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(Manuscript received 10 January 2014, in final form 21 March 2014)

ABSTRACT

A series of numerical experiments are conducted to examine the impact of surface observations on the prediction of landfalls of Hurricane Katrina (2005), one of the deadliest disasters in U.S. history. A specific initial time (0000 UTC 25 August 2005), which led to poor prediction of Hurricane Katrina in several previous studies, is selected to begin data assimilation experiments. Quick Scatterometer (QuikSCAT) ocean surface wind vectors and surface mesonet observations are assimilated with the minimum central sea level pressure and conventional observations from NCEP into an Advanced Research version of the Weather Research and Forecasting Model (WRF) using an ensemble Kalman filter method. Impacts of data assimilation on the analyses and forecasts of Katrina’s track, landfalling time and location, intensity, structure, and rainfall are evaluated. It is found that the assimilation of QuikSCAT and mesonet surface observations can improve prediction of the hurricane track and structure through modifying low-level thermal and dynamical fields such as wind, humidity, and temperature and enhancing low-level convergence and vorticity. However, assimilation of single-level surface observations alone does not ensure reasonable intensity forecasts because of the lack of constraint on the mid- to upper troposphere. When surface observations are assimilated with other conventional data, obvious enhancements are found in the forecasts of track and intensity, realistic convection, and surface wind structures. More importantly, surface data assimilation results in significant improvements in quantitative precipitation forecasts (QPFs) during landfalls.

1. Introduction

Landfalling tropical cyclones (TCs), especially those with hurricane intensity, can have disastrous impacts on coastal regions through the combined effects of strong wind, rainfall, and storm surges. Because of rapid coastal development and population growth, the world has become more vulnerable than ever to the impact of hurricanes (e.g., Pielke and Pielke 1997). Extreme examples include Hurricane Katrina in the summer of 2005, Hurricane Sandy in the fall of 2012, and, most recently, Supertyphoon Haiyan in 2013. Owing to the enormous societal impact of hurricanes, it is of great importance to accurately predict the track and intensity of these storms many hours in advance. In addition, as suggested by Landsea (1993) and Elsberry (2005), hurricane damage increases exponentially with low-level wind speed. Therefore, accurate forecasting of a hurricane’s structure near its landfall is of great significance for effectively warning the public and reducing economic damage and deaths.

Over the last two decades, much progress has been made in improving forecasts of hurricane track and intensity (Gall et al. 2013). However, most studies have emphasized hurricanes’ genesis and intensification over the ocean. Few studies have emphasized the behavior of hurricanes near and after landfalls. Specifically, uncertainties in the initial conditions are one of the key causes of inaccurate numerical forecasts of hurricane track and intensity. Significant impacts on hurricane forecasting have been found with the assimilation of airborne in situ, satellite, and radar observations (e.g., Franklin and DeMaria 1992; Velden et al. 1992; Franklin et al. 1993; Burpee et al. 1996; Velden et al. 1998; Pu et al. 2002; Aberson and Etherton 2006; Zhao and Jin 2008; Pu et al. 2008; Pu and Zhang 2010; Zhang et al. 2011; Wang and Huang 2012; Wu et al. 2014). Among the literature on
atmospheric data assimilation in hurricane studies, only a few papers (e.g., Zhao and Jin 2008; Pu et al. 2008, 2009; Weng and Zhang 2012) have addressed data assimilation associated with landfalling hurricanes.

Furthermore, the interaction between the earth’s surface and a hurricane becomes more important near the hurricane’s landfall. A better representation of surface and near-surface atmospheric conditions is essential for the accurate forecasting of landfalling hurricanes. Therefore, assimilation of surface observations is likely to be very helpful in the numerical prediction of landfalling hurricanes. Nevertheless, in many numerical weather prediction practices, assimilation of surface observations is still a challenging problem (Pu et al. 2013; Hacker and Angevine 2013; Ancell et al. 2011). In a recent study, Pu et al. (2013) demonstrated that the traditional three-dimensional variational data assimilation (3DVAR) has difficulties in assimilating surface observations due to its use of static background error covariances. In contrast, an ensemble Kalman filter (EnKF) could better assimilate the surface observations. In addition, Ha and Snyder (2014) showed that EnKF could produce promising mesoscale weather analyses with the assimilation of surface observations.

In light of all the aforementioned facts, this study aims to examine the impact of ensemble assimilation of surface observations on the prediction of a landfalling hurricane. Considering that it was one of the deadliest disasters in U.S. history and that it had two consecutive major landfall events, we use Hurricane Katrina (2005) for case study. The Advanced Research version of the Weather Research and Forecasting Model (WRF; Skamarock et al. 2008) and an EnKF system, developed by the National Center for Atmospheric Research (NCAR) Data Assimilation Research Testbed (DART; Anderson et al. 2009), are employed.

The paper is organized as follows: section 2 gives a brief overview of Hurricane Katrina, related previous studies, and the scope of this paper. A description of the observations used in this study is also included. Section 3 describes the model, data assimilation system, and experimental setup. Section 4 presents an overall evaluation of the data assimilation results. Section 5 examines the influences of surface observations. A summary and discussion are provided in section 6.

2. A brief overview of Hurricane Katrina (2005), including previous studies and observations

a. A brief overview of Hurricane Katrina (2005)

Hurricane Katrina (2005) was initiated from a tropical transition event. It was designated as a tropical depression (TD) by the National Hurricane Center (NHC) at 1800 UTC 23 August 2005 over the southeastern Bahamas and later as a tropical storm (TS) at 1200 UTC 24 August. It then moved westward and made landfall in southern Florida shortly before 0000 UTC 26 August, when it was identified as a category-1 hurricane with a minimum central sea level pressure (MSLP) of 983 hPa and a maximum surface wind speed of 70 kt (1 kt = 0.5144 m s\(^{-1}\)). Then it underwent two periods of rapid intensification (RI), which promoted Katrina to category-5 strength, with maximum surface wind speeds of 150 kt, between 26 and 28 August over the warm ocean of the Gulf of Mexico. It made another landfall at 1100 UTC 29 August near New Orleans. Figure 1 shows the track of Katrina from the NHC best track from 1800 UTC 23 Aug and 0000 UTC 30 Aug.

b. Previous studies

McTaggart-Cowan et al. (2007) stated that Katrina remained a poorly organized hurricane to the east of Florida before it made landfall. When the landfall occurred, the missing eyewall segments filled in and a well-defined eye formed. Therefore, Katrina’s prelandfall stage and near-coast structure during its journey; namely, the period before 0000 UTC 26 August, is very important for its further evolution.

Owing to the devastation caused by Hurricane Katrina, research efforts were made to understand various aspects of Katrina’s predictability using data assimilation. Torn and Hakim (2009) simulated the lifetime of Hurricane Katrina using WRF and an EnKF assimilation of conventional in situ observations, reconnaissance dropsondes, and NHC TC positions. Results suggest that data assimilation reduced errors in track forecasts but not necessarily in intensity. Weng and Zhang (2012)
examined the impact of inner-core observations from airborne Doppler radar with a WRF-based EnKF. Results suggest that the EnKF analyses successfully depict the inner-core structure of the hurricane vortex, leading to significantly smaller track forecast errors relative to either the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) operational forecasts or the WRF simulation initialized from GFS analysis. Langland et al. (2009) studied the impacts of Geostationary Operational Environmental Satellite (GOES) rapid-scan wind observations on 24–120-h track forecasts of Hurricane Katrina with a series of data assimilation and forecast experiments using the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Naval Research Laboratory (NRL) Atmospheric Variational Data Assimilation System (NAVDAS). They found that the greatest improvements from assimilating GOES rapid-scan winds were achieved in the 84–120-h track forecasts rather than in short-range forecasts. Among all their
experiments, the 108-h forecast initialized from 0000 UTC 25 August (shown as “Langland CNL” and “Langland RS1” in Fig. 2a) had the largest track error (i.e., greater than 650 km). Specifically, the predicted Katrina passed Florida and then moved northward rather than westward, eventually turning back to the Florida peninsula. Even the forecasts that started earlier predicted the tracks better than the forecasts initialized from 0000 UTC 25 August. Results clearly indicate the poor prediction skill of forecasts initialized from 0000 UTC 25 August (see Fig. 5 in Langland et al. 2009). Aberson (2010) also reported that the forecasts of Hurricane Katrina’s track and intensity initialized from 0000 UTC 25 August in various configurations (as displayed in Fig. 11 of Aberson 2010) all failed to predict the westward movement of Katrina when it was passing over the Gulf of Mexico, even if the forecasts were improved with the assimilation of dropsondes (shown as “Aberson GFDL” and “Aberson AVNO” in Fig. 2a).

c. Scope of this study and observations

Inspired by the poor forecasts initialized at 0000 UTC 25 August 2005 in previous studies (Langland et al. 2009; Aberson 2010) and the promising results from the mesoscale WRF simulations with the EnKF method (Weng and Zhang 2012; Pu et al. 2013), we chose this particular time (0000 UTC 25 August 2005) as an initial time to begin data assimilation experiments in this study. In addition, although several previous studies have done numerical simulation with the assimilation of various observations, none of these studies have emphasized the impact of surface observations. Thus, in this study we will examine the impacts of surface observations on the prediction of Hurricane Katrina’s landfalls. We hypothesize that the assimilation of surface observations could help adjust low to midlevel atmospheric conditions that are related to a hurricane and its environment, as these observations carry information concerning near-surface atmospheric conditions. In addition, since the first landfall over Florida can always be captured (although with the wrong location and time in some cases), but the second landfall is missed in most cases, we will also examine whether data assimilation can improve prediction such that the second landfall after the storm passed the Gulf of Mexico can be predicted. Therefore, the numerical simulation will be focused on a period between 0000 UTC 25 August and 0000 UTC 30 August 2005 to cover both landfall events. The data assimilation will be performed in the first 18 h for most of the experiments based on data availability. Several types of observations are available during the study period. The NCEP Automated Data Processing (ADP) Global Upper Air and Surface Weather Observations are routinely composed of both surface and upper air reports. These conventional observations include land surface, marine surface, radiosonde, pilot balloon (pibal) and aircraft reports from the Global Telecommunications System (GTS), profiler and U.S. radar-derived winds, Special Sensor Microwave Imager (SSM/I) oceanic winds and total cloud water (TCW) retrievals, and satellite wind data from the National Environmental Satellite Data and Information Service (NESDIS). We noticed that the NCEP conventional observations do not include surface mesonet data over land during our study period. Surface mesonet observations are currently not commonly assimilated into NCEP operational global and regional models.

Prior to Katrina’s landfall in southern Florida, Quick Scatterometer (QuikSCAT) observations are available near 0000 and 1200 UTC 25 August 2005. Meanwhile, there are surface mesonet observations (Horel et al. 2002) over land, complementing the QuikSCAT ocean surface winds.

Figure 3 displays the distributions of each type of observation at 0000 UTC 25 August. It shows that QuikSCAT ocean surface wind vectors and mesonet wind vectors are not included in the NCEP ADP data decoded in this study, creating an opportunity to demonstrate the impact of surface data assimilation on the prediction of Hurricane Katrina. Similar distributions and coverage of observations are found at 1200 UTC August 2005 (figure not shown).

Before data assimilation, all NCEP ADP data passed through a complex quality control procedure. The QuikSCAT ocean surface wind vectors used here are retrieved products (wind speed and direction at 10-m height at 25-km horizontal resolution) produced by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) from the SeaWinds scatterometer sensors on board the QuikSCAT satellite with quality flags (Hoffman and Leidner 2005). Observations with low- and high-speed flags are excluded in preprocessing before data assimilation because low winds could have poor directional readings and high winds could be a result of rain contamination. Any observations flagged with rain contamination are also rejected.

3. The EnKF system and experimental design

a. An ensemble Kalman filter data assimilation system for WRF

An EnKF data assimilation system has been developed by DART (Anderson et al. 2009) at NCAR with WRF as one of its modules. In this study we use the DART WRF EnKF system with version 3.1 of the Advanced Research version of WRF (ARW-WRF;
Skamarock et al. 2008). DART WRF uses observations to update the WRF state (analysis) variables including wind components, temperature, mixing ratio of water vapor, cloud liquid water, rain, ice and snow, surface pressure, geopotential height, and column mass of dry air. The assimilation of any type of observation can produce increments for all of the analysis variables through the forecast ensemble sample covariance (Anderson et al. 2009). The ensemble state before data assimilation is called the “prior state” (or prior) and the ensemble state after data assimilation is called the “posterior state” (or posterior).

Small ensemble size and model errors affect the performance of the EnKF. Thus, localization and covariance inflation are commonly used in many applications. Specifically, DART WRF uses a hierarchical Bayesian approach (Anderson 2007; Anderson et al. 2009; Romine et al. 2013), in which covariance inflation values are adaptively estimated and can vary temporally and spatially.

The vertical and horizontal localization scales are also adjustable.

b. Experimental design

Figure 1 displays the triple two-way nested domains at 27-, 9-, and 3-km horizontal grid spacing resolutions that are utilized in the simulation. The innermost domain, at the 3-km grid spacing (hereafter 3-km domain) moves with the storm and only the initial location is shown in Fig. 1. All data assimilation experiments are performed in the 27- and 9-km domains, while all forecasts are conducted in all three domains. The initial conditions from 3 km are interpolated from the 9-km domain. All domains have 37 vertical levels from the surface to 50 hPa. Results shown in all figures are from the 3-km domain.

Physical parameterization options include the WRF single-moment 6-class microphysics scheme (WSM6; Hong and Lim 2006), the Mellor–Yamada–Janjic (MYJ) planetary boundary layer scheme (Mellor and Yamada...
1982), the Kain–Fritsch cumulus parameterization scheme (Kain and Fritsch 1992), the Noah land surface model (Chen and Dudhia 2001a,b), the Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997), and the longwave and Dudhia shortwave radiation scheme (Dudhia 1989). The cumulus scheme is used only in the 27- and 9-km grid spacing domains (domains 1 and 2).

A deterministic forecast was first conducted at 0000 UTC 25 August with WRF initialized by the NCEP GFS Final Analysis (FNL) at 0.5° × 0.5° resolution. Figure 2a compares the track simulation from the WRF deterministic run (Deter) with the NHC best track and confirms the poor predictability of Katrina’s track at the initialization time of 0000 UTC 25 August as described in Langland et al. (2009) and Aberson (2010).

The WRF ensemble guess fields (prior state of EnKF) for 0000 UTC 25 August are spun up from the ensemble forecasts using 30 ensemble members perturbed at 1200 UTC 24 August, with the initial perturbations generated from the NCEP FNL using the fixed covariance perturbations (FCPs; Torn et al. 2006). In FCPs, ensemble perturbations are derived by drawing random perturbations from a 3DVAR built with WRF (WRF 3DVAR; Barker et al. 2004). A set of ensemble simulations (Ens_NoDA) is then extended from 0000 UTC 25 August to 0000 UTC 30 August without assimilation of observations. As shown in Fig. 2a, the ensemble mean track simulated by Ens_NoDA falls within the envelope of the previous forecasts, confirming the poor predictability of Katrina from 0000 UTC 25 August.

Because of the 12-h spinup from the initial perturbation time, there is a large spread of storm center positions at 0000 UTC 25 August. A single observation, the MSLP of Katrina from the NHC best track, is assimilated first to ensure a reasonable initial location of the hurricane before assimilating any other observations. This is carried out via an observation operator in DART/WRF that is designed to assimilate the storm position, including the longitude, latitude, and minimum central sea level pressure at the storm center, and then to adjust other state variables (Chen and Snyder 2007; Torn and Hakim 2009). A 120-h forecast (0000 UTC 25 August–0000 UTC 30 August) is then conducted after the assimilation of the central MSLP. As a result, the initial hurricane position in each individual member is forced to come closer to the best track position and thus the ensemble average also approaches the best track position after the assimilation. The assimilation leads to a significant improvement in the track forecasts, as the ensemble mean track captures the two landfalls of Katrina (Fig. 2a). However, the reduction in the spread of the ensemble track is moderate and the track errors are still large because of the limiting constraint of the single MSLP observation. The predicted track diverges from the best track immediately after the initial time. It moves too far north, crosses the central Florida peninsula, enters the Gulf of Mexico, and makes landfall in western Florida (Fig. 2a). Figure 2b shows the comparison of intensity, MSLP, and maximum surface wind speed (MSW) between the best track and the experiment that assimilated the central MSLP. The experiment produces a much weaker hurricane compared with the NHC best track. Considering the reasonable initial hurricane position and intensity trend as well as the moderate spread of this set of ensemble leads, we identify this experiment as a baseline experiment (hereafter BASE) that will enable further comparisons to demonstrate the impacts of assimilating additional observations on the forecast. In addition, this baseline simulation at 0000 UTC 25 August is treated as the first guess for all other data assimilation experiments as listed in Table 1.

For all experiments, the observations listed in Table 1 are assimilated along with the storm position from the NHC best track. Specifically, the SFC experiment examines the impacts of surface wind vectors, including those from QuikSCAT over the ocean and mesonet over the land, on improving the storm structure, track, and intensity. Surface wind vectors are assimilated every 6 h in an 18-h window between 0000 and 1800 UTC 25 August prior to the landfall in Florida. Both the ADP

<table>
<thead>
<tr>
<th>Expt</th>
<th>Observation types</th>
<th>Assimilation window (25 Aug)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>Minimum sea level pressure</td>
<td>0000 UTC</td>
</tr>
<tr>
<td>SFC</td>
<td>QuikSCAT/mesonet</td>
<td>0000–1800 UTC</td>
</tr>
<tr>
<td>ADP</td>
<td>NCEP ADP</td>
<td>0000–1800 UTC</td>
</tr>
<tr>
<td>ADP_SFC</td>
<td>NCEP ADP</td>
<td>0000–1800 UTC</td>
</tr>
</tbody>
</table>

FIG. 4. Schematic illustration of the data assimilation procedures. Black arrows denote data assimilation cycles when the observations are injected into DART WRF.
and ADP_SFC experiments assimilate all conventional data included in the NCEP ADP observations except that QuickSCAT and Mesonet observations are also assimilated in ADP_SFC. The surface observations used in SFC are excluded in ADP and digested in ADP_SFC. The total volume of the NCEP ADP observations, which are assimilated into ADP and ADP_SFC, is much larger than that of the surface wind vectors assimilated in SFC and

Table 2. Statistics of the first landfall (2230 UTC 25 Aug 2005).

<table>
<thead>
<tr>
<th>Expt</th>
<th>Ensemble mean landfall time</th>
<th>Probability of landfall in ±6-h window</th>
<th>Probability of missing the landfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>1800 UTC 25 Aug</td>
<td>9/30</td>
<td>8/30</td>
</tr>
<tr>
<td>SFC</td>
<td>2100 UTC 25 Aug</td>
<td>30/30</td>
<td>0/30</td>
</tr>
<tr>
<td>ADP</td>
<td>0000 UTC 26 Aug</td>
<td>30/30</td>
<td>0/30</td>
</tr>
<tr>
<td>ADP_SFC</td>
<td>0000 UTC 26 Aug</td>
<td>30/30</td>
<td>0/30</td>
</tr>
</tbody>
</table>

**Fig. 5.** Comparison of the simulated track and best track between 0000 UTC 25 Aug and 0000 UTC 30 Aug 2005: time series (at 6-h intervals) of (a) track and (b) track errors; simulated tracks from ensemble members, ensemble mean from (c) cycle 1 of SFC, (d) SFC, (e) ADP, and (f) ADP_SFC. Center locations along with the best, ensemble mean, and BASE tracks are indicated every 6 h.
ADP_SFC, as the ADP data come from many available observing platforms. Figure 4 schematically illustrates the procedures and workflow for the data assimilation experiments as listed in Table 1.

The spatial range of influence from an observation in the EnKF can be limited by the specification of the horizontal and vertical localization scale. In this study, a half radius of 250 km is used for horizontal localization and 10 km for vertical localization.

4. Impacts of data assimilation: Overall evaluation

The overall impacts of data assimilation on the analyses and forecasts are examined. Figures 5a and 5b show the ensemble mean track and the track errors, respectively, from all data assimilation experiments against the NHC best track. Compared with BASE, all data assimilation experiments lead to various degrees of improvement in Katrina’s track forecasts.

Specifically, the simulated track is improved in the SFC experiment as it produces better track simulation before the landfall in Florida and more significant improvements to the forecasts in the late phase, particularly during Katrina’s second landfall. These results are consistent with those of Chen (2007), in which surface wind observations impacted the track forecast during a relatively long period with observations being assimilated only at the initial time. In Langland et al. (2009), the greatest improvements by assimilating rapid-scan atmospheric motion vectors were achieved for 84- to 120-h track forecasts rather than for short-range forecasts. To further demonstrate the impact of surface observations on Katrina’s track forecast in a way similar to that of previous studies (i.e., with surface observations assimilated at the initial time only), Fig. 5c show the simulated tracks from all ensemble members and the ensemble mean track initialized by the output of the first data assimilation cycle (0000 UTC 25 August) in SFC. Of the 30 total members, 37% predicted landfalls in Florida within a window of 6 h of actual landfall time, making a 7% improvement over the BASE experiment in which 30% of the total members forecasted landfalls. The ensemble spread during the second landfall is quite large, indicating considerable uncertainty in the forecast. With cycling data assimilation in SFC (Fig. 5d), the ensemble spread is reduced in the first 24 h and all members generally predict storms moving westward (or northwestward) and predict the second landfall in the southern United States, indicating improved track prediction with the cycled surface data assimilation.

Compared with surface data assimilation, more significant improvement in track forecasting is attained by assimilating NCEP ADP observations (Fig. 5e). Then, with the assimilation of both surface observations and NCEP ADP data, the ADP_SFC experiment attains additional improvements in track forecasting (Fig. 5f). The track spread is much reduced from that in the ADP (Figs. 5e,f). This clearly demonstrates the value of adding

<table>
<thead>
<tr>
<th>Expt</th>
<th>Ensemble mean landfall time</th>
<th>Probability of landfall in ±12-h window</th>
<th>Probability of missing the landfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>1800 UTC 28 Aug</td>
<td>4/30</td>
<td>17/30</td>
</tr>
<tr>
<td>SFC</td>
<td>0600 UTC 29 Aug</td>
<td>22/30</td>
<td>0/30</td>
</tr>
<tr>
<td>ADP</td>
<td>0000 UTC 29 Aug</td>
<td>28/30</td>
<td>0/30</td>
</tr>
<tr>
<td>ADP_SFC</td>
<td>0000 UTC 29 Aug</td>
<td>28/30</td>
<td>0/30</td>
</tr>
</tbody>
</table>

FIG. 6. Time series (at 6-h intervals) of (a) minimum central sea level pressure (hPa), and (b) maximum surface wind speed (kt) between 0000 UTC 25 Aug and 0000 UTC 30 Aug 2005. The simulations are compared with best track data.
surface data assimilation in Katrina’s track forecasting. Specifically, although the simulated storm has a northern bias in its track, the track error in ADP_SFC is 60% less than that in SFC and 63% less than that in BASE near the first landfall time of 0000 UTC 26 August, and an average error reduction of about 10%–29% in the track is found in ADP_SFC during the second landfall event, compared with ADP. Considering that the total number of surface wind observations is much fewer than the total number of NCEP ADP observations, and that the track forecast relies more on environmental conditions, the impact from surface observations is highly significant.

Tables 2 and 3 list the forecast statistics of the two landfall events, including the landfall time from the ensemble mean, the probability of ensemble members predicting landfall within a time windows of ±6 h (12 h), and the probability that the ensemble member missed the
FIG. 9. The guess field (prior, black contours) and analysis (posterior, blue contours) of sea level pressure (hPa) for (a)–(e) SFC and (f)–(j) ADP_SFC at (a),(f) 0600 UTC 25 Aug; (b),(g) 1200 UTC 25 Aug; and (c),(h) 1800 UTC 25 Aug. In (d) and (i) forecasts are valid at 2100 UTC and in (e) and (j) forecasts are valid at 0000 UTC 26 Aug. Black dots denote the best track position of Katrina.
landfall. Specifically, the BASE experiment has 9 members falling into the ±6-h time window for the first landfall and 8 members miss the landfall. Only 4 members predict the second landfall within a ±12-h time window and 17 members missed the second landfall. All cycled data assimilation experiments predict two landfalls with much greater skill in predicting landfall times within the given time windows.

Figures 6a and 6b show the ensemble mean intensity in terms of MSLP and MSW from all data assimilation experiments against the NHC best track. Significant improvements in the intensity forecast are found in ADP and ADP_SFC. Unfortunately, the intensity forecast is not improved by the assimilation of surface wind vectors alone in SFC (Figs. 6a,b) outside the data assimilation period, indicating that the injection of surface wind vectors alone into the model is not enough to improve the intensity forecast. This negative impact may be attributed to the insufficient ability of single-level surface data to constrain the conditions in the middle to upper troposphere, as discussed in the following section.

5. The influence of surface data assimilation

Results from the above numerical experiments demonstrate that surface observations influence the prediction of Katrina’s landfall. Since surface observations are not commonly assimilated in many operational models and research applications, their impacts on the accurate prediction of landfalling hurricanes are still not well understood. In this section, detailed diagnoses are performed to examine the influence of surface observations on numerical forecasts of Katrina’s landfalls.

a. Impacts on vortex-related circulation

The impact of assimilating surface wind vectors on the hurricane track could be attributed to the change in environmental circulation. Figure 7 illustrates ensemble spreads of the pressure and $u$-wind component in the prior state and the increment of spread (posterior minus prior) at the lowest model level at 1200 UTC 25 August in SFC. It is apparent that large ensemble spreads are associated with Hurricane Katrina east of Florida, indicating the uncertainties of the main influencing systems. After data assimilation, the spreads are significantly reduced along the track of Hurricane Katrina. Figure 8 demonstrates how the circulation was changed through assimilation of surface wind observations by comparing the vector wind and divergence at 925 hPa in the BASE and the first surface data assimilation cycle (at 0000 UTC 25 August) in SFC. In BASE (Fig. 8a), the divergence (negative means the convergence) is less organized, with low wind speeds in the vicinity of the storm center at 0000 UTC 25 August. Because of assimilation of surface wind vectors, the vortex center in SFC (Fig. 8b) comes closer to the best track position, with the wind speeds refined and the circulation enhanced. The convergence is also enhanced. Cyclonic wind increments are achieved (Fig. 8c).

To further examine the impacts of surface observations on the low-level circulation, the prior and posterior states of sea level pressure from a sample ensemble member in SFC and ADP_SFC are illustrated in Fig. 9. The prior and posterior states are shown in each data assimilation cycle and the posterior states are shown for the following short-term forecasts. Figures 9a–e show the evolution of Katrina’s circulations in SFC. At 0600 UTC 25 August (Fig. 9a), the vortex is much stronger in the posterior state, with an MSLP of less than 1000 hPa, a decrease of over 5 hPa compared to the prior state. At 1200 UTC 25 August (Fig. 9b), the vortex in the prior state is far from the best track position due to the northward bias in the track, as shown in Figs. 5. Data assimilation (posterior) relocates the vortex to the correct location and also enhances the intensity. The posterior state at 1800 UTC intensifies the storm and corrects its
position through data assimilation. Note that there are two circulations appearing at 1800 UTC (Fig. 9c). The one to the north of the best track position is driven by environmental flows and evolves from the previous circulation. The one to the south results from the relocation by the assimilation. It is more intense, with an MSLP of 999 hPa, 4 hPa lower than the one to the north. However, during the following 3 h (less than 6 h prior to landfall), the circulation in the south (Fig. 9c) weakens and ultimately disappears in the forecast (Fig. 9d), while the storm continues to move toward land. In contrast, the circulation in the north intensifies and becomes a hurricane. Then it makes landfall at 2100 UTC 25 August with a large track error. Figure 9e shows the predicted sea level pressure at 0000 UTC 26 August, at which time the storm was moving across the Florida peninsula. ADP_SFC assimilates observations from the NCEP ADP data along with the surface observations (as used in SFC). Figures 9f–j show the evolution of surface circulations in ADP_SFC. Compared with those in SFC,
the positions of Katrina in ADP_SFC are relocated (Figs. 9f,g,h) toward the best track position during the analysis period. Specifically, ADP_SFC results in better vortex representation at 1800 UTC 25 August (Fig. 9h, compared with Fig. 9c). The forecasted locations of vortex centers are also better reproduced in ADP_SFC (Figs. 9i,j versus Figs. 9d,e).

b. Impacts on low-level (near surface) wind structure

Hurricane damage increases exponentially with low-level wind speed (Elsberry 2005). Accurate representation of low-level wind structure is an important factor in analyses and forecasts. Figures 10 and 11 show the surface winds from a member whose track is closest to the ensemble mean track in various data assimilation experiments at 1800 UTC 27 August and 1800 UTC 28 August, compared with the National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division’s (HRD’s) surface wind analyses (http://www.aoml.noaa.gov/hrd/Storm_pages; Powell et al. 2010). The HRD surface wind speed analysis (Fig. 10a) at 1800 UTC 27 August displays an asymmetric structure, with stronger winds east of Katrina’s center and a maximum wind speed of 85 kt in the southeast quadrant. BASE (Fig. 10b)

Fig. 13. West–east cross sections of wind speed (m s$^{-1}$) through the center of the hurricane at 1800 UTC 27 Aug of (a) HRD airborne Doppler radar–derived wind fields, (b) SFC, (c) ADP, (d) ADP_SFC, and (e) the difference between (d) and (c). The x axis is the radial distance from the center of the hurricane increasing to the east.
predicts much weaker wind speed and less organized wind structure. All data assimilation experiments, to various degrees, capture the asymmetric wind structure and predict strong surface wind speed. Specifically, SFC (Fig. 10c) predicts a wind speed maximum in the northern part of the storm. The strong winds are well simulated. ADP (Fig. 10d) produces similar wind structure but more reasonable wind speeds compared with SFC. ADP_SFC (Fig. 10e) performs the best overall, with a maximum wind speed of 85 kt to the east of the storm center. The surface wind analysis at 1800 UTC 28 August (Fig. 11a) shows strong surface wind, with wind speeds of 130 kt to the east Katrina’s center and a maximum wind speed of 135 kt in the northeast quadrant. The maximum wind speeds in BASE (Fig. 11b) are 115 kt. SFC and ADP (Figs. 11c and 11d) simulate the asymmetrically stronger wind speed of 130 kt in the eastern part of the vortices. ADP_SFC (Fig. 11e) performs the best, since it successfully predicts the asymmetrically stronger wind on the east side and a maximum speed of 135 kt in the northeast quadrant. The simulated eyes in all simulations are larger than in the analyses, partly because the model resolution is not high enough to resolve the eye structure.

Although an individual ensemble member could well capture the structure and intensity of surface wind, it is possible that the ensemble mean of surface wind speed is less organized and its intensity weaker (or stronger) than observations because of the spread of vortex centers.
(track spread) among ensemble members. However, it is expected that the ensemble mean could still provide statistical guidance to the structure of surface wind. Figure 12 compares the surface wind vector and speed of ensemble means (over all 30 members) for ADP (Figs. 12a,c) and ADP_SFC (Figs. 12b,d) at 1800 UTC 27 August (Figs. 12a,b) and 1800 UTC 28 August (Figs. 12c,d). It is apparent that assimilation of surface observations has resulted in more organized surface wind structures. The intensity of surface wind has also been enhanced by the forecast from the experiment with surface data assimilation. This is partly because the assimilation of surface observations causes reduction of the track spread (as show in Figs. 5e,f). Compared with Figs. 10a and 11a, the experiment with surface data assimilation (ADP_SFC; Figs. 12b,d) provides improved guidance in terms of wind speed distributions and maximum wind position, relative to the forecast from the experiment without surface data assimilation (ADP; Figs. 12a,c). Specifically, in ADP_SFC, Fig. 12b shows that the maximum winds are east of hurricane center, which is consistent with HRD surface wind analysis (Fig. 10a). Meanwhile, Fig. 12d (ADP_SFC) illustrates the stronger and more organized wind structure compared with Fig. 12c (ADP).

c. Impacts on vortex inner-core structure

Assimilation of vortex inner-core observations such as those from Doppler radar (e.g., Pu et al. 2009) offers a direct way to initialize hurricane inner-core structure. However, assimilating data outside the inner-core region could also modify the hurricane vortex structure through background covariances and model dynamics during the data assimilation cycles. In addition, the adjustments in initial conditions influence the hurricane vortex structures in subsequent forecasts through dynamic and physical evolution. To examine the influence of data assimilation in each experiment on the vortex inner-core structure, Fig. 13 illustrates the vertical west–east cross sections of simulated wind speeds at 1800 UTC 27 August from the ensemble member whose track is closest to the ensemble mean track, compared with the HRD airborne Doppler radar–derived winds at approximately the same time. The maximum winds from the radar derivation are on top of the boundary layer (500–2000 m). Wind speeds of about 55 m s$^{-1}$ extend out to a radial distance of 70 km
from the center on the east side (Fig. 13a). Wind speeds of less than 15 m s\(^{-1}\) are found within 4 km of the hurricane center. Compared with radar observations, all experiments overestimate the size of the eye. ADP and ADP_SFC (Figs. 13c,d) realistically extend the maximum wind to a distance of 70 km, while SFC (Fig. 13b) extend the maximum wind to only 50–55 km. Overall, with additional mid- to upper-level observations from the NCEP ADP observations, ADP and ADP_SFC lead to better prediction of the inner-core wind structure, compared with SFC. In addition, Fig. 13e shows that including surface observations in ADP_SFC does result in better vortex inner-core structure, compared with ADP, as the eye and eyewall structures are enhanced (with decreased wind speed in the eye and increased wind speed in the eyewall regions) in ADP_SFC.

Figure 14 shows the east–west cross section of relative humidity and temperature anomalies, calculated by the differences between the temperature at grid points and an average temperature within a 300-km radius from the simulated Katrina’s center at 0600 UTC 26 August (12-h forecasts after the end of the data assimilation cycle at 1800 UTC 25 August). It is apparent that changes of temperature and moisture occur in both the vortex core region and the outer bands in all experiments (SFC, ADP, and ADP_SFC) throughout the troposphere due to the cycled data assimilation. With assimilation of surface data only, SFC (Fig. 14a) leads to a warm-core structure of Katrina that was missed in BASE (figure not shown). In ADP (Fig. 14b), the warm-core structure becomes even clearer, with an organized moisture structure aligning with it. In addition, with surface data assimilation, the warm-core structure is further enhanced in ADP_SFC (Fig. 14c), compared with that in SFC. Specifically, the midlevel warm core (between 700 and 500 hPa) is more organized and an upper-level warm core (300–400 hPa) is formed (Fig. 14c). The moisture field also aligns better with the warm-core structure. This proves that the assimilation of surface observations not only causes refined surface wind fields but also impacts the thermodynamic structures in the troposphere and helps organize and strengthen the vortex.

d. Impacts on convective structures

To further explore the advantages of assimilating surface observations in ADP_SFC over ADP, Fig. 15 compares the convective structures of ADP and ADP_SFC with Tropical Rainfall Measuring Mission (TRMM) satellite-derived data as presented by hourly rainfall rates at 0300 UTC 27 August and 0300 UTC 29 August during the development of Hurricane Katrina. The satellite image shows that two major spiral bands are present at about 0300 UTC 27 August (Fig. 15a). Multiple spiral but somewhat symmetrical rainbands appear at 0300 UTC 29 August (Fig. 15d). Simulations in both ADP and ADP_SFC generally capture the convective features.
of Hurricane Katrina’s evolution during this period. For instance, they properly simulate the formation of the eye and the multiple spiral bands. However, ADP_SFC captures detailed structures better than ADP. At 0300 UTC 27 August, while ADP (Fig. 15b) reproduces only one major rainband east of Katrina’s center, ADP_SFC (Fig. 15c) clearly captures the two spiral bands east of Katrina’s center, which is more consistent with TRMM data. At 0300 UTC 29 August, ADP_SFC (Fig. 15f) simulates stronger convection in the eyewall regions and also the outer spiral band in the west and northeast. ADP (Fig. 15e) simulates the eyewall rainband but almost misses the outer rainbands.

e. Impacts on quantitative precipitation forecasting

Heavy precipitation due to a hurricane landfall can cause serious damage. Thus, quantitative precipitation is an important factor for evaluating the various data and forecast impacts. Figures 16 and 17 show the ensemble mean of daily rainfall (i.e., 24-h accumulated rainfall) from data assimilation experiments valid at 1200 UTC 26 August and 1200 UTC 29 August, corresponding to the two landfall events in Florida and Louisiana. Compared with NCEP Climatology-Calibrated Precipitation Analysis (CCPA; Hou et al. 2014) data (Figs. 16a and 17a), SFC mispredicts the rainfall center during the first landfall because of its significant track error (Fig. 16b). All experiments capture the rainfall center during the second landfall in the southern United States. Both ADP and ADP_SFC satisfactorily capture the rainfall pattern during the two landfall periods (Figs. 16c,d and 17c,d). The assimilation of NCEP ADP data significantly improves the rainfall forecast and produces reasonable rainfall distributions and amounts (Figs. 16c and 17c), relative to SFC, which assimilates only the surface observations. However, with assimilation of both NCEP ADP and surface observations, ADP_SFC results in the best forecast of 24-h accumulated rainfall in all simulations relative to the CCPA data. Specifically, the positive impact of the surface observations is clearly revealed by comparing the rainfall forecasts of ADP and ADP_SFC at 1200 UTC 29 August, as ADP_SFC produces a better forecast in terms of the intensity and location of the rainfall, especially for the second landfall. The influence of the surface data on forecasts of more than 72 h confirms that the effects of surface observations can be prolonged.

To quantify the contribution of surface observations to predicting precipitation, an equitable threat score (ETS) is evaluated for 24-h accumulated rainfall in the ADP and ADP_SFC experiments against the CCPA data during the two landfalls. The verification scores used in this study are derived from a contingency table approach (Wilks 1995). The ETS is computed using the following equation:

\[
ETS = \frac{A}{A + B + C}
\]
For a given threshold, $A$ represents the number of grid points that exceed the threshold in both the model forecast and the CCPA data; $B$ denotes the number of grid points that exceed the threshold in the model forecast, but not in the CCPA data; and $C$ is the number of grid points that do not reach the threshold in the model forecast, but that exceed the threshold in the CCPA analysis.

Figure 18 shows the comparison of ETS scores between the two experiments. It is apparent that the ADP_SFC significantly improves the prediction of heavy rainfall [more than 4 in. (1 in. = 25.4 mm)] when compared with ADP, although both experiments perform almost the same in light rainfall (less than 2 in.). The great impact of surface observations on quantitative precipitation forecasts (QPFs) is evident. In addition, the improved QPF could be attributed to the better representation of the convective structure of the hurricane in the analyses and forecasts, as illustrated in Fig. 15.

6. Summary and discussion

A series of numerical experiments are conducted to examine the impact of surface observations on the prediction of landfalls of Hurricane Katrina (2005), one of the deadliest disasters in U.S. history. A specific initial time (0000 UTC 25 August 2005), which led to poor prediction of Hurricane Katrina in several previous studies, is selected to begin data assimilation experiments. QuikSCAT ocean surface wind vectors and surface mesonet observations are assimilated with the minimum central sea level pressure and conventional observations from NCEP into WRF using the DART WRF EnKF system. Impacts of data assimilation on the analyses and forecasts of Katrina’s track, landfalling time and location, intensity, structure, and rainfall are evaluated.

It is found that the ensemble-based data assimilation results in improvement in Katrina’s track forecasts. Compared with a baseline experiment (BASE) that assimilates only Katrina’s position and minimum sea level pressure, assimilation of QuikSCAT and mesonet surface observations (SFC experiment) leads to significant improvements in predictions of Katrina’s track. Assimilation of NCEP ADP conventional observations also leads to better hurricane track forecasts compared with BASE and SFC. However, with assimilation of both surface observations and NCEP ADP conventional observations, an additional 10%–29% improvement in track forecast is found when predicting Katrina’s second landfall.

Further examination shows that assimilation of surface observations has an influence on the hurricane vortex structure through modifying thermal and dynamical fields such as wind, humidity, and temperature and enhancing low-level convergence and vorticity due to the evolution of model dynamics during the data assimilation cycles. However, single-level surface observations do not enable the model to predict reasonable intensities because of their lack of impact in the mid- to upper troposphere. When surface observations are assimilated with other conventional data, obvious enhancements are found in the forecasts of track and intensity, realistic convection, and surface wind structures. More importantly, surface data assimilation results in significant improvements in representation of the surface wind structure and quantitative precipitation forecasts (QPFs) during the landfall events. Since surface wind and QPF are the key factors that determine the degree of damages from a landfalling hurricane, assimilation of surface observations has great potential for improving hurricane landfall forecasting. More case studies and tests in an operational environment are needed for future applications.

Acknowledgments. The authors are grateful to the NCAR WRF development group and Data Assimilation Research Testbed (DART) team. Specifically, they would like to thank Dr. Jeffrey Anderson and his group (Dr. Glen Romine and Hui Liu and Ms. Nancy Collins)
for their help in the use of DART WRF. The authors would also like to express their appreciation to Dr. Juanzhen Sun from NCAR and three anonymous reviewers for their comments on the manuscript, which helped improve the presentation of this paper.

This study is supported by National Science Foundation (NSF) Grant AGS-1243027, NASA Grant NNX 13AO38G, and the Office of Naval Research (ONR) Award N000141310582. The computer time from the NOAA Tjet supercomputing system supported by Dr. Robert Gall through the Hurricane Forecasting Improvement Program (HFIP) is greatly appreciated. In addition, high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory and sponsored by the National Science Foundation, is acknowledged.

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