The influences of ocean on intensity of Typhoon Soudelor (2015) as revealed by coupled modeling

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Typhoon Soudelor (2015) moved northwestward toward Taiwan and passed several mesoscale ocean eddies over the open ocean. A high-resolution air–sea coupled model HWRF is employed to simulate Soudelor. Coupled model with low- or high-resolution ocean conditions can largely reduce the over-intensification of the typhoon from uncoupled modeling. Coupled modeling with a more realistic finer-resolution Hybrid Coordinate Ocean Model (HYCOM) analysis helps better capture the rapid weakening of the super-intense typhoon for the first 2 days and the following re-intensification before 80 hr, due to the initial more realistic ocean conditions. The rapid weakening is related to the existence of initial cold core ocean eddies near the earlier typhoon, while the warm core eddies tend to decrease the typhoon-induced SST cooling and thus induce the re-intensification of the later typhoon. The typhoon boundary layer is shallower at the rear-right quadrant of the moving typhoon than at that at other quadrants. The coupled modeling results show that a much shallower boundary layer lower than 200 m is produced at the rear-right quadrant for the super-intense typhoon as the typhoon passes over cold core eddies and induces stronger SST cooling. In addition, stronger typhoon cold wake in coupled experiments induces larger inflow angles at lower levels at the rear-right quadrant than other studies. The simulated track near and after landfall at east Taiwan is also improved for the coupled experiment compared to the uncoupled experiment.

KEYWORDS
cold core eddy, typhoon–ocean interaction, Typhoon Soudelor (2015)

1 | INTRODUCTION

The ocean is regarded as an energy source of tropical cyclones (TCs) through the interface with turbulent transfer. Sea surface enthalpy fluxes inside about 7–8 times the radius of the maximum wind speed can clearly influence TC intensity (Miyamoto and Takemi, 2010). The improvement on simulated TC intensity due to ocean coupling has been well elucidated (e.g., Bender and Ginis, 2000; Davis et al., 2008; Yablonsky et al., 2015), in particular, for Megi (2010) over the western North Pacific (WNP; e.g., Wu et al., 2016). Thermal structures of the upper ocean in the vicinity of a TC path can influence the TC intensity. In particular, mesoscale warm core ocean eddies (WCE) provide relatively warmer ocean temperature compared to the surrounding water and can lessen the TC-induced upper ocean cooling, while the cold core eddies (CCE) tend to produce large ocean cooling and reduce the upward surface enthalpy fluxes (e.g., Lin et al., 2005; Walker et al., 2014). On the other hand, ocean eddies may change the ocean mixed-layer depth which is the most important factor in determining the magnitude of the feedback to TC (Wu et al., 2007). Indeed, two rich eddy zones exist in the WNP with the southern eddy zone located at lower latitudes which often highly impacts the passing...
typhoons (e.g., Lin et al., 2005; Wu et al., 2007). Over 90% of the typhoons were collocated with at least one warm or cold ocean eddy during their lifetimes in the WNP from 2002 to 2011 (Ma et al., 2017).

TC-induced ocean cooling may change the lower atmosphere by both dynamic and thermodynamic processes (e.g., Lee and Chen, 2012; 2014; Chen et al., 2017). Sea surface temperature (SST) cooling caused by a TC-induced cold wake tends to produce a stable boundary layer over the cold wake, and the air parcels at this region will stay for a longer time near the surface, which is found to enhance the transport of energetic air into the inner band of the TC. (Lee and Chen, 2014). Stronger inflow at lower layers over the cold wake due to the enhanced pressure gradient brings moister air to the inner core of the TC as identified by idealized simulations (Chen et al., 2017). These cooling-induced atmospheric processes at lower levels may increase the storm efficiency and somewhat offset the thermodynamic effects of decreased enthalpy fluxes due to SST cooling (Lee and Chen, 2014; Chen et al., 2017).

Typhoon Soudelor (2015) headed northwestward toward Taiwan and passed several mesoscale ocean eddies prior to landfall. Soudelor weakens rapidly after the most intense stage and then re-intensifies near landfall at eastern Taiwan (for the typhoon information see http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/s/201513.html.en). In this study, it is our major concern to realize how the intensity and boundary-layer structure of Soudelor can be modulated by different ocean conditions, in particular, with pre-existing ocean eddies. To tackle these issues, an air–sea coupled model is applied to simulate Soudelor with sensitivity experiments to identify the influences of ocean conditions and air–sea coupling on typhoon intensity and structure changes. The intensity changes of Soudelor and associated boundary-layer structural variations when the typhoon passes over ocean eddies are first identified by coupled modeling in this study.

2 | MODEL AND EXPERIMENTS

The Hurricane Weather Research and Forecast system (HWRF) version 3.7a (https://dtcenter.org/HurrWRF/users/index.php; Tallapragada et al., 2016), which is a coupled model system consisting of Weather Research and Forecasting Model - Nonhydrostatic Mesoscale Model (WRF-NMM; https://dtcenter.org/wrf-nmm/users/index.php) and the Princeton Ocean Model (POM) for Tropical Cyclones (MPIPOM-TC; Yablonsky et al., 2015), is used to simulate Typhoon Soudelor (2015) over the WNP. The HWRF has been widely applied in many studies for simulating tropical cyclones/hurricanes (e.g., Gopalakrishnan et al., 2013; Chen and Gopalakrishnan, 2015; Yablonsky et al., 2015). The model physics schemes used in this study are the same as the operational HWRF of National Centers for Environmental Prediction (NCEP). Three nested domains at 18-, 6- and 2-km resolution, respectively, are employed with the two inner moving meshes to trace the typhoon. The model physics schemes used here include the simplified Arakawa-Schubert cumulus parameterization in the parent domain and coarser inner domain, and Ferrier-Aligo cloud microphysics scheme, National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) planetary boundary layer parameterization and the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) longwave and shortwave scheme in all the three domains (for the references of the physics schemes, see Tallapragada et al., 2016). The model initial and boundary conditions use the NCEP Global Data Assimilation System (GDAS) Final Analysis 0.25 × 0.25° data with 6-hr resolution. The ocean conditions of HWRF are initialized by one of the two following data sets: EN4.2.0 monthly temperature below the ocean surface and the daily coarser GFS SST at the ocean surface, or by the high-resolution HYCOM analysis at all depths. During model integration, SST over the WNP is predicted by POM in coupled experiments or remains unchanged in uncoupled experiments. The simulation time of the experiments is from 0000 UTC August 4, 2015 to 0600 UTC August 9, 2015 for a total of 126 hr. The experiments using the coupled model and uncoupled model with the initial HYCOM data (i.e., ocean temperature and salinity) are denoted by CH and UH, respectively. The coupled and uncoupled experiments with the initial GFS SST and EN4.2.0 analysis data are denoted by CG and UG, respectively.

3 | RESULTS AND DISCUSSIONS

3.1 | Track and intensity

As observed by Japan Meteorological Agency (JMA), Soudelor first appeared as a tropical depression at 162.2°E, 13.3°N at 1800 UTC July 29, 2015. It moved northwestward straightly toward Taiwan before landfall. Soudelor developed to a tropical storm at 0600 UTC August 1, 2015 and then intensified rapidly. It was upgraded to a severe tropical storm at 1800 UTC August 1, 2015 and reached typhoon category in 12 hr. Afterward, it reached its most intense state at 1800 UTC August 3, 2015 and kept its intensity for 12 hr with a minimum sea-level pressure (MSLP) of 900 hPa and a maximum wind speed (MWS) of 115 kt given by JMA or a MSLP of 907 hPa and a MWS of 155 kt (category 5) as estimated by Joint Typhoon Warning Center (JTWC). Soudelor weakened rapidly in about 2 days and then reached a quasi-steady state before landfall at Taiwan according to the observation from JMA (shown later in Figure 2). Note that there is slight re-intensification of Soudelor (with a MSLP changed from 959 to 944 hPa and a MWS from 85 to 105 kt) from JTWC as it approached landfall. The typhoon
made landfall at Hualian County (near central eastern Tai-
wan) at 2100 UTC August 7, 2015 and then rapidly
weakened.

The simulations start from the most intense state of Sou-
delor at 0000 UTC August 4, 2015. Compared with the best
tracks from both JMA and JTWC, all the experiments have
similar northward biased tracks as seen in Figure 1a. This
northward bias can be attributed to the simulated weaker
subtropical high systems with less westward extension for
all the experiments (figures not shown). The simulated
typhoons in Experiments CH and UG make landfall at the
northern tip of Taiwan at about 90–96 hr, while those in UH
and CG move around Taiwan and make landfalls at Fujian
Province of China. The simulated track near and after land-
fall at east Taiwan is also improved for the coupled experi-
ment CH compared to the uncoupled experiment UH. However, these experiments obtain different simulated
typhoon intensities (Figure 2) in spite of their similar tracks.
CH intensity weakens rapidly from the most intense state
and gives MSLP closest to the JTWC and JMA observations
for the first 2 days, while weakening is not such rapid in CG
with an over-intensified MSLP at this stage. When the
typhoon is closer to Taiwan, the re-intensification as
observed by JTWC can be well captured in CH, while absent
in CG. On the other hand, the uncoupled experiments UH
and UG maintain their stronger intensities for the first 3 days
when the typhoon is away from Taiwan because of the
absence of the typhoon-induced SST cooling (Figure 3a,b).
Note that the SSTs in the uncoupled experiments are the
same as the initial SST of the coupled experiments. After
80 hr, the typhoon intensities in the uncoupled experiments
weaken more rapidly than those in the coupled experiments.
The air–sea coupled processes significantly improve the
intensity simulation of the typhoon prior to landfall in terms
of both MSLP and MWS.

3.2 | Impacts of ocean eddies on SST change

The pre-existing mesoscale ocean eddies can be located and
identified by the satellite observed sea surface height anom-
alies (SSHs). Positive SSHs implies Warm Core Eddy
(WCE), while negative SSHs indicates Cold Core Eddy
(CCE; Lin et al., 2005). Figure 1b shows the SSHs in the
basin covering the path of Soudelor from July 24, 2015 to
August 3, 2015 observed by Jason-2 satellite altimeter. A
number of mesoscale ocean eddies were observed, which
already emerged before the interaction with the upcoming
typhoon. Typhoon Soudelor passes over several CCEs and

FIGURE 1 (a) Tracks of Typhoon Soudelor (2015) including the best
track of JMA (solid black line) and JTWC (dashed black line), the simulated
tracks using the uncoupled model with fixed HYCOM SST (UH) and GFS
SST (UG) initialized at 0000 UTC August 4, 2015, and using the coupled
model with initial HYCOM data (CH) and GFS and EN4.2.0 data
(CG) from 0000 UTC August 4, 2015 to 0600 UTC August 9, 2015. The
simulated tracks are calculated by the GFDL vortex tracker. Circle symbols
mark typhoon centers every 24 hr; (b) sea surface height anomaly (shading, m)
from July 24, 2015 to August 3, 2015 observed by Jason-2 satellite
altimeter and the observed and simulated (CH) track of Soudelor

FIGURE 2 (a) The time evolution of minimum mean sea-level pressure
for the simulated experiments (CH: blue, CG: red, UH: green, UG: cyan)
and the observed by JMA (black solid line) and JTWC (black dashed line); (b)
as in (a) but for the maximum wind speed at 10-m height
then a sizable WCE prior to landfall. The ocean conditions in the coupled experiments CH and CG are compared to investigate the influence of these eddies. Although the simulated typhoon tracks display a northward bias, the typhoon still penetrates through those ocean eddies.

At the initial time, CH shows similar SST distributions as those in CG (Figure 3a,b). Indeed, CH initialized by the more realistic HYCOM analysis data with finer resolution can include more realistic variations of mesoscale ocean eddies. We find that the initial ocean temperature profiles in both CCE and WCE regions for HYCOM analysis used in CH are closer to the in-situ observations of Argo floats than those in CG (figures not shown). Except for the typhoon-induced cold wake at the back of the moving typhoon, a relatively cooler SST region is located north of the typhoon path in both experiments. This cooler SST may be attributed to the upper-layer cooling induced by Typhoon Halola (2015) which passed about 10 days before the initial time of our simulations. The along-track cross-section of ocean potential temperature averaged in a radius of 200 km shows that the initial upper ocean temperature at the CCE region in the vicinity of the typhoon path is cooler in CH than that in CG, while warmer in the WCE region (figures not shown).

After 2 days, the typhoon moves across the CCE region. Stronger SST cooling is induced by the wake at the rear of the typhoon in CH than in CG, as evident in Figure 3c,d. The minimum SST near the typhoon track is cooler than 25 °C in CH, while warmer than 25.5 °C in CG. Consequently, the upward enthalpy fluxes at the air–sea interface averaged in the finest domain of WRF (within a radius of about 400 km from the typhoon center) in the first 2 days are 322.64 W/m² for UH, 208.44 W/m² for CH and 221.01 W/m² for CG. The cooler along-track SST and smaller enthalpy fluxes in CH are consistent with the developed

![FIGURE 3](a) Initial SST (color shading, °C) at 0000 UTC August 4, 2015, simulated track (dashed) and best track (solid) for CG, and asterisk for the simulated typhoon center; (b) as (a) but for CH; (c, d) as in (a, b) but for the simulated SST at 0000 UTC August 6, 2015 for CG and CH, respectively; (e, f) as in (c, d) but at 0000 UTC August 8, 2015 for CG and CH, respectively.
weaker typhoon intensity at this time (see Figure 2). The uncoupled experiment UH produces much larger enthalpy fluxes due to the absence of the typhoon-induced SST cooling, which is in agreement with the simulated much stronger typhoon intensity. Note that the relatively cooler SST also exists north of the typhoon due to the initial cooler SST. When the typhoon moves closer to Taiwan, it passes over a sizable WCE (see Figure 1b). The simulated SST near the typhoon in CH is somewhat warmer than that in CG (Figure 3e,f) because of the weaker typhoon-induced cooling of the initial warmer upper ocean. The enthalpy flux averaged from 24 to 48 hr is 235.43 W/m² for CH and 210.37 W/m² for CG. As a result, the re-intensification of the typhoon is present in CH in response to these larger enthalpy fluxes, while absent in CG (see Figure 2).

3.3 | Responses of the lower atmosphere to SST change

To further identify the atmospheric responses of the stronger typhoon-induced SST cooling over ocean CCE, we separate the typhoon to four quadrants through the location relative to the moving typhoon center. The height of thermodynamic typhoon boundary layer (TBL) can be defined as the height of the level with virtual potential temperature \( \theta_v \) 0.5 K higher than the surface value (Lee and Chen, 2012; 2014). Figure 4 shows the daily averaged TBL height when the typhoon passes over CCEs. The TBL heights in CH exhibit significant variations, but mainly with east–west asymmetry along the typhoon moving direction (Figure 4a). Outside of the inner typhoon vortex, the induced TBL can be as high as 1 km. The typhoon-induced SST cooling produces a much shallower TBL less than 200 m trailing in the rear of the typhoon, which is much lower than the simulated TBL of Typhoon Chio-Wan (2009) (Lee and Chen, 2014). This shallower TBL in Soudelor can be attributed to the induced stronger SST cooling in response to the pre-existence of the CCEs (see Figure 1b) and the super-intensity of the typhoon. On the other hand, the TBL heights in UH are north–southward asymmetric and more suppressed to the north of the vortex center (Figure 4b) as induced by the initial cooler SST in the vicinity of the typhoon path (see Figure 3b).

We further investigate the dynamic effect of such strong SST cooling over CCE on the typhoon intensity which is related to the storm relative inflow angle at lower levels as shown in Figure 5. The inflow is averaged from 1200 UTC 5 August to 1200 UTC August 6, 2015 (36–60 hr). The front quadrants are associated with larger inflow angles outside of the eyewall than the rear quadrants as shown in Figure 5a,d. Indeed, the inflow angles at the rear quadrants become positive (i.e., outflowing) inward of the eyewall in CH, and even become much more enhanced at the rear-right quadrant in UH (Figure 5f). Stronger outflow inside the eyewall for UH supports the stronger updrafts in the eyewall of the more intense typhoon. The inflow angles of the typhoon near the surface are somewhat larger in UH than those in CH due to the stronger convergence of the former, except for the rear-right quadrant (Figure 5d,f). For both experiments, larger near-surface inflow angles are produced to the right of the moving typhoon center. The typhoon-induced cold wake in the coupled experiment CH tends to produce larger low-level inflow angles to increase the storm efficiency at the rear-right quadrant compared with those in UH (Figure 5d,f), in agreement with previous studies (e.g., Lee and Chen, 2014; Wu et al., 2016; Chen et al., 2017). The inflow angles near the surface at the rear-right quadrant in the coupled experiment can be as large as 25°, which are considerably larger than those presented in Lee and Chen (2014).

4 | CONCLUSIONS

Typhoon Soudelor (2015) moved northwestward toward Taiwan and passed several mesoscale ocean eddies over the
open ocean. It is our main concern to realize how these eddies would influence the intensity and boundary-layer structure changes of the typhoon. In this study, a high-resolution air–sea coupled model HWRF thus is employed to simulate Soudelor. Ocean coupling with low- or high-resolution ocean conditions is found to largely reduce the over-intensification of Soudelor from uncoupled modeling, due to the presence of typhoon-induced SST cooling along the track. Furthermore, coupled modeling with a more realistic finer-resolution HYCOM analysis helps better capture the rapid weakening of the super-intense typhoon for the first 2 days and the following re-intensification before 80 hr, due to the initial more realistic ocean conditions. The rapid weakening is related to the existence of initial cold core ocean eddies near the earlier typhoon, while the warm core eddies tend to decrease the typhoon-induced SST cooling and thus induce the re-intensification of the later typhoon. The typhoon boundary layer is shallower at the rear-right quadrant of the moving typhoon than that at other quadrants. Our coupled modeling results for the super-intense typhoon support previous studies, but with a much shallower boundary layer at the rear-right quadrant of the moving typhoon than that at other quadrants. Our coupled modeling results for the super-intense typhoon support previous studies, but with a much shallower boundary layer at the rear-right quadrant of the moving typhoon than that at other quadrants.

**FIGURE 5** Storm relative inflow angle (shading, negative values for inward) of typhoon translational direction and the contour lines at every 10° averaged from 1200 UTC August 5, 2015 to 1200 UTC August 6, 2015, (a) at the front-left quadrant for CH; (b) as in (a) but at the front-right quadrant; (c) as in (a) but at the rear-left quadrant; (d) as in (a) but at the rear-right quadrant; (e) as in (b) but for UH; (f) as in (d) but for UH.
experiment compared to the uncoupled experiment, although not as significantly as for intensity forecast. This study provides a further understanding of the TC boundary-layer structure under air–sea interaction and supports recommendation to apply an air–sea coupled model in the prediction of TC across the ocean eddies.

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