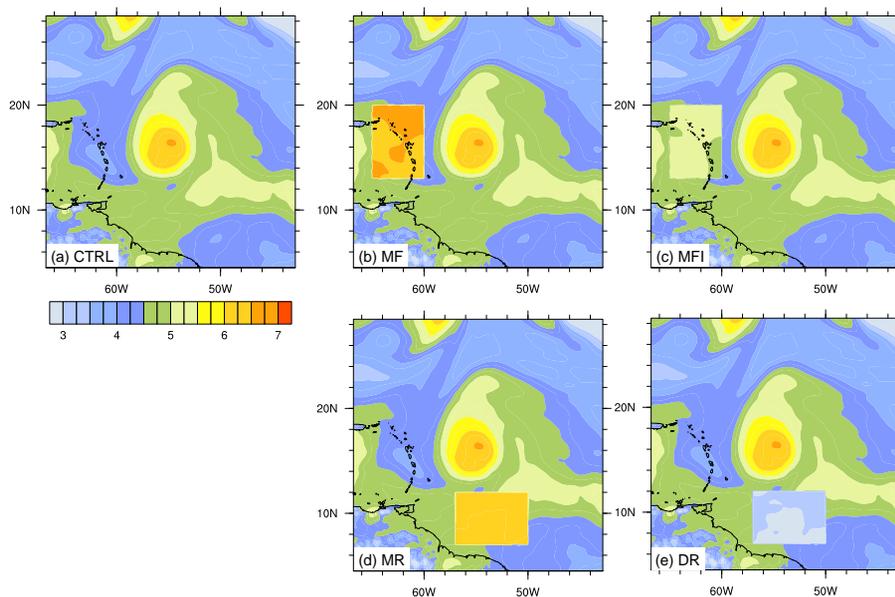


Figure 1. Column-integrated PWV (cm) at the initialization of the WRF simulations: **(a)** CTRL; **(b)** MF; **(c)** MFI; **(d)** MR; **(e)** DR.

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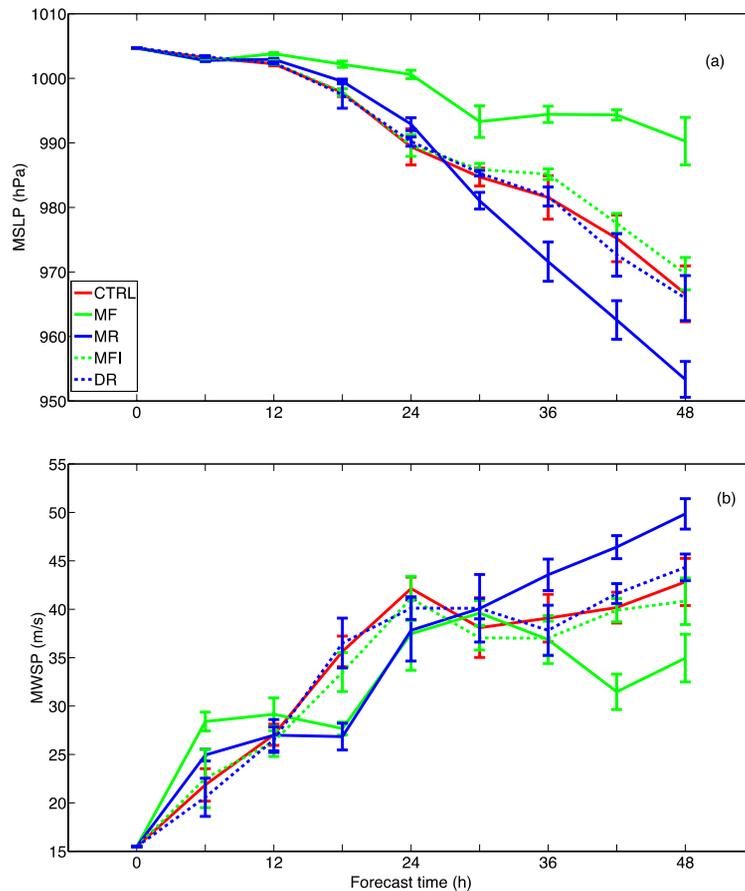


Figure 2. Time series of the model simulated ensemble mean and standard deviation of **(a)** MSLP (hPa) and **(b)** MWSP (ms^{-1}).

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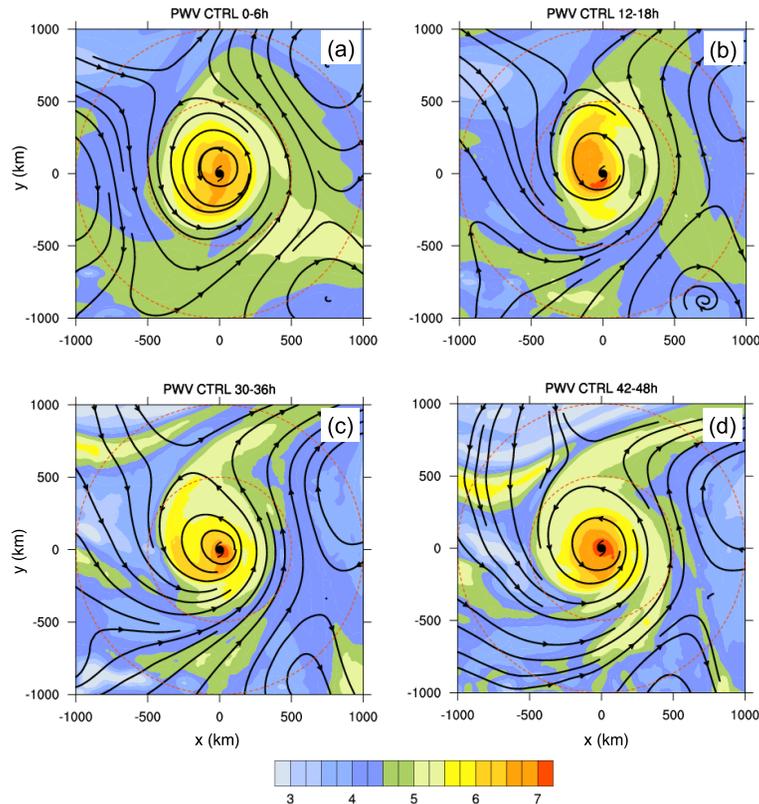


Figure 3. The mean translated streamline below 5 km and column-integrated PWV (cm) in the WRF CTRL simulation in the storm following coordinate: **(a)** 0–6 h; **(b)** 12–18 h; **(c)** 30–36 h; **(d)** 42–48 h. The hurricane symbol shows the TC center. The dashed red circles represent the radius of 500 and 1000 km, respectively. All the data are taken from the outer model domain.

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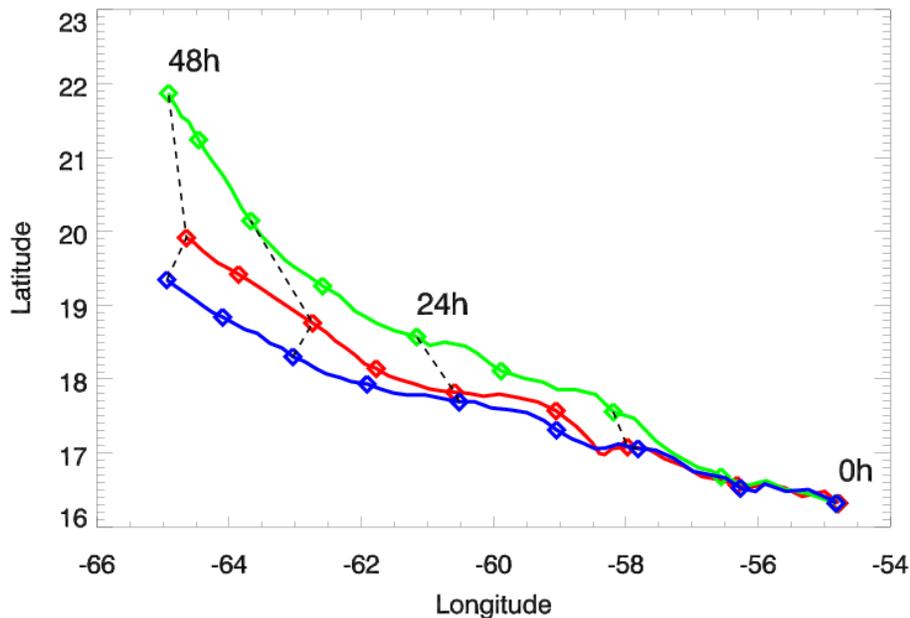


Figure 4. Storm tracks for CTRL (red), MF (green) and MR (blue). Every 6 h is identified with a diamond symbol. Black dashed lines connect storm position at the same forecast time for every 12 h.

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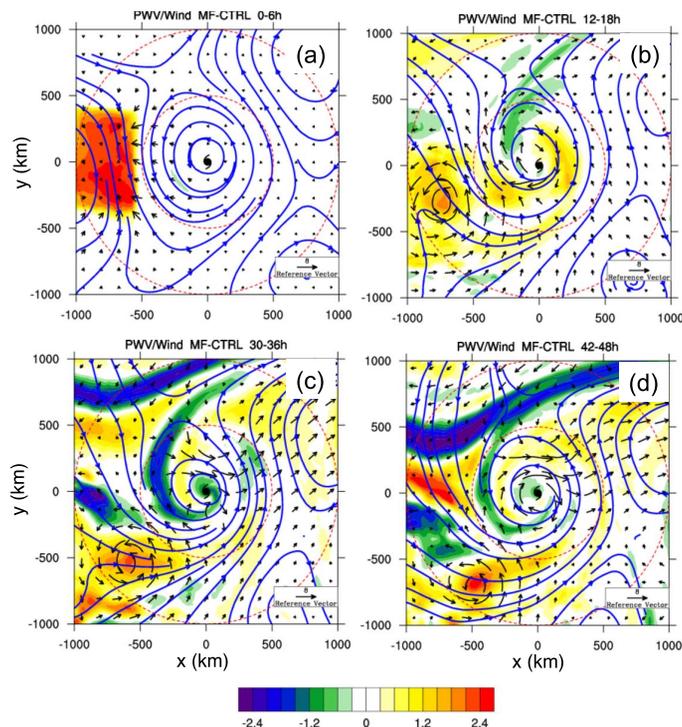


Figure 5. Differences of mean wind vector (ms^{-1}) below 5 km and column-integrated PWV (cm) (shading) between the MF and CTRL simulations in the storm following coordinate: **(a)** 0–6 h; **(b)** 12–18 h; **(c)** 30–36 h; **(d)** 42–48 h. The blue streamline is the translated streamline at the co-moving coordinate for the CTRL experiment at the corresponding time. The hurricane symbol shows the TC center. The dashed red circles represent the radius of 500 and 1000 km, respectively. All the data are taken from the outer model domain.

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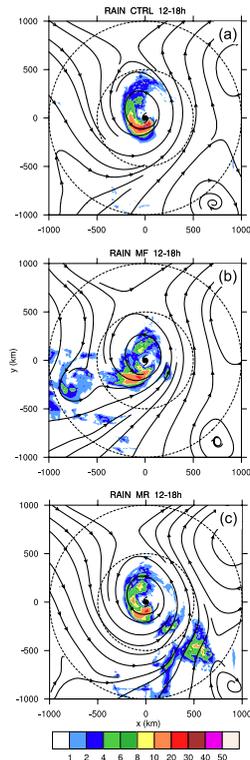


Figure 6. Mean rain rate (mm h^{-1}) and streamlines below 5 km during 12–18 h in the storm following coordinate: **(a)** CTRL; **(b)** MF; **(c)** MR. The hurricane symbol shows the TC center. The dashed black circles represent the radius of 500 and 1000 km, respectively. All the data are taken from the outer model domain.

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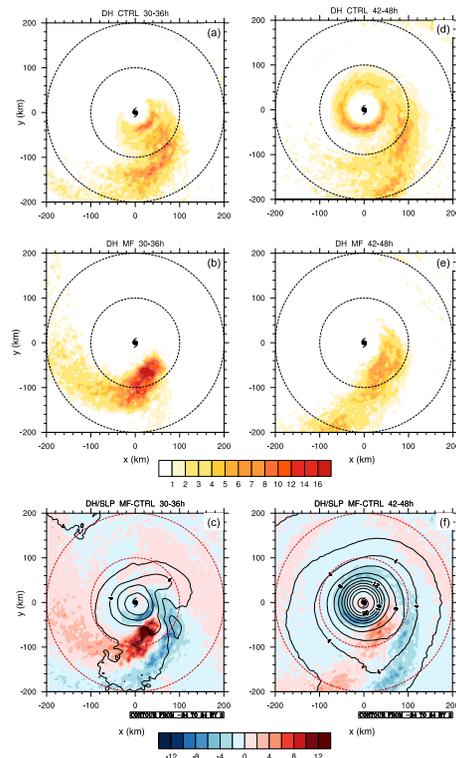


Figure 7. (a) Diabatic Heating (DH; K day^{-1}) of CTRL in 30–36 h; (b) DH of MF in 30–36 h; (c) the difference of DH and SLP between MF and CTRL in 30–36 h; (d) DH of CTRL in 42–48 h; (e) DH of MF in 42–48 h; (f) the difference of DH and SLP between MF and CTRL in 42–48 h in the storm following coordinate. The hurricane symbol shows the TC center. The dashed red circles represent the radius of 100 and 200 km, respectively. All the data are taken from the inner model domain.

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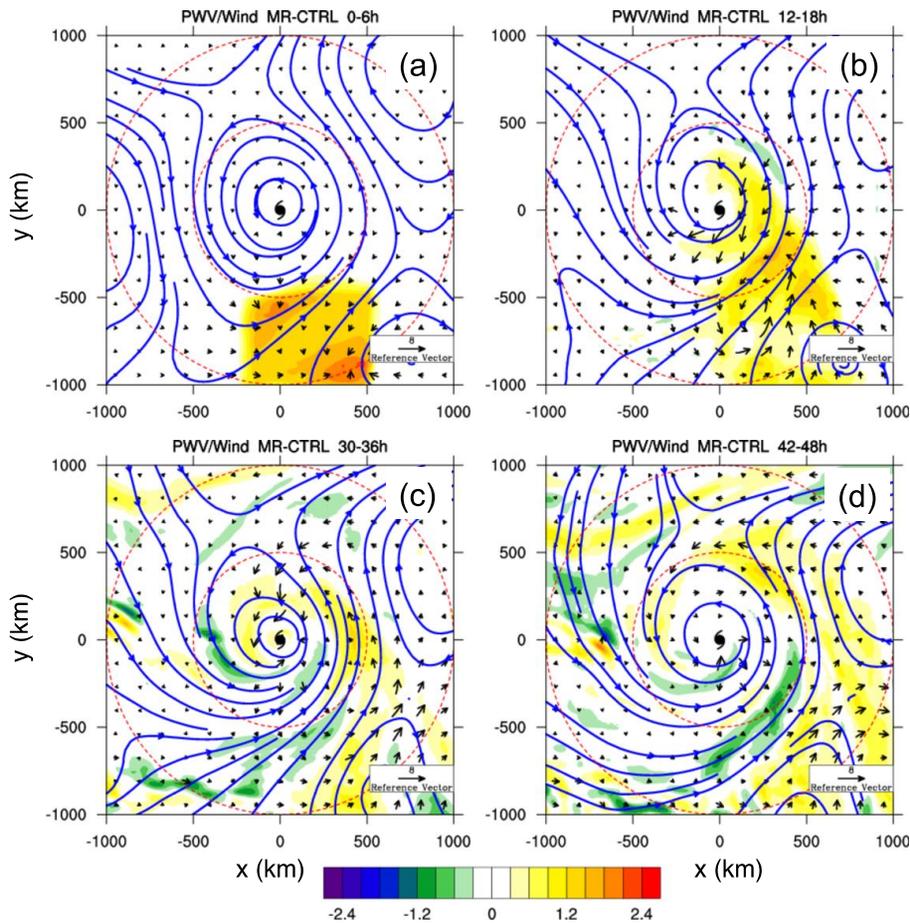


Figure 8. Same as Fig. 5, but for differences between the MR and CTRL experiments.

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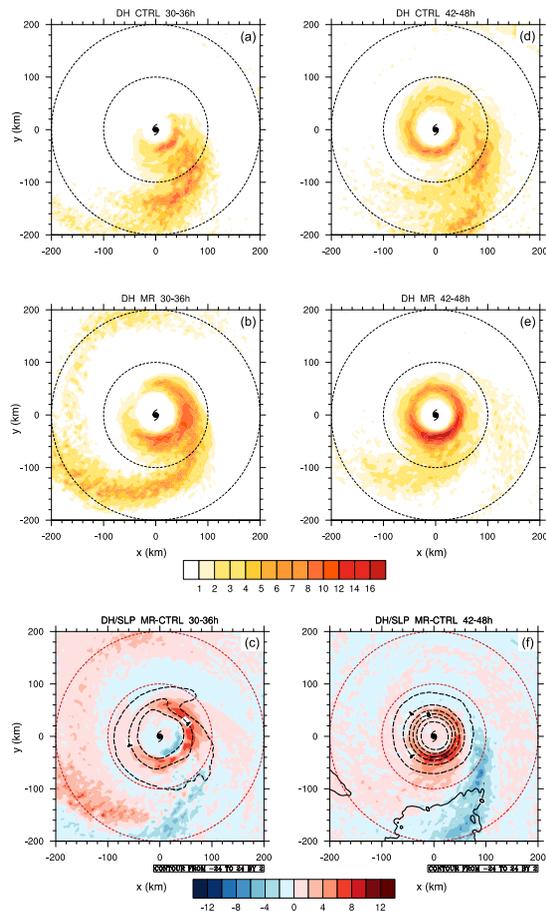


Figure 9. Same as Fig. 7 but for the MR and CTRL experiments.

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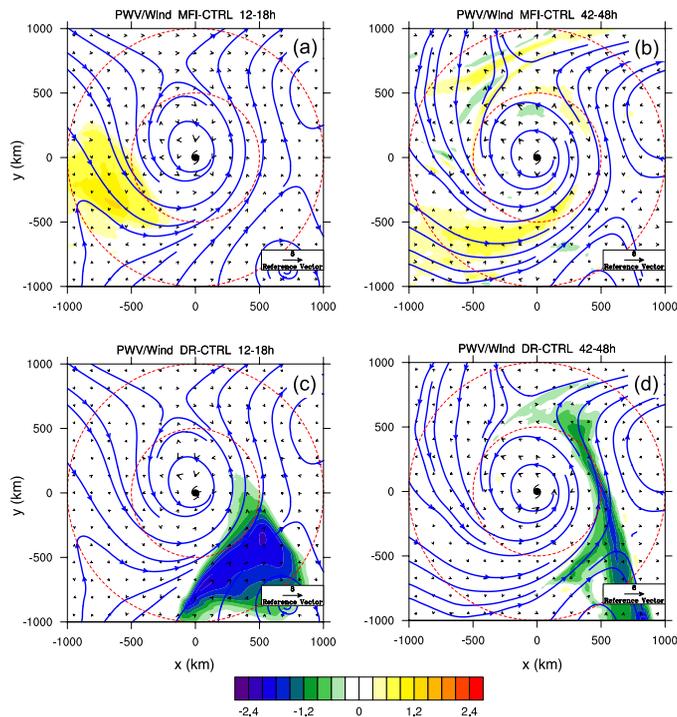


Figure 10. Difference of mean wind vector below 5 km and column-integrated PWV (cm) in the storm following coordinate: **(a)** MFI-CTRL for 12–18 h; **(b)** MFI-CTRL for 42–48 h; **(c)** DR-CTRL for 12–18 h; **(d)** DR-CTRL for 42–48 h. The blue streamline is the translated streamline at the co-moving coordinate for the CTRL case at corresponding time. The hurricane symbol shows the TC center. The dashed red circles represent the radius of 500 and 1000 km, respectively. All the data are taken from the outer model domain.

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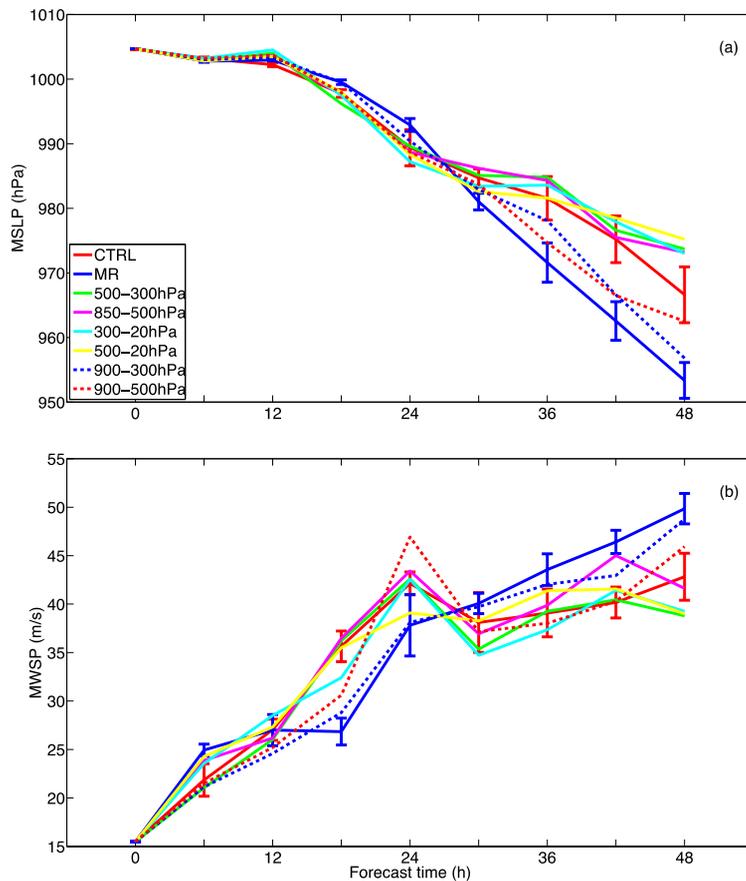


Figure 11. Time series of the model simulated **(a)** MSLP (hPa) and **(b)** MWSP (ms^{-1}). CTRL in red; MR in blue; other simulations are same as the MR run, but with modification of moisture in differently prescribed pressure layer.