Rapid Decay of Slowly Moving Typhoon Soulik (2018) due to Interactions With the Strongly Stratified Northern East China Sea

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Abstract

Typhoon Soulik decayed rapidly via two-way interaction with the northern East China Sea, the extratropical shelf region, before landing on the Korean Peninsula on 23 August 2018. In the northern East China Sea, where the water column is strongly stratified with warm surface and cold subsurface waters, a large cold wake emerged with intense sea surface cooling, which is primarily caused by vertical mixing in the water column. This abrupt sea surface cooling rapidly increased the downward enthalpy flux, mostly in the form of latent heat flux. The slow translation speed of Typhoon Soulik and strong thermal stratification in the region transferred its energy into the ocean, as the typhoon had a long residence time over the wake, and consequently led to rapid decay with energy loss to typhoon intensity ratio of $-4.4 \pm 1.0$ hPa (kJ cm$^{-2}$ s$^{-1}$).

Plain Language Summary

Understanding and predicting tropical cyclones, including typhoons, are very important for reducing and preventing damages to life and property. In August of 2018, Typhoon Soulik was predicted to make landfall on the Korean Peninsula as a strong cyclone with high winds. However, the typhoon rapidly weakened over the northern East China Sea before making landfall—a failed prediction. This study reveals that the rapid decay was caused by two-way interactions between the typhoon and the ocean on the continental shelf. Strong mixing with cold subsurface water due to the high winds associated with the slowly moving typhoon significantly lowered the sea surface temperature, leading to energy loss into the ocean for a sufficiently long period of time to cause rapid decay. These results provide quantitative evidence of energy exchange between the typhoon and the ocean, which can help to improve forecasts of tropical cyclone intensity particularly in the stratified shelf region.

1. Introduction

It is becoming increasingly important, particularly considering the large uncertainty of future tropical cyclone (TC) intensity in a warming ocean, to better understand interactions between the ocean and TCs. In spite of the notable improvements to TC track predictions over recent decades, predictions of TC intensity remain far from accurate (DeMaria et al., 2014; Gao et al., 2017; Kaplan et al., 2010). Given the importance to TC intensity of energy exchange in the form of surface enthalpy flux (i.e., the sum of sensible and latent heat fluxes; Emanuel, 1986; Jaimés et al., 2015; Price, 2009) between the ocean and TCs, the sea surface temperature (SST) has been shown to be a key player (DeMaria & Kaplan, 1994; Lin et al., 2003; Price, 1981). Recent studies have suggested that subsurface ocean temperatures need to be considered when predicting intensities because SST, as an oceanic response to TCs, including sea surface cooling (SSC), is significantly affected by the preconditions of subsurface thermal stratification and mixed layer depth (Lin et al., 2008, 2013; Nam et al., 2012; Shay et al., 2000). Background wind fields, such as vertical wind shear, entrainment of dry air, and translation speed, have also been considered as important factors affecting changes in TC intensity (Braun et al., 2012; Gao et al., 2016; Mei et al., 2012; Wang et al., 2015).

TC-ocean interaction in the shelf region is unique compared with that in the open ocean. Only a few studies have been conducted on TC-ocean interaction in the continental shelf region (Glenn et al., 2013, 2016; Potter et al., 2019; Price, 2009) and one of the major issues is the existence of bottom cold water, which significantly...
increases the stratification over the water column. This leads to larger SSC (~5–10 °C) than that in the open ocean (~1–2 °C) when a TC passes over. Previous studies, however, only focused on very limited cases of TC intensity variations in the shelf region due to rare in situ observations of the interaction processes. It is, thus, essential to investigate more and better cases of TC-ocean interaction on thermally stratified shelf under various conditions for a better understanding of TC intensity variations.

In the extratropical shelf region of the northern East China Sea (NECS) where TCs or typhoons frequently pass by, a strong contrast in the subsurface thermal structure of the ocean has been reported around Jeju Island, Republic of Korea (white lines in Figure 1). On the eastern side of the island, warm water carried by the Tsushima Warm Current (TWC or Eastern Kuroshio Branch), a branch of the Kuroshio Current, prevails over the upper ocean year-round (Lie & Cho, 1994, 2016), whereas cold subsurface waters, known as the Yellow Sea Bottom Cold Water (YSBCW), produced in the Yellow Sea west of the Korean Peninsula in winter, expands equatorward and the thermal stratification is significantly enhanced by seasonal surface heating during summer on the western side. Such a zonal contrast in the preconditions of the subsurface thermal stratification is believed to cause contrasting SSC (i.e., strong on the western side) during TC passage, ultimately resulting in stronger (eastern side) or weaker (western side) TCs (Lee et al., 2016; Moon, 2005; Moon & Kwon, 2012).

Despite efforts at understanding and predicting typhoon intensity variation, the intensity of Typhoon Soulik (1819), which passed over the western side of Jeju Island, was significantly overpredicted, indicating insufficient understanding of the quantitative influence of the thermal condition of the ocean, among others, on TC intensity. Here the strong case of rapid weakening of Typhoon Soulik over the strongly stratified extratropical shelf region is analyzed. We present the results of a quantitative analysis of the TC-ocean interactions for Typhoon Soulik, including the TC-induced SSC, size and distribution of the cold wake, changes in enthalpy flux, and TC-ocean energy transfer, taking into consideration the residence time over the cold wake in the NECS. The consequent variations in TC intensity and their implications on other TCs over the extratropical shelf regions are also analyzed.

2. Data and Methods

The best track data from the Regional Specialized Meteorological Center (Kunitsugu, 2012) were used to characterize the intensity and translation of Typhoon Soulik. The spatiotemporal structure of the ocean response to the typhoon was examined by analyzing the optimally interpolated cloud-free daily satellite products extracted from microwave and infrared SSTs at a spatial resolution of 10 km (Gentemann et al., 2009). The time series of wind, specific humidity, and subsurface temperatures observed at depths of 2, 5, 11, 16, 22, 32, and 37 m at the Ieodo Ocean Research Station (I-ORS; 32°7.4′N, 125°10.9′E constructed at a water depth of 41 m; cross in Figure 1) with a typical sampling interval of 10 min were used to analyze the temporal variations in the vertical thermal structure, surface enthalpy flux, and ocean heat content per unit area (Ha et al., 2019). Since the location of I-ORS is in the cold wake during the typhoon period, the data fairly represent the ocean response in the region. The climatological means of subsurface ocean temperatures and the surface geostrophic currents in August were obtained from the World Ocean Atlas 2018 (WOA18) temperature data (horizontal resolution of 0.25° grid; Locarnini et al., 2018) and the sea surface height (horizontal resolution of 0.25° grid from 1993–2015) provided by the Copernicus Marine Environment Monitoring Service (Taburet et al., 2019), respectively. The specific humidity and air temperature at 10 m above the sea surface along the typhoon track were obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) reanalysis data (time interval of 1 hr and horizontal resolutions of 0.5° latitude × 2/3° longitude; Gelaro et al., 2017).

Three-hourly time series of the position, central pressure ($P_c$), and maximum wind speed ($W_{max}$) of Typhoon Soulik were calculated by linearly interpolating the best track data. Then, the displacement of the typhoon was calculated every 3 hr and the translation speed ($U_h$) was defined as the displacement divided by the time interval. The steering flow of the typhoon, defined as the mean wind between 850 and 200 hPa for the period from 18–20 August 2018 (i.e., 2 days before the typhoon entered the region), and the vertical wind shear between 250 and 850 hPa and the mean relative humidity averaged over 500–700 hPa were estimated from the MERRA-2 data. All variables along the typhoon track (center positions) were estimated by three-
A depth-averaged ocean temperature from the surface to the target depth, $T_{da}(t)$, and the ocean heat content relative to 10 °C water per unit area ($OHC$) at the I-ORS were estimated as

$$ T_{da}(t) = \frac{1}{h} \int_{-h}^{0} T(z,t) \, dz, \quad (1) $$

and

$$ OHC(t) = \rho_0 c_{wp} \int_{-h}^{0} [T(z,t)-10] \, dz, \quad (2) $$

respectively, where $t$ is the time and $z$ is the vertical coordinate; $\rho_0$ is the density of the reference seawater (1,025 kg m$^{-3}$); $c_{wp}$ is the specific heat of water at constant pressure (4,178 J kg$^{-1}$ °C$^{-1}$). The vertical integrations in equations (1) and (2) were performed using a trapezoidal method. As ocean response to the typhoon, the $OHC$ is defined using the reference temperature of 10 °C considering the minimum temperature observed at the I-ORS (10.8 °C), whereas the conventional $OHC$, which affects the typhoon intensity (i.e., TC heat potential), is estimated as 26 °C. It should be noted that the reference temperature only affects the mean $OHC$ and not the temporal variations used here. Heat fluxes between the ocean and the atmosphere (positive upward) at the maximum wind region were calculated using the bulk formula (equation (3a)),

$$ Q_s = \rho_a c_p C_h |W_{max}| (SST-T_a), \quad (3a) $$

$$ Q_l = \rho_a c_{vap} C_q |W_{max}| (q_s-q_a), \quad (3b) $$

where $Q_s$ and $Q_l$ are the sensible and latent heat fluxes, respectively; $C_h$ and $C_q$ are the exchange coefficients of sensible and latent heat fluxes estimated using the methods proposed by Jaimes et al. (2015); $\rho_a$ is the air...
density ($1.22 \text{ kg m}^{-3}$); $c_p$ is the specific heat of air at a constant pressure ($1,004 \text{ J kg}^{-1} \text{ °C}^{-1}$); and $L_{\text{vap}}$ is the latent heat of vaporization ($2.5 \times 10^6 \text{ J kg}^{-1}$). The air temperature and the specific humidity at 10 m height are denoted as $T_a$ and $q_a$, respectively, and $q_s$ is the saturated specific humidity at the SST. Here we assume that $q_s$ is at 98% saturation at the SST. The differences in temperature and moisture between the ocean and the atmosphere are $\Delta T = SST - T_a$ and $\Delta q = q_s - q_a$, respectively. Uncertainties in the enthalpy flux are estimated using the root-mean-square deviation between the enthalpy flux observed from the I-ORS data and that estimated from the satellite-based SST, $q_s$ and $T_a$ from MERRA-2, and $W_{\text{max}}$ during the typhoon period.

The horizontal wind fields in and around the TC are simply reconstructed for the estimation of the area-integrated kinetic energy and heat energy transfer from the surface enthalpy flux over the cold wake region. The wind field, assumed as axisymmetric, is estimated to follow the modified Rankine Vortex (Mueller et al., 2006) as

$$W = W_{\text{max}} \frac{r_w}{R_m}, \text{ when } r_w < R_m,$$
$$W = W_{\text{max}} \frac{R_m}{r_w}, \text{ when } r_w > R_m,$$

$$(4)$$

with $x = \frac{\ln(50\text{ knot})}{\ln(30\text{ knot})}$ and $R_m = r_w \frac{W_{\text{max}}}{W_{\text{max}}}$,

where $W$ is the surface wind speed with respect to the distance from the TC center ($r_w$); $R_m$ is the radius of maximum wind; $x$ is the horizontal scale factor with two radii of wind speed of 50 knots ($rs_{50\text{ knot}}$) and 30 knots ($r_{30\text{ knot}}$) that are derived from the best track data. The kinetic energy of TC at $r_w = R_m$ is calculated as $\frac{1}{2} \frac{p_{\text{air}}}{g} W_{\text{max}}^2$; and the area-integrated kinetic energy over the cold wake region as $\int \frac{1}{2} \frac{p_{\text{air}}}{g} W^2 \text{d}A$, where $p_{\text{air}}$ is the air pressure at the sea surface ($=10^5 \text{ N m}^{-2}$), $g$ is the gravity constant ($=9.8 \text{ m s}^{-2}$), and $A_{\text{cw}}$ is the area of the cold wake region (circle with a radius of 80 km). The heat energy transfer per unit area is calculated by time-integrating $Q_a + Q_l$ during the decay period and the total heat energy transfer over the cold wake region is estimated by area and time integrating the enthalpy flux over $A_{\text{cw}}$ from the reconstructed $W$, $\Delta T$, and $\Delta q$ at the cold wake region during the decay period.

3. Results
3.1. Rapid Decay of Typhoon Soulik

Typhoon Soulik developed from a tropical depression to a TC off northwestern Guam, United States, at 00:00 UTC 16 August 2018 (15.6°N, 143°E; hereafter, time information is presented in UTC). The typhoon gradually strengthened, translating northwardwest, and produced its maximum intensity with $P_c = 950 \text{ hPa}$ and $W_{\text{max}} = 44 \text{ m s}^{-1}$ from 18:00 on 20 August (27.0°N, 133.3°E) and maintained its intensity until it passed the Kuroshio Current (Figure 1). After it passed the Kuroshio region (03:00 22 August; 30.7°N, 129.2°E) and before making landfall (09:00 23 August; 34.3°N, 126.1°E), the typhoon decayed rapidly in the NECS. It can be observed that $P_c$ increased by 22.5 hPa and $W_{\text{max}}$ decreased by 12 m s$^{-1}$ over a 30-hr period (Figures 1a and 2a). Off the western side of Jeju Island, the typhoon recurved from northwestward to northeastward, and produced its minimum translation speed, $U_h \approx 2 \text{ m s}^{-1}$ (Figures 1a and 2b). After making landfall, the typhoon passing by the Korean Peninsula was downgraded to a tropical depression at 12:00 on 24 August (40.1°N, 132.0°E).

3.2. Ocean Response to Typhoon Soulik

Abrupt SSC was observed at the I-ORS during the passage of Typhoon Soulik in the NECS (Figures 1 and 3a). Before the typhoon passed by the I-ORS, the water column was strongly stratified: the near-surface (depth level of 2 m) water temperature was 26.4 °C and the near-bottom (depth level of 37 m) water temperature was 13.7 °C at 12:00 on 21 August (Figure 3a). As the typhoon approached to the I-ORS, the near-surface temperature abruptly decreased to 20.2 °C (00:20 23 August) (Figure 3a). The near-bottom temperature dramatically increased up to 23.5 °C (13:40 22 August) along with the severe SSC (by 6.2 °C at I-ORS). The entire
The water column was nearly uniform for a few hours after the typhoon passed by the I-ORS (17:00 on 22 August), showing a vertically constant temperature (22.2 °C; SSC by 4.2 °C), which is only 0.2 °C lower than the depth-averaged temperature ($T_{37\text{m}}$) before the typhoon (22.4 °C; averaged from 12:00 on 21 August to 10:00 on 22 August), indicating intense vertical mixing of the water column from the surface to

Figure 2. Time series of variables along the track of Typhoon Soulik: (a) central pressure ($P_c$) and maximum wind velocity ($W_{\text{max}}$); (b) temperature and translation speed ($U_h$), with sea surface temperature (SST) and upper 30-m-averaged temperature $T_{30\text{m}}$; (c) specific humidity at 10 m height ($q_a$) and saturated specific humidity at the SST ($q_s$); difference in (d) temperature and moisture between the ocean and atmosphere ($T$ and $q$); (e) sensible and latent heat fluxes ($Q_s$ and $Q_l$) and their sum with its uncertainties (gray shade). The vertical dotted and dashed lines denote the moments when Typhoon Soulik started to decay (03:00 22 August) and its center position was closest to the I-ORS (15:00 22 August).
the bottom (Figure 3a) by the typhoon. According to this result, vertical mixing played a dominant role in the total SSC (4.2 °C out of 6.2 °C, 70%) compared with other processes (2.0 °C out of 6.2 °C, 30%). After the passage, \( T_{da}^{37m} \) continuously decreased to 16 °C. The decrease in the OHC at I-ORS from 180 kJ cm\(^{-2}\) (12:00 21 August) to 100 kJ cm\(^{-2}\) (00:20 23 August) along with the decrease in the SST to 20.2 °C while the typhoon resided over the cold wake can hardly be explained by the surface enthalpy flux. In the heat budget of a water column, the OHC cannot be changed by vertical mixing within the water column but only by the surface enthalpy flux and horizontal heat transport. The gain in OHC due to the typhoon’s energy loss (\( OHCEF \), e.g., time integration of the surface enthalpy flux from 12:00 21 August) estimated from the I-ORS observations cannot account for the change in the OHC observed at the I-ORS (Figure 3b). Thus, the decrease in the OHC was primarily due to the horizontal advection of the vertically mixed/upwelled colder water around the I-ORS after the typhoon passed by. Similarly, the gradual SSC even after the strong vertical mixing was caused by horizontal advection (accounting for 30%; i.e., 2.0 °C out of 6.2 °C).

Before Typhoon Soulik entered the NECS, the satellite-based SST on 21 August exceeded 26 °C everywhere in the region (28–36°N, 122–130°E; Figure 1b), with the warmer (>29 °C) water in the southern and the eastern areas. After the typhoon passed by the NECS, the SST on 23 August exhibited dramatic cooling in the southwestern region off Jeju Island (Figure 1c). The lowest SST (<20 °C) with the largest SSC (~8.1 °C) was observed in the region between the I-ORS and Jeju Island. The cold wake, defined here as the area where the SSC was higher than 5 °C, was large with a horizontal area of ~2 × 10^4 km\(^2\) (i.e., \( A_{cw} \); Figure 1a). The cold wake on the western side of Jeju Island is related to the preconditions of the subsurface thermal structure before the typhoon passage. The precondition, shown from the climatological mean \( T_{da}^{30m} \) in August, indicates the zonal contrast in the subsurface thermal distribution (i.e., cooler/warmer subsurface waters on the west/east of the island), yielding \( T_{da}^{30m} < 24^\circ C \) within the cold wake (Figure 1a). This contrast in the thermal structure is associated with the equatorward extension of the YSBCW on the western side and a thick
layer of upper-ocean warm water carried by the TWC on the eastern side of the island (Figure 1a). Vertical mixing by the typhoon along with the thermal precondition induced this cold wake in the limited area.

The variation in SST along the track of Typhoon Soulik mainly followed the subsurface thermal structure of the ocean. The along-track SST following the typhoon center reached its maximum (29 °C) at 18:00 on 21 August when the center was located over the Kuroshio Current (Figure 1). The SST gradually decreased until the typhoon center was located over the cold wake, where the YSBCW is located and reached its minimum (22 °C) at 21:00 on 22 August (Figures 1 and 2b). The SST variation following the track of the typhoon center was very similar to those of the climatological mean in August, $T_{\text{SST}}^{\text{cl}}$ (Figure 2b). This is because the cold wake, with such intense SSC, could be induced only when the typhoon passed over the western side of the island, where cold subsurface waters reside every summer (August). The SSC would not have been so severe if the typhoon passed over the eastern side, as the enhanced vertical mixing by typhoon winds does not effectively decrease the SST where the warm water in the upper ocean carried by the TWC is thick. Unlike the typical case, the maximum SSC occurred on the left side of the typhoon tracks, which also highlights the influence of the subsurface thermal precondition on the SSC.

### 3.3. Response of Typhoon Soulik to the Ocean

It is clear from the comparison between the enthalpy flux and the typhoon intensity that the rapid decay of Typhoon Soulik was primarily due to the reduced upward enthalpy flux (Figure 2). The upward enthalpy flux along the TC track reached its maximum (approximately +480 W m$^{-2}$) at 18:00 on 21 August, when the typhoon center was located in the Kuroshio region and the typhoon maintained its high intensity (not shown). The enthalpy gradually decreased and Typhoon Soulik started to decay when the sign of the enthalpy flux changed from upward to downward after 03:00 on 22 August (Figures 2a and 2e). The enthalpy flux continued to decrease (increasing downward flux) and reached its minimum (approximately $-810$ W m$^{-2}$) on 21:00 22 August.

Enthalpy flux ($Q_l$: ~80% and $Q_s$: ~20%) was the most sensitive parameter to the SSC. The $Q_s$ along the TC track decreased from 12:00 on 21 August to 21:00 on 22 August (Figures 2b and 2e), which is primarily due to the SSC (>6 °C) rather than the change in $T_a$ (~1.6 °C). Furthermore, the $Q_l$ is largely determined by the decrease in $\Delta q_l$, which is explained by the decrease in $q_s$ ($8.2 \times 10^{-3}$ kg kg$^{-1}$) rather than that of $q_a$ ($1.5 \times 10^{-3}$ kg kg$^{-1}$) during the period (Figures 2b and 2e). Thus, the response of the typhoon to the ocean was primarily controlled by the SSC, induced in-turn by the ocean response to the typhoon via the vertical mixing of the water column between warm surface water and cold subsurface water, as well as through the horizontal advection of vertically mixed/upwelled colder water into the area.

Two factors should be considered regarding the rapid decay of Typhoon Soulik, resulting from the reduced upward enthalpy flux: (1) the strongly stratified precondition needed to shape the severe cold wake and (2) the slow translation of the typhoon, which maximized the residence time over the cold wake. Since the YSBCW extends equatorward on the western side of Jeju Island and the surface water is warmed by seasonal heating during summer (August), thermal stratification becomes very strong in the area, allowing the cold wake to develop and be enhanced by vertical mixing due to the high winds accompanying typhoons. The decrease in the enthalpy flux controlled by the SSC is further enhanced by the remarkably slow (~2 m s$^{-1}$) translation of the typhoon over the cold wake. The minimum translation speed ($U_{\text{tr}}$) is found where the zonal steering flow vanishes and the typhoon center recurves (Figure 1a), ensuring that the typhoon remains over the cold wake for a long time (~15 hr (from 12:00 on 22 August to 03:00 on 23 August). During the rapid decay period (from 03:00 on 22 August to 09:00 on 23 August), the typhoon lost its energy (per unit area: $4.3 \pm 0.6$ kJ cm$^{-2}$ and area-integrated over the cold wake region: $6.4 \times 10^{17}$ J) to the ocean together with the long residence time and the strong downward enthalpy flux over the cold wake, which is about one order of magnitude larger than the change in the typhoon's kinetic energy (per unit area: 0.5 kJ cm$^{-2}$ and area-integrated over the cold wake region: $3.9 \times 10^{16}$ J). The ratio of energy transfer from the typhoon to the ocean to the resultant increase in the central pressure, $P_c$, during the decay period was $-4.4 \pm 1.0$ hPa (kJ cm$^{-2}$)$^{-1}$.

### 4. Discussions and Conclusions

Typhoon Soulik exhibits a strong case of rapid decay of TC in the shelf region. In previous studies, weakening of the intensity was not so large (increase in the central pressure of <10 hPa) or intensification even
occurred because of the short residence time over the cold wake with fast (~10 m s⁻¹) translation (Glenn et al., 2013, 2016) or the absence of cold water below the surface (Potter et al., 2019; Price, 2009). The rapid decay of typhoon Soulik, comparable to the previous definition (i.e., decrease in the maximum wind speed by more than 20 knots in 24 hr; DeMaria et al., 2012), occurred with the ideal conditions of (1) severe SSC associated with thermal precondition and (2) sufficient time period associated with slow translation for ocean–TC interaction on the well stratified shelf region. The quantitative results of the rapid decay of TC presented here are applicable to other shelves (e.g., the Mid-Atlantic Bight in the United States).

This study suggests that the downward energy flux between the typhoon and the ocean was a dominant factor for the rapid decay of Typhoon Soulik. The ratio of the increase in the central pressure (Pc) to the downward enthalpy flux of Typhoon Soulik (~0.012 ± 0.003 hPa (W m⁻²)⁻¹, from 18:00 on 21 August to 21:00 on 22 August) was comparable with that obtained from a numerical experiment (the order of 10⁻² hPa (W m⁻²)⁻¹; Halliwell et al., 2015) on open ocean typhoons under restricted atmospheric conditions (with no impacts of vertical wind shear, entrainment of dry air, etc.). Furthermore, the amount of heat transfer is significantly larger than that of kinetic energy decrease during the decay period. These indicate that the downward enthalpy flux with a long residence time is sufficient to decay the intensity of the typhoon. In addition, in the period of Typhoon Soulik, the vertical wind shear between 250 and 850 hPa decreased in the vicinity of the Korean Peninsula and the relative humidity averaged over 500–700 hPa was not significantly low near the vortex center, which are not favorable to rapid decay (not shown).

In this paper, we highlighted the importance of two-way interaction processes between the ocean and typhoons on the stratified shelf based on the strong case of rapid decay of Typhoon Soulik. The interactions are sensitive to the typhoon track because the NECS has a zonal contrast in its thermal stratification; for example, they are significantly affected by cold subsurface water for typhoons translating northward on the western side of Jeju Island. In the strongly stratified waters off the western side of the island, vertical mixing was enhanced by the high winds associated with the typhoon, along with horizontal advection, causing abrupt SSC (>8 °C), which led to enhanced downward enthalpy flux. The slow (<2 m s⁻¹) translation speed over the large (~2 × 10⁶ km²) cold wake resulted in a high time-integrated energy transfer from the typhoon to the ocean (4.3 ± 0.6 kJ cm⁻²), enough to decay the typhoon rapidly, at the rate of ~4.4 ± 1.0 hPa (kJ cm⁻²)⁻¹. This strong case of rapidly decaying Typhoon Soulik over the NECS provides a better understanding of TC (including hurricane) intensity, which will improve the accuracy of intensity predictions by considering two-way interactions, particularly between slowly translating typhoons and the strongly stratified extratropical shelf ocean.

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