Observed near-surface currents under high wind speeds

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Received 21 February 2012; revised 9 August 2012; accepted 8 October 2012; published 28 November 2012.

[1] From the Surface Velocity Program (SVP) drifter current and QuikSCAT wind data, the relationship between the observed near-surface current vectors and surface wind vectors for the northwestern Pacific Ocean under high winds (20–50 m s^{-1}) are obtained with quantitative estimations of near-surface drift ratio (current speed versus wind speed) r (∼2%) and near-surface drift angle α (∼0°–10° to the right of the winds). These estimations keep unchanged after removing the surface geostrophic component. From the SVP drifter current and daily WindSat wind data, the estimated r is still approximately 2%. Three linear regression equations are obtained between the observed near-surface current speeds and the surface wind stress for the high wind range.

Citation: Chang, Y.-C., G.-Y. Chen, R.-S. Tseng, L. R. Centurioni, and P. C. Chu (2012), Observed near-surface currents under high wind speeds, *J. Geophys. Res.*, *117*, C11026, doi:10.1029/2012JC007996.

1. Introduction

[2] Momentum transfer from atmosphere to ocean generates surface currents through wind shear stress and wave-induced Stokes drift. In fact, the eddy viscosity is not constant in the ocean, and the momentum transfer through wind shear stress tends to give a rather linear increase in surface current with the wind speed. This process is strongly affected by the stratification [*Rascle and Ardhuin*, 2009]. The Stokes drift contributes to the surface current typically with a quadratic function of the wind speed when estimated from realistic wave spectra [*Ardhuin et al.*, 2009]. From previous laboratory experiments and field observations, the surface drift speed is represented by a percentage (r) of the wind speed (called surface drift ratio here), varying between 1.5% and 4.1%, with a surface drift angle (α_s), changing between 0° and 34° to the right of the wind direction in the northern hemisphere [*Wu*, 1968; *McNally*, 1981; *Wu*, 1983; *Peterson*, 1985; *Brown*, 1991].

[3] High-frequency (HF) radars are commonly used to measure the surface drift currents. For wind speeds of 0–12 m s^{-1}, the surface drift ratio is found 1.5%–2.5% with 25–30 MHz radars [*Essen*, 1993], 2.0%–3.0% with 16 MHz radar in the coastal water [*Shay et al.*, 2007], 2.1% with a 30 MHz radar in the southern hemisphere [*Mao and Heron*, 2008]; and the surface drift angle is identified as 10°–45° to the left of the wind in the southern hemisphere [*Mao and Heron*, 2008]. After filtering tides from 2 yr time series of surface currents from 12 MHz radar off the west coast of France for wind speeds of 0–20 m s^{-1}, the surface drift ratio is found 1.0%–1.8% and the surface drift angle is −10°–−40°. Here, negative (positive) angles are to the right of the wind in the Northern (Southern) Hemisphere [*Ardhuin et al.*, 2009].

[4] All the existing studies on the surface drift ratios and angles are under low wind speeds of 0–20 m s^{-1}. Questions arise: Are these results valid under high wind speeds of 20–50 m s^{-1}? If not, what are the quantitative relationships between the surface drift (ratio, angle) and the wind speed? To answer these questions, the Surface Velocity Program (SVP) drifter and NASA QuikSCAT wind data (1999–2009) for the northwestern Pacific Ocean are analyzed in this study to obtain quantitative relationships. The SVP drifter is a good tool, which can measure the velocity response in the ocean surface mixed layer (ML) under high wind speeds of 20–50 m s^{-1}.

2. Data and Method

[5] Direct velocity measurements in the ocean surface ML were obtained with SVP drifters buoyed at a nominal depth of 15 m. The 6 hourly positions and velocity drifter data were obtained online at the NOAA/AOML website, http://www.aoml.noaa.gov/phod/dac/dacdata.html. Synoptic wind fields were obtained from the completely reprocessed NASA QuikSCAT ocean surface wind vectors (being released on 28 April 2011) with spatial resolution of 25 km by 25 km and temporal coverage of twice daily. The new geophysical model function (GMF) referred to as Ku-2011 [*Ricciardulli and Wentz*, 2011] is used for the reproduction to improve wind speed retrievals at high wind speed. The newly developed GMF uses the WindSat retrievals as the ground truth to calibrate the wind speed. *Meissner and Wentz* [2009] developed a new algorithm for the WindSat

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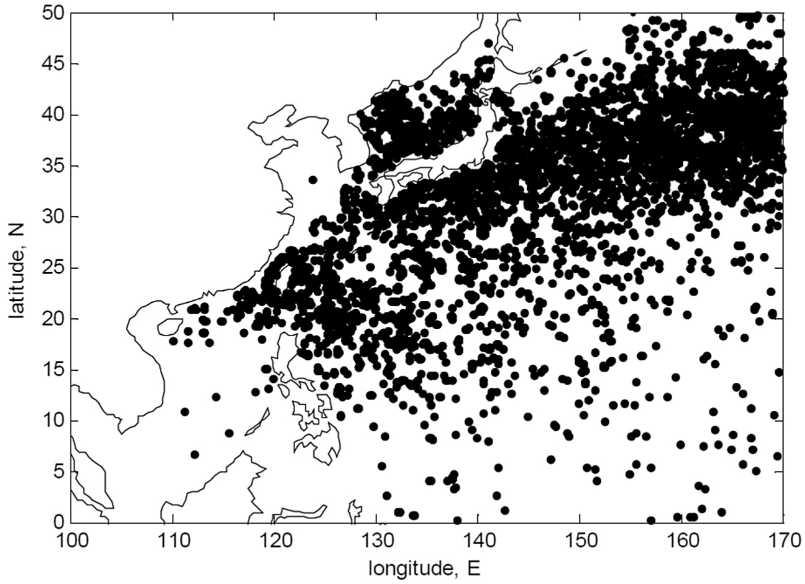

Figure 1. Horizontal distribution of the Surface Velocity Program (SVP) drifter data (total: 14,332) in the northwestern Pacific (100°–170°E, 0°–50°N) under high wind speeds (20–50 m s^{-1}) during 1999–2009.

winds with the validity even in rain and storm conditions. The WindSat is a polarimetric microwave radiometer developed by the Naval Research Laboratory (NRL) and launched on 6 January 2003 aboard the Department of Defense Coriolis satellite. WindSat is designed to demonstrate the capability of polarimetric microwave radiometry to observe the oceanic surface wind speed. The WindSat is used as the optimal calibration for the existing QuikSCAT

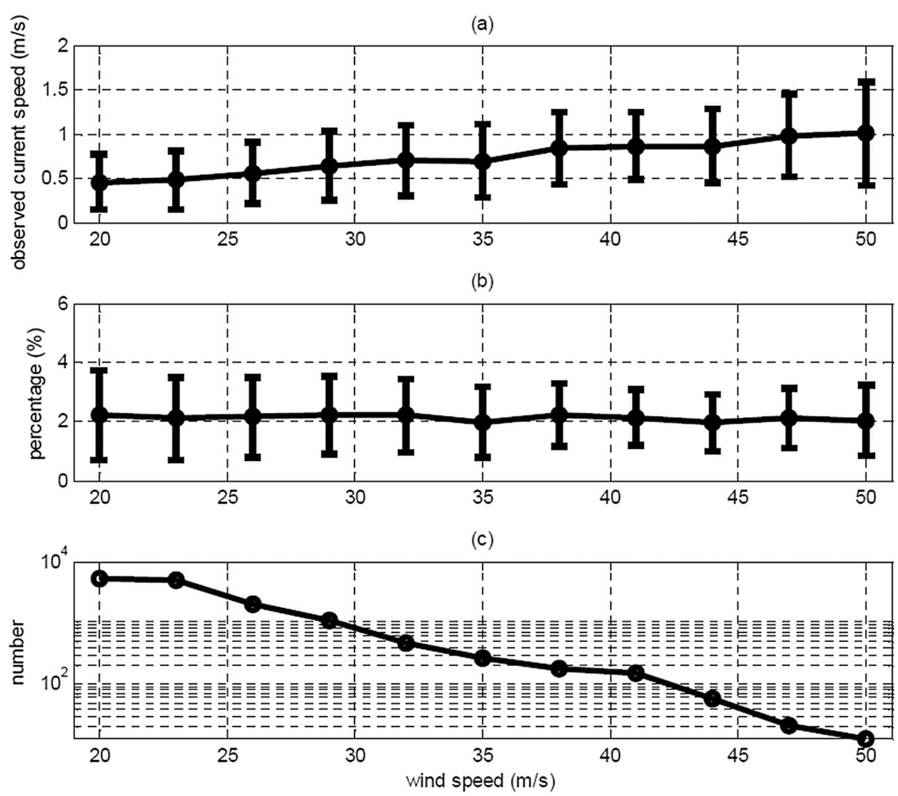

Figure 2. Dependence of (a) observed current speed and (b) near-surface drift ratio (r) on surface wind speed under high winds with the error bars showing one standard deviation; (c) dependence of pair number of concurrent wind and surface current observations on surface wind speed.

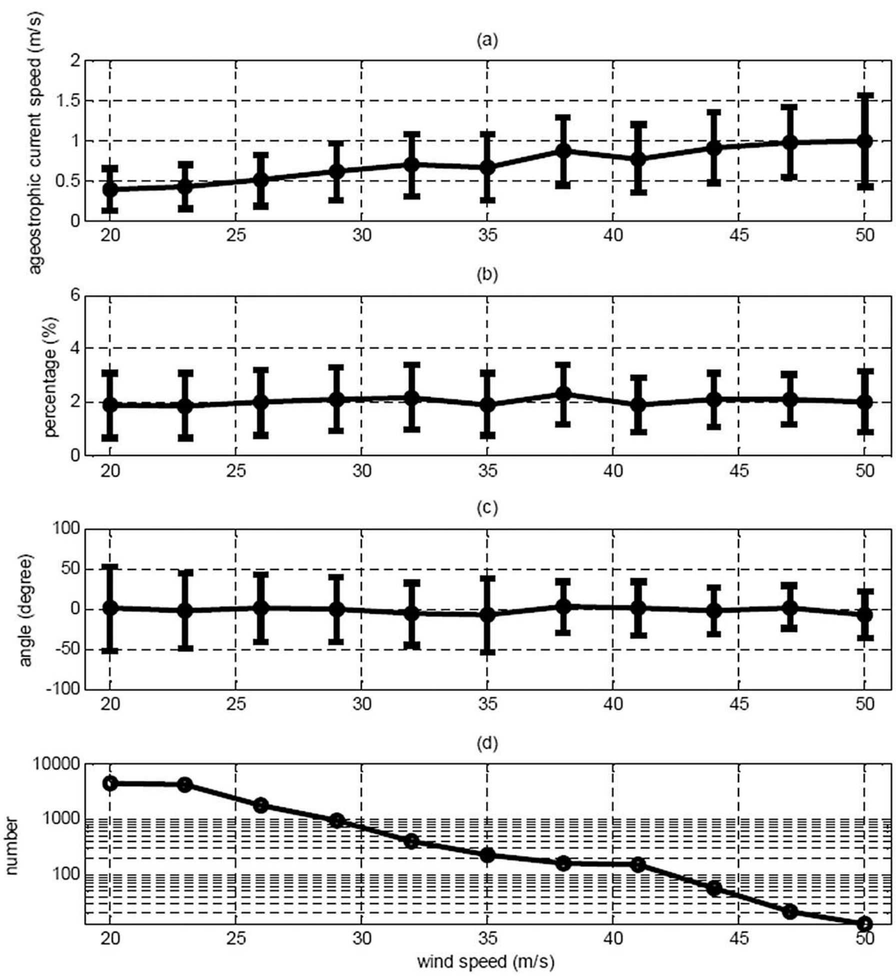

Figure 3. Dependence of ageostrophic (a) current speed, (b) near-surface drift ratio, and (c) surface drift angle on surface wind speed with the error bars showing one standard deviation; (d) dependence of pair number of concurrent wind and surface current observations on surface wind speed.

(wind speed up to 30 m s^{-1}) and the new QuikSCAT (wind speed up to about 35 m s^{-1}) [*Ricciardulli and Wentz*, 2011].

3. Observed Currents Under High Winds

[6] The observed high wind data (>20 m s^{-1}) from QuikSCAT and current data from the SVP drifter for the northwestern Pacific (100°–170°E, 0°–50°N) during 1999–2009 (total 14,332 data points) were analyzed to determine the near-surface drift ratio and angle under the high winds (Figure 1). Figure 2a shows 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 (σ). The mean and standard deviation of current speed were calculated for each bin of wind speed. For a normal distribution, approximately 68% of the values lie within $\pm\sigma$ from the mean, and approximately 95% of the values lie within $\pm 2\sigma$ from the mean. The tides cause major error on the mean SVP drifter measurements, particularly on continental shelf, in straits, and in passages. Knowledge of inherent uncertainty of tides (i.e., main error in the standard deviations) is needed before compositing observational currents from the drifter data. Furthermore, the same tidal component causes larger error at low surface winds (<20 m s^{-1}) than at high surface winds (>20 m s^{-1}), because the wind-driven current component is weaker at low surface winds than at high surface winds. A linear regression,

$$U = 0.019W + 0.06 \left(20\,\mathrm{m\,s^{-1}} < W < 50\,\mathrm{m\,s^{-1}}\right), \qquad (1)$$

is obtained for high winds between the observed current speed (U) and the surface wind speed (W) with a high correlation coefficient (0.987). The mean observed near-surface drift ratio ($r = U/W$) varies little (1.9%–2.2%) for the whole high wind range (Figure 2b).

4. Ageostrophic Currents Under High Winds

[7] Quantitative dependence of the ML current on high wind speed is still poorly understood. The ML current can be decomposed into geostrophic and ageostrophic components. The surface geostrophic current is calculated from the weekly AVISO sea surface height data. Subtraction of the geostrophic current from the SVP drift current leads to the

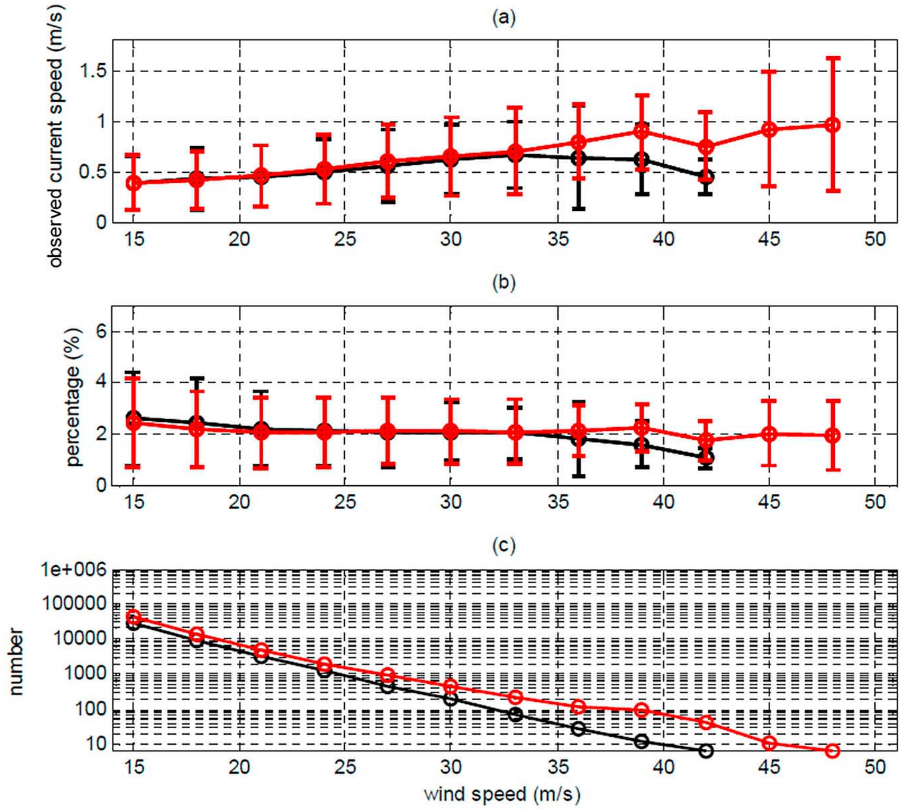

Figure 4. Dependence of (a) observed current speed and (b) near-surface drift ratio (r) on surface wind speed under high winds from QuikSCAT (red line) and WindSat (black line) data with the error bars showing one standard deviation; (c) dependence of pair number of concurrent wind and surface current observations on surface wind speed.

ageostrophic current. Figure 3a shows the relationship between the mean ageostrophic current speeds and the observed wind speeds of QuikSCAT with one standard deviation as error bars. A linear regression,

$$U_{ageo} = 0.021W - 0.03 \; \left(20\,\mathrm{m\,s^{-1}} < W < 50\,\mathrm{m\,s^{-1}}\right) \quad (2)$$

is obtained between the ageostrophic current speed (U_{ageo}) and wind speed (W) with a high correlation coefficient (0.978). The mean near-surface drift ratio for ageostrophic current (r_{ageo}) varies little (1.9%–2.2%) for the whole high wind range (Figure 3b). The mean ageostrophic current is almost aligned with the wind vector for the wind speed from 20 to 30 m s^{-1}, and 37 to 42 m s^{-1}, with the maximum drift angle of 10° to the right of the wind vector at wind speed of 35 m s^{-1} (Figure 3c).

[8] To investigate the sensitivity of the near-surface drift ratio and angle on the surface wind data, the daily WindSat wind data of 2003–2009 were also used. Since the measured maximum wind speed of WindSat is only 42 m s^{-1}, a wider wind range (15–50 m s^{-1}) (Figure 4) was used. The ratios derived from two different wind data (QuikSCAT and WindSat) are similar under the wind speeds of 15–33 m s^{-1} (~2%, Figure 4b), begin to have a difference of 0.2% for wind speed of 37 m s^{-1}, and have an evident difference of 0.6% (QuikSCAT: 1.7%–2.2%; WindSat: 1.1%–1.6%) for wind speed larger than 39 m s^{-1}. It implied that the near-surface drift ratio (~2%) under high wind speeds (15–37 m s^{-1}) was supported by the two different wind data sets. The surface wind stress (τ),

$$\tau = \rho_{air} C_d W^2, \quad (3)$$

is often used by oceanographers. Here, ρ_{air} is the air density (~1.3 kg m^{-3}); C_d is the drag coefficient, which varies with W. Three semiempirical formulas from *Jarosz et al.* [2007], *Powell et al.* [2003], and *Black et al.* [2007] are used in this study to represent such dependence of C_d on W (after *Zedler et al.* [2009]). Then, the estimated wind stress can be calculated from the wind speed of QuikSCAT. Three linear regression equations are obtained from the estimated wind stress (τ) and mean drifter-measured current speed (U) from SVP drifters (Figure 5a),

$$U = 0.337\tau + 0.106, \quad (0.9\ \mathrm{Pa} < \tau < 4.7\ \mathrm{Pa}, C_d \text{ from } \textit{Jarosz et al.}\ [2007]), \quad (4)$$

$$U = 0.336\tau + 0.128, \quad (0.9\ \mathrm{Pa} < \tau < 4.7\ \mathrm{Pa}, C_d \text{ from } \textit{Powell et al.}\ [2003]), \quad (5)$$

$$U = 0.394\tau + 0.131, \quad (0.8\ \mathrm{Pa} < \tau < 4.3\ \mathrm{Pa}, C_d \text{ from } \textit{Black et al.}\ [2007]), \quad (6)$$

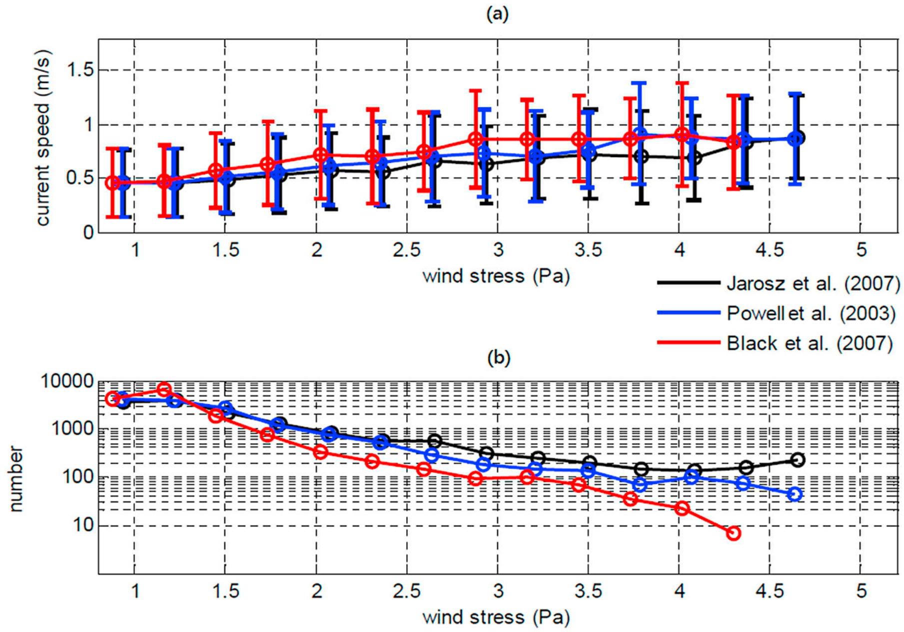

Figure 5. Dependence of (a) observed current speed on surface wind stress from three C_d forms of *Jarosz et al.* [2007], *Powell et al.* [2003], and *Black et al.* [2007] under high winds with the error bars showing one standard deviation and (b) dependence of pair number of concurrent wind stress and surface current observations on surface wind stress.

with three high correlation coefficients (0.96, 0.97 and 0.93). For the high wind range (0.9 Pa < τ < 4.7 Pa), the mean drifter-measured ocean current speeds represented by

$$U \sim 0.34\tau + 0.11, \quad (7)$$

which shows that the mean drifter-measured ocean current speed (U) increases linearly with the estimated surface wind stress for the high winds.

[9] With a moving tropical cyclone (TC), the wind-driven current speed in ML (U_s) is given by [*Price*, 1983; *Jaimes and Shay*, 2009],

$$U_s = \frac{\tau R_{\max}}{hU_h}, \quad (8)$$

where h is the ML thickness, R_{max} is the radius of the TC's maximum tangential velocity, and U_h is the TC's translation speed. For a typical TC in the western Pacific, the mean ML thickness in the western equatorial Pacific is $h \sim 29$ m [*Lukas and Lindstrom*, 1991]; the mean translation speed of all TCs (1985–2009) is U_h = 4.9 m s^{-1} in the study area, which was estimated from the best-track data of the Joint Typhoon Warning Center (http://metocph.nmci.navy.mil/jtwc.php), and the mean radius of the maximum tangential velocity of TCs is R_{max} = 47 km [*Hsu and Yana*, 1998]. Substitution of these values into equation (8) leads to

$$U_s \sim \frac{R_{\max}}{hU_h}\tau \sim 0.33\tau. \quad (9)$$

[10] The value of 0.33 is close to the ratio (0.34) between observed current speed (U) and wind stress (τ) in equations (4) and (5). What does it mean? This implies the drift ratio of 0.34 and the linear increase of the observed ML current with the wind speed or wind stress under high winds.

5. Summary

[11] In the northwestern Pacific Ocean, the near-surface drift ratio is found around 2% for both total (geostrophic plus ageostrophic) and ageostrophic current speeds, and the near-surface drift angle is small with the maximum value of 10° for 35 m s^{-1} winds from analysis on the SVP drifter current and QuikSCAT wind data (1999–2009) under high winds (20–50 m s^{-1}). The near-surface drift ratio relationship is also found near 2% under high wind speeds of 15–37 m s^{-1} from analysis of the SVP drifter and daily WindSat wind data (2003–2009). Regression analysis also shows that the mean drifter-measured ocean current speeds in the surface mixed layer increases linearly with the surface wind stress for the high winds (20–50 m s^{-1}).

[12] **Acknowledgments.** This research was completed with grants from Aim for the Top University Plan from the Ministry of Education (00C030200) and National Science Council (NSC 100-2611-M-110-004) of Taiwan. Peter C. Chu was supported by the Naval Oceanographic Office.

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