We would like to thank the referees for their suggestions and comments. We have listed the referees' comments and written a response below each comment.

Reviewers' comments are in black text; our responses are in blue text.

Anonymous Referee #1
Recommendation:
Accept with Minor Revision

Overview:
This paper investigates the influence of environmental moisture on the intensification of tropical cyclone (TCs) using the Weather Research and Forecasting (WRF) model. Guided by the results of the observational study by Wu et al. (2012), a series of simulations have been conducted with dry/moist air located in different quadrants relative to TC motion. It is shown that generally, the impact of environmental moisture on TC intensification is rather limited. Among the five simulations in this study, only the two extreme cases (i.e., relative humidity are set to the maximum value at each level) show significant impact on storm intensification. Specifically, more moisture in rear of the storm favors TC intensification while more moisture in front of the storm leads to weakening.

In summary, this paper is well written, containing new and exciting results highly relevant to the outstanding issue of TC intensification, although I have some concerns regarding the modeling framework and initialization. Therefore, I recommend that this paper be accepted after minor revision.
We appreciate the referee's evaluation.

Major comments:
1. Section 2.1, line 17-18 (Page 16115), "Simulations are conducted with a parent grid at 9 km horizontal resolution and a vortex-following nested grid at 3 km resolution." Since the simulation is initialized from ECMWF reanalysis (at a resolution around 1x1), the coarsest WRF grid at 9 km horizontal resolution may be too small and could lead to some problems. I suggest that you add another domain at 27 km horizontal resolution and see how the results of your simulations differ.
We have conducted one sensitivity experiment (CTRL-27km) with 3 nested domains at 27 km, 9 km and 3 km horizontal resolutions. As shown in the following figure, there is no significant difference in MSLP (Figure 1a) between the original 2-nested domains and the 3-nested domains. The MSWP in CTRL-27km is also consistent with the original CTRL (Figure 1b). We mentioned in the manuscript that the results are not sensitive to the nested domains in the second paragraph of section 2.1 as following:

"Experiments show that simulated results are not sensitive to the horizontal resolution of the parent grid with similar inner domains."

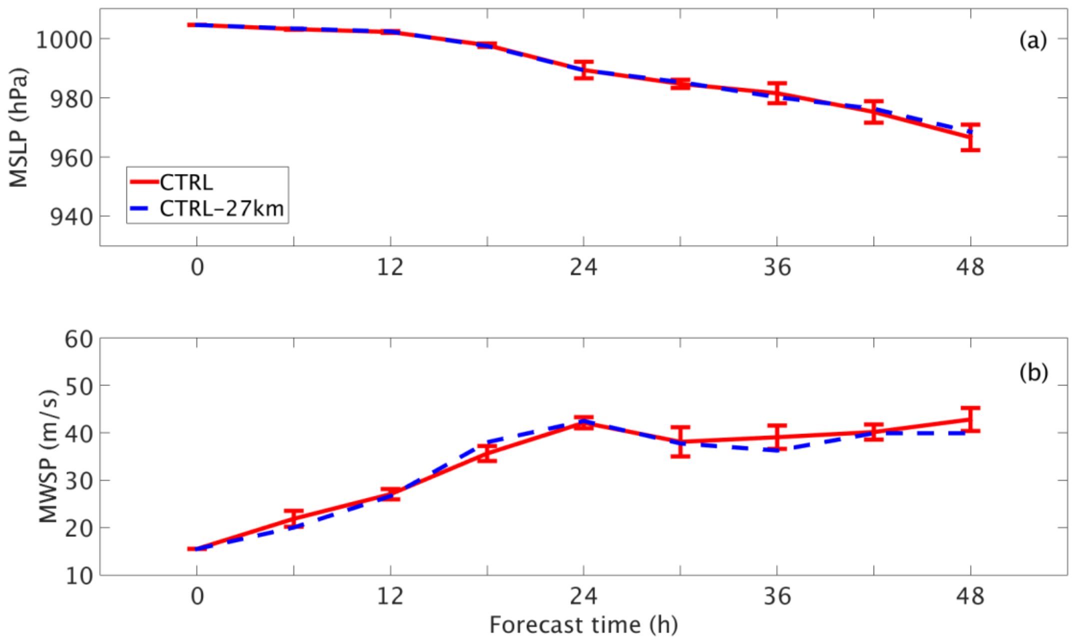

Figure 1. The simulated (a) MSLP (hPa) and (b) MSWP (m/s) in CTRL (red solid line) and CTRL-27km (blue dashed line).

Minor comments:
2. Section 2.2, line 20-22 (Page 16116). Do you mean the maximum RH within the parent domain? Or do you consider any specific radius within the storm center?
It is "the maximum RH within the outer radius of the storm". It is clarified in the revised manuscript.

3. Section 4.1, line 10, change "MRI" to "MFI"
Done.

4. Fig2b, there is a sudden change in MWSP at 30 h for MF and MR experiment, which inconsistent with the trend in MSLP. What is the cause? Is that because of the changes in the storm size for each simulation?
The trend in MSLP is consistent with the trend in MWSP in Fig. 2 of the manuscript. The sudden change at hour 30 is likely due to the intrusion of dry in MF and import of moist air in the MR. Shown in the following Figure 2, the storm sizes in MF, CTRL and MR are slightly different, but the storm size does not change dramatically at hour 30 in each experiment.

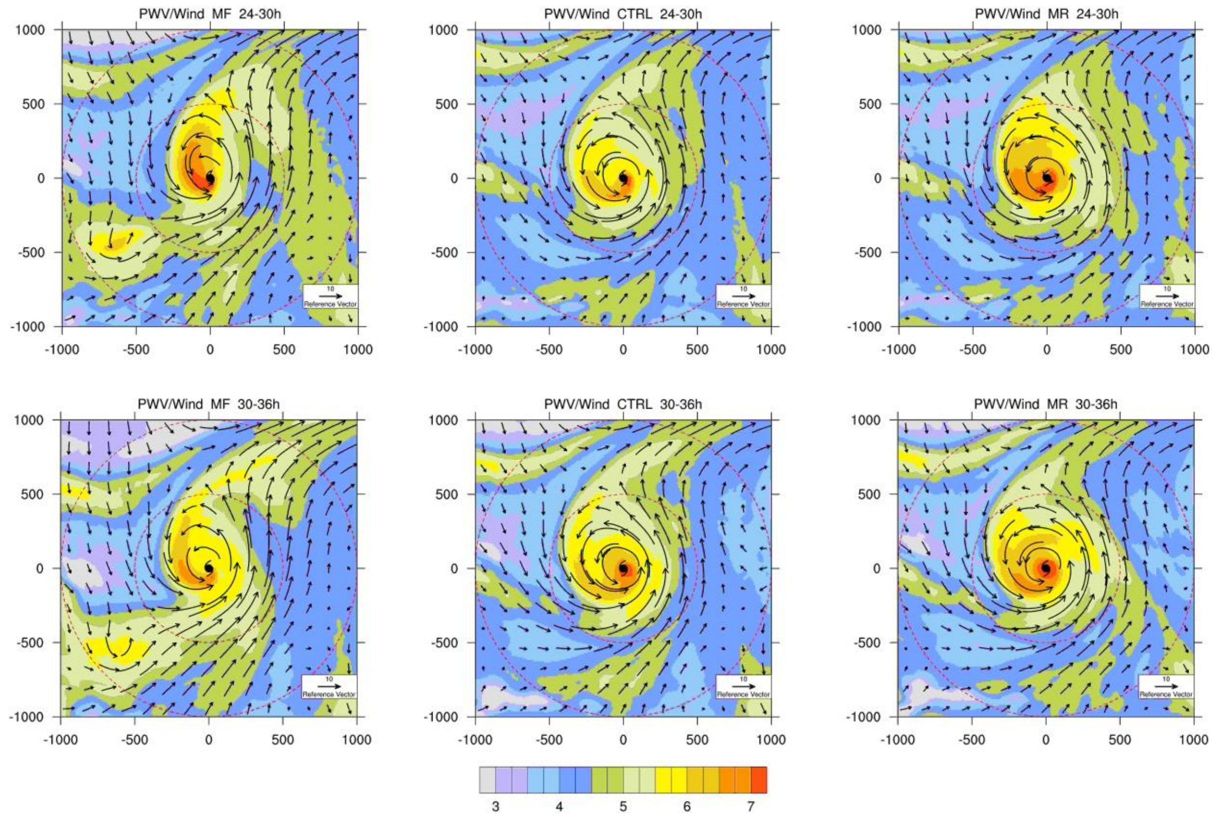

Figure 2. Mean wind vector (m s-1) below 5 km and column-integrated PWV (cm) (shading) at 24-30 h (upper panel) and 30-36 h (lower panel) for MF (left panel), CTRL (middle panel) and MR (right panel).

5. Page 16224, line 11, change “ability” to “abilities”
Done.

6. Fig. 5 shows the differences between the MF and CTRL experiment. It will be clearer if you add another two panels showing the mean wind vector (m/s) and PWV (cm) for each of them (one for MF, one for CTRL). Same for Fig. 8.
Thank you for the suggestion. For space concern, we add the mean wind and PWV for MF and MR together with CTRL in the supplementary Figure 1. It is also included here for your reference (Figure 3).

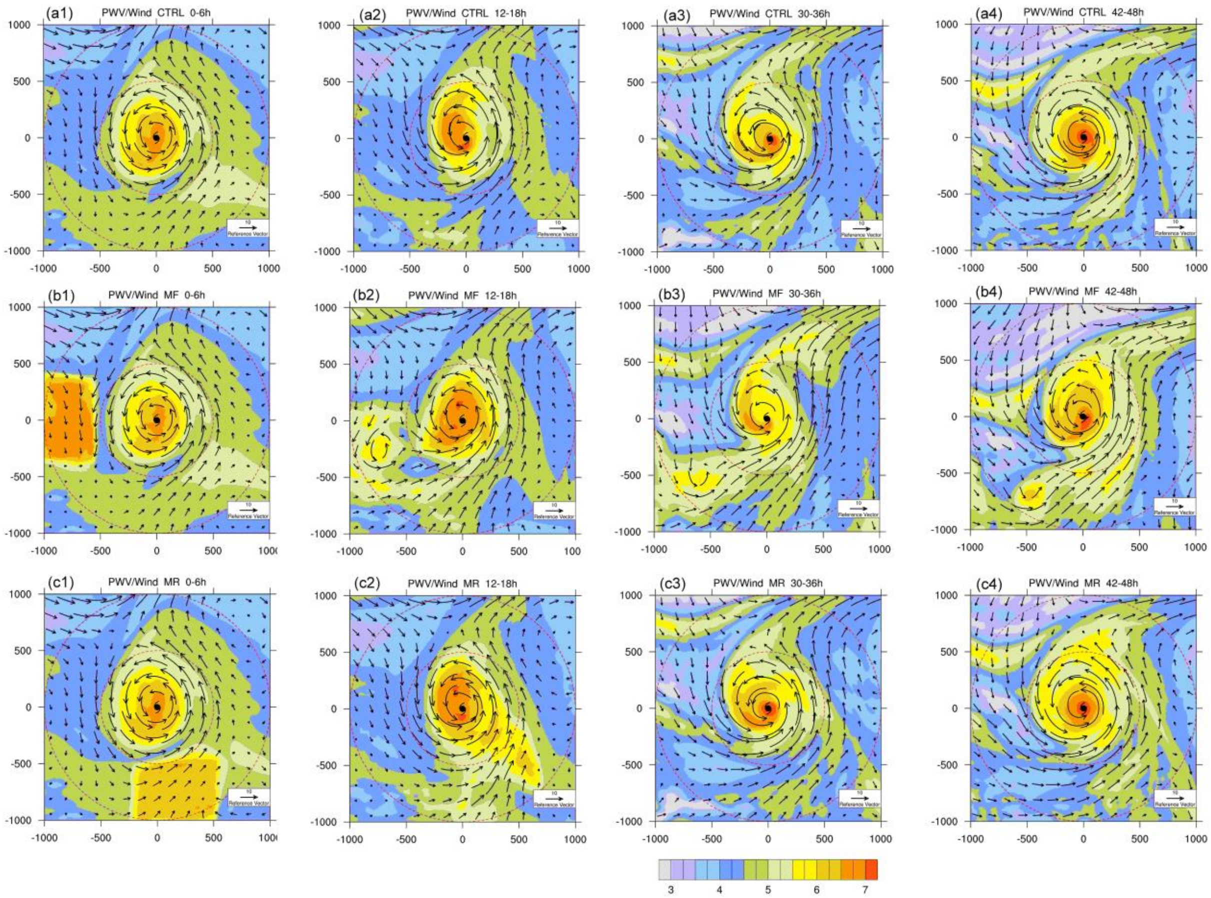

Figure 3. Mean wind vector (m s-1) below 5 km and column-integrated PWV (cm) (shading) for CTRL (panel a), MF (panel b) and MR (panel c) at (1) 0-6 h; (2) 12-18 h; (3) 30-36 h; (4) 42-48h.

Anonymous Referee #2

Summary:

This paper explores the effects of changes to the environmental moisture field on a developing tropical cyclone. In particular, rather than changing the moisture field everywhere, changes ahead of and behind the cyclone are considered separately. Each particular case is represented by a mini-ensemble of 5 simulations with small variations to the initial condition; this is a considerable improvement over many previous studies.

Thanks for the referee's positive comments.

It is found that an increase in moisture ahead of the storm can lead to overall weakening, while an increase in moisture behind the storm leads to strengthening. However, the mechanisms for the changes are, in hindsight, due to the unrealistic formation of secondary, satellite vortices around the storm caused by the strong and deep moisture perturbations.

We have tested moisture perturbations of different magnitudes and concluded "modification of environmental moisture has insignificant impacts on the storm in this case unless it leads to convective activity that deforms the quasi-Lagrangian boundary of the storm and changes the moisture transport into the storm".

Recommendation: May be acceptable after major revisions

Major comments:

1. The general modeling framework and initialization are fairly reasonable, except for one problem: The simulations are initialized with global model data, but then run for only 48 hours. When a high-resolution model like WRF is initialized from global models, there is generally a "spin-up" or adjustment period of about 12 hours. This means that 1/4 of the whole simulation includes this adjustment period.

Considering reviewer's comments, we have conducted three simulations (CTRL+12hr, MF+12hr and MR+12hr) initiated 12 hours earlier and run for 60 hours. The results are shown in the following Figure 4. The CTRL+12hr simulation produces a slighter higher intensity at Hour 60 than the original CTRL at Hour 48. However, the differences in storm intensity at the end of simulations between the CTRL and MF/MR are consistent with those shown in the manuscript. Thus, the extra spin-up does not change the conclusions. We mentioned these extra simulations in the first paragraph of section 4.1 as following:

"Similar experiments with initialization at 12 hours earlier show consistent results to the CTRL, MF and MR experiments, except a more intense storm developed in the experiment with a moist perturbation in the rear (figure not shown)."

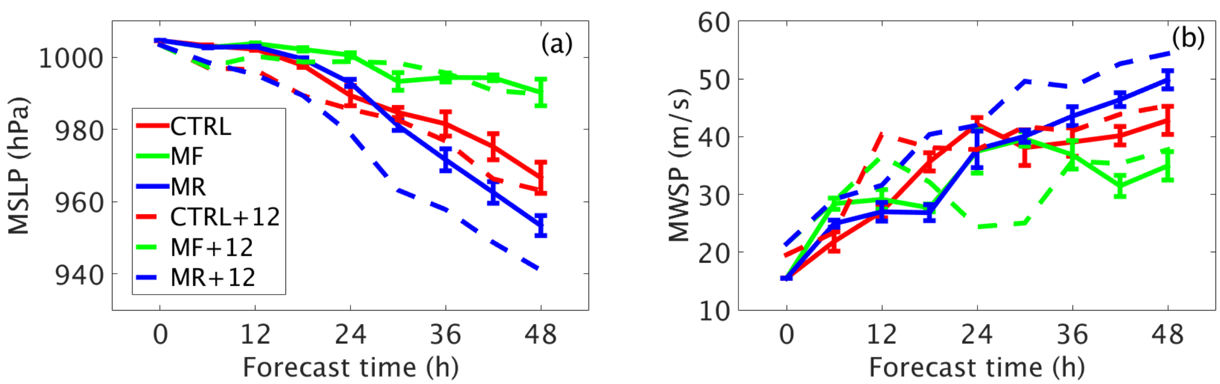

Figure 4. The simulated (a) MSLP (hPa) and (b) MWSP (m/s) for CTRL (solid red), MF (solid green), MR (solid blue), CTRL+12hr (dashed red), MF+12hr (dashed green) and MR+12hr (dashed blue).

2. The strategy for the moisture perturbations seem reasonable at first, but turns out to have unrealistic effects: they initiate convection so strong that they generate new circulations outside of but fairly close to the storm. For the MF case, the vortex is very strong, with a mean tangential wind of about 8-10 m/s (as best as I can tell from the plots) averaged over 0-5 km height. This is practically a tropical cyclone in its own right. For the MR case, the vortex is weaker but the net result is the same.

The height-varying experiments further prove the point: large changes only occur if the moisture perturbations extend into the boundary layer. So, if the instantly imposed moisture perturbations are strong and extend into the boundary layer, then in the first 12 hours (the adjustment period), they generate convection which is strong enough to significantly change the circulation around the primary TC, in one case causing it to be affected by dry air, and in the other case to be affected by moist air, leading to intensity changes in each case.

But this not how moisture interacts with real storms. For example, in this case, if the air to the north of the storm (Earl) had not been dry and there was no dry slot in front of it, that does not mean a burst of convection would occur creating a small vortex which then would have caused changes (weakening, in fact) to Earl. Or, to put it another way, similar effects could have been created by adding vortices to the flow instead of moisture changes. The question of how Earl or similar hurricanes might have evolved if there had been no dry slot in front, or an extra moist slot behind, is unfortunately not answered by the paper in its present form.
We agree with the reviewer that whether the enhanced environmental moisture could affect the primary cyclone depends on the intensity of the moisture perturbation and the background moisture values. Although our experiments are based on the specific atmospheric conditions for Earl, the general conclusions drawn from the series of experiments is that the particular MF and MR simulations have different impacts. The MFI case shows a rather insignificant impact with intermediate strength of moisture perturbations. Thus, our general conclusions about “modification of environmental moisture has insignificant impacts on the storm in this case unless it leads to convective activity that deforms the quasi-Lagrangian boundary of the storm and changes the moisture transport into the storm” would hold regardless the special distributions associated with Earl. In the case of Earl, in some quadrants, it may take very vigorous convective activity to “open up” the TC circulation. But in other quadrants and/or cases, less provocation would be needed.

While I am always reluctant to ask for new simulations when reviewing a paper, I see little choice in this case. I recommend repeating the simulations with the following changes: 1) Use a 72 hour simulation, with the first 24 hours for an adjustment period; then add the moisture changes at t = 24 h. This separates the adjustment and moisture responses.
We have run a 72 hour simulation as suggested. However, the 72 hour simulation cannot reproduce the intensification of the storm. Alternatively, we run a 60 hour simulation with the first 12 hours for model adjustment. Results are shown in Figure 4.

2) Use less radical moisture changes, which are more representative of the variations that occur in the Tropical Atlantic.
The MFI experiment in the manuscript is an intermediate perturbation. The CTRL, MFI and MF cases represent the dry, intermediate moist and extreme moist environments at the front of the storm, respectively. The dry, intermediate moist and extreme moist environments at the rear of the storm are represented by the DR, CTRL and MR experiments, respectively.

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 relative to the storm path. 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~~that deforms the quasi-Lagrangian boundary of the storm and changes the moisture transport into 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~~In contrast, 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 km 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).

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.

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 section 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 section 4. The findings from this study are summarized in section 5.

2. WRF experiments and analysis framework

a. 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 0000 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 0600 UTC 29 August to 0000 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 0000 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. Experiments show that simulated results are not sensitive to the horizontal resolution of the parent grid with similar inner domains. 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.

As the model is initialized solely from the coarse-resolution reanalysis, the initial TC is weaker and less organized than the actual storm was and thus at least a portion of its subsequent intensification represents a response to the improved resolution. *Our focus is on how environmental moisture perturbations directly and indirectly influence how the storm organizes subsequent to initialization*. To assess potential impacts of the initial conditions, the WRF control (CTRL) simulation consists of five ensemble members with randomly generated RH perturbations of less than 1% added to the initial specific humidity field at all model horizontal and vertical grids. In the following discussions, the CTRL and other sensitivity experiments refer to the ensemble means of the respective five ensemble members.

b. Experiment design

The sensitivity experiments are conducted by placing moisture perturbations of varying magnitudes at different locations relative to the storm at the initial time (Fig. 1). The zones are rectangular in shape and sharply bounded and, as a consequence, could serve as focal points for convective activity if conditions are sufficiently favorable. We explored tapering the edges of the moisture perturbations and found it did not materially alter our conclusions.

In the Moist Front (MF) experiment (Fig. 1b), an artificially moistened zone of 5 degrees in longitude and 7 degrees in latitude is placed in front of the storm (relative to its roughly westward propagation). Within the moist zone, the RH of all model grids from 900 hPa to the model top of 20 hPa are set to the maximum RH ~~around~~ within the outer radius of the storm at each level by modifying specific humidity without changing temperature. In the Intermediate Moist Front (MFI) simulation (Fig. 1c), the moist zone is located at the same place as for MF but the magnitude of the moisture perturbation is smaller (70% of the maximum RH at each level). Thus, the CTRL, MFI and MF cases represent the dry, intermediate moist and moist environments at the front of the storm, respectively.

In the Moist Rear (MR) simulation, a moist zone with the same area and magnitude of RH perturbations as in the MF run is placed to the south, roughly in the storm's 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.

c. 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 Figure 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; 2012b). 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 24-30h, 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 m s^{-1} from 6-h 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 h, 12-18 h, 30-36 h and 42-48 h) are displayed. At the initial time (Fig. 3a), the storm core (indicated by the relative large PWV > 5 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 3d), the storm center keeps moistening while the dry air approaches the opening of the storm Lagrangian structure to the southwest of the storm.

4. Impacts of Environmental Moisture

a. Summary of sensitivities in TC intensity and track

Figure 2a shows the evolution of MSLP from four sensitivity experiments for comparison with the CTRL simulation. Except for the first 6 h of the 48-h integration, the MF experiment (with an ensemble mean of 990 hPa at the 24-h simulation) has higher MSLP than the CTRL simulation (whose ensemble mean is 967 hPa at that same time). The MR experiment produces comparable (or slightly higher) MSLP to the CTRL simulation in the first 24 h. Afterwards, the storm in the MR experiment strengthens much faster than its CTRL counterpart. The MSLP in the MR simulation reaches 953 hPa at the 48-h forecast, the lowest among all the experiments. Similar experiments with initialization at 12 hours earlier show consistent results to the CTRL, MF and MR experiments, except a more intense storm developed in the experiment with a moist perturbation in the rear (figure not shown). Both the MF~~R~~I and DR simulations have minor impacts on hurricane intensity, compared to the CTRL, throughout the 48-h integration.

Similar trends of storm evolution appear in the simulated MWSP (Fig. 2b). Both the MF and MR simulations produce a stronger storm at the 6-h forecast than the CTRL run. Between 18 h and 24 h, the strength of the storm is comparable between MF and MR, but weaker than that in the CTRL. After 30 h, the MF experiment produces a weaker storm relative to the CTRL simulation while the storm intensifies faster in the MR run. By the end of the simulation at 48 h, the ensemble mean MWSP is 35 m s^{-1} for MF, 43 m s^{-1} for CTRL, and 50 m s^{-1} for MR. Consistent with MSLP, both the MFI and DR experiments have no significant impacts on the magnitude of MWSP relative to the CTRL.

Regarding storm track (Fig. 4), the storm in the MF experiment moves further northwestward than the CTRL case. A significant track difference starts to show at 12 h, corresponding to the change in the MSLP. In the first 24 h, the track differences are less than 110 km. When the storm executes a gradual curve to the northwest, the track differences increase with a maximum difference of 220 km at 48 h. In the last 24 h, the significant deflection to the north with lower SST may partly contribute to the weaker storm in the MF experiment. The MR experiment has relatively small changes on the 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.

b. 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-5d) and diabatic heating fields (Fig. 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).

c. 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 26h (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 9b). Subsequently, the MR storm starts strengthening faster than the CTRL (Fig. 2 and Fig. 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.

d. 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 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.

e. 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 hPa, 900-300 hPa, 850-500 hPa, 500-300 hPa, 500-20 hPa, and 300-20 hPa, respectively. It is found that only the RH enhancements including the boundary layer (900-300 hPa 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 intensification process of a storm is simulated in the WRF CTRL simulation. When the moisture perturbation is not large enough to create additional convection outside of the storm, as in the MFI and DR experiments, the storm Lagrangian boundary serves as a barrier to protect the storm from intrusion of environmental air. No significant impact on the storm intensity and track is observed in the MFI and DR experiments.

However, when convective activity is promoted by the moisture perturbation and deforms the storm Lagrangian structure, as in the MF experiment, a storm that is weaker than the CTRL case occurs due to intrusion of dry environmental air from the northwest into the vortex through the convective-induced open Lagrangian structure, which leads to the asymmetry of convection in the storm inner core. The storm is also deflected to further northwest and approaches dry air, especially in the last 24 h, which may also contribute to the weaker storm in the MF experiment.

In contrast, convective deformation of the vortex in the MR experiment facilitates the entrainment of additional moisture from the south and results in more symmetric and powerful convection in the inner core with a higher intensity than the CTRL case. The intensification is primarily contributed by enhanced moisture in the boundary layer. The distortion of the storm Lagrangian structure and changes in the moisture pathway play the key roles in the different response of the MF and MR cases.

This study demonstrates that the Marsupial Paradigm is a useful tool to study the interaction of a TC vortex with its environment at any stage of the storm development, not only limited to TC formation. Dunkerton et al. (2009) proposed that a closed circulation is favorable for TC formation. This study hypothesized an open storm Lagrangian structure can also benefit TC formation and intensification as long as the opening is towards a favorable environment (e.g., moist air).

Based on these results and previous studies (Braun et al. 2012; Ge et al. 2013; Hill and Lackmann 2009; Kimball 2006; Tao and Zhang 2014; Wang 2009; Ying and Zhang 2012), we conclude that environmental moisture has limited impacts on storm intensity if it does not enter the storm vortex, similar to the insignificant impacts of dry air beyond 270 km noted in Braun et al. (2012). If the moisture enhancement produces 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 abilities~~y~~ 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 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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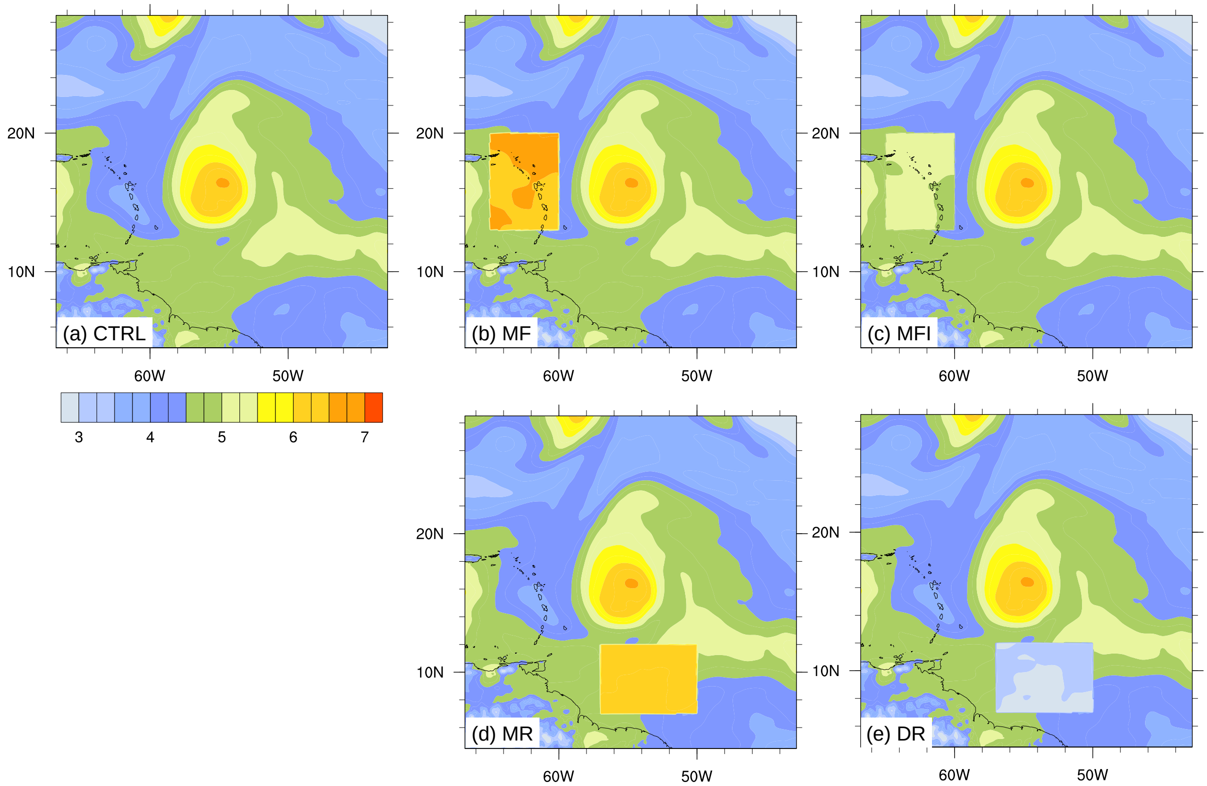
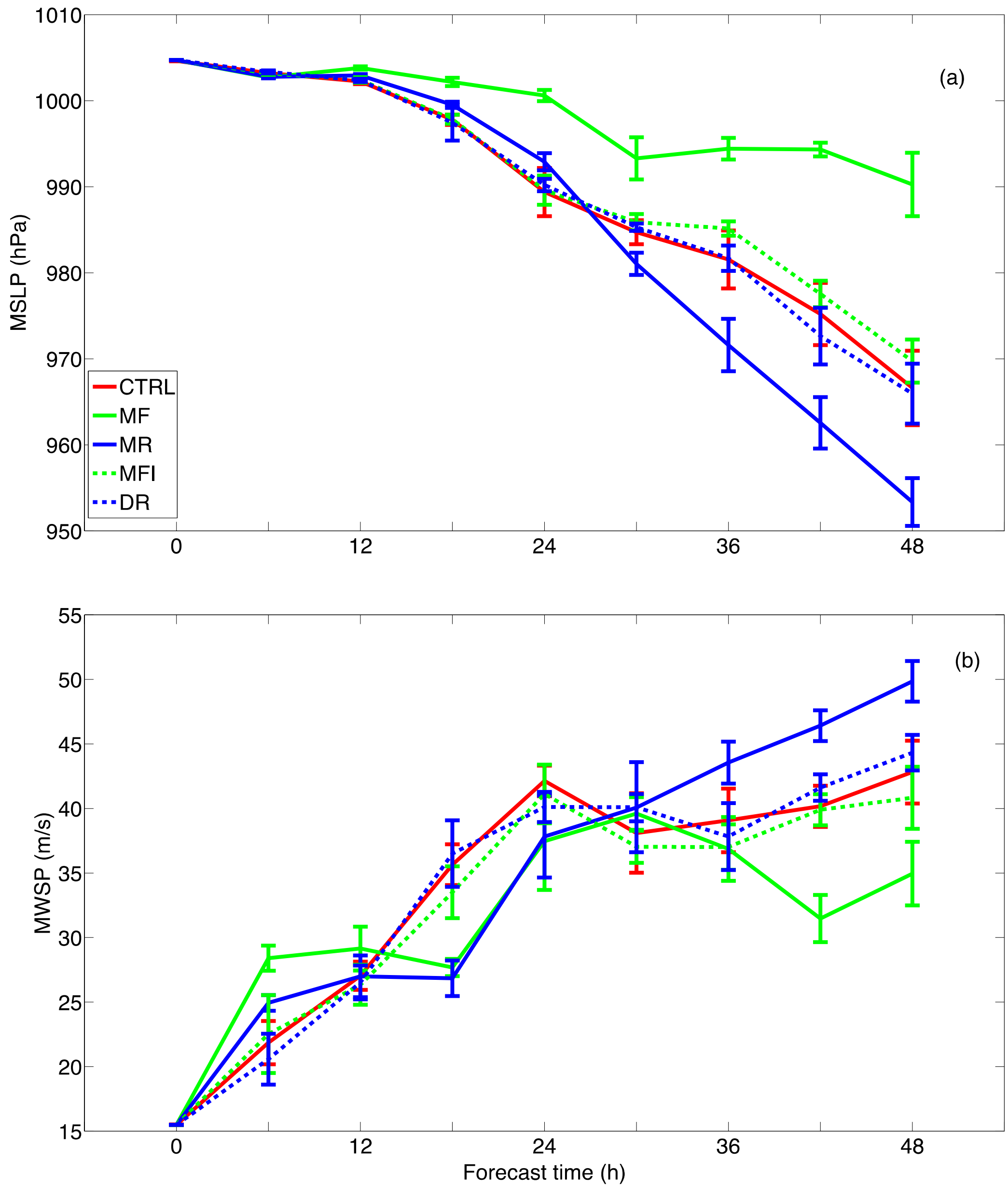


Figure 1. Column-integrated PWV (cm) at the initialization of the WRF simulations: (a) CTRL; (b) MF; (c) MFI; (d) MR; (e) DR.



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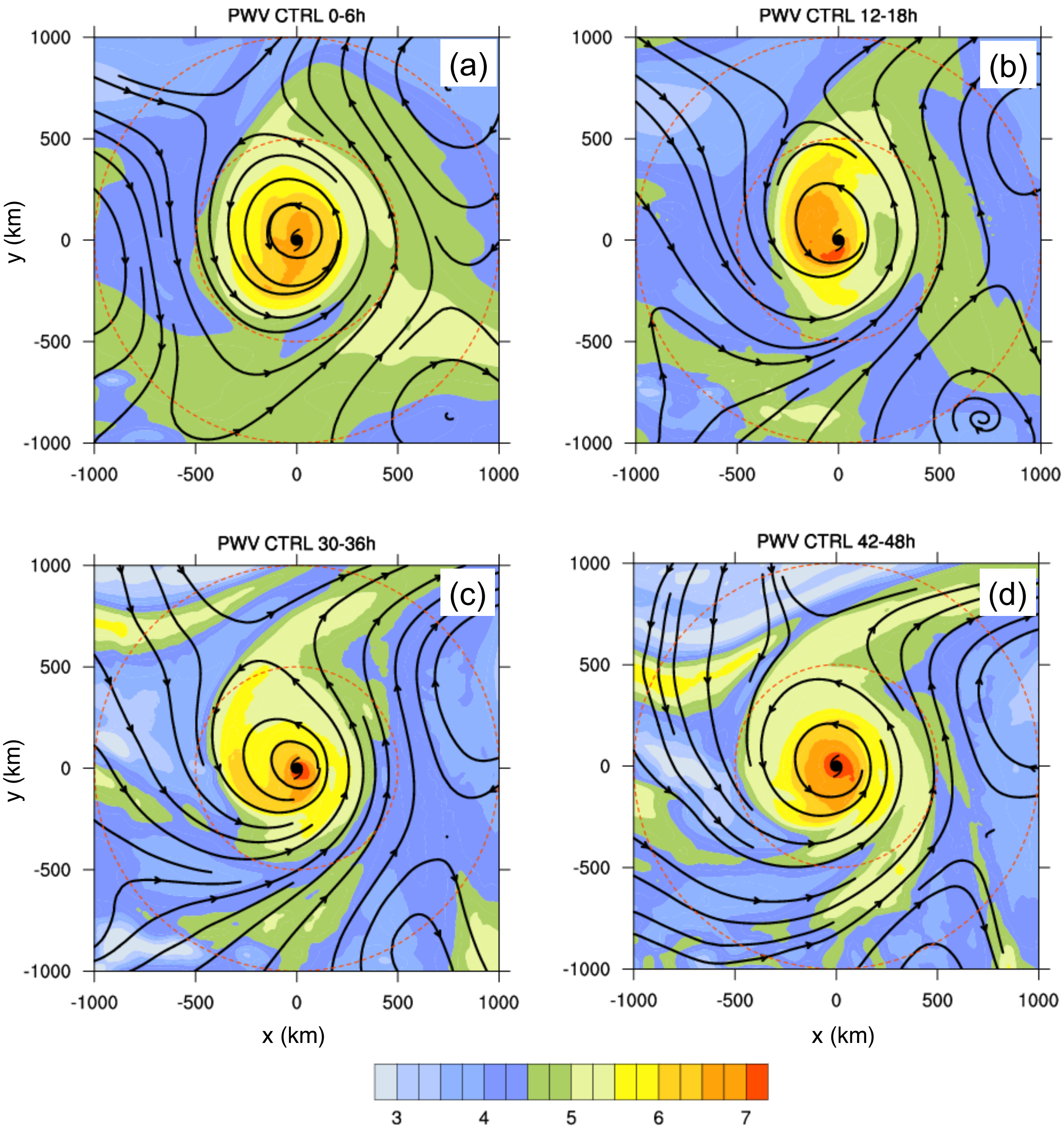

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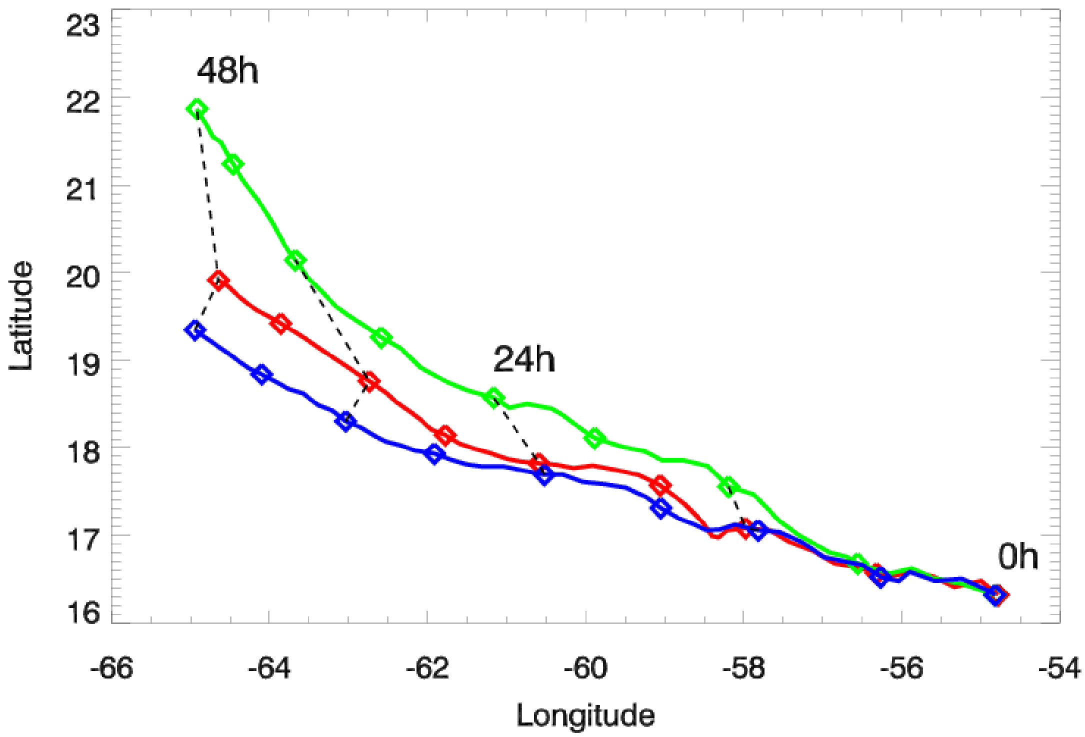

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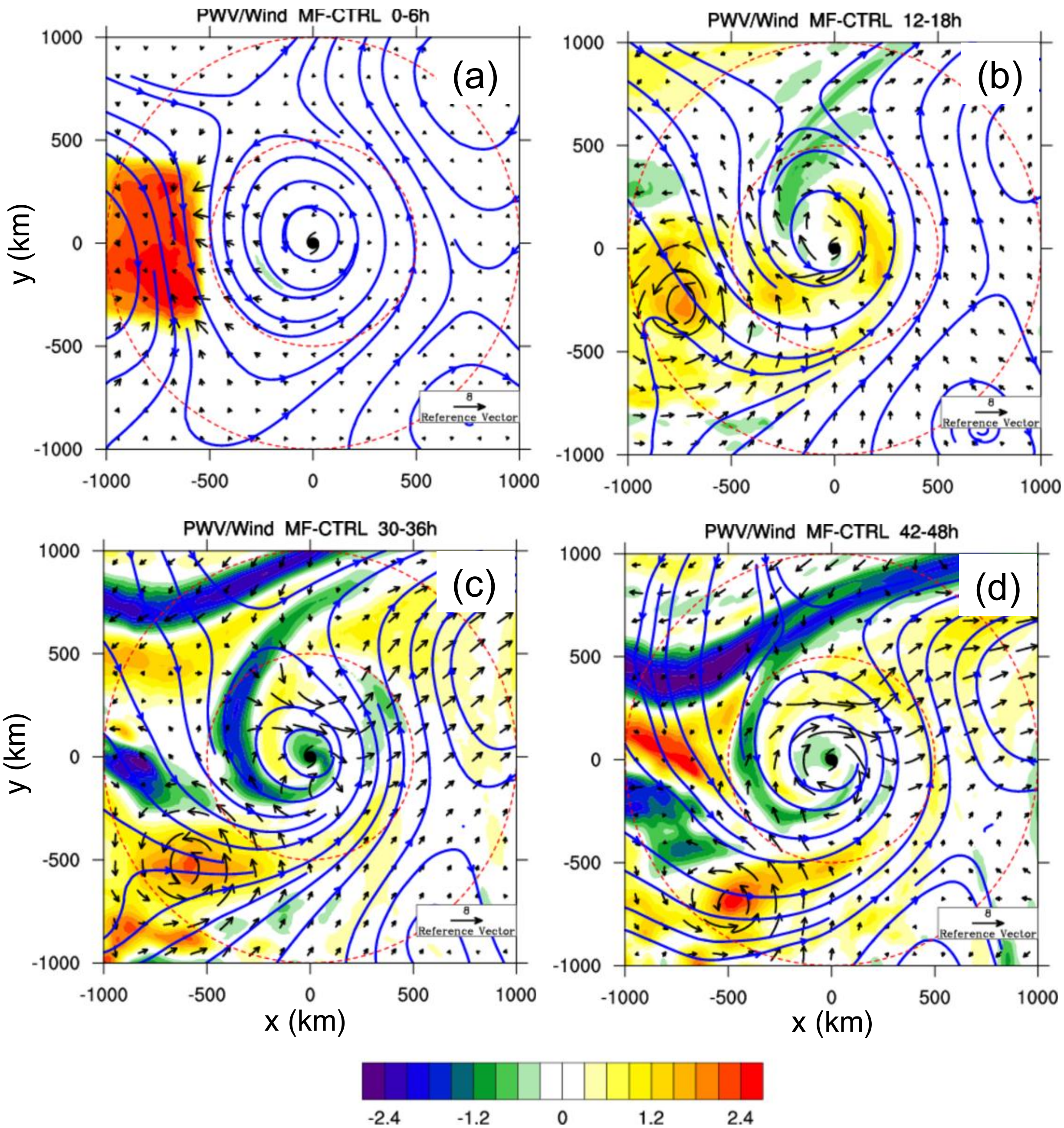

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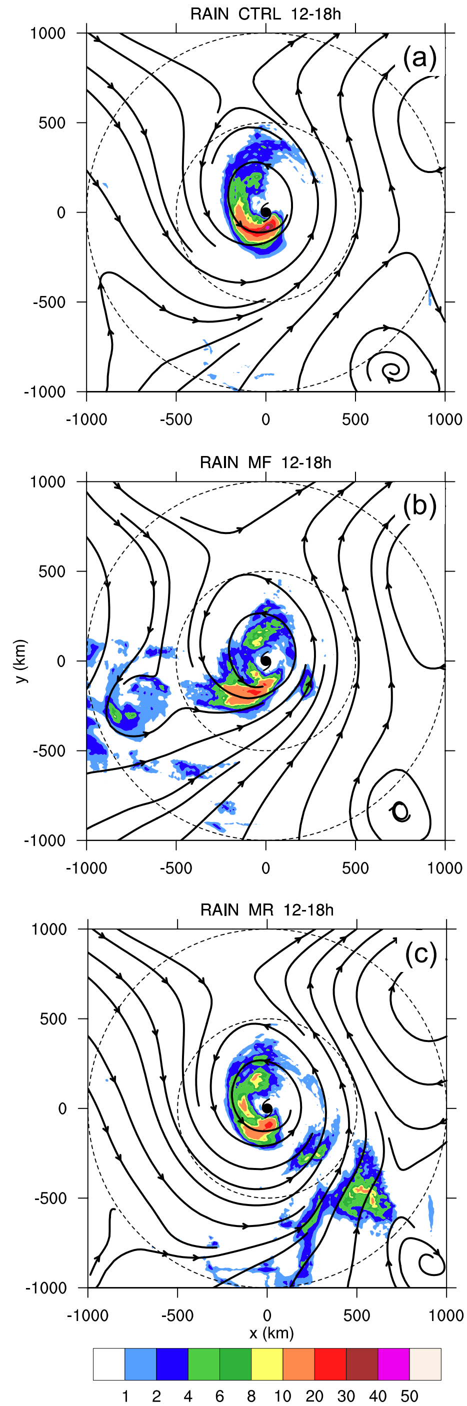

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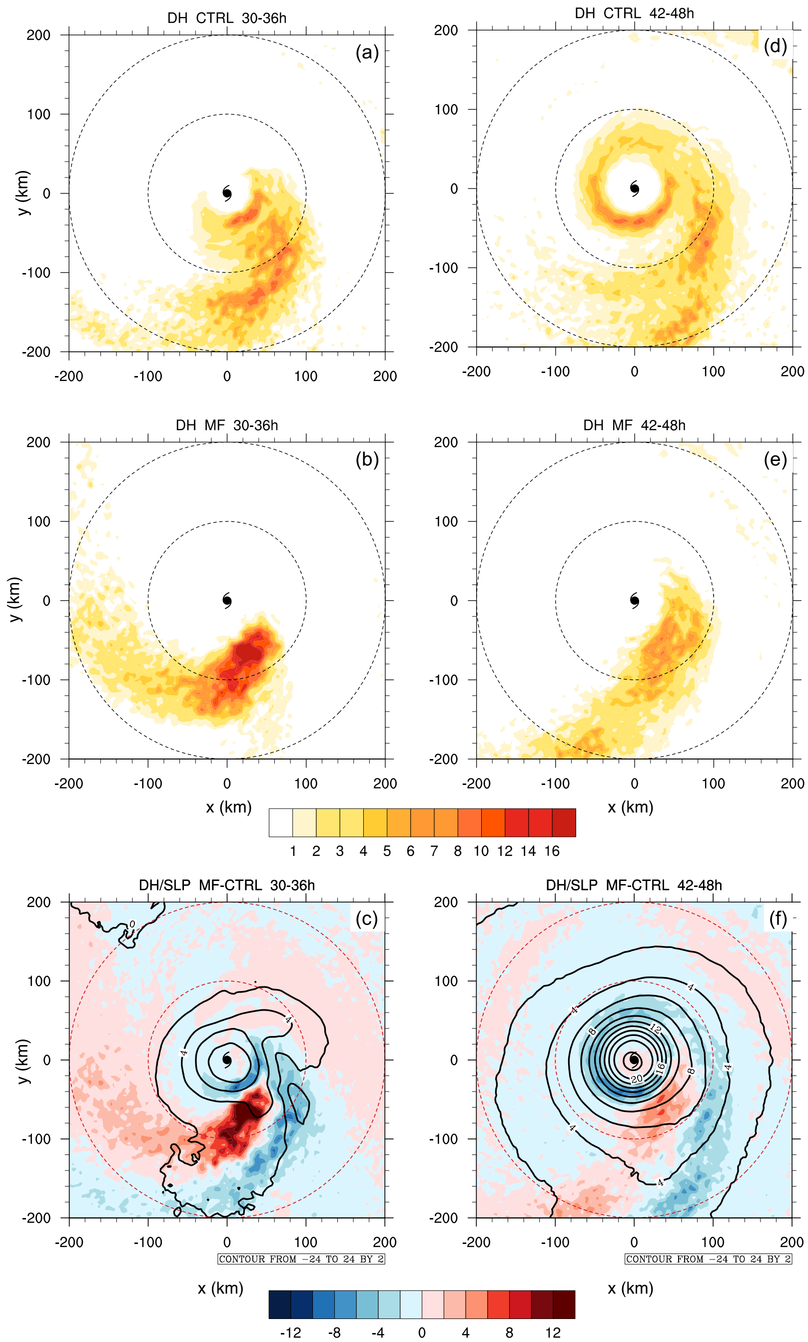

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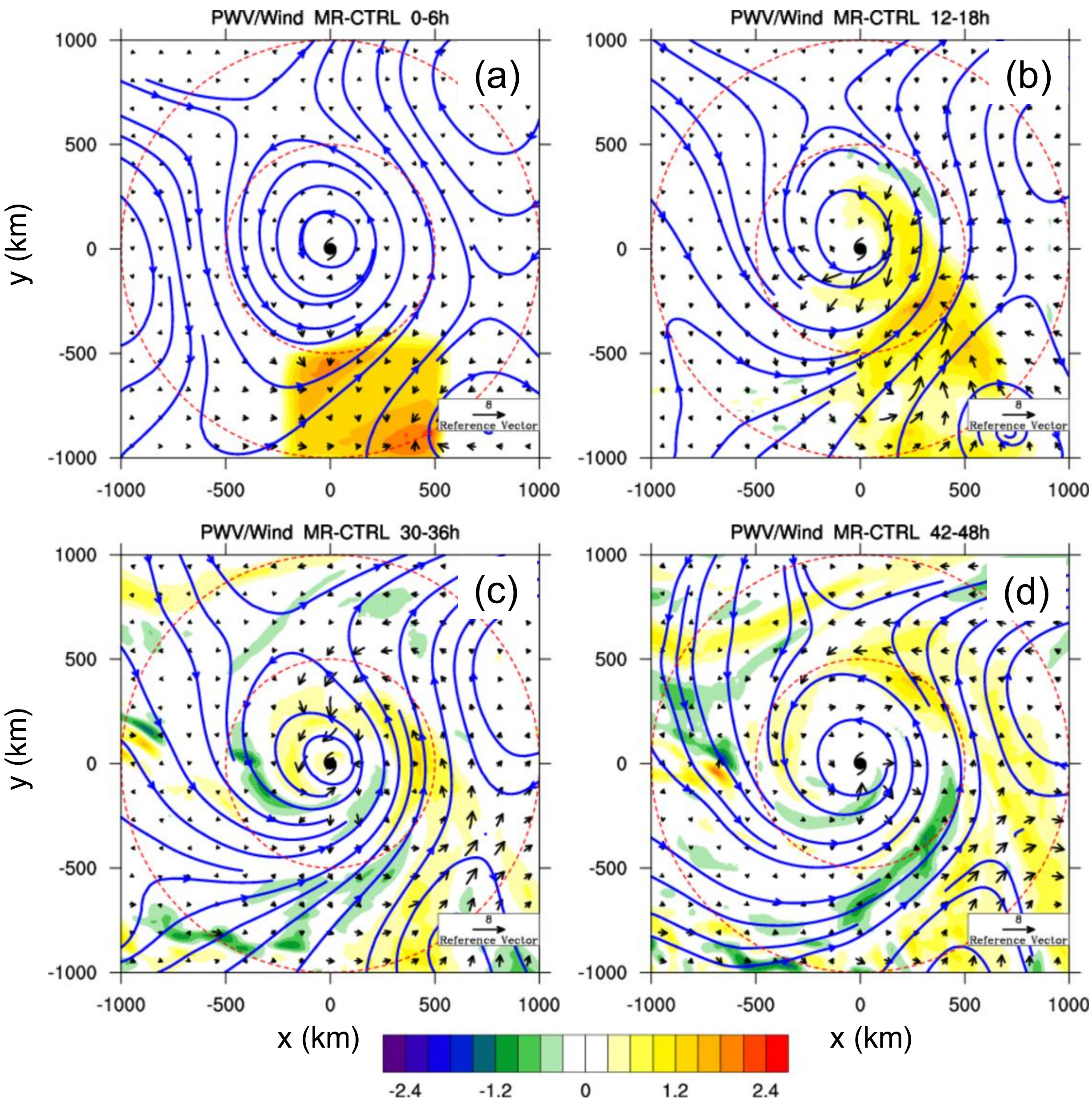
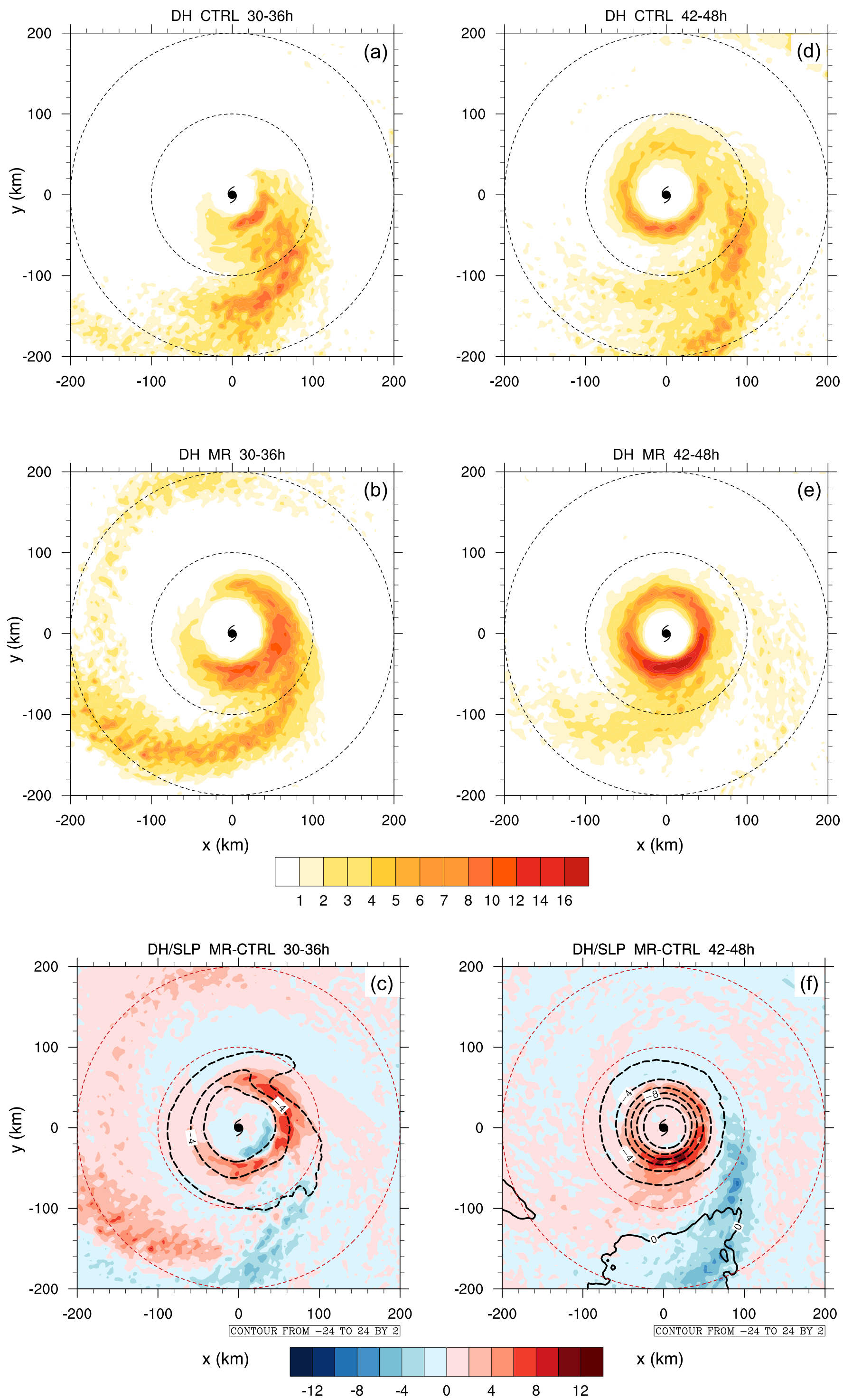


Figure 8. Same as Fig. 5, but for differences between the MR and CTRL experiments. Mean wind vectors and column-integrated PWV for CTRL and MR at each time are shown in supplementary Figure 1.



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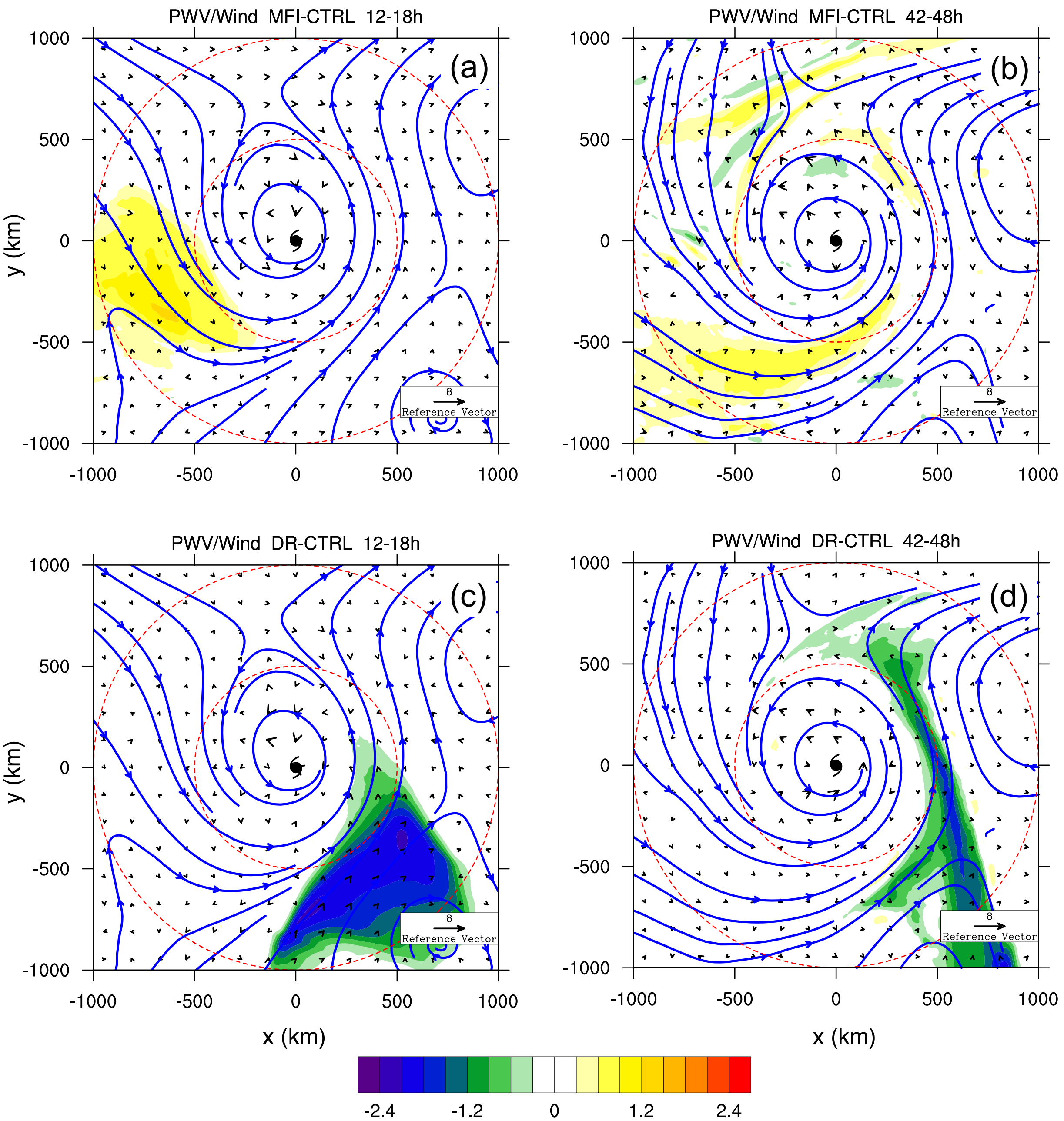
507 Figure 9. Same as Fig. 7 but for the MR and CTRL experiments.



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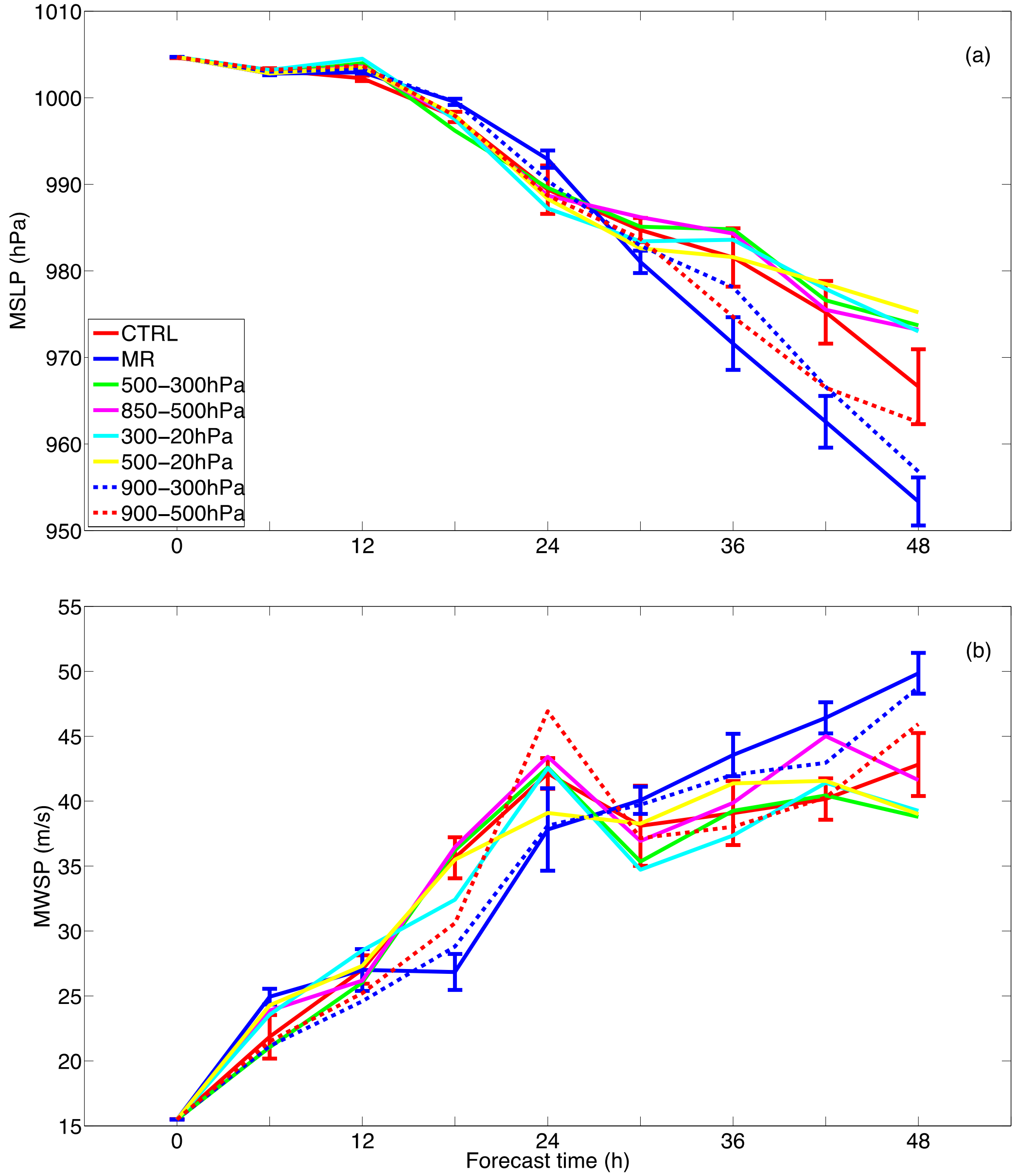

Figure 11. Time series of the model simulated (a) MSLP (hPa) and (b) MWSP (m s^{-1}). CTRL in red; MR in blue; other simulations are same as the MR run, but with modification of moisture in differently prescribed pressure layer.