



Observed near-surface currents under four super typhoons



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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 (2.9 m s^{-1}) Maon, 2.1 m s^{-1} for typical-moving Chaba (5.1 m s^{-1}), 1.4 m s^{-1} for fast-moving Jangmi (6.8 m s^{-1}), and 1.2 m s^{-1} for fast-moving Saomai (8.1 m s^{-1}). 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.

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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 $0.3\text{--}1.0 \text{ m s}^{-1}$ 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 hurricane Frances 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 $0.4\text{--}1.6 \text{ m s}^{-1}$ 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 ($4.5R_{max}$) for Hurricane Katrina and $17.5R_{max}$ 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, $F_r = U_h/c_1$, with U_h the TC's translation speed, and c_1 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 $F_r > 1$, the response is baroclinic with a wake consisting of the near-inertial waves as the dominant feature. For $F_r < 1$, the oceanic response is barotropic without wake, but with upwelling in the TC's center

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Table 1
Observed maximum current speeds in earlier studies and corresponding storm track data.

Storm's name	Hurricane scale	U_h ($m s^{-1}$)	Instrument	Distance (km)	Depth (m)	Reference	U_{max} ($m s^{-1}$)
Frederic (1979), Gulf of Mexico	Category-3	6.5	Current meter	80	21	Shay and Elsberry (1987)	0.9
Allen (1980), Gulf of Mexico	Category-4	3.5	Current meter	60	200	Brooks (1983)	0.9
Norbert (1984), Pacific	Category-1	3.2	AXCP	89	35	Price et al. (1994)	1.1
Josephine (1984), Atlantic	Tropical storm	3.5	AXCP	35	70	Price et al. (1994)	0.8
Gloria (1984), Atlantic	Category-1	6.8	Current meter	100	159	Brink (1989)	0.3
Gloria (1985), Atlantic	Category-1	6.8	AXCP	131	55	Price et al. (1994)	1.7
Gilbert (1988), Gulf of Mexico	Category-3	5.6	AXCP	50	30	Shay et al. (1992)	1.4
Felix (1995), Atlantic	Category-1	6.9	Current meter	65	25	Dickey et al. (1998)	1.0
Isidore (2002), Gulf of Mexico	Category 3	4.0	AXCP	*	60	Shay and Uhlhorn (2008)	1.7
Lili (2002), Gulf of Mexico	Category 4	7.0	AXCP	*	50	Shay and Uhlhorn (2008)	1.1
Fabian (2003), Atlantic	Category-3	8.6	ADCP	102	60	Black and Dickey (2008)	1.6
Frances (2004), Atlantic	Category-4	6.0	EM-APEX	55	30	Sanford et al. (2011)	1.5
Ivan (2004), Gulf of Mexico	Category-4	5.8	ADCP	15	6	Teague et al. (2007)	2.1
Harvey (2005), Atlantic	Tropical storm	6.3	ADCP	5	18	Black and Dickey (2008)	0.4
Nate (2005), Atlantic	Category-1	6.7	ADCP	123	18	Black and Dickey (2008)	0.4
Hai-tang (2005), Pacific	Category-2	2.6	SVP drifter	130	15	Chang et al. (2010)	1.7
Katrina (2005), Gulf of Mexico	Category-5	6.3	ADCP	120	120	Jaimes and Shay (2009)	0.8
Rita (2005), Gulf of Mexico	Category-5	4.7	ADCP	200	100	Jaimes and Shay (2009)	0.4
Shanshan (2006), Pacific	Category-4	2.6	SVP drifter	80	15	Chang et al. (2010)	2.0

(Chang and Anthes, 1978; Geisler, 1970). 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 are mainly determined by the wind stress with maximum current speed to the right of the storm track at the distance of $1-2R_{max}$ (mean $R_{max} = 47$ km) (Brooks, 1983; Chang et al., 2013; Hsu and Yana, 1998). Questions arise: What are the characteristics of OML currents to the right of the storm track at $\sim 1-2R_{max}$ under category-5 super typhoons from direct velocity measurements? How high can the observed velocity be under the high wind speed of ~ 70 m s^{-1} ? What are the differences of observed currents under the slow-moving, typical-moving, and fast-moving super typhoons? What are the general relationships between the maximum current speeds and the Saffir–Simpson hurricane scale? The goal of this study is to answer these questions. To do so, the SVP drifter data in the northwestern Pacific are used to represent the observed upper ocean currents during four super typhoons.

2. Four super typhoons

Chaba, Maon, Saomai, and Jangmi became category-5 (super) typhoons in the northwestern Pacific Ocean on 22 August 2004, 7 October 2004, 9 August 2006, and 27 September 2008, with the minimum sea level pressures of 879, 898, 898, and 918 mbar, respectively. Chaba (2004) had typical translation speeds; Maon (2004) had variable translation speeds; and Saomai (2006) and Jangmi (2008) had fast translation speeds. As their intensities reached category 5, their translation speeds (U_h) were 4.1–5.2 m s^{-1} , 2.9–15.4 m s^{-1} , 7.0–8.7 m s^{-1} , and 6.7–6.8 m s^{-1} respectively. The characteristics of the four super typhoons as well as corresponding drifters' information are listed in Table 2.

Table 2
Characteristics of the four super typhoons (Chaba, Maon, Saomai, and Jangmi).

Storm's name	Chaba 2004	Maon 2004	Saomai 2006	Jangmi 2008
Time as a super typhoon	1200 22 Aug–0600 26 Aug	1800 07 Oct–0000 09 Oct	0600 09 Aug–0600 10 Aug	0600 24 Sep–1200 30 Sep
Minimum sea level pressure (mbar)	879	898	898	918
U_h ($m s^{-1}$) as a super typhoon	4.1–5.2	2.9–15.4	7.0–8.7	6.7–6.8
Drifter's ID	39606	2236911	54688	70324
Date as the distance $D < 400$ km	1800 21 Aug–1200 23 Aug	1200 05 Oct–1200 08 Oct	0000 09 Aug–0000 10 Aug	1800 26 Sep–0600 28 Sep

3. TC and current velocity data

Data about the four super typhoons with a temporal resolution of 6 h were acquired from the best-track data from the Joint Typhoon Warning Center (JTWC, <http://metocph.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_h 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_h 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

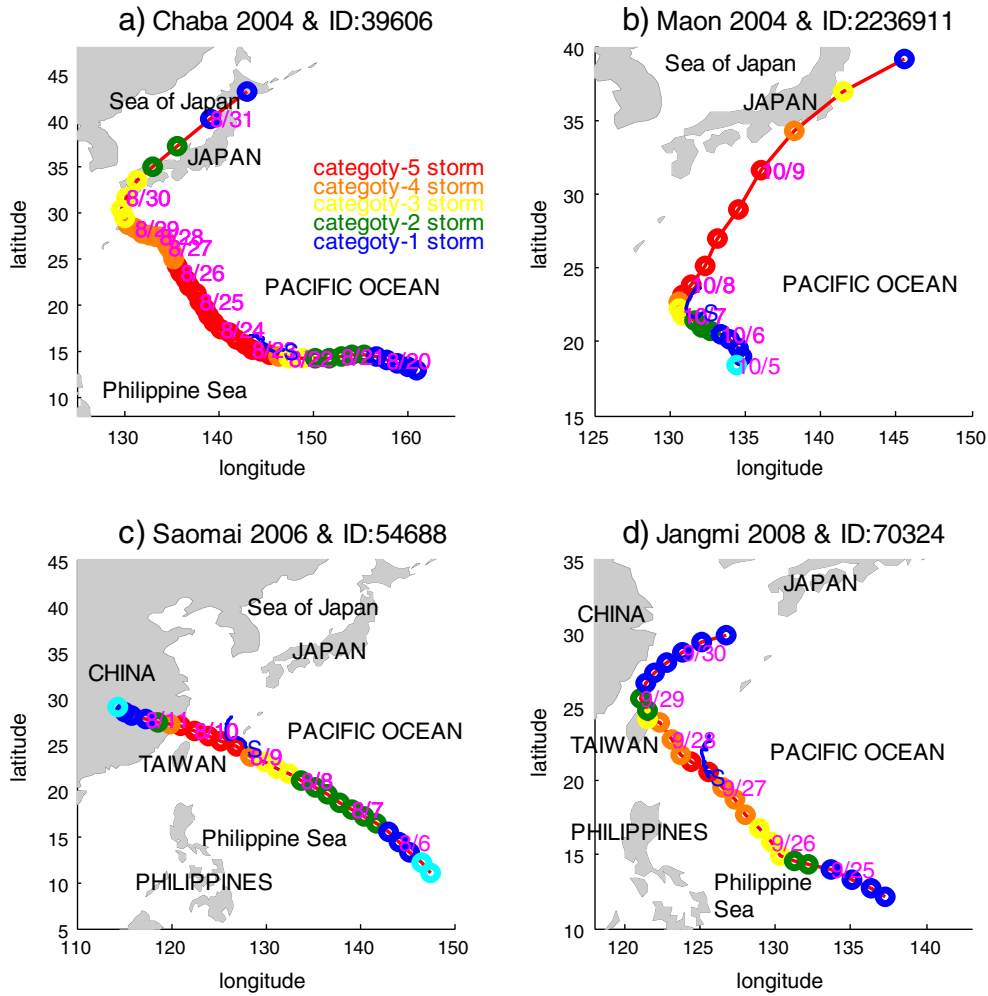


Fig. 1. Tracks of four super typhoons (red curve) [(a) Chaba, (b) Maon, (c) Saomai, (d) Jangmi] and four SVP drifters (blue curve) [(a) 39606, (b) 2236911, (c) 54688, (d) 70324] for the northwestern Pacific Ocean in (a) August 2004, (b) October 2004, (c) August 2006, and (d) September 2008 at 6 hour time interval with the storm's intensities by color circles.

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 $D \sim R_{max}$ 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 ($U_h = 2.9 \text{ m s}^{-1}$, $D = 52 \text{ km}$).

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 ($D = 287, 108, \text{ and } 74 \text{ km}$), it strengthened to a category-5 typhoon. But the observed current velocities increased slowly ($U_{obs} = 0.7, 1.1, \text{ and } 1.2 \text{ m s}^{-1}$), with a maximum velocity of 1.2 m s^{-1} ($U_h = 8.1 \text{ m s}^{-1}$, and $D = 74 \text{ km}$).

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 ($D = 484 \text{ km}$, $U_h = 6.4 \text{ m s}^{-1}$). The drifter-measured U_{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_{obs} increased to 0.8 m s^{-1} ($D = 88 \text{ km}$). 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 ($D = 86 \text{ km}$). 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_{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 $D = 52\text{--}85 \text{ km}$, i.e., within 1–2 R_{max} from the TC center [mean $R_{max} = 47 \text{ km}$ (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 TC's 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 $\sim 1\text{--}2R_{max}$ (Brooks, 1983; Chang et al., 2013). Within this range the linear regression was conducted between U_{obs} (unit: m s^{-1}) on the right side of the storm center ($45^\circ \leq \text{Direction} \leq 135^\circ$, see Table 3) and U_h at $D \sim 1\text{--}2R_{max}$ ($D = 38\text{--}95 \text{ km}$, see Table 3),

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

as shown in Fig. 8 (blue color "x" and lines) with a high correlation coefficient (–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

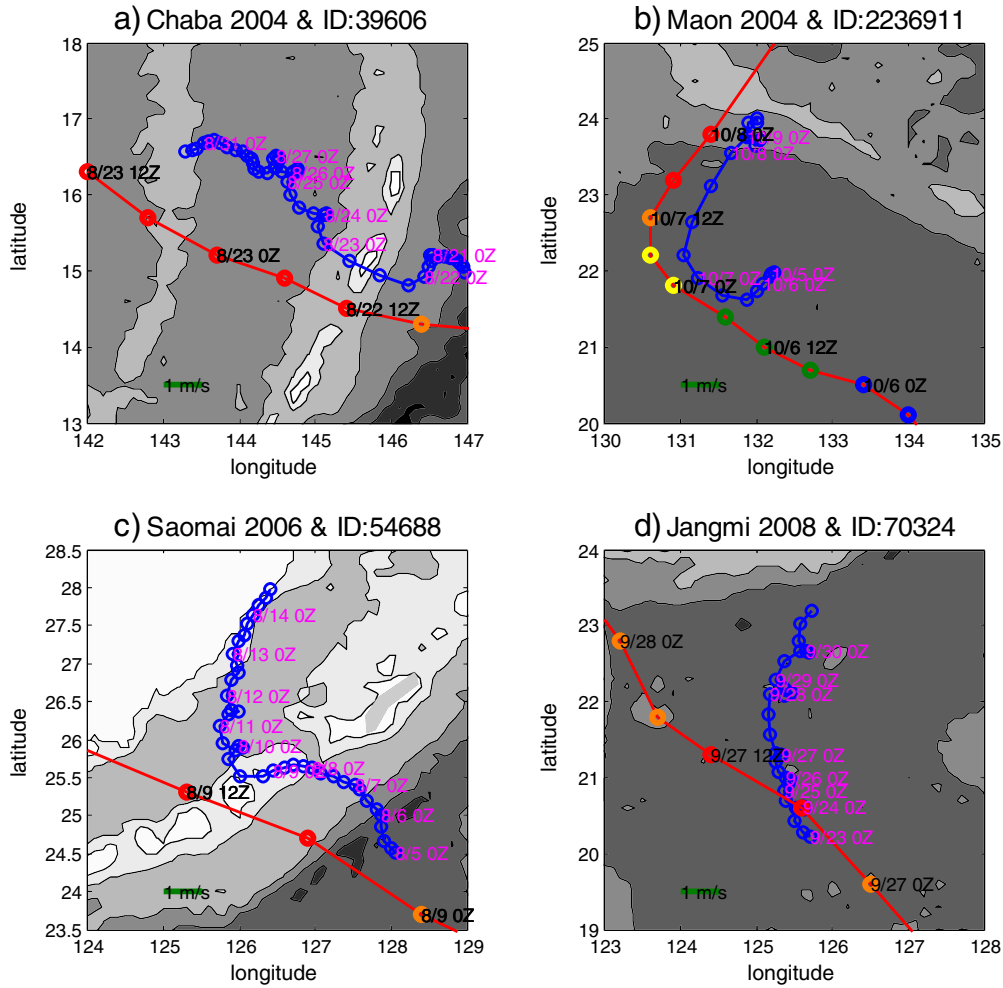


Fig. 2. Four storms' paths and four drifters' trajectories, both in 6-hourly interval.

$m s^{-1}$, the corresponding current velocities at $\sim 1-2 R_{max}$ are approximately 2.5 ± 0.6 , 2.2 ± 0.6 , 2.0 ± 0.5 , 1.7 ± 0.5 , 1.5 ± 0.6 , and $1.2 \pm 0.6 m s^{-1}$. Figs. 4–7 show significant decrease of the OML velocity at several R_{max} away from the TC track, especially 150 to 200 km ($\sim 3-4R_{max}$) 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 $D \sim 0.5-3R_{max}$ ($D = \sim 24-141 km$), the linear regression was further conducted under category-5 storms between U_{obs} (unit: $m s^{-1}$) on the right side of the storm center ($30^\circ \leq Direction \leq 150^\circ$, see Table 3) and U_h at $D = \sim 0.5-3R_{max}$,

$$U_{obs} = -0.247U_h + 3.13 \quad (2.9 m s^{-1} \leq U_h \leq 8.7 m s^{-1}) \quad (2)$$

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_{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_{max}) on the TC's intensity (S)

Quantitative dependence of the maximum velocity (U_{max}) on the Saffir–Simpson hurricane scale (S) has not been established. Table 4 shows the qualitative relationship between U_{max} and S . In order to construct a statistical relationship between mean U_{max} (unit: $m s^{-1}$) inside

$D \sim 3R_{max}$ ($D < \sim 150 km$) 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,

$$U_{max} = 0.234S + 0.689 \quad (0 \leq S \leq 5) \quad (3)$$

which shows a strong linear relationship with a high correlation coefficient (0.98) between U_{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_{max} (unit: $m s^{-1}$) inside $\sim 3R_{max}$ and S for slow- and fast-moving storms, we separated storms into “slow-moving” ($U_h = 2.0-4.0 m s^{-1}$), “typically-

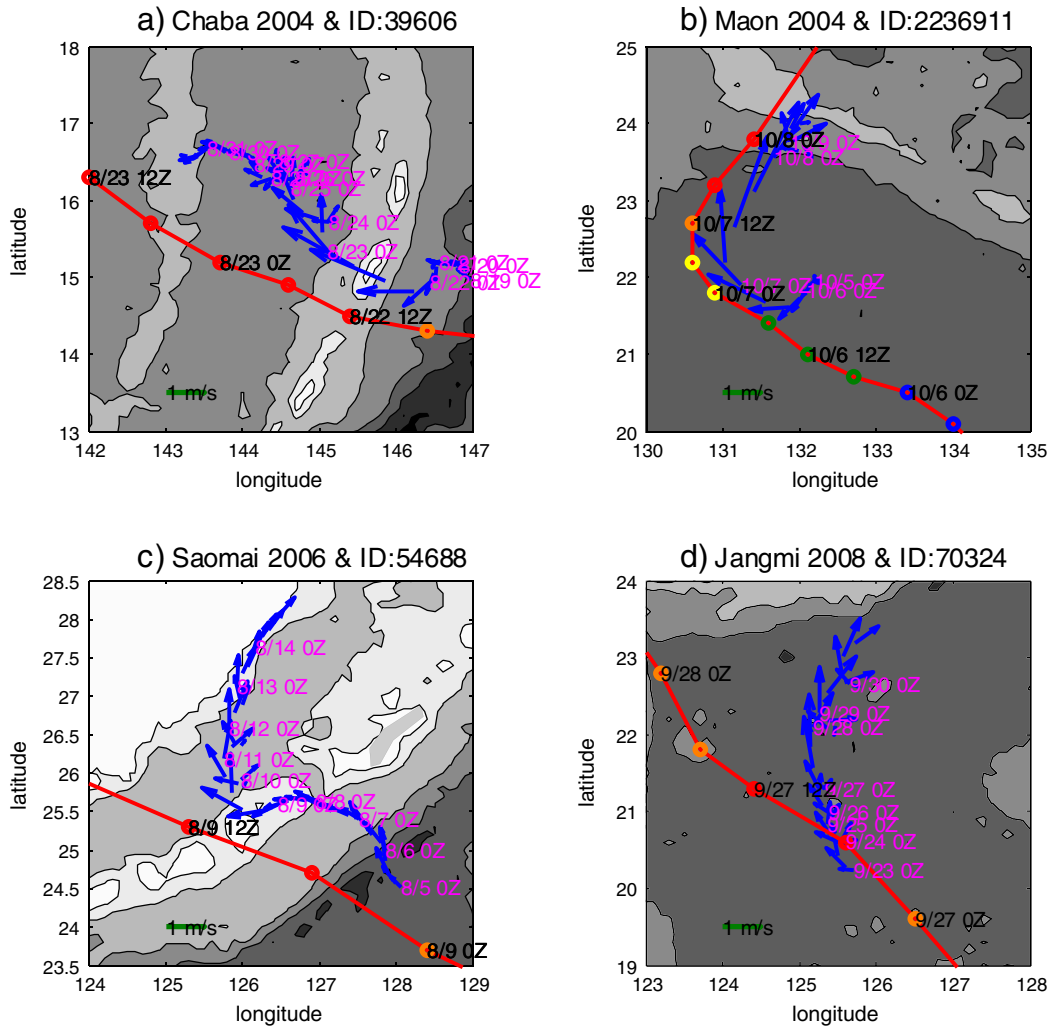


Fig. 3. Four storms' paths and observed current vectors, both in 6-hourly interval.

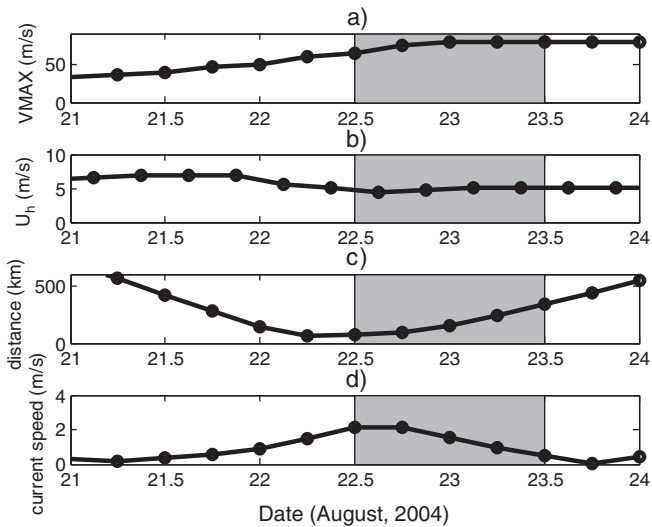


Fig. 4. Time evolution (6 hourly) of (a) storm's maximum sustained wind speed (VMAX), (b) storm's translation speed (U_h), (c) distances (D) between storm's center and drifter 39606 and (d) observed current speeds during Chaba. Shadings denote the duration during which the drifter was under a super typhoon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

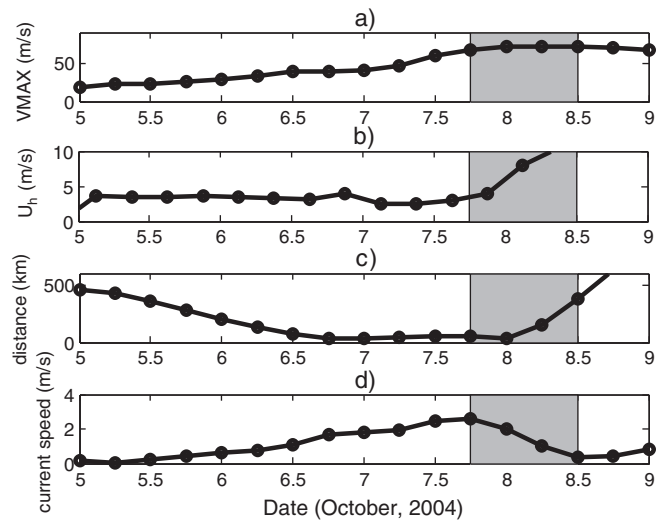


Fig. 5. Time evolution (6 hourly) of (a) storm's maximum sustained wind speed (VMAX), (b) storm's translation speed (U_h), (c) distances (D) between the storm's center and drifter 2236911 and (d) observed current speeds during Maon. Shadings denote the duration during which the drifter was under a super typhoon and affected by the typhoon ($D < 400$ km).

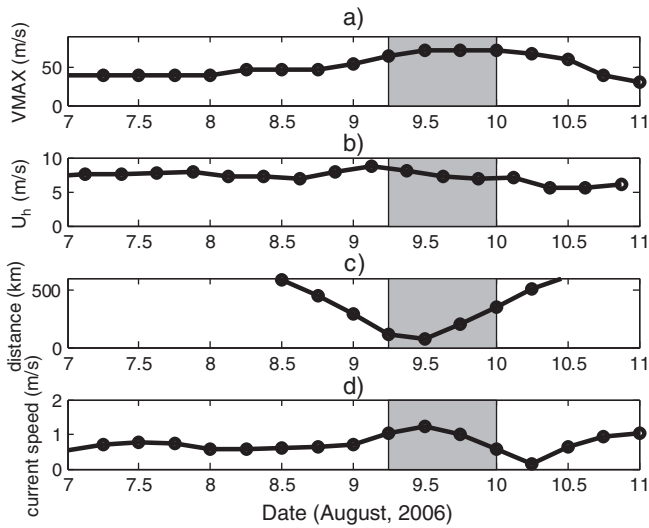


Fig. 6. Time evolution (6 hourly) of (a) Saomai's maximum sustained wind speed (VMAX), (b) storm's translation speed (U_h), (c) distances (D) between storm's center and drifter 54688 and (d) observed current speeds during Saomai. Shadings denote the duration during which the drifter was under a super typhoon and affected by the typhoon ($D < 400$ km).

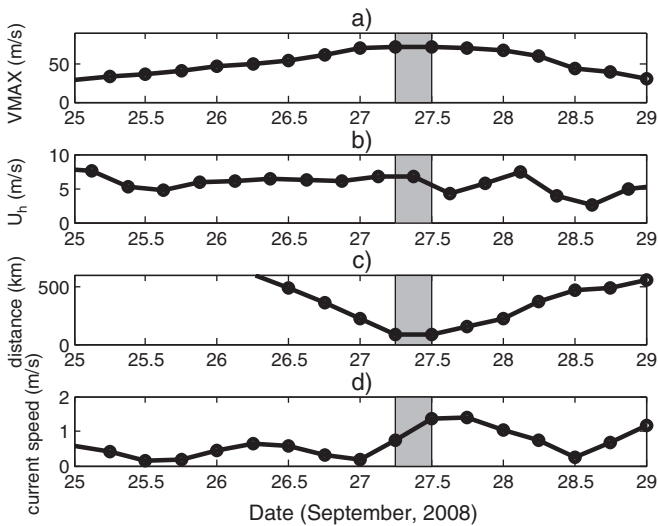


Fig. 7. Time evolution (6 hourly) of (a) Jangmi's maximum sustained wind speed (VMAX), (b) storm's translation speed (U_h), (c) distances (D) between storm's center and drifter 70324 and (d) observed current speeds during Jangmi. Shadings denote the duration during which the drifter was under a super typhoon and affected by the typhoon ($D < 400$ km).

Table 3
Observed (U_{obs}) and ageostrophic (U_{ageo}) current velocities under super typhoons with $D < 400$ km.

Name & ID	Time	Scale	U_h ($m s^{-1}$)	D (km)	Direction (degree)	U_{obs} ($m s^{-1}$)	U_{ageo} ($m s^{-1}$)
Chaba & 39606	1200 22 Aug	Category 5	5.1	69	120	2.1	1.9
	1800 22 Aug	Category 5	4.5	95	135	2.1	2.0
	0000 23 Aug	Category 5	4.7	152	150	1.6	1.5
	0600 23 Aug	Category 5	5.2	238	*	1.0	1.1
	1200 23 Aug	Category 5	5.0	338	*	0.5	0.7
Maon & 2236911	1800 7 Oct	Category 5	2.9	52	60	2.6	2.5
	0000 8 Oct	Category 5	3.9	38	100	2.0	2.0
	0600 8 Oct	Category 5	7.9	153	150	1.0	1.1
	1200 8 Oct	Category 5	10.6	382	*	0.4	0.5
Saomai & 54688	0600 9 Aug	Category 5	8.7	108	40	1.1	0.8
	1200 9 Aug	Category 5	8.1	74	135	1.2	1.2
	1800 9 Aug	Category 5	7.2	196	*	1.0	1.0
	0000 10 Aug	Category 5	7.0	351	*	0.6	0.6
	1200 27 Sep	Category 5	6.8	85	110	1.4	1.4

moving" ($U_h = 4.0\text{--}6.0 m s^{-1}$) and "fast-moving" ($U_h = 6.0\text{--}8.0 m s^{-1}$) categories. Two linear regressions,

$$U_{max} = 0.334S_{slow} + 0.814 \quad (0 \leq S_{slow} \leq 5), \quad (4)$$

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

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_{max} under Ivan 2004 (Teague et al., 2007) had a larger current speed of $2.1 m s^{-1}$, because the U_{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 Stoke 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_s)

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

$$U_s = \frac{\tau_s R_{max}}{\rho_0 h U_h}, \quad (6)$$

where τ_s is the magnitude of the surface wind stress; ρ_0 is the characteristic density of seawater ($\sim 1025 kg m^{-3}$); 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_s during Hurricanes Gloria and Josephine. Thus, we use $h = 50$ m to calculate U_s in Eq. (6).

The wind stress (τ_s) is given by

$$\tau_s = \rho_a C_D W^2 \quad (7)$$

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

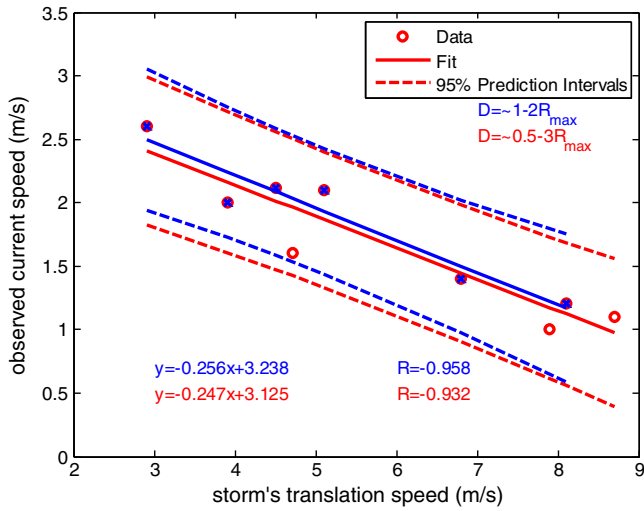


Fig. 8. Dependence of the observed current velocity (U_{obs}) on the storm's translation speed (U_h) under three category-5 storms at $-1-2R_{max}$ (blue color) and $-0.5-3R_{max}$ (red color).

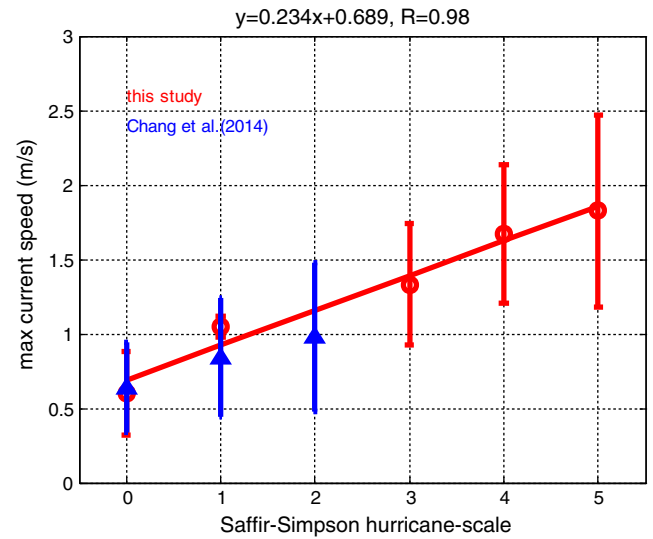


Fig. 9. Dependence of observed current speed on the Saffir–Simpson hurricane scale (S) with the error bars showing one standard deviation ($S = 0$: the tropical storm, $S = 1$: the category-1 storm, $S = 2$: the category-2 storm, ..., etc.).

study to represent such dependence of C_D on W (Zedler et al., 2009). Thus, the estimated wind stress τ 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 (V_{MAX}) 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

Table 4
Quantitative dependence of the maximum current velocity (U_{max}) on the Saffir–Simpson hurricane scale (S) under slow-moving ($U_h = 2.0-4.0 m s^{-1}$), fast-moving ($U_h = 6.0-8.0 m s^{-1}$), and all storms ($U_h \sim 4.9 m s^{-1}$) (Chang et al., 2013) and comparison between the observed U_{max} and the scaled wind-driven velocity U_s .

Typhoon scale (Saffir–Simpson)	Storm's translation speed	Max current velocity, U_{max} ($m s^{-1}$)	Wind-driven horizontal velocity, U_s ($m s^{-1}$), [C_D from Powel et al. (2003), Black et al. (2007), and Jarosz et al. (2007)]
Tropical storm ($W = 30 m s^{-1}$)	Slow-moving	0.8	0.7, 0.5, 0.8
	All	0.7	0.4, 0.3, 0.5
	Fast-moving	0.6	0.3, 0.2, 0.4
Category-1 ($W = 40 m s^{-1}$)	Slow-moving	1.2	1.1, 0.9, 1.3
	All	0.9	0.7, 0.6, 0.8
	Fast-moving	0.7	0.5, 0.4, 0.6
Category-2 ($W = 45 m s^{-1}$)	Slow-moving	1.5	1.4, 1.1, 1.4
	All	1.2	0.8, 0.7, 0.8
	Fast-moving	0.9	0.6, 0.5, 0.6
Category-3 ($W = 55 m s^{-1}$)	Slow-moving	1.8	1.7, 1.7, 1.7
	All	1.4	1.0, 1.0, 1.0
	Fast-moving	1.0	0.7, 0.7, 0.7
Category-4 ($W = 65 m s^{-1}$)	Slow-moving	2.2	2.4, 2.4, 2.4
	All	1.6	1.5, 1.5, 1.5
	Fast-moving	1.1	1.0, 1.0, 1.0
Category-5 ($W = 70 m s^{-1}$)	Slow-moving	2.5	2.7, 2.7, 2.7
	All	1.9	1.7, 1.7, 1.7
	Fast-moving	1.3	1.2, 1.2, 1.2

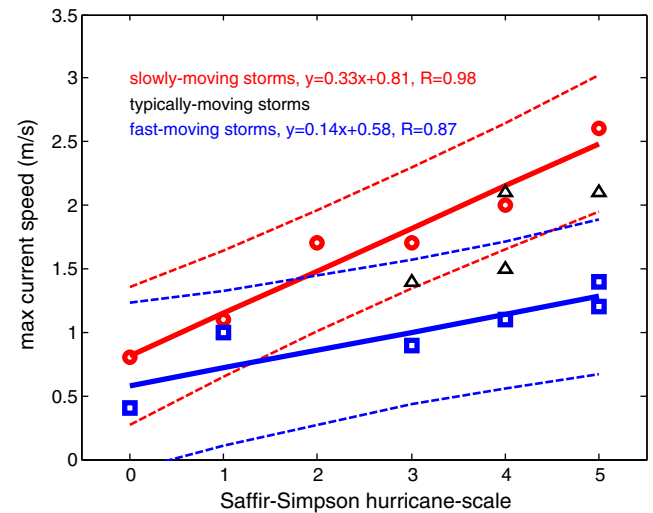


Fig. 10. Dependence of the maximum current velocity (U_{max}) on all storms' intensity levels (S) for slow-moving (red color, $U_h = 2.0-4.0 m s^{-1}$), typical-moving (black color, $U_h = 4.0-6.0 m s^{-1}$), and fast-moving storms (blue color, $U_h = 6.0-8.0 m s^{-1}$) in earlier and this studies ($S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

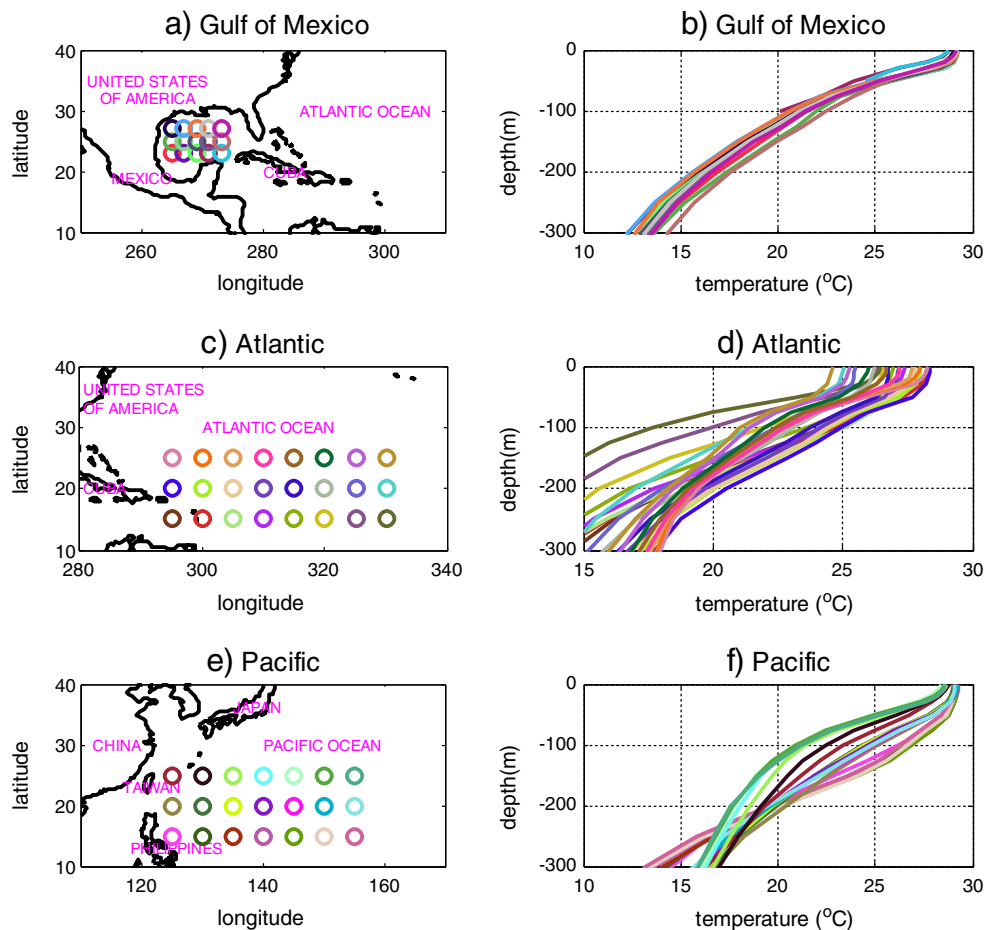


Fig. 11. Locations and temperature ($^{\circ}\text{C}$) of NODC objectively analyzed mean data (a)–(b) in the Gulf of Mexico, (c)–(d) the northwestern Atlantic, and (e)–(f) the northwestern Pacific, during summer.

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 under the four category-5 super typhoons from direct velocity measurements with maximum current velocities of 2.1, 2.6, 1.2, and 1.4 m s^{-1} at $\sim 1\text{--}2 R_{max}$ ($D = 69, 52, 74,$ and 85 km). A unique and novel approach was provided to identify the strong near-surface currents in the wake of intense tropical cyclones. The general relationships between the observed current velocity and the storm's translation speed and between the maximum current velocities and the Saffir–Simpson hurricane scale are also provided. Our results are congruent with recent studies (Olabarrieta et al., 2012; Warner et al., 2010; Yablonsky and Ginis, 2009; Zambon et al., submitted for publication) and provide useful tool for model validation.

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