Land-Surface Diurnal Effects on the Asymmetric Structures of a Postlandfall Tropical Storm

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Abstract After a tropical storm makes landfall, its vortex interacts with the surrounding environment and the underlying surface. It is expected that diurnal variation over land will affect storm structures. However, this has not yet been explored in previous studies. In this paper, numerical simulation of postlandfall Tropical Storm Bill (2015) is conducted using a research version of the NCEP Hurricane Weather Research and Forecasting (HWRF) model. Results indicate that during the storm’s interaction with midlatitude westerlies over the Great Plains, the simulated storm with the SLAB land-surface scheme is stronger, with faster eastward movement and attenuation, and more asymmetric structures than that with the NOAH land-surface scheme. More symmetric structures correspond with a slower weakening and slower eastward movement of the storm over land. Further diagnoses suggest an obvious response of the storm’s asymmetric structures to diurnal effects over land. Surface diabatic heating in the storm environment is important for the storm’s asymmetric structures and intensity over land. Specifically, during the transition from nighttime to daytime, the evident strengthening of convective instability, atmospheric baroclinicity, and the lateral advection of high $\theta_e$ air in the storm environment, associated with the rapid increase in surface diabatic heating, are conducive to the development of vertical vorticity and storm-relative helicity, thus contributing to the maintenance of the storm’s symmetric structures and intensity after landfall.

1. Introduction

Asymmetric structures influence hurricane motion, intensity, rainfall, and near-surface wind distribution (e.g., Montgomery & Kallenbach, 1997; Nolan et al., 2001; Saunders et al., 2019; Wang, 2002). A hurricane’s asymmetric structures are induced by a combination of factors including environmental wind shear, interaction with midlevel and upper-level synoptic systems, nonuniform surface characteristics, and the hurricane’s internal processes (Chen & Yau, 2003; Lowag & Black, 2008). However, most of these previous studies on hurricane asymmetric structures, as well as their relation with track and intensity, have generally been done over the ocean (e.g., Alvey et al., 2015; Kieper & Jiang, 2012; Rogers et al., 2013; Wang & Holland, 1996). So far, few studies have emphasized the asymmetric structure of a hurricane after its landfall.

When a hurricane moves poleward and recurves into midlatitude westerlies after landfall, the hurricane itself, its surrounding baroclinic environment, and land-surface processes interact with each other, leading to asymmetric structures becoming more prominent and complex. Accurate prediction of the asymmetric structures, track, intensity, and rainfall of hurricanes is more difficult and challenging for numerical weather prediction models (Blackwell, 2000; Elsberry, 2005), especially when simulating or forecasting so-called postlandfall hurricanes over land (Bosart & Lackmann, 1995). In contrast to normal hurricanes that weaken rapidly after landfall, these unique hurricanes can survive for a longer time and even strengthen again over land (Arndt et al., 2009). Previous studies have indicated that the maintenance or reintensification of these tropical cyclones is strongly related to interactions with diabatic heating effects associated with the land surface and the presence of an inland baroclinic environment. For instance, Emanuel et al. (2008) found that warm-core cyclones can indeed intensify when the underlying soil is sufficiently warm and wet. Arndt et al. (2009) suggested that the reintensification of Hurricane Erin (2007) was likely due to the complex interaction of the remnant circulation and moist soil surface, and the ambient environmental baroclinic conditions. Evans et al. (2011) showed that soil moisture content was important to the reintensification of Tropical Storm Erin (2007) over land. A recent study by Zhang et al. (2019) perturbed initial soil moisture in the SLAB land-surface scheme based on comparing original model-derived data and reanalysis data such as...
soil moisture anomalies from the Climate Prediction Center (CPC) and volumetric fractional 0–10 cm soil moisture content from NLDAS2-NOAH; their results indicate that an increase in soil moisture before a tropical storm's landfall tends to produce a storm with weaker intensity and faster movement after its landfall, through boundary layer vertical mixing and surface diabatic heating processes (Zhang et al., 2019). Chen and Yau (2003) found that asymmetric structures arise from the near discontinuity of surface friction and the latent heat flux in a simulated landfalling hurricane. In addition, previous studies on the relationship between inland convection and land-surface processes have also indicated that the evolution of baroclinic zones, drylines, the development of low-level jets, capping inversions, and the evolution of precipitating systems are all sensitive to land-surface processes and their parameterizations (e.g., Beljaars et al., 1996; Betts et al. 1996; Eltahir, 1998; Lanicci et al., 1987).

Although it has been recognized that the diurnal variation of surface diabatic heating (defined as surface enthalpy fluxes; namely, the sum of surface sensible and latent heat fluxes) and the environmental baroclinicity over land are significant compared to tropical ocean areas, it is still unclear (1) how a hurricane’s asymmetric structures over land respond to land-surface diabatic heating, especially in a diurnal cycle; (2) what key mechanisms are associated with the diurnal effects on a hurricane’s asymmetric structures after landfall; and (3) whether asymmetric structures relate to and influence a storm’s intensity over land. To elaborate and understand the above issues, the postlandfall Tropical Storm Bill (2015) is used to study the sensitivity of numerical simulations to land-surface processes based on the NCEP Hurricane Weather Research and Forecasting (HWRF) model.

The next section introduces the model, tropical storm, and data. The land-surface schemes, experimental design, and diagnosis methods are described in Section 3. Simulation results of the track, intensity, and precipitation are shown in Section 4. The response of the storm's asymmetric structures to a diurnal cycle and its mechanisms are elucidated in Section 5. Section 6 discusses the relation between the simulated asymmetric structures and the intensity. Concluding remarks are made in Section 7.

2. Description of HWRF, the Tropical Storm Case, and Data

The HWRF model is an operational hurricane forecast system of the National Centers for Environmental Prediction (NCEP). Here, we used the research (community) version released from the Developmental Testbed Center (DTC), version 3.6a (Tallapragada et al., 2014). The model configurations are the same as those in Zhang et al. (2017) and F. Zhang and Pu (2017), including two-way interactive, triple-nested grid domains of 27, 9, and 3 km. The 27 km grid domain is fixed, while the other domains are movable.

Tropical Storm Bill (Berg, 2015) made landfall on Matagorda Island at 1645 UTC June 16, 2015 with maximum winds of 50 kt. Its remnant low survived for the next few days over land during its interactions with midlatitude westerlies, producing heavy rainfall, flooding, and tornadoes over the central Great Plains. The low ultimately dissipated just after 0000 UTC June 21 over the mountainous terrain of central West Virginia. Compared to other normal decay cases such as Hurricanes Dennis, Katrina, and Rita in 2005, Tropical Storm Bill is a unique landfall case because it made landfall with a much weaker intensity but sustained itself for a much longer time (~103 h) after its landfall.

The following data are used to validate the simulation results: National Hurricane Center (NHC) best-track data (Landsea & Franklin, 2013), upper-level synoptic flows from the ERA-Interim daily analysis (Dee et al., 2011), and precipitation analysis from the NCEP Climatology Calibrated Precipitation Analysis (CCPA; Hou et al., 2014).

3. Experiment Design and Diagnosis Methods

HWRF has implemented two land-surface schemes: SLAB (Deardorff, 1978; Tuleya, 1994) and NOAH (Chen & Dudhia, 2001). The SLAB scheme, which has only one soil layer, is a simple model that predicts surface temperature only, based on the surface energy balance. Soil moisture in the SLAB scheme is invariant during the whole period of model integration; however, the effect of soil moisture on land-surface processes, such as surface temperature, is still included in the SLAB scheme through its impact on thermal conductivity, which in turn can affect surface enthalpy fluxes. Therefore, the SLAB scheme can still
adequately simulate thermal evolution, similar to a more complicated multilevel land model, as indicated by Deardorff (1978) and Tuleya (1994). Another land-surface model is NOAH, which has four soil layers and one canopy layer; it predicts soil moisture and temperature, water stored in the canopy, snow stored on the ground, etc. Soil moisture and soil temperature are updated at each integration time in the NOAH scheme. A detailed discussion of the two schemes in HWRF can be found in Zhang et al. (2019).

Two experiments are designed in this study. (1) SLAB: uses the default land-surface scheme in HWRF; and (2) NOAH: uses the NOAH land-surface scheme. The simulation time for Tropical Storm Bill is from 0000 UTC June 16 to 0000 UTC June 21, 2015. NCEP Global Forecast System (GFS) Data Assimilation System (GDAS) analysis (Roads et al., 1997) was used to derive the initial and boundary conditions for the HWRF simulations. Apart from the land-surface scheme, other physics schemes used in the two experiments are completely the same. Diagnosis methods such as the tropospheric baroclinicity parameter \( \sigma_{BL} \) (unit: s\(^{-1}\)), Storm-Relative Helicity \( SRH \) (unit: m\(^2\) s\(^{-2}\)), and Moist Potential Vorticity \( MPV \) (unit: PVU and \( 1\text{PVU} = 10^{-6}\text{ m}^2\text{ s}^{-1}\text{ K} \text{ kg}^{-1} \)) are used in this study.

Tropospheric baroclinicity is common in the midlatitude atmosphere; when it predominates, storms have a much less active large-scale feedback and can develop primarily from externally imposed forcings such as mesoscale components of synoptic-scale baroclinic systems (Hopper & Schumacher, 2009). It is evaluated based on the growth rate of the most unstable normal mode for the Eady (1949) problem (Hotta & Nakamura, 2011):

\[
\sigma_{BL} = 0.31 \frac{f}{N} \left| \frac{\partial u}{\partial z} \right|
\]

where \( N^2 = \frac{g}{\theta_e} \frac{\partial \theta_e}{\partial z} \) denotes the buoyancy (Brunt-Väisälä) frequency (unit: s\(^{-1}\)), \( f \) is the Coriolis parameter (unit: s\(^{-1}\)), \( g \) is the gravity (unit: m s\(^{-2}\)), \( u \) is the horizontal wind velocity vector (unit: m s\(^{-1}\)), \( \theta_e \) is the virtual potential temperature (unit: K), and \( z \) is the height above ground level (unit: m). A higher \( \sigma_{BL} \) represents stronger synoptic-scale baroclinic systems in the storm environment.

Storm-relative helicity is a quantity proportional to streamwise vorticity and storm-relative winds (Markowski et al., 1998):

\[
SRH = \frac{1}{h} \int_{(0, h)} (\vec{V} - \vec{C}) \cdot \vec{\omega}_e dz
\]

where \( \vec{V} \) is the environment wind vector (unit: m s\(^{-1}\)), \( \vec{C} \) is the storm motion vector (unit: m s\(^{-1}\)), \( \vec{\omega}_e \) is the horizontal vorticity vector (unit: s\(^{-1}\)), \((0, h)\) is the depth of integration (unit: m), and \( dz \) is the vertical dimension (unit: m). \( SRH \) is a measure of the potential for cyclonic updraft rotation in the storm environment and its contribution of environmental vorticity to the storm.

Moist Potential Vorticity \( MPV \) is an important quantity to reflect the thermodynamic and baroclinic characteristics of the atmosphere in a moist environment (Hoskins et al., 1985). It is defined in the following form in pressure coordinates:

\[
MPV = -g (\zeta_p + f) \frac{\partial \theta_e}{\partial p} + g \left( \frac{\partial v}{\partial p} \frac{\partial \theta_e}{\partial x} - \frac{\partial u}{\partial p} \frac{\partial \theta_e}{\partial y} \right)
\]

where \( MPV_1 = -g (\zeta_p + f) \frac{\partial \theta_e}{\partial p} \) and \( MPV_2 = g \left( \frac{\partial v}{\partial p} \frac{\partial \theta_e}{\partial x} - \frac{\partial u}{\partial p} \frac{\partial \theta_e}{\partial y} \right) \) are the vertical and horizontal components of \( MPV \), respectively; \( g \) is gravity (unit: m s\(^{-2}\)), \( \zeta_p \) is relative vorticity (unit: s\(^{-1}\)), \( f \) is the Coriolis parameter (unit: s\(^{-1}\)), \( \theta_e \) is equivalent potential temperature (unit: K), \( u \) and \( v \) are the zonal and meridional wind, respectively (unit: m s\(^{-1}\)), \( x \) and \( y \) are the zonal and meridional position relative to the coordinate origin (unit: m), and \( p \) is vertical pressure level (unit: Pa). A positive and negative \( MPV_1 \) represents a convective stable and unstable atmosphere, respectively. \( MPV_2 \) is composed of vertical wind shear and a horizontal gradient of \( \theta_e \); thus its absolute value can be regarded as moist baroclinicity. The baroclinicity and
convectively unstable environment induced by surface diabatic heating are conducive to the development of vertical vorticity (Wu et al., 1996).

4. Simulation Results

Figure 1 compares the simulated storm track against observations from the best track. The storm tracks in the simulations with the two schemes are similar to the best track during the early phase of the storm's landfall over Texas and Oklahoma. However, the simulated storm in both SLAB and NOAH moves faster than the best track after shifting from north to northeast over the Great Plains at 0600 UTC June 18, 2015. In particular, the simulation with the SLAB scheme (SLAB, hereafter) produces a faster storm track than the simulation with the NOAH scheme (NOAH, hereafter), which can be clearly seen by comparing the storm's position from 0600 UTC June 19 to 0600 UTC June 20, 2015. This is mainly because the simulated steering winds in the middle and upper atmosphere become evident, especially after 0600 UTC June 18 in the two experiments. SLAB produces a stronger steering wind than NOAH does (not shown). Compared to the geopotential height at 500 hPa in ERA-Interim reanalysis, at 1200 UTC June 19 NOAH better captures environment flows in the midlatitude westerlies than SLAB does (not shown). In the last 18 h of simulation, the storm in the simulation with SLAB takes a more eastward track across the highest terrain of the Appalachians and follows the coastal plain of Maryland, while the simulated storm with NOAH moves northeastward through the rough terrain of Pennsylvania. Overall, NOAH performs better than SLAB when the storm recurves into the midlatitude westerlies over the central Great Plains. Except for the possible influence of the Appalachian Mountains during the last 18 h of simulation, there is no obvious change in terrain during the simulation period for either experiment, indicating that terrain does not substantially affect the simulation results.

Figure 2 compares the HWRF simulations of track and intensity against the best track in the different experiments. Results in Figure 2a show that the simulated track error in SLAB grows more quickly with time than in NOAH after landfall. Figure 2b shows that the overall storm intensity is weaker in NOAH than in SLAB after landfall; in addition, the simulated storm intensity in SLAB is closer to the best track during the early phase of landfall until 0600 UTC June 18 but less close from 0600 UTC June 18 to 1800 UTC June 19 when the storm interacts with midlatitude westerlies over the Great Plains. Figure 2c shows that the simulation discrepancies in Sea Level Pressure (SLP) between the two schemes are small during the early phase of landfall, but become
evident after 0600 UTC June 18; NOAH performs better from 0600 UTC June 18 to 1200 UTC June 19 when the storm is active over the Great Plains. Note that compared to NOAH, the simulated SLP in SLAB decreases from 0000 UTC June 20, 2015 to the end of the simulation and has smaller simulation biases; this is mainly because of the influence from the western Atlantic Ocean in SLAB during this period (Figure 1).

Figure 3 compares the accumulated precipitation distribution between simulations and observations after landfall. The observed precipitation is concentrated mainly on the coastline of Texas, southern Oklahoma, and the northern Great Plains in Missouri, Illinois, and Indiana. Compared to observations, the two simulations overestimate the rainfall in eastern Texas; neither experiment reproduces the precipitation in southern Oklahoma. The SLAB experiment overestimates rainfall in the northern Great Plains and generates some unrealistic rainfall in central and southern Texas and the east coast of the United States; such overestimations and unrealistic precipitation, however, are alleviated and remedied in NOAH. The above results of Figures 1–3 indicate that after landfall, the simulated track error grows more quickly with time in SLAB than in NOAH, while the overall intensity is stronger in SLAB than in NOAH. The discrepancies in the track, intensity, and precipitation between the two schemes become evident after June 18, when the storm interacts with midlatitude westerlies.

5. Response of the Storm’s Asymmetric Structures to the Diurnal Cycle and its Mechanisms

To further investigate whether the storm’s rainfall and SLP asymmetric structures change in the diurnal cycle, Figure 4 compares the simulated precipitation in the past 6 h and SLP between SLAB and NOAH in three diurnal cycles from June 17 to June 19. Results show that during the early phase of landfall, the
observed storm in terms of surface rainfall is stronger at 1800 UTC (noon, LST, hereafter) June 17 than at 0600 UTC (midnight, LST, hereafter) June 17. The observed heavy rainfall near the Oklahoma-Texas border is better simulated in SLAB than in NOAH; SLAB and NOAH produce very similar rainfall patterns and storm structures. They are both concentric and spiral to the storm center, suggesting that the diurnal effects on the storm structure are marginal during this period. During the next diurnal cycle, when the storm interacts with midlatitude westerlies over the Great Plains, at 0600 UTC June 18 (nighttime), the simulated precipitation in the two schemes shows a similar pattern, and in both the cases it is concentric around the storm center, similar to the observations. Although SLAB produces a stronger storm than NOAH, with lower SLP and stronger precipitation at 1800 UTC June 18 (daytime), the simulated storm exhibits more asymmetric structures in SLAB than in NOAH; for instance, the observed precipitation with clearly spiral structures is better captured in NOAH. The simulated precipitation in SLAB, however, is elongated northeastward. In addition, the 1,016 isobaric surface is blocked to the northeast of the storm in NOAH but elongated northeastward in SLAB, suggesting that the storm in NOAH is not conducive to northeastward movement. During the third diurnal cycle on June 19, similar to the results on June 18, SLAB simulates rainfall that is elongated northeastward, while NOAH produces spiral precipitation structures that are closer to observations. The 1,016 isobaric surface is elongated northeastward in SLAB but is blocked in front of the storm in NOAH. The weakening of the simulated storm is still more rapid in SLAB than in NOAH.

In summary, the response of the storm’s asymmetric structures to the diurnal cycle becomes distinct after June 18. That is, the change in the storm’s asymmetric structures is not apparent in the diurnal cycle.

Figure 3. Accumulated precipitation (unit: mm) after the storm’s landfall, valid from 1800 UTC 16 June 2015 to 0000 UTC 21 June 2015. (a) CCPA, (b) SLAB, and (c) NOAH. CCPA, Climatology Calibrated Precipitation Analysis.
Figure 4. Comparison of simulated precipitation (shaded; unit: mm) in the past 6 h, and sea level pressure (contours; unit: hPa) for (b1–b6) SLAB and (c1–c6) NOAH against (a1–a6) observed precipitation in the past 6 h, valid for three diurnal cycles at (a1, b1, c1) 0600 UTC June 17 (nighttime), (a2, b2, c2) 1800 UTC June 17 (daytime), (a3, b3, c3) 0600 UTC June 18 (nighttime), (a4, b4, c4) 1800 UTC June 18 (daytime), (a5, b5, c5) 0600 UTC June 19 (nighttime), and (a6, b6, c6) 1800 UTC June 19 (daytime), respectively.
of June 17 during the early phase of landfall, while it becomes evident when the storm interacts with midlatitude westerlies over the Great Plains after June 18. This might be because the storm is strongly influenced by the ocean on June 17, making it hard to separate ocean and land impacts. Moreover, because the variation in surface diabatic heating is more significant in the diurnal cycle of June 18 than in other diurnal cycles (see Figure 9 below), and the discrepancies in the track, intensity, and precipitation between the two schemes become evident after June 18 (see Figures 1–3) as well, therefore, the results from 0600 UTC June 18 (midnight, LST) to 1800 UTC June 18 (noon, LST) will be emphasized in the following sections, to further examine the mechanisms associated with the diurnal effects on the storm’s asymmetric structures.

Figure 5 shows the cross sections of azimuthally averaged tangential wind, the slope of the Radius of Maximum Wind (RMW), and vortex tilt below 300 hPa. In this study, azimuthal averages are computed using 5-km radial increments out to \( r = 500 \) km from the storm center. The slope of RMW (also called eyewall slope) is defined by the radius of the maximum azimuthally averaged tangential wind at each pressure level; vortex tilt is assessed after first locating the TC center, which maximizes the vorticity centroid within a radius of 200 km as a function of altitude. These quantities are commonly used to characterize how the eyewall and center of a storm change with height, and both are used to describe a storm’s vertical structures (Hazelton et al., 2015; Reasor et al., 2004; Stern et al., 2014). Compared with NOAH, SLAB produces stronger azimuthally averaged tangential winds in the nighttime, especially at the lower levels (e.g., below 700 hPa). Although the storm in both SLAB and NOAH weakens overall from nighttime to daytime, the storm in NOAH has a larger region of more intense azimuthally averaged tangential winds than SLAB at about 200 km from the center between 850 and 700 hPa. Further diagnosis indicates that SLAB produces a more sloped eyewall than NOAH during the transition from nighttime to daytime. No evident differences in vortex tilt are found between SLAB and NOAH. Since the azimuthally averaged tangential wind and eyewall slope represent the axisymmetric component of a storm and the vertical
distribution of axisymmetric structures, respectively, these results illustrate that the storm's symmetric structures can be better maintained in NOAH than in SLAB during the transition from nighttime to daytime over the Great Plains.

Commonly, track, intensity, and asymmetric structures of a tropical cyclone can be strongly affected by interactions between its vortex and the ambient environment, as well as the underlying surface over midlatitude land regions (Chen & Yau, 2003; Lowag & Black, 2008). The underlying surface and the ambient environment over midlatitude land regions are manifested mainly by surface diabatic heating and baroclinicity; therefore, we speculate that these simulation discrepancies could be related in large part to the storm's asymmetric structures and are subject to the diurnal effects of surface diabatic heating in different land-surface schemes, since the only difference between the two simulations is land-surface parameterization.

To illustrate the possible association of the asymmetric structures of vortices with diurnal variation, diagnoses are conducted to examine the relation between vortex structures with surface diabatic heating and baroclinicity during the nighttime and the daytime. Following Nguyen et al. (2017), quadrant-averaged thermodynamic quantities that reflect the storm's asymmetric structures will be analyzed here. The four quadrants, including Downshear Left (DSL), Upshear Left (USL), Upshear Right (USR), and Downsline Right (DSR), are defined counterclockwise relative to the vertical wind shear direction. Vertical wind shear is defined as the averaged wind vector difference between 200 and 850 hPa. Results in Table 1 show that vertical wind shear direction is similar in the two experiments and is nearly northeastward in both nighttime and daytime. The vertical wind shear speed increases from nighttime to daytime, with a higher value in SLAB than in NOAH.

Figure 6 shows the difference of azimuthally averaged equivalent potential temperature (θ_e), radial wind, Planetary Boundary Layer Height (PBLH), and surface diabatic heating between daytime and nighttime in a different quadrant. Here the azimuthally averaged radial wind is defined as the azimuthally averaged centripetal or centrifugal (nonaxisymmetric) component of a storm; negative and positive azimuthally averaged radial wind represents inflow and outflow relative to the storm center, respectively. PBLH is determined based on the critical Richardson number—that is, a higher PBLH usually implies stronger boundary layer instability (Troen & Mahrt, 1986). During the transition from nighttime to daytime, the storm weakens more rapidly in NOAH than in SLAB and has lower θ_e near the storm core region in all quadrants (Figures 6a–6h). The θ_e air away from the storm center (e.g., >200 km) decreases in all quadrants in SLAB while it increases in the DSL, USL, and USR quadrants in NOAH, corresponding well with the more pronounced increase in surface diabatic heating and PBLH in NOAH than in SLAB. Considering the boundary layer inflows in the storm's DSL quadrant in SLAB (Figure 6a), DSL and USL quadrants in NOAH (Figures 6e and 6g), these results suggest that compared to SLAB, the lateral advection of relatively higher θ_e air away from the storm center in NOAH tends to play a role in energy supply. According to recent observations of Nguyen et al. (2017), the above features suggest that NOAH produces a storm with more symmetric structures than SLAB does. In other words, the evident increase in θ_e in the storm's left-of-shear and upshear quadrants caused by the corresponding increase in surface diabatic heating and atmospheric instability during the transition from nighttime to daytime, combined with the lateral advection of higher environmental θ_e air, is essential to the maintenance of the storm's symmetric structures after landfall.

To gain more physical insight into the evolution of the storm's asymmetric structures over land, Figures 7 and 8 further diagnose the MPV, MPV1, and MPV2 at 850 hPa, and surface diabatic heating in a diurnal cycle. Results indicate that in both nighttime and daytime, MPV is composed mainly of positive MPV1 near the storm center, and mainly of MPV2 and negative MPV1 away from the storm center. Previous studies have revealed that the hurricane boundary layer is nearly neutral, where shear is the dominant source of turbulence (e.g., Keptert, 2012; Zhang et al., 2009); therefore, positive MPV1 can represent the storm itself while MPV2 and negative MPV1 can reflect moist baroclinicity and convective instability in the storm environment. During the nighttime (Figure 7), the storm is stronger in SLAB than in NOAH, with larger MPV1 near the storm center; in addition, MPV1 in the two schemes has a similar pattern and is concentric
Figure 6. Difference of azimuthally averaged (a)–(h) equivalent potential temperature ($\theta_e$; shaded; unit: K), radial wind (contours; unit: m s$^{-1}$) below 300 hPa, PBLH (green line; unit: m), and (i–l) surface diabatic heating (unit: W m$^{-2}$) between 1800 UTC June 18 (daytime) and 0600 UTC June 18 (nighttime) (daytime minus nighttime) in different quadrant in (a)–(d) SLAB and (e)–(h) NOAH. (a, e, i) DSL quadrant, (b, f, j) DSR quadrant, (c, g, k) USL quadrant, and (d, h, l) USR quadrant. PBLH, Planetary Boundary Layer Height; DSL, Downshear Left; USL, Upshear Left; USR, Upshear Right; DSR, Downshear Right.
around the storm center. During the daytime (Figure 8), although the simulated storm is still stronger with larger MPV1 in SLAB than in NOAH, it exhibits more asymmetric structures in SLAB than in NOAH. For instance, MPV1 elongates eastward in SLAB but is located near the storm and is basically concentric around the storm center in NOAH, similar to the analyses shown in Figure 4. This suggests that the storm's symmetric structures can be better maintained in NOAH than in SLAB during the transition from nighttime to daytime. It is also found that compared to SLAB, the negative MPV1 in the storm environment becomes more obvious in NOAH during the daytime, corresponding to the rapid increase in surface diabatic heating, indicating that the convectively unstable environment outside the storm is stronger in NOAH and is thus conducive to the development of vertical vorticity in the storm environment. Further diagnosis indicates that during the transition from nighttime to daytime, MPV2, especially in the downshear quadrants of the storm, strengthens more obviously in NOAH than in SLAB, suggesting that compared to SLAB, the moist baroclinicity in the downshear quadrants of the storm environment is evidently enhanced in NOAH and thus is conducive to the development of vertical vorticity. Moreover, in the downshear quadrants of the storm, the larger MPV2 in NOAH agrees well with the larger gradient of surface diabatic heating, compared to SLAB, suggesting that the rapid increase in surface diabatic heating and its uneven distribution are important to the increase of moist baroclinicity.

Overall, in the storm environment, strong surface diabatic heating during the daytime results in an increase in convectively unstable and moist baroclinicity, which is conducive to an increase in vertical vorticity and is also important to the maintenance of the storm's symmetric structures after landfall.

6. Relation Between Asymmetric Structures and Storm Intensity

The above results show that SLAB produces more asymmetric storm structures than NOAH during the transition from nighttime to daytime. The asymmetric structures in SLAB correspond with a faster eastward movement and faster attenuation of the storm's intensity over the Great Plains. Previous studies over
the ocean found that rapidly intensifying tropical cyclones typically correspond with symmetric structures more than slowly intensifying, steady state, or weakening tropical cyclones (Alvey et al., 2015; Kieper & Jiang, 2012; Rogers et al., 2013); however, it is unclear why the simulated storm in SLAB is stronger but has more asymmetric structures than NOAH. To address this issue, Hovmöller diagrams of azimuthally averaged surface diabatic heating and boundary layer vertical mixing at 950 hPa, which are important factors that affect the intensity of landfalling hurricanes (Miller, 1964; Zhang & Pu, 2017), are compared in Figure 9. Results show that there are clear diurnal variations in surface diabatic heating and boundary layer vertical mixing in both simulations; they are distinct in the regions away from the storm center. In addition, surface diabatic heating and boundary layer vertical mixing are stronger during the daytime in NOAH than in SLAB, and they are comparable during the nighttime. Near the storm center, however, the diurnal variations are not evident, with weaker surface diabatic heating; in addition, it is notable that boundary layer vertical mixing near the storm center is much stronger in NOAH than in SLAB during the early phase of landfall before 0600 UTC June 18, 2015. On this basis, we speculate that the impacts of surface diabatic heating and boundary layer vertical mixing on the storm’s evolution might be different inside the storm (storm itself, hereafter) and outside the storm (storm environment, hereafter).

According to Zhang et al. (2009) and Kepert (2012), the hurricane boundary layer is nearly neutral, where the buoyancy effects are marginal; in this condition, surface diabatic heating over land should be weak and there should be no evident diurnal variation inside a storm, while it should be strong during the daytime and have evident diurnal variations in the storm environment. Therefore, similar to distinguishing the storm itself and the storm environment in the view of MPV, surface diabatic heating and the associated diurnal variation can also be used to distinguish the storm itself and its environment. According to Figure 9, a radius of 160 km can be roughly used to distinguish the storm itself and its environment. Recent studies by Zhang et al. (2017) and Zhang and Pu (2017) showed that strong boundary layer vertical mixing leads to a weak storm after landfall, and this appears to be valid for this case as well; namely, inside the storm, the stronger boundary layer vertical mixing during the early phase of landfall in NOAH could be the important and dominant factor that leads to the weaker storm intensity in NOAH, compared to that in SLAB.

Figure 8. Same as Figure 7, but for 1800 UTC June 18 (daytime).
To further understand the role of surface diabatic heating and boundary layer vertical mixing in the storm environment on the storm's evolution over land, a cross section of azimuthally averaged boundary layer vertical mixing, $\theta_e$, $\sigma_{BI}$, SRH, and surface diabatic heating in a diurnal cycle is compared in Figure 10. It is found that the increase in daytime surface diabatic heating leads to an increase in boundary layer vertical mixing in the storm environment. Although the storm in both SLAB and NOAH weakens overall from the nighttime to the daytime (with decreased $\theta_e$ inside the storm), $\theta_e$ in the storm environment increases and becomes much larger in NOAH than in SLAB during the transition from nighttime to daytime, indicating that the stronger cold dry air in the storm environment in SLAB is conducive to the destruction of the hurricane's symmetric structures and thus does not benefit the maintenance of storm intensity, compared to NOAH (e.g., Kimball, 2006; Powell, 1987; Zhang & Pu, 2017). Further diagnosis of $\sigma_{BI}$ and SRH indicates that the baroclinicity and SRH in the storm environment also become stronger in NOAH than in SLAB during the transition from nighttime to daytime. Moreover, the 338 K isotherm in the storm environment bows downward from a radius of 325 km to about 225 km with stronger SRH and baroclinicity, suggesting that strong baroclinicity and SRH, accompanied by a large instability in the storm environment during the daytime, provide a strong potential for the generation of vertical vorticity. As a result, the storm's symmetric structures and intensity after landfall can be well maintained in NOAH, in agreement with the analyses in Figures 6–8. These results are also consistent with those of previous studies. For instance, Molinari and Vollaro (2010) found intense supercells embedded in a tropical cyclone's circulation and suggested that the large helicity in a tropical cyclone's environment might promote intense supercells and contribute to
a tropical cyclone’s intensification. Weisman et al. (2013) suggested that a large SRH in the storm environment can help spin up vertical vorticity in the vicinity of the storm.

To summarize, compared to SLAB, stronger boundary layer vertical mixing in the environment during the daytime induced by stronger surface diabatic heating in NOAH contributes to the maintenance of the storm’s symmetric structures and is conducive to the maintenance of the storm’s intensity over land. The weaker storm intensity over land in NOAH than in SLAB can be attributed mainly to the stronger boundary layer vertical mixing inside the storm in NOAH than in SLAB during the early phase of landfall.

In order to understand the key reasons for the stronger surface diabatic heating and boundary layer vertical mixing during the daytime in NOAH than in SLAB in the storm environment, and the stronger boundary layer vertical mixing in NOAH than in SLAB inside the storm, it is necessary to review the parameterizations of surface diabatic heating and boundary layer vertical mixing in the HWRF model.

Surface sensible (SH) and latent heat (LH) fluxes are parameterized as:

\[
SH = \rho c_p C_u u u \left( T_a - T_u \right) \tag{4}
\]

\[
LH = \rho L_r C_q M u u \left( q_a - q_u \right) \tag{5}
\]

where \( L_r \) and \( c_p \) are constant; \( \rho \) is air density near the surface; \( M \) is soil moisture; \( T_a \) and \( q_a \) denote temperature and specific humidity, respectively; variables with subscript “a” denote the near-surface atmosphere (e.g., the lowest model level atmosphere) while those with subscript “u” denote the land/ocean surface (hereafter); \( C_u \) and \( C_q \) are the dimensionless bulk transfer coefficients for thermal and moisture, respectively (Stull, 1988); \( C_u \) generally equals \( C_q \) in surface layer parameterization.
Boundary layer vertical mixing \((K_m)\) is parameterized as:

\[
K_m = kw_z\left(\alpha\left(1 - \frac{z}{h}\right)^p\right)
\]

(6)

\[
w_i = \frac{u_*}{\phi_m}
\]

(7)

\[
\tau = \rho u_*^2
\]

(8)

where \(k = 0.4\) is the Von Kármán constant; \(w_i\) represents the mixed-layer velocity scale; \(z\) is the height above the surface; \(\alpha\) is the profile shape exponent; \(p = 0.2\) is the profile shape exponent; \(\tau\) is surface momentum flux, which is proportional to the square of the surface frictional velocity \(u_*\); and \(\phi_m\) represents near-surface atmospheric stability, which decreases with decreasing stability and is smaller in an unstable atmosphere than in a stable atmosphere (see Figure 1 in Businger et al., 1971). As a result, for specific \(z\) and \(h\), boundary layer vertical mixing is influenced mainly by \(u_*\) (or \(\tau\)) and \(\phi_m\). In other words, boundary layer vertical mixing increases with increasing \(u_*\) (or \(\tau\)) and decreasing \(\phi_m\) (atmospheric stability).

Figure 11 compares Hovmöller diagrams of azimuthally averaged land-air interaction quantities (e.g., \(T_g\), \(T_g - T_a\), \(q_g\), \(q_g - q_a\), \(\mu\), \(\mu_a\), and \(\tau\)) in SLAB and NOAH. Note that since both SLAB and NOAH use the same near-surface layer scheme, the impacts of \(C_q\) and \(C_h\) on the simulation discrepancies should be marginal. The key differences after the storm’s landfall are discussed below.

In the storm environment, compared to SLAB, soil moisture \(M\) is smaller in NOAH, which increases surface albedo and decreases soil heat capacity. Thus, NOAH produces a much higher surface temperature \((T_g)\), with larger diurnal variation. Moreover, NOAH also produces much higher \(T_g - T_a\) and \(q_g - q_a\) than SLAB, especially during the daytime; surface momentum flux \(\tau\) and near-surface wind are comparable between the two schemes. Since the increase of \(T_g - T_a\) in NOAH tends to weaken atmospheric stability in the lower atmosphere (Stull, 1988), \(\phi_m\) should be lower in NOAH than in SLAB. As a result, compared to SLAB, NOAH produces drier soil in the land-surface and higher surface temperature \((T_g)\), \(T_g - T_a\), and \(q_g - q_a\), which are the key reasons for the stronger surface diabatic heating; the higher \(T_g - T_a\) simulated with NOAH, which leads to a lower \(\phi_m\), is the key reason for the stronger boundary layer vertical mixing in the storm environment.

Inside the storm, it is notable that during the early phase of landfall before 0600 UTC June 18, 2015, NOAH produces evidently higher surface momentum flux \((\tau\) or \(u_*\)) than SLAB; in addition, \(T_g - T_a\) is also higher in NOAH than in SLAB, suggesting that NOAH simulates a lower \(\phi_m\) than SLAB. Therefore, compared to SLAB, the much larger \(u_*\) (or \(\tau\)), combined with the lower \(\phi_m\) in NOAH, is the key reason for a stronger boundary layer vertical mixing in NOAH during the early phase of landfall, according to Equations 6–8.

7. Concluding Remarks

Hurricanes usually exhibit an asymmetric structure due to interactions among the hurricane itself, its surrounding environment, and the underlying surface. The sensitivity study in this paper illuminates the importance of diurnal effects over land in the evolution of the hurricane’s asymmetric structures after landfall.

Compared to NOAH, the simulation with the SLAB scheme produces stronger storm intensity in terms of minimum SLP in the storm center, surface rainfall, etc., while simulating faster eastward movement during the storm’s interaction with midlatitude westerlies over the Great Plains; meanwhile, SLAB also produces more asymmetric storm structures than NOAH, including a more eastward stretch of precipitation and a more sloped eyewall. More symmetric structures in NOAH correspond with a slower weakening of the storm over land, compared to SLAB. These results indicate that the simulation of Tropical Storm Bill (2015) is sensitive to land-surface schemes.
The response of the storm's asymmetric structures to diurnal effects over land is evident. Surface diabatic heating in the storm environment is weaker during the nighttime but becomes more distinct during the daytime. As a consequence, the evident strengthening of convective instability, atmospheric baroclinicity, and the lateral advection of high environmental $\theta_e$, which are conducive to the development of vertical vorticity and storm-relative helicity, are essential to the maintenance of the storm's symmetric structures and intensity after landfall.

Moreover, it is found that boundary layer vertical mixing inside the storm plays a dominant role in determining the storm's intensity after landfall. In the storm environment, surface diabatic heating, and the corresponding strong boundary layer vertical mixing become strong during the daytime, contributing to the storm's symmetric structures and retarding the weakening of the storm's intensity over land. In other words, although more symmetric structures tend to maintain the storm's intensity over land, their impacts on storm intensity are weaker compared to boundary layer vertical mixing inside the storm.

Land-surface and boundary layer processes and their interactions could be a productive area of future research on landfalling hurricanes and their further evolution over land. Results in this study provide insights into the complicated processes that occur during the interactions among the hurricane itself, its ambient environment, and land-surface processes. More importantly, the findings from this study identify the important contributions of boundary layer vertical mixing and surface diabatic heating in the environment to the storm's asymmetric structures and intensity after landfall, especially in a diurnal cycle. Future work should focus on more cases to further validate the reliability of these results. Since land-surface and atmospheric radiation can interact with each other, future work should also address the importance of radiative diurnal effects on storm evolution. Moreover, with a tropical cyclone case over the ocean, Bhalachandran et al. (2020) revealed that asymmetries of a tropical cyclone could grow or decay independent of the symmetric component of the vortex. Therefore, to better understand the land-surface's diurnal effects on asymmetric structures of a tropical cyclone, the interaction between vortex-scale and subvortex-scale waves under strong environment-vortex influences should be investigated for postlandfall tropical storms.

Data Availability Statement
Data for this research include best-track data (available in https://www.nhc.noaa.gov/data/), upper-level synoptic flows from the ERA-Interim daily analysis (Dee et al., 2011), and precipitation analysis from CCPA (Hou et al., 2014).

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