Observed near-surface currents under four super typhoons

Yu-Chia Chang, Peter C. Chu, Luca R. Centurioni, Ruo-Shan Tseng

1. Introduction

The characteristics of current velocities in the upper ocean under moving tropical cyclones (TCs) were obtained in many theoretical, observational, and numerical studies. Direct current measurements under TCs during their passages include moored current meters, airborne expendable current profilers (AXCPs), drifting buoys, electromagnetic-autonomous profiling explorer (EM-APEX) floats, Surface Velocity Program (SVP) (Niiler, 2001) drifters, and acoustic Doppler current profilers (ADCPs). Maximum current velocities of 0.3–1.0 m s\(^{-1}\) were observed from earlier current meter moorings in the ocean mixed layer (OML) and thermocline as hurricanes passing by within about 60–100 km of these moorings (Brink, 1989; Brooks, 1983; Dickey et al., 1998; Shay and Elsberry, 1987). Strong rightward-biased currents in the upper OML were identified from 0.8 to 1.7 m s\(^{-1}\) from AXCPs under tropical storm (TS), category-1, category-3, and category-4 hurricanes (Price et al., 1994; Sanford et al., 1987; Shay and Uhlhorn, 2008), and from 1.0 to 1.5 m s\(^{-1}\) from 3 profiling EM-APEX floats under category-4 hurricanes 2004 (D’Asaro et al., 2007; Sanford et al., 2011).

Maximum current velocities of 2.0 m s\(^{-1}\) and 1.7 m s\(^{-1}\) were observed under a category-4 typhoon (Shanshan 2006) and a category-2 typhoon (Haitang 2005) in the Pacific Ocean and the Taiwan Strait (Chang et al., 2010) from the SVP drifter data. Maximum velocities of 0.4–1.6 m s\(^{-1}\) in the OML were observed from an ADCP mooring under three fast-moving storms (Black and Dickey, 2008). Maximum velocities of 0.8 m s\(^{-1}\) and 0.4 m s\(^{-1}\) were also observed from 3 ADCPs inside the radius of wind speeds of 28 m s\(^{-1}\) and 18 m s\(^{-1}\) during category-5 Hurricanes Katrina and Rita in 2005 (Jaimes and Shay, 2009). However, the ADCPs were located at 4.5 times of the radius of maximum wind (4.5R\(_{\text{max}}\)) for Hurricane Katrina and 17.5R\(_{\text{max}}\) for Hurricane Rita. The strongest currents with a maximum velocity of 2.1 m s\(^{-1}\) were measured on the shelf of northeastern Gulf of Mexico in 2004 by an array of 14 ADCPs during category-4 Hurricane Ivan passing through (Mitchell et al., 2005; Teague et al., 2007). The observed maximum current velocities and the storm’s track in the earlier studies are listed in Table 1.

In addition to current acceleration, existing modeling studies showed that TCs enhance drastically the upper ocean mixing and in turn affect the fluxes of heat and moisture across the air–ocean interface and change the dynamic height and sea surface temperature with the bias towards the right-side (Chang and Anthes, 1978; Chu et al., 2000; Jacob and Shay, 2003; Olabarrieta et al., 2012; Price, 1981; Price et al., 1994; Warner et al., 2010; Yablonsky and Ginis, 2009; Zambon et al., submitted for publication); and that TCs’ passage affects upper ocean responses to the Kuroshio currents in the northwestern Pacific (Kuo et al., 2011; Tsai et al., 2008; Wu et al., 2008).

Two types of oceanic response to a moving TC exist depending on the Froude number, F\(_{\text{r}}\) = U\(_{\text{t}}\)/C\(_{\text{t}}\), with U\(_{\text{t}}\) the TC’s translation speed, and C\(_{\text{t}}\) the phase speed of the first baroclinic mode, which is about 2.8 m s\(^{-1}\) in the northwestern Pacific Ocean during summer (Chang et al., 2013). For F\(_{\text{r}}\) > 1, the response is baroclinic with a wake consisting of the near-inertial waves as the dominant feature. For F\(_{\text{r}}\) < 1, the oceanic response is barotropic without wake, but with upwelling in the TC’s center.
### Title

**Observed near-surface currents under four super typhoons**

### Authors

Naval Postgraduate School, Naval Ocean Analysis and Prediction Laboratory, Department of Oceanography, Monterey, CA, 93943

### Abstract

The upper ocean currents under four category-5 (super) typhoons [Chaba (2004), Maon (2004), Saomai (2006) and Jangmi (2008)] were studied using data from four drifters of the Surface Velocity Program (SVP) (Niiler 2001) in the northwestern Pacific. Maximum current velocities occurring to the right of the super typhoon tracks were observed as 2.6 m s\(^{-1}\) for slow-moving Maon, 2.1 m s\(^{-1}\) for typical-moving Chaba, 1.4 m s\(^{-1}\) for fast-moving Jangmi, 6.8 m s\(^{-1}\) for fast-moving Saomai. Furthermore, dependence of the mixed layer current velocity under a super typhoon on its translation speed and statistical relationships between the maximum current speed and the Saffir-Simpson hurricane scale are also provided.

### Distribution/Availability Statement

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### Security Classification

- **Report**: Unclassified
- **Abstract**: Unclassified
- **This Page**: Unclassified
The initial horizontal scales of TCs’ wake depend directly on the scales of the atmospheric forcing (Gill, 1984). The typhoon wind-forcing on the ocean mixed layer (OML) currents is near-resonant on the right side but not on the left side of the track (Price, 1981, 1983; Price et al., 1994). Thus, the OML currents were acquired from the best-track data from the Joint Typhoon Warning Center (JTWC, http://meto2.nmci.navy.mil/jtwc.php). The SVP drifter has a drogue centered at a depth of 15 m beneath the sea surface to measure OML velocities. The velocity data with a 6-hourly resolution were obtained from the Global Drifter Program (GDP) website (http://www. aoml.noaa.gov/phod/dac/dacdata.php) (Hansen and Poulain, 1996). The estimated accuracy of the velocity measurements is $10^{-2}$ m s$^{-1}$ using SVP drifters in a 10 m s$^{-1}$ wind (Niiler et al., 1995).

The four SVP drifters (Argos ID: 39606, 2236911, 54688, and 70324) measured the near-surface current velocities under the four super typhoons [Chaba (2004), Maon (2004), Saomai (2006), and Jangmi (2008)] (see Fig. 1). Figs. 2 and 3 show the drifters’ trajectories, observed current vectors, and storms’ tracks. The four drifters were all located on the right sides of the four storm tracks as the typhoons passed by.

Chaba (2004) was a typical-moving TC. At 00:00 on 22 August, it was in category-3 with a translation speed of 7.0 m s$^{-1}$ and a distance (D) of 140 km between the drifter 39606 and storm center. The observed current velocity ($U_{obs}$) from the drifter was 0.9 m s$^{-1}$. When Chaba reached category-4 intensity at 06:00 on 22 August, its translation speed $U_{0}$ decreased to 5.5 m s$^{-1}$; and the observed current velocity increased to 1.5 m s$^{-1}$ with $D = 59$ km. Six hours later, Chaba was identified as a category-5 typhoon, and the translation speed $U_{0}$ decreased slightly to 5.1 m s$^{-1}$ (Fig. 4). A maximum velocity of 2.1 m s$^{-1}$ was measured with $D = 69$ km.

Maon (2004) was a slow-moving TC. As the storm gradually approached the drifter 2236911 ($D = 278, 201, 135, 73,$ and 31 km), it still moved slowly with the translation speeds of 3.2–3.6 m s$^{-1}$ within 30 h (Fig. 5). Maon strengthened from a category-1 to category-2 intensity during this period. The observed current velocities gradually
increased (0.4, 0.7, 0.8, 1.1, and 1.7 m s$^{-1}$). Due to the slower $U_h$ and the curved storm track (Fig. 3b), the drifter moved towards the storm’s center, and stayed at $D - R_{\text{max}}$ for the following 36 h (18:00 on 6 October–00:00 on 8 October). During that period, Maon rapidly intensified, and became a category-5 typhoon at 18:00 on 7 October. At that time, a maximum velocity of 2.6 m s$^{-1}$ was measured ($U_h = 2.9$ m s$^{-1}$, $D = 52$ km).

Saomai (2006) was a fast-moving storm. Its translation speeds were usually 6–9 m s$^{-1}$ (Fig. 6). As approaching rapidly to the drifter 54688 ($D = 287$, 108, and 74 km), it strengthened to a category-5 typhoon. But the observed current velocities increased slowly ($U_{\text{obs}} = 0.7$, 1.1, and 1.2 m s$^{-1}$), with a maximum velocity of 1.2 m s$^{-1}$ ($U_h = 8.1$ m s$^{-1}$, and $D = 74$ km).

Jangmi (2004) was also a fast-moving TC. At 12:00 on 26 September, Jangmi became a category-4 storm, and approached the drifter 70324 ($D = 484$ km, $U_h = 6.4$ m s$^{-1}$). The drifter-measured $U_{\text{obs}}$ was 0.6 m s$^{-1}$ (Fig. 7). When Jangmi reached category 5 intensity at 06:00 on 27 September, its translation speed $U_h$ decreased to 6.7 m s$^{-1}$, and $U_{\text{obs}}$ increased to 0.8 m s$^{-1}$ ($D = 86$ km). But, the drifter was in front of the storm center at that time (Direction = 25°). Six hours later, it was still a category-5 typhoon, and the translation speed $U_h$ increased slightly to 6.8 m s$^{-1}$. The drifter was on the right side of the storm center (Direction = 110°). A maximum velocity of 1.4 m s$^{-1}$ was measured ($D = 86$ km). Thus, besides the storm’s intensity, the two parameters ($D, U_h$) are also important for causing high current speeds.

4. Dependence of observational current velocity ($U_{\text{obs}}$) on $U_h$

The maximum current velocities under Chaba, Maon, Saomai, and Jangmi were 2.1, 2.6, 1.2, and 1.4 m s$^{-1}$ (Figs. 4, 5, 6, and 7) when they were in category 5, with the distance $D = 52$–85 km, i.e., within 1–2 $R_{\text{max}}$ from the TC center [mean $R_{\text{max}} = 47$ km (Hsu and Yana, 1998)]. Although the four drifters were under comparable storm intensities with similar distances ($D$), different maximum current velocities (2.1, 2.6, 1.2, and 1.4 m s$^{-1}$) were observed. Note that the TCs translation speeds ($U_h$) were very different: 5.1, 2.9, 8.1, and 6.8 m s$^{-1}$, as the maximum velocities were observed.

Traditionally, the ocean OML currents during typhoon passage are mainly determined by the wind stress with a maximum current speed located to the right of the storm track at $-1-2R_{\text{max}}$ (Brooks, 1983; Chang et al., 2013). Within this range the linear regression was conducted between $U_{\text{obs}}$ (unit: m s$^{-1}$) on the right side of the storm center (45° $\leq$ Direction $\leq$ 135°), see Table 3) and $U_h$ at $D = 1-2R_{\text{max}}$ ($D = 38-95$ km, see Table 3),

$$U_{\text{obs}} = -0.256U_h + 3.24 \left(2.9 \text{ m s}^{-1} \leq U_h \leq 8.1 \text{ m s}^{-1}\right)$$

as shown in Fig. 8 (blue color “x” and lines) with a high correlation coefficient ($r = 0.958$). The p-value is 0.05 and 95% prediction interval was used. As the translation speeds of super typhoons are 3, 4, 5, 6, 7, and 8
m s⁻¹, the corresponding current velocities at ~1–2 $R_{\text{max}}$ are approximately 2.5 ± 0.6, 2.2 ± 0.6, 2.0 ± 0.5, 1.7 ± 0.5, 1.5 ± 0.6, and 1.2 ± 0.6 m s⁻¹. Figs. 4–7 show significant decrease of the OML velocity at several $R_{\text{max}}$ away from the TC track, especially 150 to 200 km (~3–4$R_{\text{max}}$) from the storm center.

Due to more sampling velocity data points were available in this study for each storm during the stage of very strong winds in larger range of $D – 0.5 – 3R_{\text{max}}$ ($D = –24–141$ km), the linear regression was further conducted under category-5 storms between $U_{\text{obs}}$ (unit: m s⁻¹) on the right side of the storm center ($30^° \pm$ Direction $\pm 150^°$, see Table 3) and $U_h$ at $D = –0.5 – 3R_{\text{max}}$.

$$U_{\text{obs}} = –0.247U_h + 3.13 \left(2.9 \text{ m s}^{-1} \leq U_h \leq 8.7 \text{ m s}^{-1}\right)$$

as shown in Fig. 8 (red color circles and lines) with a high correlation coefficient ($–0.932$). The 95% prediction interval was also used. The dependence of $U_{\text{obs}}$ on $U_h$ under super typhoons is quite stable from the comparison between Eq. (1) and Eq. (2).

5. Dependence of the maximum velocity ($U_{\text{max}}$) on the TC’s intensity ($S$)

Quantitative dependence of the maximum velocity ($U_{\text{max}}$) on the Saffir–Simpson hurricane scale ($S$) has not been established. Table 4 shows the qualitative relationship between $U_{\text{max}}$ (unit: m s⁻¹) inside $D – 3R_{\text{max}}$ ($D < –150$ km) and the Saffir–Simpson hurricane scale ($S$) from a tropical storm to a category-5 super typhoon, the mean OML velocity data under all storms from the earlier studies (shown in Table 1) and from the SVP drifters under the four category-5 typhoons from this study are combined to get a linear regression equation using a 95% prediction interval,

$$U_{\text{max}} = 0.234S + 0.689 \left(0 \leq S \leq 5\right)$$

which shows a strong linear relationship with a high correlation coefficient ($0.98$) between $U_{\text{max}}$ and $S$ with one standard deviation as the error bars (Fig. 9).

Chang et al. (2012) used 11 years of wind and drifter data to show the relationship between the mean SVP drifter-measured ocean current speeds and the observed wind speeds of QuikSCAT with the error bars of one standard deviation for high wind speed of 20–50 m s⁻¹. The SVP drifter-measured ocean current velocities have errors of 0.3, 0.4, and 0.5 m s⁻¹ for 20, 35, and 47 m s⁻¹ winds, respectively. The results of Chang et al. (2012) were also plotted in Fig. 9 as the color blue. The mean velocity and error bars of one standard deviation in the study under $S = 0, 1, 2$ (red color) are consistent with the results of Chang et al. (2012).

Using 40 years of storm track data, Mei et al. (2012) suggested 5.4 m s⁻¹ as the mean $U_h$ for category-5 storms, and 4.5 m s⁻¹ for tropical storms. In order to construct general relationships between $U_{\text{max}}$ (unit: m s⁻¹) inside $–3R_{\text{max}}$ and $S$ for slow- and fast-moving storms, we separated storms into “slow-moving” ($U_h = 2.0–4.0$ m s⁻¹), “typically-
Fig. 3. Four storms’ paths and observed current vectors, both in 6-hourly interval.

Fig. 4. Time evolution (6 hourly) of (a) storm’s maximum sustained wind speed (VMAX), (b) storm’s translation speed ($U_h$), (c) distances ($D$) between storm’s center and drifter 39606 and (d) observed current speeds during Chaba. Shadings denote the duration during which the drifter was under a super typhoon and affected by the typhoon ($D < 400$ km).

Fig. 5. Time evolution (6 hourly) of (a) storm’s maximum sustained wind speed (VMAX), (b) storm’s translation speed ($U_h$), (c) distances ($D$) between the storm’s center and drifter 2236911 and (d) observed current speeds during Maon. Shadings denote the duration during which the drifter was under a super typhoon and affected by the typhoon ($D < 400$ km).
moving” \( U_h = 4.0 - 6.0 \text{ m s}^{-1} \) and “fast-moving” \( U_h = 6.0 - 8.0 \text{ m s}^{-1} \) categories. Two linear regressions,

\[
U_{\text{max}} = 0.334S_{\text{slow}} + 0.814 \quad (0 \leq S_{\text{slow}} \leq 5),
\]

\[
U_{\text{max}} = 0.141S_{\text{fast}} + 0.577 \quad (0 \leq S_{\text{fast}} \leq 5),
\]

are obtained with a 95% prediction interval (Fig. 10). Four maximum velocities under typical-moving storms fall in the region between the two regression lines. The \( U_{\text{max}} \) under Ivan 2004 (Teague et al., 2007) had a larger current speed of 2.1 m s\(^{-1}\), because the \( U_{\text{max}} \) was observed at 6 m depth by an ADCP. The observed velocity of 2.1 m s\(^{-1}\) at 6 m depth could contain a higher Stokes drift velocity. These general relationships between maximum OML velocity and all storms’ intensity levels from observed data would also benefit modeling and simulation.

6. Current velocity scale \( U_h \)

The current velocity scale \( U_h \) (or called the expected current velocity) in the OML to a moving storm is estimated by Price (1983),

\[
U_h = \frac{\tau_s R_{\text{max}}}{\rho_0 W^2},
\]

where \( \tau_s \) is the magnitude of the surface wind stress; \( \rho_0 \) is the character-

istic density of seawater (\( \approx 1025 \text{ kg m}^{-3} \)); and \( h \) is the OML depth, which is usually taken as 50 m in the northwestern Pacific during summer from the National Oceanographic Data Center (NODC) objectively analyzed monthly mean data (Chang et al., 2013). The climatological (summer) World Ocean Atlas (WOA) temperature profiles from NODC were used to show the OML depth at each grid point in the Gulf of Mexico, the North Atlantic, and the North Pacific in Fig. 11. The summer OML depths are about 50 m in the western equatorial Pacific and Atlantic. The summer OML depth in the Gulf of Mexico is closer to 40 m. In the previous study, Price et al. (1994) also used OML depths of 50 m and 60 m in the Gulf of Mexico to calculate \( U_h \) during Hurricanes Gloria and Josephine. Thus, we use \( h = 50 \) m to calculate \( U_h \) in Eq. (6).

The wind stress \( (\tau_s) \) is given by

\[
\tau_s = \rho_0 C_D W^2
\]

where \( \rho_0 \) is the air density; \( C_D \) is the drag coefficient; and \( W \) is the wind speed at 10 m height. Typically, \( \rho_0 \) is about 1.22 \text{ kg m}^{-3} for the moist air (Zedler, 2009). Recent results indicated a saturation value of \( C_D \) at the wind speed of 28–33 m s\(^{-1}\) (Donelan et al., 2004; Jarosz et al., 2007; Powell et al., 2003). Three semi-empirical formulas from Powell et al. (2003), Black et al. (2007), and Jarosz et al. (2007) are used in this

### Table 3

<table>
<thead>
<tr>
<th>Name &amp; ID</th>
<th>Time</th>
<th>Scale</th>
<th>( U_h ) (m s(^{-1}))</th>
<th>( D ) (km)</th>
<th>Direction (degree)</th>
<th>( U_{\text{obs}} ) (m s(^{-1}))</th>
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study to represent such dependence of $C_D$ on $W$ (Zedler et al., 2009). Thus, the estimated wind stress $\tau$ under category-5, -4, -3, -2, -1 storms and tropical storm can be calculated from the wind speeds of 70, 65, 55, 45, 40, and 30 m s$^{-1}$ (see Table 4). The estimated storm’s $U_h$ was also listed in Table 4. The scaled current speeds ($U_s$), which were estimated from $C_D$ of Jarosz et al. (2007), are more similar to the observed $U_{max}$ (Table 4). Since the direct surface wind measurements are sparse under tropical cyclones, uncertainty exists in the estimate of maximum sustained wind speed (VMAX) and $R_{max}$.

The effects of OML depth, Stokes drift, and local background flow should also be addressed. The OML depth was taken as 40–50 m for the northwestern Pacific during summer in previous studies (Chang et al., 2013; de Boyer Montegut et al., 2004), however, it varies in time and space depending on the fluxes of momentum, heat, and moisture across the air–ocean interface, the gradient below the mixed layer, and upwelling (Chu, 1993; Chu et al., 1990; Chu and Garwood, 1991). Ardhuin et al. (2009) indicated that the surface wind-related Lagrangian velocity is the sum of the strongly sheared Stokes drift and a relatively uniform quasi-Eulerian current in the open ocean. The wave data in the four super typhoons are not available. The SVP drifter measurements are drogued to 15-m depth, which is still in a region of significant swell influence (Terray et al., 1996). The spatially asymmetric wave Stokes drift velocity imposed in the large-eddy simulation is generated by a spectral wave prediction model adapted to a category-4 hurricane (Frances 2004) moving at a speed of 5.5 m s$^{-1}$ (Sullivan et al., 2012). The largest Stokes drift at the water surface occurs in along-track component of approximately 0.5 m s$^{-1}$ on the right side of the storm track. The Stokes drift velocity decays with depth rapidly from the surface on a scale (i.e., the Stokes depth). The local background flow or vorticity can change the current structure and the frequency of the near-inertial

![Fig. 8. Dependence of the observed current velocity ($U_{max}$) on the storm’s translation speed ($U_h$) under three category-5 storms at $-1-2R_{max}$ (blue color) and $-0.5-3R_{max}$ (red color).](image)

![Fig. 9. Dependence of observed current speed on the Saffir–Simpson hurricane scale (S) with the error bars showing one standard deviation ($S = 0$: the tropical storm, $S = 1$: the category-1 storm, $S = 2$: the category-2 storm, ... etc.).](image)

![Fig. 10. Dependence of the maximum current velocity ($U_{max}$) on all storms’ intensity levels (S) for slow-moving (red color, $U_h = 2.0-4.0$ m s$^{-1}$), typical-moving (black color, $U_h = 4.0-6.0$ m s$^{-1}$), and fast-moving storms (blue color, $U_h = 6.0-8.0$ m s$^{-1}$) in earlier and this studies ($S = 0$: the tropical storm, $S = 1$: the category-1 storm, $S = 2$: the category-2 storm, ... etc.).](image)

### Table 4

<table>
<thead>
<tr>
<th>Typhoon scale (Saffir–Simpson)</th>
<th>Storm’s translation speed</th>
<th>Max current velocity, $U_{max}$ (m s$^{-1}$)</th>
<th>Wind-driven horizontal velocity, $U_s$ (m s$^{-1}$)</th>
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<td>All</td>
<td>Fast-moving 1.2</td>
<td>1.2, 1.2, 1.2</td>
<td></td>
</tr>
</tbody>
</table>
current. Background divergent flow will damp near-inertial motions (Gill, 1984; Jaimes and Shay, 2010).

7. Conclusions

This study characterizes the response of upper ocean velocity to the four super typhoons [Chaba (2004), Maon (2004), Saomai (2006), and Jangmi (2008)] in the northwestern Pacific from the analysis on the observed ocean current data from four SVP drifters and typhoon track data from JTWC. Strong OML currents occur to the right of the storm track served ocean current data from four SVP drifters and typhoon track data Jangmi (2008) in the northwestern Pacific.

Conclusions are congruent with recent studies (Olabarrieta et al., 2012; Warner et al., 2010; Yablonsky and Ginis, 2012) and provide useful tool for model validation.

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