## Dynamics and Predictability of Hurricane Nadine (2012) Evaluated through Convection-Permitting Ensemble Analysis and Forecasts

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#### ABSTRACT

The governing dynamics and uncertainties of an ensemble simulation of Hurricane Nadine (2012) are assessed through the use of a regional-scale convection-permitting analysis and forecast system based on the Weather Research and Forecasting (WRF) Model and an ensemble Kalman filter (EnKF). For this case, the data that are utilized were collected during the 2012 phase of the National Aeronautics and Space Administration's (NASA) Hurricane and Severe Storm Sentinel (HS3) experiment. The majority of the tracks of this ensemble were successful, correctly predicting Nadine's turn toward the southwest ahead of an approaching midlatitude trough, though 10 members forecasted Nadine to be carried eastward by the trough. Ensemble composite and sensitivity analyses reveal the track divergence to be caused by differences in the environmental steering flow that resulted from uncertainties associated with the position and subsequent strength of a midlatitude trough.

Despite the general success of the ensemble track forecasts, the intensity forecasts indicated that Nadine would strengthen, which did not happen. A sensitivity experiment performed with the inclusion of sea surface temperature (SST) updates significantly reduced the intensity errors associated with the simulation. This weakening occurred as a result of cooling of the SST field in the vicinity of Nadine, which led to weaker surface sensible and latent heat fluxes at the air-sea interface. A comparison of environmental variables, including relative humidity, temperature, and shear yielded no obvious differences between the WRF-EnKF simulations and the HS3 observations. However, an initial intensity bias in which the WRF-EnKF vortices are stronger than the observed vortex appears to be the most likely cause of the final intensity errors.

## 1. Introduction

This study examines sources of forecast uncertainty and error for Hurricane Nadine, a long-lived North Atlantic tropical cyclone that occurred in 2012. Simulations initialized at 0000 UTC 20 September 2012 with a convection-permitting hurricane forecast and analysis system [the Weather Research and Forecasting (WRF) Model and an ensemble Kalman filter (EnKF), collectively WRF-EnKF] are examined to better understand the large forecast uncertainties and errors that occurred during this period in terms of both track and intensity. The examination of this stage of Nadine's lifetime also benefits from extensive observations taken during the National Aeronautics and Space Administration's (NASA) Hurricane and Severe Storm Sentinel (HS3) mission, which are compared to the simulations in

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FIG. 1. Enhanced infrared imagery of Hurricane Nadine from a NOAA satellite at (a) 1200 UTC 20 Sep, (b) 1200 UTC 21 Sep, (c) 1200 UTC 22 Sep, (d) 1200 UTC 23 Sep, (e) 1200 UTC 24 Sep, and (f) 1200 UTC 25 Sep 2012.

order to develop a better understanding of Nadine's behavior.

Nadine developed from a tropical wave that emerged from the African coast on 7 September (Brown 2013). The disturbance was classified as a tropical depression by 1200 UTC 10 September as it tracked westnorthwestward around a large subtropical ridge, before being upgraded to Tropical Storm Nadine at 0000 UTC 12 September. Nadine continued to intensify, reaching hurricane strength by 1800 UTC 14 September as it moved northward through a break in the subtropical ridge. After the storm turned east, its convection began to decrease, and the system was downgraded to a tropical storm at 0000 UTC 17 September. Around this time Nadine turned northeastward toward the Azores, and it continued on this track until a blocking ridge to the north of the tropical cyclone (TC) induced a turn toward the east-southeast on 0000 UTC 20 September. This time corresponds with the initialization time of the simulations of interest in this study. Also at this time, a mid- to uppertropospheric trough and an associated cold front began to approach Nadine from the northwest, expanding Nadine's wind field and causing the convection associated with the storm to diminish (Brown 2013; Figs. 1a-c). As a result of this interaction, Nadine was reclassified as a nontropical low at 1800 UTC 21 September. Low-level steering flow then moved Nadine toward the southsoutheast into a more conducive environment where deep convection was able to redevelop, allowing for the

reclassification of Nadine as a tropical storm by 0000 UTC 23 September (Fig. 1d). During the remaining 48 h of the simulation window, another blocking ridge caused Nadine to complete a cyclonic loop and continue to move slowly toward the west-northwest as it slightly weakened (Figs. 1e,f). Beyond the simulation window, Nadine reintensified to hurricane strength and reached its maximum intensity at 1200 UTC 30 September.

Although National Hurricane Center (NHC) forecast errors for Hurricane Nadine were generally low (Brown 2013), periods of increased uncertainty and error existed. In particular, there were a few 4- and 5-day track forecasts whose errors exceeded those of the 5-yr averages as Nadine initially approached the Azores on 20 September. Therefore, one goal of this study is to utilize the WRF-EnKF 60-member ensemble simulation to investigate the environmental variables that led to the uncertainty in the track forecasts. In addition, because WRF-EnKF intensity forecasts initialized during this period performed poorly, the reasons for intensity error are explored through an analysis of the sensitivity to the sea surface temperature (SST) field and through comparisons between the ensemble simulations and observational data.

Section 2 describes the WRF-EnKF setup and operational data utilized, while section 3 presents the composite analyses of Nadine's track and intensity forecasts with comparisons to the HS3 observations. Finally, section 4 outlines the main conclusions of this study.

## 2. Methodology and data

## a. WRF-EnKF hurricane analysis and forecast system

The deterministic and 60-member ensemble forecasts for Nadine are generated using version 3.5.1 of the Advanced Research version of the WRF model (ARW; Skamarock et al. 2008) and an EnKF data assimilation algorithm. The model setup is similar to what is described in Weng and Zhang (2012), but with the added capability of continuous cycling assimilation of all conventional nonradiance observations besides airborne reconnaissance measurements (Weng and Zhang 2014). Three two-way nested domains are used with horizontal grid spacings of 27, 9, and 3 km, which contain areas of  $10\,200\,\mathrm{km} \times 6600\,\mathrm{km}$  (378  $\times$  243 grid points), 2700 km  $\times$  $2700 \text{ km} (303 \times 303 \text{ grid points})$ , and  $900 \text{ km} \times 900 \text{ km}$  $(303 \times 303 \text{ grid points})$ . The outermost domain is fixed and encompasses the majority of the North Atlantic Ocean and North America. The inner two domains are movable, with the center of the domain remaining aligned with the center of the tropical cyclone of interest. The three domains have 44 vertical levels with the top level at 10 hPa. The Grell-Devenyi cumulus parameterization scheme (Grell and Devenyi 2002) is employed in the outermost domain only. Additional parameterization schemes include the WRF singlemoment 6-class with graupel scheme (Hong et al. 2004) for microphysics and the Yonsei State University (YSU) scheme (Noh et al. 2003) for the planetary boundary layer. A one-dimensional ocean mixed layer model based on Pollard et al. (1972) is also applied with an initial mixed layer depth of 50 m and a temperature lapse rate below the depth of the mixed layer of 0.14 km<sup>-1</sup>. The bulk exchange coefficients used to parameterize surface fluxes are obtained from the Pennsylvania State University (PSU) option (Green and Zhang 2013). The WRF-EnKF system is initialized at 1200 UTC 9 September with the operational Global Forecast System (GFS) analysis, and the first data assimilation is conducted over all three domains at 0000 UTC 10 September after 12h of ensemble integration. The system performs cycling assimilation every 3h until Nadine dissipates (0000 UTC 4 October). The operational GFS forecasts from 6h prior are used as lateral boundary conditions for the deterministic forecast, while the ensemble lateral boundary conditions are generated by adding perturbations derived from the background error covariance of the WRF-VAR data assimilation system (Barker et al. 2004) to the deterministic lateral boundary conditions. The ensemble forecasts analyzed in this study are initialized with the EnKF analysis perturbations from 0000 UTC 20 September.

#### b. HS3 observations of Hurricane Nadine

Five HS3 flights were performed to collect observational data throughout the extensive lifetime of Hurricane Nadine by utilizing an unmanned Global Hawk aircraft. These flights occurred on 11-12, 14-15, 19-20, 22-23, and 26-27 September. Two of these flights collected observations during the 5-day simulation window of this study (19-20 and 22-23 September), which correspond to hours 0-12 and 72-84 in the simulation. Only the Global Hawk equipped with the "environmental" instrument configuration was operational during this year of the HS3 experiment, collecting data through the utilization of NOAA/National Center for Atmospheric Research (NCAR) dropsondes (Black et al. 2011), the University of Wisconsin's Scanning High-Resolution Interferometer Sounder (Revercomb et al. 1998), and the NASA Goddard Space Flight Center (GSFC) Cloud Physics lidar (McGill et al. 2002). Seventy-six dropsondes were deployed during the 19-20 September flight, while 53 dropsondes were used throughout the 22-23 September flight. Since the WRF-EnKF assimilation window ends 90 min after the simulations are initialized, only two of the dropsondes from the 19-20 September flight were assimilated for the ensemble simulations analyzed in this study. The majority of the data collected can thus be utilized to independently verify how representative the simulations of Nadine were to the observed TC.

#### 3. Results and discussion

## a. Forecast performance comparison of WRF-EnKF and operational ensemble

Given the unique and lengthy track of Hurricane Nadine, the performance of the WRF-EnKF system is first evaluated against that of an operational ensemble. Figure 2 shows a 126-h section (0000 UTC 20 September-0600 UTC 25 September) of the best track of Nadine as well as the corresponding ensemble member forecast tracks from the WRF-EnKF system (Fig. 2a) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Fig. 2b). There is clear divergence within both the operational ensembles (ECMWF and GFS; not shown) and the WRF-EnKF ensemble as a result of the different forecasts of the interaction between Nadine and an approaching midlatitude trough. Although the deterministic runs of the models at this time forecasted the southwestward turn ahead of the trough (not shown), the NHC official forecasts maintained the eastward trajectory for Nadine based on previous forecasts that had favored that scenario (Brown 2013). It is clear that as a result of the considerable spread and large uncertainty present in the ECMWF and the WRF-EnKF ensembles 40

35

30

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Latitude (degrees)

Best Track

GOOD

POOR

Other



20 20 al WRF-EnKF b)ECMWF 15∟ -60 15L -60 -30 -20 -10 -20 -50 -40 -30 -10 Longitude (degrees) Longitude (degrees) FIG. 2. The 5-day track forecasts for the (a) 60-member WRF-EnKF and (b) 50-member ECMWF ensemble forecasting systems for Hurricane Nadine initialized at 0000 UTC 20 Sep 2012 grouped by track performance. The WRF-EnKF composite groups are GOOD, with the 10 members with the smallest cumulative track RMSE between the member and the best track [blue in (a)], and POOR, with the 10 members that curve eastward by the midlatitude trough [red in (a)], while the ECMWF composite groups are EC\_GOOD, as in GOOD but for the ECMWF en-

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Latitude 25

semble [blue in (b)], and EC\_POOR, with 10 members that are curved eastward by the midlatitude trough [red in (b)]. The remaining members in each ensemble are plotted in cyan and the thick lines indicate means of the composite groups (position marked every 12 h). The NHC best track for Hurricane Nadine is overlaid in black with positions marked every 12 h.

(Fig. 2), Nadine posed a significant operational forecast challenge that is worth exploring in further detail.

To help diagnose causes for the considerable uncertainty in the WRF-EnKF forecasts, the methodology employed in Munsell et al. (2013) and Munsell and Zhang (2014) was used to create two composite groups of 10 ensemble members based on the performance of their track forecasts. The 10 ensemble members with the smallest cumulative root-mean-square track error compose the composite group GOOD, and the composite group POOR consists of the 10 members whose storms are steered eastward by the approaching midlatitude trough. Figure 2a highlights the members of the composite groups, as well as the mean tracks of the composites. The mean track of GOOD compares well with the best track. In addition, the mean tracks demonstrate that the members of GOOD and POOR have very similar positions over the first 24 h of the simulation before slight variations in position begin to develop over the next 24 h. Significant divergence in the mean tracks begins around 48 h, and therefore the analysis of the environmental influences on track uncertainty is focused on the period of time leading up to this track bifurcation.

The corresponding evolution of minimum sea level pressure (SLP in hPa; Fig. 3a) and maximum 10-m wind speed (kt;  $1 \text{ kt} = 0.5144 \text{ m s}^{-1}$ ; Fig. 3b) reveals that although most of the members yielded successful track forecasts, the entirety of the ensemble predicted a steady intensification of Nadine that was not observed. Intensity errors associated with POOR were smaller than those associated with GOOD, though the tracks of POOR are completely different than the best track of Nadine so that the cyclones in these members encounter completely different environmental conditions than the observed storm. We next present a series of sensitivity experiments designed to diagnose the causes of the large intensity error from the WRF-EnKF forecasts during this period.

## b. Intensity errors associated with the WRF-EnKF ensemble: SST sensitivity

In the original ensemble forecast of Nadine, the SST field was prescribed from the GFS analysis and only evolved as a result of the 1D ocean model throughout the simulation. It has long been recognized that SST has a large influence on the potential formation and intensification of a tropical cyclone (e.g., Miller 1958; Gray 1968; Emanuel 1988; DeMaria and Kaplan 1994). Given the length of this simulation, significant changes in the observed SST field could have been induced by upwelling from the storm itself (Price 1981) or by shifts in the surface wind-driven currents (Kelly 1985; Emery et al. 1986).

To determine if significant changes in SST occurred over this 5-day period of Nadine's lifetime, the real-time, global, sea surface temperature (RTG\_SST) analysis fields developed by the National Centers for Environmental Prediction/Marine Modeling Analysis Branch are plotted for the initialization time (0000 UTC 20 September; Fig. 4a) and the final time (0600 UTC 25 September; Fig. 4b) of the



FIG. 3. Evolutions of the (a) minimum SLP (hPa) and (b) the maximum 10-m wind speeds (kt) of the best track of Hurricane Nadine (black) and the 60 ensemble members of the WRF-EnKF forecast initialized at 0000 UTC 20 Sep 2012 grouped by track performance: GOOD in blue, POOR in red, and the remaining members of the ensemble in cyan. The thick lines indicate the means of the composite groups GOOD and POOR.

simulation. The initial SST field shows that the storm occupied an area of the eastern Atlantic with SSTs typically considered to be too cold (lower than 26°C) for TC development or intensification. In addition, the final SST field is noticeably cooler than the initial field, and the disparity is more clearly illustrated in the difference field (Fig. 4c). The largest region of cooling (up to  $3^{\circ}$ C) is located in the area to the right of Nadine's track, which is consistent with observational studies (Stramma et al. 1986; Shay et al. 1992) that found that the largest amount of upwelling and therefore cooling of the sea surface occurs to the right of the track of the TC. Therefore, the initially cool SSTs encountered by the simulated storms continue to become cooler (as low as 22°-24°C) as they move southward, particularly for the members of GOOD during the latter half of the simulation.

To examine the impact of the changing SST field on the intensity of the members of this ensemble, a sensitivity experiment is performed. Utilizing the RTG\_SST daily analysis fields beginning at 0000 UTC 20 September, the 20 ensemble members composing the composite groups GOOD and POOR are reintegrated with an updated SST field. Updates of the SST are performed every 6h, with the intermediate fields between the daily analysis fields at 0000 UTC derived through linear interpolation.

Though updating the SST field does not substantially change the mean tracks of GOOD or POOR (not shown), there is a significant impact upon intensity (Fig. 5). The evolution of the means of minimum SLP (Fig. 5a) and maximum 10-m winds (Fig. 5b) indicate a noticeable divergence in intensity after 48 h, after which point the members of GOOD with updated SST fields have significantly weaker storms than the members of GOOD from the original ensemble. Although intensification still occurs when the SST updates are included in the simulation, which was not



FIG. 4. Real-time, global sea surface temperature (RTG\_SST) analysis fields developed at the National Centers for Environmental Prediction/Marine Modeling and Analysis Branch (NCEP/MMAB) at (a) 0000 UTC 20 Sep and (b) 0600 UTC 25 Sep 2012, contoured every 1°C with the best track of Hurricane Nadine (black line with position marked every 12 h). The dashed line indicates the 26°C contour. (c) The differences between the two SST fields with contours every 0.5°C, as well as the best track and the mean tracks of the composite groups (GOOD, blue; POOR, red).



FIG. 5. Evolutions of the (a) minimum SLP (hPa) and (b) maximum 10-m wind speeds (kt) of the best track of Hurricane Nadine (black) and the means of the composite groups GOOD (blue) and POOR (red) for the original forecasts (thin) and the simulations with the 6-h updates of SST (thick).

observed in Nadine, utilizing the SST updates significantly reduces the intensity errors. Because the utilization of the SST updates yields improved intensity forecasts, particularly for the GOOD composite group, the remainder of the analysis performed in this study uses the results from the SST update sensitivity experiment.

An additional sensitivity experiment was performed utilizing two randomly selected members from both GOOD and POOR to test the influence of the simple 1D mixed layer ocean model on the final intensity of the members in this ensemble. The two GOOD and the two POOR members were reintegrated using both the constant SST field as well as the SST updates with the 1D ocean model turned off. The resulting intensities of the simulations without the ocean model are for the most part consistent with the intensities when the ocean model is employed for both the constant SST and the updated SST experiments (not shown). Therefore, the exclusion of the simple mixed layer ocean model has an insignificant influence on the intensity evolution, and the presence of the SST updates far outweighs the impact of the one-dimensional ocean model on the intensity forecasts in this ensemble.

# c. Influences on surface fields and subsequent intensity as a result of SST updates

This section examines the means by which the evolving SST fields impact the intensity evolution. First proposed by Riehl (1954), it has continuously been demonstrated that the sea surface acts as a source of "fuel" that aids in the development, maintenance, or intensification of a tropical cyclone through the transfer of sensible and latent heat at the air-sea interface (e.g., Ooyama 1969; Emanuel 1986). Figure 6 shows the mean sensible

(Fig. 6a) and latent (Fig. 6b) heat fluxes of the composite groups GOOD and POOR averaged over an area within 300 km of the TC surface center for the original forecast and the SST sensitivity experiment. For both experiments the sensible and latent fluxes are initially comparable, but after 6 h (the time of the first SST update) the mean surface sensible and latent heat fluxes in both composites of the SST update experiment decrease significantly. Though the fluxes increase over the next 24 h in the sensitivity experiment, they remain weaker than in the constant SST simulations.

As the simulations evolve, the surface sensible and latent heat fluxes associated with the GOOD ensemble members slowly decrease, whereas the surface fluxes of GOOD in the constant SST experiment continue to steadily increase. During this portion of the simulation, the simulated storm moves southward into a region of the Atlantic in which relatively warmer SSTs were observed in the analysis field at the initialization time. However, because an overall cooling of the SSTs throughout this region occurred over the course of the 5-day simulation window, the inclusion of the SST updates leads to the divergence in surface flux strength. Meanwhile, the surface fluxes of POOR are similar in both sets of experiments because the POOR ensemble members turn eastward ahead of the approaching midlatitude trough and into a region in which the SST field does not evolve drastically throughout the simulation window.

To determine if there is a relatively uniform or asymmetric pattern in the reduction of the surface fluxes in the SST update experiment, storm-centered composites of the sensible heating and the latent heating field of GOOD at 24h for both the constant SST (Figs. 7a,d) and the updated SST (Figs. 7b,e) experiments are plotted. The differences between the two



FIG. 6. Evolution of the mean 300-km area-averaged (a) sensible and (b) latent heat fluxes  $(Wm^{-2})$  for the composite groups GOOD (blue) and POOR (red) of the original forecasts (thin) and the simulations with the 6-h updates of SST (thick).

fields (updated SST – constant SST) are also displayed (Figs. 7c,f). There is a clear reduction in the sensible heat flux throughout the western portion of the updated SST experiment composite (Fig. 7b). The differences between the composites are particularly noticeable in the inner-core region (within 200 km of the surface center) of Nadine, where a reduction of up to  $40 \text{ W m}^{-2}$  is seen (Fig. 7c). This decrease appears to be in part driven by the comparably weaker intensity of the

simulated vortices in the updated SST composites, while the area of reduced sensible heating to the northwest of Nadine corresponds with the observed region of greatest cooling of the SST field, as previously shown in Fig. 4c. The inclusion of the SST updates also leads to a reduction in the surface latent heat flux in the same regions of significant SST cooling (Fig. 7e). The latent heat fluxes are reduced by over  $100 \text{ Wm}^{-2}$  in the region to the northwest of the surface center of Nadine (Fig. 7f).



FIG. 7. Storm-centered composites (750 km  $\times$  750 km box around each ensemble surface center) of (top) surface sensible and (bottom) latent heat flux (W m<sup>-2</sup>) (color shading every 10 W m<sup>-2</sup> and every 25 W m<sup>-2</sup>) overlaid (left, middle) with the 10-m wind speeds (vectors) of the GOOD composite group at 24 h for the (a),(d) constant and (b),(e) updated SST experiments. (c),(f) The difference fields are plotted with contours every 10 W m<sup>-2</sup>. The surface wind vectors have been smoothed 10 times for clearer visualization (using a 1:2:1 smoother in both the *x* and *y* directions).



FIG. 8. Surface maps of storm-centered composite 2-km simulated radar reflectivity (color shading every 5 dBZ beginning at 5 dBZ), minimum SLP (gray contour lines every 10 hPa), and 10-m winds (vectors) for the GOOD and POOR composite groups at (left to right) 0, 24, and 48 h for a portion of the outermost domain in the forecast system. Composite deep-layer (850-200 hPa) shear vectors (red) and 850–500-hPa vortex tilt vectors (magenta) originate from the composite surface center. The minimum SLP contours and the surface wind vectors have been smoothed 10 times for clearer visualization (using a 1:2:1 smoother in both the *x* and *y* directions).

It is clear from the analysis of the horizontal structure of the sensible and latent heat fluxes that the overall cooling of the SST field that results from the inclusion of updated SST analyses throughout the simulation reduces the surface fluxes, particularly in the inner-core region to the west of Nadine's surface center and in the region of the most pronounced SST cooling to the northwest of Nadine. This reduction in both the sensible and latent heat exchange at the air-sea interface prevents the GOOD members from the updated SST experiment from intensifying as quickly as the GOOD members from the constant SST simulation.

## *d.* Ensemble track divergence analysis: Exploration of synoptic influences

This section uses the composite groups GOOD and POOR to examine the causes for track divergence in greater detail. The overall synoptic environments of the composite groups are assessed in Figs. 8 and 9, which show the storm-centered 2-km radar reflectivity field, minimum SLP contours, 10-m surface wind vectors, the 850–200-hPa deep-layer shear vector, and the 850–500-hPa vortex tilt vector before track divergence at 0, 24, and 48 h (Fig. 8), and after track divergence at 72, 96, and 120 h (Fig. 9). In both composites Nadine is initialized as a tropical storm with an asymmetric precipitation structure. There is a lack of significant convection associated with the storm at this time, but the strongest convection and the majority of the precipitation is located in the northwest quadrant near the inner core for GOOD and on the north side for POOR. Consistent with past studies (Corbosiero and Molinari 2002; Rogers et al. 2003), these precipitation regions are located in the downshear-left quadrants of the TCs.

Stark differences between the composites emerge during the first 72 h. By 24 h, an approaching midlatitude trough has begun to interact with the members of both groups (Figs. 8b,e) causing an extension of the precipitation to the northeast. Stronger convection between Nadine and the trough in the POOR composite suggests a stronger interaction between the two. By 48 h, the eastward passage of the midlatitude trough has led to a shift in the shear vector in both composites resulting in a distribution of convection in the storm that is concentrated in the southern-to-southeastern part of the storm (Figs. 8c,f). At 72 h, the trough has passed and is no longer interacting with the GOOD composite. In POOR, the interaction between the trough and Nadine is significantly reduced but still occurring as a result of the more eastward motion of Nadine in the POOR ensemble members (Figs. 9a,d). During this period, the area encompassed by the precipitation of the simulated



FIG. 9. As in Fig. 8, but for 72, 96, and 120 h. Shown to the right of the gray line in (e) and (f) are data that fall outside the 9-km inner domain.

storm is reduced, particularly in the GOOD composite where stronger values of radar reflectivity are now observed throughout the inner-core region of Nadine.

Differences between the composites continue to grow after 72 h. Though the strength of convection increases by 96 h in both composites, in the POOR composite the convection is more asymmetric and not as compact as in the GOOD composite (Figs. 9b,e). Because the storm is located farther eastward in the POOR composite members, the trough and storm are closer, increasing the westerly vertical wind shear and contributing to the asymmetric structure in convection. The storm in the GOOD composite continues to intensify through the end of the simulation, and its structure becomes very symmetric and compact (Fig. 9c). Storms in the POOR composite are less intense and more asymmetric (Fig. 9f). It should be noted that because of the divergence in track (Fig. 2a), these storm-centered composites are embedded in completely different environments, resulting in very different structures and intensities in these ensemble members.

It is crucial to understand the environmental influences during the early stages of the simulations that lead to the divergence in the track forecasts of Nadine. Past TC ensemble sensitivity studies (Zhang and Sippel 2009; Torn and Hakim 2009; Sippel and Zhang 2010; Tao and Zhang 2014; Munsell and Zhang 2014) have shown that small, or even unobservable, environmental differences can lead to considerably different track and/or intensity forecasts. Consequently, the following analysis of factors leading to track divergence will be confined to the 24h before the tracks of the members diverge. A potential vorticity (PV) approach will be utilized in order to better understand potential impacts that the midlatitude trough has on the subsequent track of the members of GOOD and POOR. This technique has proven to be effective at providing insight into the complex interactions that can occur between tropical cyclones and midlatitude systems (Hoskins et al. 1985; Morgan and Nielsen-Gammon 1998; Atallah and Bosart 2003). Figure 10 shows the upper-level (300-200 hPa) and lower-level (850-700 hPa) layer-averaged potential vorticity and wind composites for GOOD and POOR at 3-h intervals leading up to track divergence near 48h. Unlike the storm-centered maps in Figs. 8 and 9, the GOOD and POOR composites are created in a fixed domain.

Figure 10 reveals very similar structures in both composites from 30 to 36 h. The PV plots at 30 h suggest that low-level PV is stronger in the POOR composite; however, the maximum values of PV in the individual ensemble members are comparable in GOOD and POOR. This apparent difference in low-level PV is simply a result of more position spread among the GOOD ensemble members. Although the strongest values of PV associated with the upper-level trough are located to the northeast of Nadine, the upper-level PV filament wrapping around



FIG. 10. Upper-level [averaged over the 300–200-hPa layer; warm color shadings every 2 PVU from 2 (yellow) to 8 (red)] and lower-level [averaged over the 850–700-hPa layer; cool color shadings every 0.3 PVU from 0.7 (green) to 2.8 (magenta)] PV composites for GOOD and POOR at (top left to bottom right) 30, 33, 36, 39, 42, and 45 h. Upper-level winds (black vectors) and lower-level winds (gray vectors) are also plotted.

the surface vortex in both composites suggests some degree of trough–storm interaction. This interaction continues in both composites through 36 h.

By 39 h, subtle differences begin to emerge between the GOOD and POOR PV composites. In the POOR composite the midlatitude trough is located farther west, and the surface center of Nadine is farther east, so that the distance between Nadine and the trough is noticeably smaller. The distance between the trough and Nadine in POOR continues to decrease through 45 h, and at



FIG. 11. Differences between the upper-level (color shading every 0.5 PVU) and lower-level (gray shading every 0.1 PVU) PV and wind (vectors) composites as shown in Fig. 10 for (a) 30, (b) 33, (c) 36, (d) 39, (e) 42, and (f) 45 h.

this time the upper-level PV filament wrapping around the storm is somewhat stronger than in GOOD, and the low-level PV within the trough is somewhat closer to the storm center. Meanwhile, the distance between Nadine and the trough in the GOOD composite has increased sufficiently so that the upper-level PV filament encapsulating Nadine has weakened somewhat. This separation between Nadine and the upper-level trough occurs immediately prior to the forecast track divergence, which suggests that the positions of the trough and Nadine at the times leading up to the separation in tracks determine the final position of Nadine.

To help illuminate the differences between the GOOD and POOR composites, Fig. 11 shows the difference between the PV and wind fields of the composite groups (GOOD – POOR) for the same hours as in Fig. 10. Although significant differences were not visually apparent between the composites at 30 h in Fig. 10, the difference plot at this time (Fig. 11a) reveals a displacement in the position of the midlatitude trough such that the trough is farther to the east in GOOD. These differences in trough position appear to result from differences in the mean background flow. There was no variance in trough position in the initial conditions of GOOD and POOR, but stronger upper-level westerlies in the vicinity of the trough in GOOD seem to have produced quicker eastward advection of

the trough so that it was positioned farther east by 24 h (not shown). By 36 h, the difference in the position of the midlatitude trough has increased and there is also a clear difference in the location of the low-level vortex (Fig. 11c). These differences continue to grow from 39 to 45 h (Figs. 11d–f).

The PV difference plots clearly reveal that the difference in location of the midlatitude trough develops prior to the difference in position of the low-level vortex. This suggests that because the trough in the POOR composite is located farther to the west and closer to Nadine, the storms in POOR experience more of the westerly flow in the base of the trough. This difference in flow produces the subsequent separation in the position between GOOD and POOR and ultimately leads to the eastward tracks observed in the POOR ensemble members.

To confirm the proposed track divergence hypothesis, the evolution of the magnitude and direction of the steering flow vectors in the composites is explicitly calculated for the times leading up to the forecasted track divergence. The midtropospheric flow (700–500 hPa) averaged over radii between 5° and 7° of latitude from the TC surface center is typically highly correlated with tropical cyclone movement (Chan and Gray 1982). Since Nadine was a relatively small tropical cyclone, a smaller area is chosen to average over (radii between 200 and



FIG. 12. Evolution (every 3 h between 30 and 45 h) of the environmental steering flow vectors (winds averaged over radii between 200 and 500 km from the surface center and between the 700- and 500-hPa vertical levels) for the composite groups GOOD (blue) and POOR (red). The steering flow vectors are oriented in the direction that the compass rose specifies and magnitudes are indicated by the length of the vectors ( $m s^{-1}$ ).

500 km) in order to put more focus on the near-storm environment. Figure 12 shows the midtropospheric steering flow vectors averaged over this near-storm environment for the GOOD and POOR composites for the hours leading up to the track divergence, as in Figs. 10 and 11. At 30 h, the directions of the GOOD and POOR composite steering flow vectors are similar, as the environmental flow that Nadine is embedded in is primarily northwesterly. However, by 33 h, the POOR steering flow vector is oriented approximately 30° farther to the east than the GOOD steering flow vector. This separation in the orientation of the vectors is maintained throughout the simulations until track divergence, which suggests that this difference in steering flow direction leads to the storms in the POOR composite being steered farther eastward, as demonstrated in Fig. 11. These variations in the position of the vortex center of Nadine that develop over the 24 h leading up to track divergence determine whether Nadine is picked up by the approaching trough (POOR) or is steered toward the southwest ahead of the approaching trough (GOOD), as is observed in the best track.

To further support the claim that the track divergence can be attributed to differences in the direction of the midlatitude trough-induced steering flow between 24 and 48h, a similar analysis is performed utilizing the corresponding ECMWF operational ensemble initialized at 0000 UTC 20 September. This ensemble comprises 50 members, and as was done for the WRF-EnKF ensemble, the 10 members with the smallest cumulative root-mean-square track error were classified as the members of the composite group EC\_GOOD. Furthermore, the 10 members with the largest cumulative rootmean-square track error became the composite group EC\_POOR. Both the individual tracks of these 20 chosen members and the mean tracks of the two composite groups (Fig. 2b) demonstrate that a similar pattern of evolution is observed between both the most and least successful track forecasts of Nadine in the ECMWF and the WRF-EnKF ensembles.

Since a very similar track divergence was observed in both ensembles, the midtropospheric steering flow vectors for the composite groups were calculated in the same manner as the WRF-EnKF steering vectors for the



FIG. 13. As in Fig. 12, but for the ECMWF ensemble, environmental steering flow vectors of EC\_GOOD (blue) and EC\_POOR (red) at (a) 30, (b) 36, and (c) 42 h.

times leading up to the departures in the forecasted tracks. Since the ECMWF ensemble data are only archived at 6-h intervals, the steering flow vectors for each composite group are presented at 30, 36, and 42 h (Figs. 13a-c). The direction of the steering flow at 30 h in both EC\_GOOD and EC\_POOR is northwesterly, as was observed in the WRF-EnKF ensemble. However, by 36 h the EC\_POOR vector is approximately 20° farther east than the EC\_GOOD steering flow vector. This difference in orientation increases by 42 h and appears to lead to the divergence of the forecasted tracks. Although the steering flow vectors are not identical in the WRF-EnKF and ECMWF ensembles, the difference between the composites is consistent. In particular, the EC\_POOR steering vector is approximately 20°-40° farther east (to the left) of the EC\_GOOD vectors, further supporting the track divergence hypothesis.

## e. Deviations among intensity forecasts: WRF-EnKF simulations versus HS3 observations

Though inclusion of 6-h SST updates significantly reduces intensity errors in the WRF-EnKF ensemble, substantial errors still remain. To explore what additional factors may have contributed to the erroneous intensification, observational data that were collected during the 19-20 September HS3 flight were examined. Figure 14 displays comparisons between vertical profiles of relative humidity, temperature, and the zonal component of wind for 3, 6, 9, and 12h from the NOAA-NCAR dropsondes deployed during HS3 and the GOOD composites. Although there are limited data availability at 0 h, the initial conditions comparisons are consistent with the analyses at the other times (not shown). The dropsondes that were deployed within 90 min of the given time were utilized to create the observational composite profiles. The GOOD composite profiles were generated by averaging the profiles from

the model grid points in each of the ensemble members that were closest to the geographical location at which the dropsonde was deployed. Because the focus of this section is on examining the incorrect intensification of GOOD during the latter stages of the simulation, analysis of POOR is not included.

At all times, the temperature and the zonal wind profiles compare very favorably between the HS3 observations and the GOOD composites. Differences between the observational and GOOD temperature composite profiles are mostly below 2K, while discrepancies between the zonal wind composite profiles rarely exceed  $2 \text{ m s}^{-1}$ . The relative humidity profiles of the composite groups at 3 and 6 h are similar to the observed profiles at these times, except in the upper troposphere where dropsondes used in HS3 are known to have a dry bias (DeSlover et al. 2013). At 9 and 12 h, there is a bigger difference between the observed and simulated moisture profiles, particularly in the mid- to upper troposphere. Though it is possible that the increased midlevel moisture present in the simulations leads to later intensity errors, the simulated storm still intensifies in sensitivity experiments in which the midlevel moisture is lowered (not shown). It should also be noted that the corresponding POOR profiles compare very favorably to the GOOD profiles at these times (not shown), providing further evidence that the near-storm environment and intensity of the TC itself do not contribute to the subsequent track divergence.

Because the temporal range of the HS3 observations is somewhat limited, the evolution of the thermodynamic environment of GOOD is compared to relative humidity values obtained from the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) throughout the simulation window (Fig. 15a). Consistent with the SHIPS calculations (from the NCEP GFS analysis), the composite mean area-averaged (between



FIG. 14. Composite vertical profiles of (top) RH, (middle) temperature, and (bottom) zonal winds for the NOAA–NCAR dropsondes (black), GOOD (blue), and the differences between them (dropsondes – GOOD, red) at (left to right) 3, 6, 9, and 12 h. The number of profiles used to create the composite profiles for each time is indicated in the bottom-left corner of the plots in the first row.

200 and 800 km from each member's surface center) relative humidity of GOOD is calculated over the low levels (850-700 hPa), midlevels (700-500 hPa), and upper levels (500-300 hPa) of the atmosphere. The GOOD midlevel and upper-level relative humidity evolutions are very similar to the SHIPS data, as dry environmental air (RH of  $\sim 30\%-35\%$ ) surrounds Nadine throughout the 5-day period. There is a slight discrepancy between the patterns of evolution of the simulated and observed low-level relative humidity results, with the GOOD low-level moisture being lower than the SHIPS data. In addition, the GOOD storm-centered composite mean of a horizontal cross section of 700-hPa relative humidity from 0600 UTC 20 September and observational 700-hPa moisture values obtained from the NOAA–NCAR

dropsondes throughout the 19–20 September HS3 flight demonstrate that the spatial distribution of the simulated and observed relative humidity fields are for the most part in agreement (Fig. 16a). As was first indicated by the vertical profiles, there is some evidence that the midlevel environment was drier than in the simulations, particularly in the region to the west of the storm's surface center. However, the general agreement between the evolution of the observed and simulated vertical and horizontal moisture fields suggests that WRF-EnKF intensity bias cannot be attributed to disparities in the thermodynamic environments.

Since the thermodynamic profiles of temperature and moisture are unable to explain the WRF-EnKF intensity error, we turn our focus to vertical wind shear, which has



FIG. 15. (a) Area-average (between 200 and 800 km from the surface center) low-level (850–700 hPa; magenta), midlevel (700–500 hPa; green), and upper-level (500–300 hPa; orange) RH evolution of the composite group GOOD (solid) and SHIPS (dashed). Evolutions of the (b) magnitude (m s<sup>-1</sup>) and (c) direction (°) of deep-layer (850–200 hPa) wind shear for the mean (thick) and the individual ensemble members (thin) of the composite group GOOD (blue). The AMSU (gray) and the SHIPS (black) deep-layer shear are also plotted.

long been acknowledged to have a negative influence on the intensity of tropical cyclones (e.g., Simpson and Riehl 1958; Gray 1968; DeMaria and Kaplan 1994, 1999). Shown are the magnitude (Fig. 15b) and direction (Fig. 15c) of the area-averaged (between 200 and 500 km from the surface center) deep-layer wind shear (850-200 hPa) for both the ensemble members and the resulting mean of the composite group GOOD. Observational data are also plotted from the Advanced Microwave Sounding Unit (AMSU; Zehr et al. 2008) and SHIPS. The mean initial shear magnitude is fairly large (approximately  $18 \text{ m s}^{-1}$ ), but it decreases over the next 42 h to approximately  $2-3 \text{ m s}^{-1}$ , and it does not significantly exceed  $5 \text{ m s}^{-1}$  through 68 h. Shear subsequently began to increase to a more moderate magnitude of approximately  $10 \,\mathrm{m\,s^{-1}}$  by the end of the simulation. The only discrepancy between the observed and simulated shear occurs after approximately 72 h, when the GOOD composite shear magnitude is 2- $5 \,\mathrm{m \, s^{-1}}$  weaker than the observational shear. While it is possible that this difference in shear is contributing to the intensity bias present in the WRF-EnKF simulations, by this time much of the bias is already present (Fig. 5). It is therefore not clear how much the shear discrepancy is a cause or result of the preexisting intensity bias. In addition to and consistent with the above analysis, the POOR composite shear evolution is nearly identical to that of GOOD prior to track divergence (not shown), indicating that environmental shear does not play a role in determining the final track in this ensemble.

Since the observational and simulated thermodynamic and dynamic environments compare favorably, the evolution of the structure of Nadine's vortex will next be investigated as a possible source of the erroneous intensification seen in the WRF-EnKF simulations. It is first important to note that the initial intensity of the WRF-EnKF storm is stronger than the observed storm in terms of both minimum SLP (by approximately 5-10 hPa; Fig. 5a) and maximum 10-m winds (by approximately 10kt; Fig. 5b). Previous ensemble sensitivity studies in particular have shown that a bias in the initial intensity can have a significant impact on the final intensity of the vortex (Sippel et al. 2011; Munsell et al. 2013). To examine this initial intensity discrepancy further, a storm-centered horizontal cross section of the GOOD composite mean 950-hPa tangential winds at 6 h is plotted along with the NOAA-NCAR dropsonde 950-hPa tangential wind observations from the 19-20 September HS3 flight (Fig. 16b). At distances outside the TC inner core (greater than 200 km from the surface center), the observations for the most part compare favorably with the simulated composite vortex. However, in



FIG. 16. (a) Storm-centered horizontal cross-section of 700-hPa RH (color shading every 5%) for the GOOD composite group at 6 h. Markers indicate storm-centered positions of the NOAA–NCAR dropsondes that were deployed during the 19–20 September HS3 flight and are filled according to the value of RH recorded closest to 700 hPa (white indicates no data available). (b) As in (a), but for 950-hPa tangential winds (color shading every  $2 \text{ m s}^{-1}$ ).

the region to the northwest of the surface center, it appears that simulated wind speeds are slightly too strong. Furthermore, in the region closer to the inner core of the vortex, greater differences in the tangential winds and the associated surface circulation arise. Although the dropsonde locations are somewhat spatially limited in the area of strongest tangential wind to the west of the surface center, it appears that the simulated vortex is approximately  $5 \,\mathrm{m \, s}^{-1}$  stronger than was observed. More noticeably, in the area to the north and east of the surface center, the dropsonde tangential winds are as much as  $10 \,\mathrm{m\,s^{-1}}$ weaker than the simulated tangential winds. Based on this comparison, the simulated GOOD composite circulation is at least  $5 \text{ m s}^{-1}$  too strong near the center, too broad, and is distinctly more symmetric than the observed vortex of Nadine.

An initially stronger simulated vortex can contribute to the eventual erroneous intensification in the WRF-EnKF ensemble in a variety of ways. As a result of the dependence on both the temperature and wind speed difference across the air-sea interface, a stronger surface circulation will yield stronger surface sensible and latent heat fluxes and, in general, increase the rate of intensification. In addition, stronger and larger vortices are not only more resistant to dynamic environmental influences, such as vertical wind shear (Jones 1995; Reasor et al. 2004), but they also are able to more effectively insulate themselves from adverse thermodynamic conditions, such as environmental dry air (Riemer and Montgomery 2011). Given the increase in vertical shear observed after 72 h, as well as the substantial amount of dry environmental air that surrounded Nadine throughout this period of its lifetime, the disparity in initial intensity between the observed and simulated vortex is the most likely cause of the erroneous intensification of the WRF-EnKF ensemble. It is further hypothesized that the primary reason for the initial intensity bias present in the WRF-EnKF simulations may at least in part result from errors that have developed over time from the continuous cycling present in the system. These cycling experiments utilized a constant SST field, which, as was shown above, is most likely not sufficient for accurately simulating intensity in this case.

## 4. Summary and conclusions

A 60-member ensemble simulation initialized at 0000 UTC 20 September 2012 by a WRF-EnKF hurricane analysis and forecast system has been utilized to explore the governing dynamics and predictability of long-lived Hurricane Nadine. The performance of the 5-day track forecasts in this ensemble is at least comparable to that of other operational models initialized at this time and was for the most part successful, with 50 of the 60 members correctly predicting Nadine's turn toward the southwest ahead of an approaching midlatitude trough approximately 48–72 h into the simulation. However, 10 members forecast Nadine to be carried eastward by the trough, and the resulting track divergence was investigated to assess aspects of the predictability of this system.

To investigate the causes for track divergence, two 10-member composite groups were created based on the cumulative track root-mean-square error (GOOD and POOR). The synoptic environments of these groups were explored in detail for the times leading up to the location of forecast divergence, which began at roughly 48h (0000 UTC 22 September). It was discovered that differences in vortex location developed among the members around 36 h, with the centers in POOR located farther east than the centers in GOOD. In addition, a difference in the location of the midlatitude trough was also observed as early as 30 h, with the trough of POOR positioned farther west than in GOOD and therefore closer to the simulated cyclone. The reduced distance between the TC and the midlatitude trough led to a stronger interaction between the two systems so that TCs in the POOR group experienced a stronger eastward component of steering flow. This was confirmed through the utilization of upper- and lower-level PV compositing techniques and the calculation of the midtropospheric steering flow vectors. The vectors revealed that in the near-storm environment, there was a clear distinction in the direction of the steering flow between the GOOD and POOR composite groups, with the POOR vector consistently oriented approximately 30° farther east.

Despite the successful track forecast, the associated intensity forecasts of the WRF-EnKF ensemble were not as skillful. Although Nadine slowly weakened during this period, all 60 members forecasted a steady intensification, particularly after track divergence at 48 h. In an attempt to explain the intensity errors associated with these forecasts, a series of sensitivity experiments examined the influence of the SST on storm intensity. In the original simulations of Nadine, the SST field remained constant and was prescribed by the GFS analysis field at the initialization time. In the sensitivity experiment, the simulations of the 10 members of GOOD and POOR were reintegrated with the inclusion of updates to the SST field every 6 h. The intensity errors associated with the simulations of Nadine were significantly reduced as a result of the SST updates, particularly for the GOOD composite members. This reduction in intensity occurred primarily as a result of an overall cooling of the SST field that occurred throughout the 5-day simulation window in the vicinity of Nadine. It was shown that this cooling led to a reduction in the surface sensible and latent heat fluxes at the air-sea interface. As the fluxes remained weaker than had been seen in the original simulation, the rate of intensification of Nadine was not as strong.

The inclusion of updates to the SST field considerably reduced the intensity errors, but the simulated storms still remained too intense. Utilizing observational data collected during the 2012 phase of NASA's HS3 experiment, comparisons between vertical profiles of moisture, temperature, and winds from the NOAA–NCAR dropsondes and the GOOD composites yielded no significant differences between the observations and the model. In addition, limited variations were discovered between the observational and simulated environmental shear; a discrepancy of approximately  $2-5 \,\mathrm{m \, s^{-1}}$  exists after 72 h. However, by this time an intensity bias was already present between the simulated and observed storms that could be traced back to initialization. The simulated storm was initially stronger by approximately 5-10 hPa in minimum SLP and 10kt in maximum 10-m winds. A comparison of the 950-hPa tangential wind fields also suggested that the simulated circulation was too strong and too large. Most notably, the simulated vortex was more symmetric, with tangential wind speeds up to  $10\,\mathrm{m\,s}^{-1}$  stronger than the observations on the northern and eastern sides of the circulation. Therefore, the stronger and slightly larger simulated vortex appears to have been more resilient to both adverse dynamic and thermodynamic environments that Nadine experienced during this period, and is the most likely cause of the intensity errors in the WRF-EnKF ensemble.

The results suggest that in similar cases of track divergence, particularly when there is a bifurcation point present in the ensemble, attention should be given to short-term forecasts or current observations of steering flow influences such as synoptic-scale features or large-scale environmental flows. Based on the analysis of this ensemble, it is probable that small yet noticeable deviations in track occur as much as 24–36 h prior to the TC reaching the bifurcation point. This information could provide forecasters with additional confidence toward one solution over the other. In addition, in cases where the TC occupies a region with a sharp SST gradient, operational models should include SST updates as frequently as possible, as an improvement in intensity forecasts seems attainable.

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