1. Introduction

Tropical cyclones (TCs), especially landfalling TCs, are one of the most severe meteorological disasters and can cause significant casualties and economic loss; thus, their accurate prediction is vital. Previous studies have confirmed that vertical eddy diffusivity (VED) in the planetary boundary layer (PBL) controls the evolution of the hurricane PBL and impacts the evolution of TCs (e.g., S. S. Chen et al. 2007; Emanuel, 1986, 1995; Ooyama, 1969; Smith, 1968; Van Sang et al., 2008; F. Zhang & Pu 2017; J. A. Zhang et al. 2011). Therefore, improved representation of VED could improve TC forecasts (F. Zhang & Pu 2017).

Fundamentally, VED combines with surface process through surface flux, which is related to the energy support of TCs and evolution. Uncertainties of VED in the PBL parametrization scheme of a mesoscale model could be caused by the model's inability to represent large eddies (LEs). Using a large-eddy simulation (LES) of Hurricane Harvey (2017) as a benchmark, the YSU PBL scheme is improved by adding effects of LEs derived from the LES. It is found that LEs' maximum intensity is linearly significantly related to the square of mean horizontal divergence below 400 m of height at the same air column with a slope coefficient of 1.97. The revised YSU scheme relates the VED of momentum ($K_m$) to the square root of LEs' intensity with a slope coefficient of 0.08 in PBL and 0.20 in a free atmosphere. Compared to the original scheme, the modified YSU scheme leads to improved forecasts of landfalling hurricanes.

Plain Language Summary The turbulent transport in the boundary layer, the low part of the atmosphere near the Earth’s surface, affects tropical cyclones’ structure and evolution. Its effects are represented by vertical eddy diffusivity (VED) in the planetary boundary layer (PBL) parameterization scheme of a mesoscale model. Due to the coarser grid spacing of the mesoscale model, the effects of large eddies in the boundary layer cannot be resolved. In this study, a large-eddy simulation (LES) of Hurricane Harvey (2017) is used as a benchmark to relate the effects of large eddies to the VED of momentum. The derived relationship is then applied to improve a popular PBL parameterization scheme, which has been widely used in the mesoscale models. It is found that compared to the original scheme, the modified YSU scheme leads to improved forecasts of landfalling hurricanes.
Hong et al., 2006) is not always comparable to observations (Gopalakrishnan et al., 2013). F. Zhang and Pu (2017) found that an overlarge VED $K_m$ of inland hurricanes in the HWRF model will accelerate TC decay.

Meanwhile, previous studies have verified that roll vortices (RVs), a type of large-scale turbulence eddies (large eddies or LEs), prevail in the hurricane PBL (Huang et al., 2018; Katsaros et al., 2000; Wurman & Winslow, 1998). Numerical simulations by Foster (2005), Gao and Ginis (2016), and Gao et al. (2017) indicate that these large-scale eddies can generate strong flux, in contrast to those predicted by the standard downgradient diffusive parameterizations of turbulence with mesoscale numerical models. The omission of RVs leads to poor hurricane wind structure and precipitation forecasts (Ernst et al., 2019).

In light of the linkage between both VED and LEs (e.g., RVs and other types of LEs) with surface fluxes and also the omission of LEs in the PBL scheme within mesoscale numerical models, in this study, we explored an improved PBL parameterization scheme with VED modified by adding the effects of LEs. We hypothesize that VED uncertainties in the mesoscale model are linked with the omission of LEs’ effects. Considering the ability of large-eddy simulation (LES) to capture large-scale rolls in a hurricane PBL (Zhu, 2008a, 2008c), we used LES simulated by LES in the Weather Research and Forecasting (WRF-LES) model during the landfall of Hurricane Harvey (2017) to characterize the effect of LEs in the hurricane PBL and then parameterized the LE effects into the Yonsei University (YSU) PBL scheme (Hong, 2010; Hong et al., 2006). Specifically, the YSU scheme uses buoyancy intensity to represent the contribution of large-scale eddy and added to the mixed-layer velocity scale ($w_s$) to calculate the VED (Hong, 2010; Hong et al., 2006). An LE velocity scale ($w_{le}$) that is related to LE vertical intensity was used to calculate the VED caused by LEs. The modified PBL scheme was evaluated using the WRF simulations of two landfalling hurricanes, Harvey (2017) and Florence (2018).

2. WRF-LES and Analysis Method

A simulation of Hurricane Harvey (2017) using the one-way nested WRF-LES model (version 3.9.1) around its landfall from 0000 UTC 25 to 1800 UTC 27 August 2017 was used to obtain LE characteristics for parameterization. In the simulation, four-level nested domains were configured with grid meshes (horizontal resolution) of $150 \times 150$ (12.5 km), $251 \times 281$ (2.5 km), $951 \times 1,131$ (0.5 km), and $1,401 \times 1,401$ (0.1 km), respectively. The outer two domains were set up with the YSU PBL scheme (Hong, 2010; Hong et al., 2006), and the inner two domains did not use the PBL scheme but used the three-dimensional turbulence kinetic energy (TKE) 1.5 closure scheme to derive the subscale turbulence. Other physical schemes include the Kain and Fritsch (Kain, 2004) deep convection scheme, which was activated only in domain 1. The Thompson cloud physics scheme (Thompson et al., 2008), Rapid Radiative Transfer Model (RRTM, Mlawer et al., 1997), Dudhia scheme (Dudhia, 1989), Noah land-surface scheme (F. Chen & Dudhia, 2001), and revised MM5 Monin-Obukhov scheme were used for cloud, long-wave radiation, short-wave radiation, land surface, and surface parameterizations, respectively.

With the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) final analysis (FNL) 0.25 $\times$ 0.25° data, 71 vertical levels with the lowest model level approximately of 2 m were used in the model. During the hurricane landfall, domain 4 was moved 3 times to follow Hurricane Harvey: first, from 0600 UTC to 1800 UTC 25 August 2017; second, from 1800 UTC 25 to 1200 UTC 26 August 2017; and finally, from 1200 UTC 26 to 1800 UTC 27 August 2017. As the width of LEs varied from several hundred to several thousand meters (Morrison et al., 2005), the inner most domain data were used to analyze the LEs in this study, called the LES result hereafter. The results from domain two were used as the standard mesoscale run with the YSU PBL scheme.

For the first two domains, the turbulence was generated directly from the YSU scheme, while for the LES, a horizontal two-dimensional Gaussian filter was introduced into the simulation results to filter out the turbulence fields:

$$G(x, y) = \frac{1}{2\pi \sigma^2} e^{-\frac{x^2 + y^2}{2\sigma^2}},$$

(1)
where \(x\) and \(y\) are the grids in the \(x\) and \(y\) directions. To better compare with the original run at the horizontal grid resolution of 2.5 km, the bandwidth, which indicates the filter region, was set at 25 × 25 for domain 4 to filter out the turbulence eddies at wavelengths less than 2.5 km. The Gaussian function standard deviation \(\sigma\) of 10 was selected as the good filter turbulence (nearly normal distributed turbulence) after the sensitivity test. The variables, i.e., \(u, v, w, t,\) and \(q\), were smoothed with the two-dimensional Gaussian filter, and the turbulence field with the LE signal, including RVs, was then produced by subtracting the smoothed field. Figure 1 compares the horizontal wind at 10-m of height from domains 1 and 4 at 1400 UTC 25 August 2017 (Figures 1a and 1b), respectively, and the sample of the vertical part of turbulence vorticity \(d\omega/dx\) from domain 4 (Figure 1c). We found a strong perturbation in LES results with coupled upward and downward turbulence (i.e., LEs). These LEs tend to be aligned along the mean wind direction, indicating RVs mainly attribute the LEs.

3. Parameterization of LEs and a Modified YSU PBL Scheme

The simulation results indicate that the LEs prevailed and controlled the turbulence in the LESs. The simulation verification shows that the LES provided better hurricane wind vertical structure and precipitation simulations compared with radar observations. The simulation with the YSU PBL scheme overestimated the precipitation for the hurricane over the ocean, while at the same time the LEs and their effects were missing (figures not shown).

3.1. LE Intensity

The purpose of LE parameterization is to restore the contribution of LEs to VED inside the YSU scheme. First, we introduce LE intensity \(I_w (\omega^w)\) to describe the intensity of related large-scale turbulence eddies; \(\omega^w\) is the vertical component of LE turbulence. According to LES results, LEs prevail where there is an inflow convergence in the same column below 400 m of height. The inflow convergence causes vertical perturbation and finally generates strong LEs. There is a link of the inflow convergence and strong LEs. However, in WRF model simulations, it is hard to differentiate the inflow and tangential wind of TCs from the \(u\) and \(v\) components of wind directly since the process requires defining TC center location, which could cost additional computations and induce uncertainties. We therefore used horizontal divergence instead of inflow divergence to link with \(I_w\). Based on dimen-
sional analysis of Iw and horizontal divergence, we assume that the maximum Iw (Iwm) is proportional to the square of the mean horizontal divergence below 400 m in a column:

\[ I_{wm} = a \cdot \text{div}^2, \quad (2) \]

where \( \text{div} \) is the mean horizontal divergence below 400 m; positive \( \text{div} \) was ignored as it reflects divergence below 400 m. The coefficient \( a \) is the linear fitting coefficient based on the LES result. Figure 2a shows the relationship of Iwm and \( \text{div}^2 \); \( a \) is equal to 1.97, and there is a significant relationship between Iwm and \( \text{div}^2 \), with a determination coefficient \( (R^2) \) of 0.78. Thus, for the modified PBL scheme, Iwm can be derived by the mean horizontal divergence in the same column below 400 m.

With Iwm, to generate the profile of Iw, we first determine the height (Hm) of Iwm occurrence. Based on the LES result, it was found that Hm always varies near the height of minimum wind speed shear \( (du/dz) \) in the same column. Figure 2b shows the mean profile of \( du/dz \) and Iw in the same column from the LES result during simulation period. It can be seen that Hm is close to the height of minimum \( du/dz \). The wind shear would impact the generation of LES and arrange the vertical distribution of Iw. Therefore, Hm is represented by the height of the minimum \( du/dz \). Then, with Hm and Iwm, derived by \( \text{div}^2 \), the normalized Iw (divided by Iwm in the same column) profile can be described by an adjust Gamma distribution function:

\[ f(h) = \left( \frac{h}{100} \right)^{H_{wm}/300} e^{-h/300}, \quad (3) \]
where \( h \) is the height above the ground; 300 is a special height that is close to \( H_m \) and usually appears in the LES results; and \( g(h) \) is the normalized Iw profile distribution function. Figure 2c gives an example of \( g(h) \) and a real normalized Iw profile at 1700 UTC 25 August 2017 from the LES result, showing a good estimate of the Iw profile. Finally, the Iw profile in a single column was derived:

\[
I_w(h) = I_{w,m} \cdot g(h),
\]

where \( h \) is the height above the ground.

3.2. Vertical Eddy Diffusivity

Similar to the YSU scheme, in which a mixed-layer velocity scale \( w_s \) is used to determine the vertical eddy diffusivity of momentum \( K_m \), in this study, we used a similar velocity scale \( w_{sr} \) for LE to determine the LE-induced \( K_{mr} \), that is, \( K_{mr} \):

\[
K_{mr} = w_{sr} \cdot h \left( 1 - \frac{h}{H_t} \right)^2,
\]

where \( h \) is the height above the ground, and \( H_t \) is the height of the top of LEs. Here, we assumed that \( H_t \) is the height above \( H_m \) and with \( I_w = 0.05 I_{w,m} \). A height of 3,000 m was used as the maximum of \( H_t \). \( K_{mr} \) is the difference in \( K_m \) between the LES result and the original run. Next we explored the relation between \( w_{sr} \) and Iw from the LES result. According to the dimensional analysis of these two variables, \( w_{sr} \) may be proportional to the square root of Iw. Therefore, a linear fitting method was applied:

\[
w_{sr} = b \cdot I_w^{1/2},
\]

where \( b \) is the linear coefficient. From Figure 2d, which shows the relationship between \( w_{sr} \) and the square root of Iw in the PBL and the free atmosphere, \( b \) is equal to 0.08 in the PBL and 0.20 in the free atmosphere. Then, combined with Iw, derived by mean horizontal divergence with the distribution function \( g(h) \), \( K_{mr} \) was determined by Equation 6 in the modified PBL scheme. Finally, this calculated \( K_{mr} \) was added to the YSU scheme derived \( K_m \) to generate the final VED of momentum.

For the VED of heat (\( K_{hr} \)) and moisture (\( K_{qr} \)) preceded by LEs, Figure 2e shows the variation of mean \( K_{hr}/K_{mr} \) and \( K_{qr}/K_{mr} \) with \( K_{mr} \) at each 10 m² s⁻¹. It was found that both \( K_{hr}/K_{mr} \) and \( K_{qr}/K_{mr} \) were very consistent with these values in the YSU scheme. This means that LEs contributed more to turbulence momentum flux than to heat and moisture flux. To simplify the calculation, we set the mean value of 4.79 × 10⁻² as a fixed value for \( K_{hr}/K_{mr} \) and \( K_{qr}/K_{mr} \) in the LE parameterization. Finally, with \( K_{mr}, K_{hr}, \) and \( K_{qr} \) were generated and added to the YSU scheme derived \( K_m, K_h, \) and \( K_q \) to obtain the final VED of \( K_m, K_h, \) and \( K_q \) in the modified PBL scheme.

4. Evaluation Results

After modifying the YSU PBL scheme with the parameterization of LE, numerical simulations were conducted for landfalling Hurricanes Harvey (same period as mentioned above) and Florence (from 0000 UTC 13 to 0000 UTC 17 September 2018) by the one-way nested WRF model with the modified PBL scheme to assess the impacts of the new PBL scheme. The simulations were done with two domains (domains 1 and 2) and with the same physics package as the outer two domains of the WRF-LES model described above, with both the original and modified PBL schemes for comparison (refer to original run and modified run, respectively). Available observations from the NOAA P3 aircraft and NCEP stage IV precipitation data (Lin & Mitchell, 2005) were used to evaluate the simulated hurricane structure and quantitative precipitation.
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forecasting (QPF). The threat score and bias of QPF were compared between the simulations with the original and modified PBL schemes according to the definition of the threat score and bias:

\[
\text{Threat score} = \frac{\text{correct}}{\text{forecast} + \text{observation} - \text{correct}},
\]

(8)

\[
\text{bias} = \frac{\text{forecast}}{\text{observation}},
\]

(9)

where \(\text{forecast}\) is the point numbers of the simulated QPF with special threshold precipitation, and \(\text{observation}\) represents the point numbers of the QPF from the stage IV data. \(\text{Correct}\) is the point numbers of the correct forecast that agree with the observation.

Figure 3 shows the hourly hurricane track (a, b) and 10-m maximum surface wind evolution (c, d) of Hurricanes Harvey (a and c) and Florence (b and d) during the simulation period against the six-hourly best track from the National Hurricane Center (NHC) report. For Hurricane Harvey, the simulated tracks are close to the actual track before its landfall. After landfall, the original run indicates that the hurricane turned southwest, while the modified run indicates that the hurricane turned east, which is more similar to the best track. For the maximum surface wind, during landfall (0000 UTC to 1200 UTC 26 August 2017), the hurricane in the modified run decayed more slowly than that in the original run, and it was closer to the best track record. The standard deviation of intensity bias was reduced from 7.48 to 5.81.

For Hurricane Florence, the modified run generated a better track simulation during landfall (30–42-h forecast), as it was closer to the best track. Results indicate that the modified YSU scheme improves the track simulation during landfall. For intensity, the forecast with modified PBL scheme provided a better hurricane intensity simulation, with maximum surface wind closer to that of the best track with standard deviation bias reduced from 8.67 to 8.13. Based on these two cases, we can conclude that the modified PBL scheme can improve the simulation of a landfalling hurricane's track and intensity, especially when the track is more complicated.

Figure 4 compares the azimuth-averaged wind profile from radar (Figure 4a), the original run (Figure 4b), and modified run (Figure 4c) of Hurricane Harvey in the same phase. From the radar observations, we found maximum wind always near the ground, while maximum wind (≥54 m s\(^{-1}\)) in the original run extended down to only about 90 m of height. With the modified PBL scheme, an azimuth-averaged wind profile with high wind (≥54 m s\(^{-1}\)) extends down to 60 m of height. Because LEs can strongly mix tangential and radial wind vertically (Gao & Ginis, 2016; Gao et al., 2017), the revised PBL scheme allowed high wind transport downward and provided a better wind profile simulation against the radar observation. At the high level, we also found that maximum wind (≥54 m s\(^{-1}\)) from forecasts with the modified PBL scheme extended up about 3,000 m, which is again closer to the radar observations that has maximum wind (>49 m s\(^{-1}\)) extended up to about 3,000 m. Note that although the model has slightly overestimated the wind speed, the modified run revealed a more realistic wind structure overall. Guimond et al. (2018) found that RV structure could extend up to several kilometers in radar observations. The introduction of LE effects into the PBL scheme led to better wind profile simulations that are more similar to radar observations.

The difference in the threat score and bias of QPF between the forecasts with the modified and original PBL schemes against the stage IV data is shown in Figures 3e and 3f, respectively. The QPF calculation ended 12 h after landfall. We found that the threat score differences were all positive and the bias scores were all negative at each precipitation threshold, implying improved QPF in forecasts with the modified PBL parameterization.

5. Summary and Conclusion

In this study, LESs of Hurricane Harvey were used to parameterize roll vortices, a type of large-scale turbulence eddy, and other large-scale eddies in the hurricane boundary layer. Their effects were then added into the YSU PBL parameterization to improve hurricane forecasts with the WRF model. Dimensional analysis indicated that LE maximum intensity is significantly linearly related to the square of the mean horizontal divergence below 400 m in the same column, with a slope coefficient of 1.97. Horizontal convergence, mainly inflow convergence, at the low level induced strong LEs above. Then, the estimated maximum Iw
Figure 3. The influence of modified PBL scheme on hurricane forecasts. (a, b) The track simulation of Hurricanes Harvey (a) and Florence (b) against the six-hourly best track (black lines) from NHC. (c, d) The evolution of maximum 10-m wind of Hurricanes Harvey (c) and Florence (d) against the six-hourly best track data (black lines) from NHC. The landfall time is represented by the black dashed line. The standard deviation biases of maximum 10-m winds are shown in figures. (e, f) Illustrate the QPF threat score difference (e) and bias difference (f) of Hurricanes Harvey and Florence between the forecasts with modified and original PBL schemes at different precipitation thresholds. The positive (negative) threat score difference (bias difference) denotes improvements from the modified PBL scheme. NHC, National Hurricane Center; PBL, planetary boundary layer; QPF, quantitative precipitation forecasting.
was multiplied by a distribution function to derive the \(I_w\) profile. To estimate the LE-induced VED, a coefficient \(srw\) was used to represent the VED of momentum \(K_m\) preceded by LEs. We then related this to the square root of \(I_w\), with a slope coefficient of 0.08 in the PBL and 0.20 in the free atmosphere. With this relationship, the \(I_w\) derived by mean horizontal divergence was used to calculate and finally generate \(K_{mr}\) in the PBL scheme. For the VED of heat and moisture, a fixed ratio value of 4.79 \(\times\) \(10^{-2}\) between \(K_{hr}\) and \(K_{mr}\) or \(K_{qr}\) and \(K_{mr}\) was used, as LEs made little contribution to heat and moist turbulence flux. Forecast experiments with Hurricanes Harvey and Florence showed that the modified PBL scheme led to improved forecasts of hurricane track, intensity, wind structure, and precipitation. Future work will emphasize operational evaluation with a large number of hurricane cases.

Data Availability Statement
The hurricanes’ best track and radar data are obtained from the NOAA National Hurricane Center (http://www.nhc.noaa.gov). The NCEP FNL data are obtained from the NCAR Research Data Archive (https://rda.ucar.edu/datasets/ds083.2/).

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References
Bu, Y. P., Fovell, R. G., & Corbosiero, K. L. (2017). The influences of boundary layer mixing and cloud-radiative forcing on tropical cyclone size. *Journal of the Atmospheric Sciences*, 74(4), 1273–1292.

Chen, F., & Dudhia, J. (2001). Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model description and implementation. *Monthly Weather Review*, 129, 569–585.

Chen, S. S., Price, J. F., Zhao, W., Donelan, M. A., & Walsh, E. J. (2007). The CBLAST-Hurricane program and the next-generation fully coupled atmosphere–wave–ocean models for hurricane research and prediction. *Bulletin of the American Meteorological Society*, 88(3), 311–318.

Doyle, J. D., Hodur, R. M., Chen, S., Jin, Y. I., Moskaitis, J. R., Wang, S., et al. (2014). Tropical cyclone prediction using COAMPS-TC. *Oceanography*, 27(3), 104–115.

Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of the Atmospheric Sciences*, 46(20), 3077–3107.

Emanuel, K. A. (1986). An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *Journal of the Atmospheric Sciences*, 43(6), 585–605.

Emanuel, K. A. (1995). Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *Journal of the Atmospheric Sciences*, 52(22), 3969–3976.

Ernst, P. A., Jisan, M. A., & Ginis, I. (2019). On the characteristics of hurricane roll vortices over land (SURFO Technical Report No. 19-02. Paper 16. https://digitalcommons.uri.edu/surfo_tech_reports/16).

Foster, R. C. (2005). Why rolls are prevalent in the hurricane boundary layer. *Journal of the Atmospheric Sciences*, 62(8), 2647–2661.

Gao, K., & Ginis, I. (2016). On the equilibrium-state roll vortices and their effects in the hurricane boundary layer. *Journal of the Atmospheric Sciences*, 73(3), 1205–1222.
