Ocean Currents Under Super Typhoons

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- Luca R. Centurioni (Scripps Institution of Oceanography)

Contents

- (1) Statistical Characteristics
- (2) Under Tropical Cyclones

- Magnitude of Near Surface Currents

  10 cm/s

- What are the statistical features?

- What are the extreme values under super typhoons?

Part – 1
Statistical Characteristics

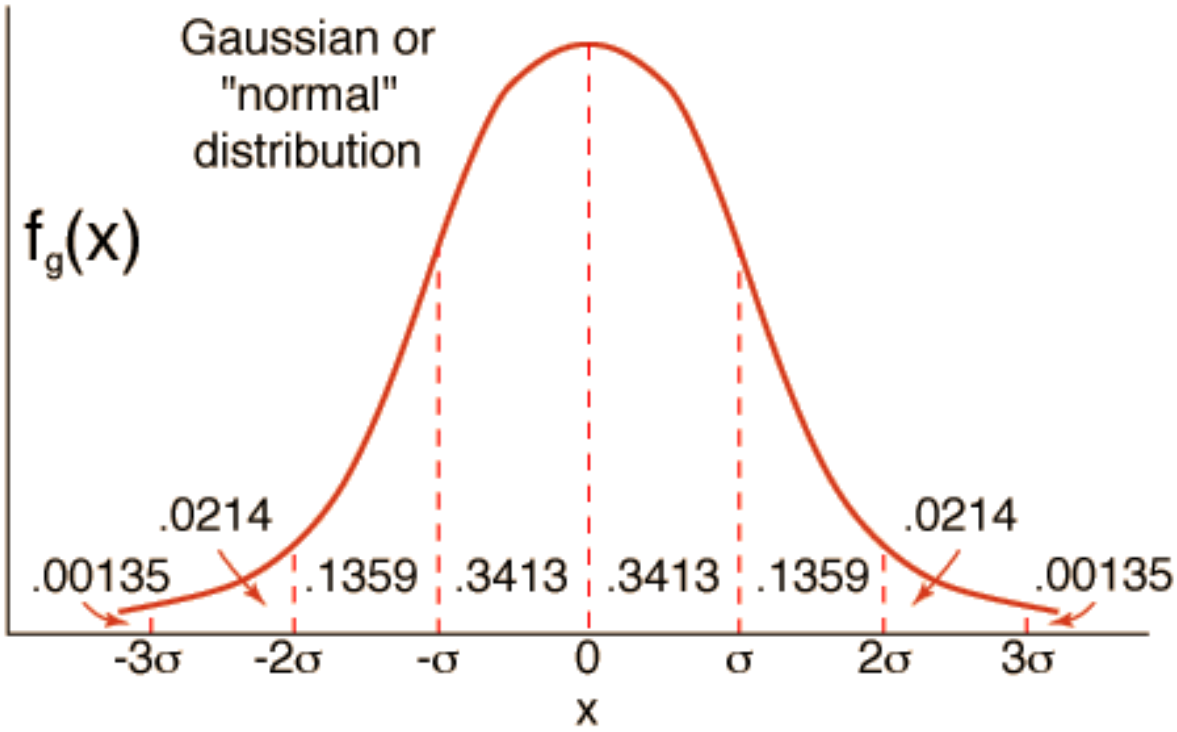
References

- Chu, P.C., 2008: Probability distribution function of the upper equatorial Pacific current speeds. *Geophysical Research Letters*, American Geophysical Union, 35, doi: 10.1029/2008GL033669.

- Chu, P. C., 2009: Statistical Characteristics of the Global Surface Current Speeds Obtained from Satellite Altimeter and Scatterometer Data. *IEEE Journal of Selected Topics in Earth Observations and Remote Sensing*, **2** (1), 27-32.

Dealing with Uncertainty

- Gaussian Distribution is often used



Gaussian Distribution

- Mean = μ
- Standard Deviation = σ
- Skewness = 0
- Kurtosis – 3 = 0

$$p(x) = \frac{1}{\sqrt{2\pi\,\sigma^2}} \cdot \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$$

Gaussian Process

- Gaussian process is much easier to analyze, so is useful to produce a first approximation to reality. A frequent mistake is to confuse first approximation with the truth.

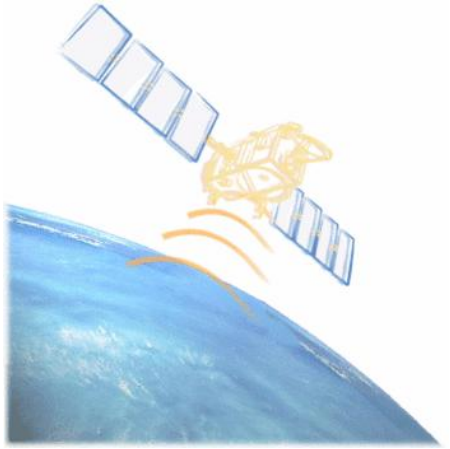
Satellite Altimeters

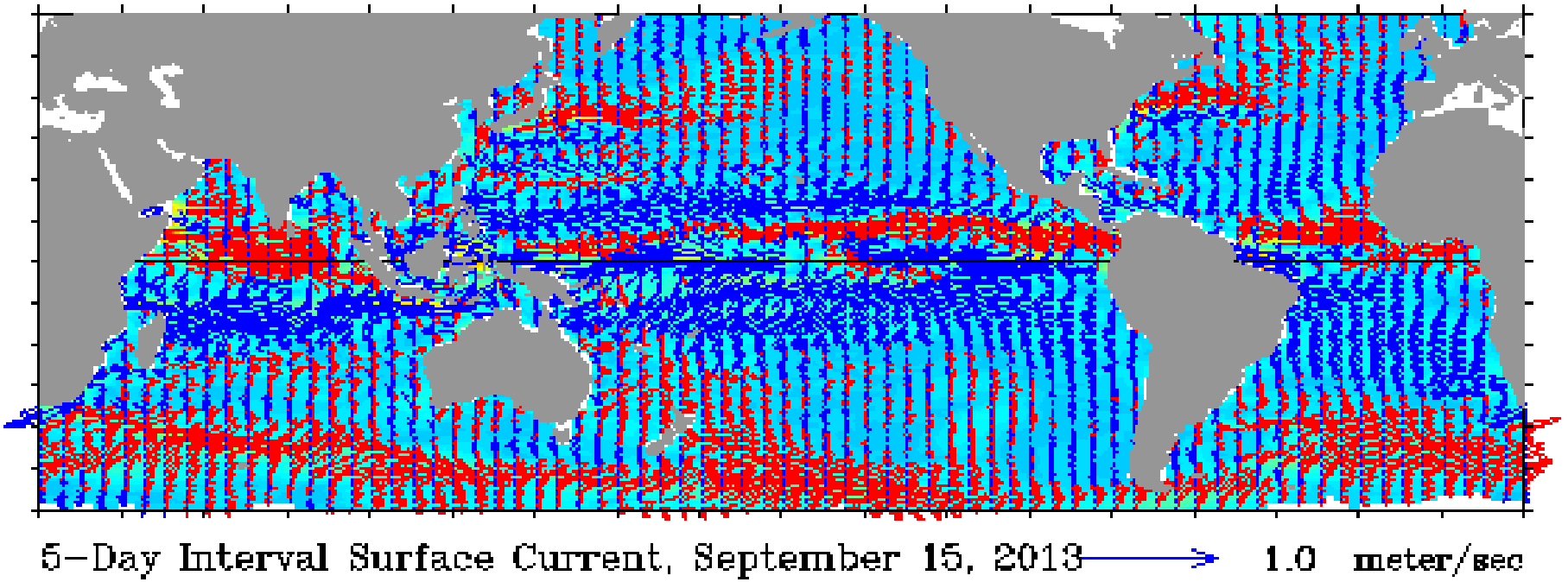
(JASON-1, GFO, ENVISAT)

Scatterometer (QSCAT)

→

Ocean
Surface Velocity





Ocean Surface currents data available for whole world' oceans at [www.oscar.noa]

Data continuously available every 5 days

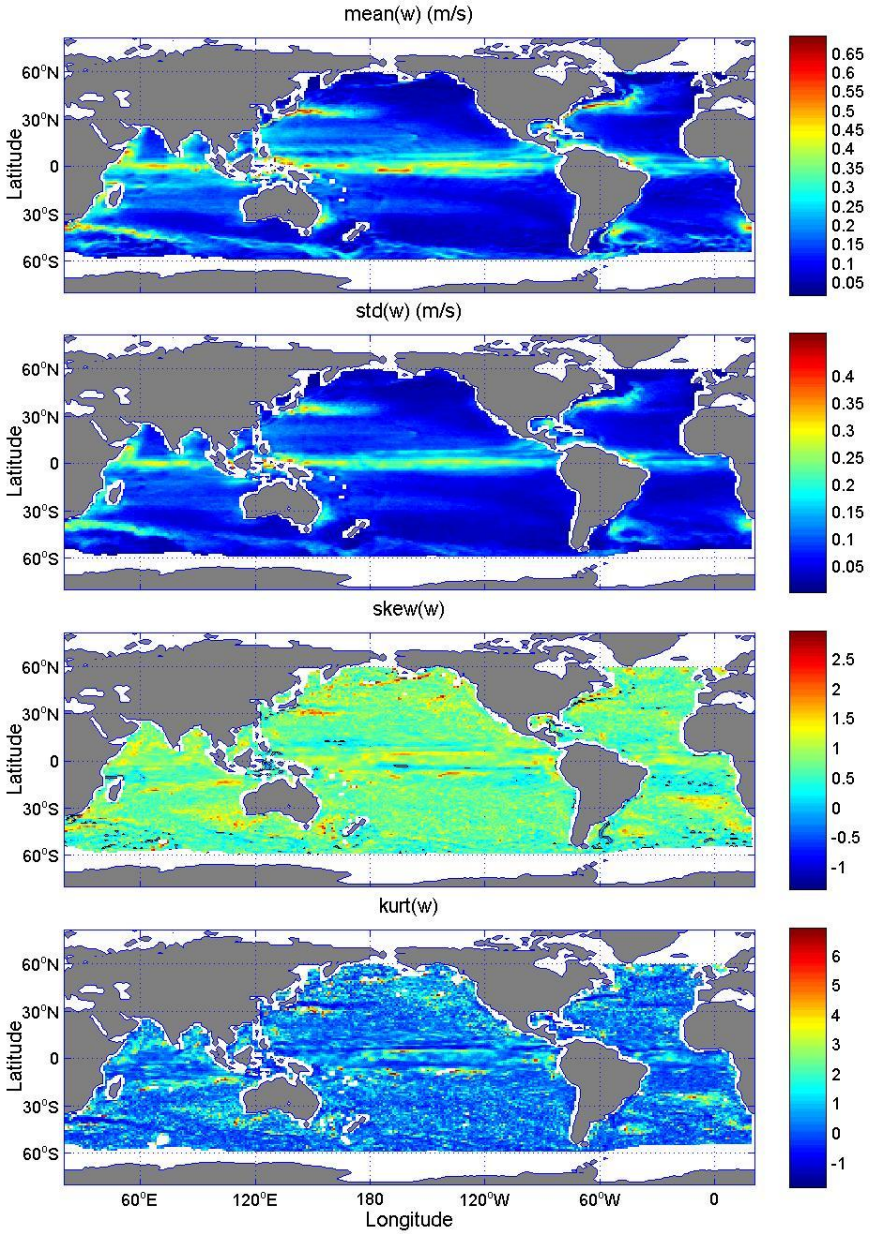
Statistical Characteristics of Global Surface Current Speed (1992-2008) (Chu 2008)

Mean

Standard Deviation

Skewness

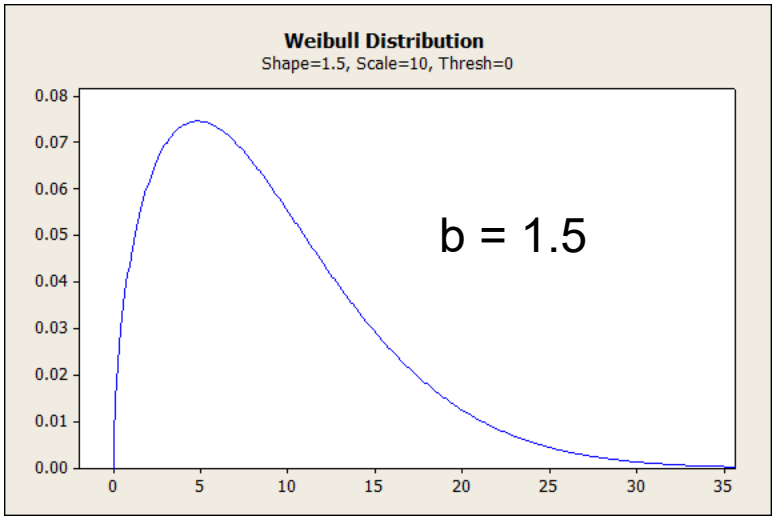
Kurtosis - 3

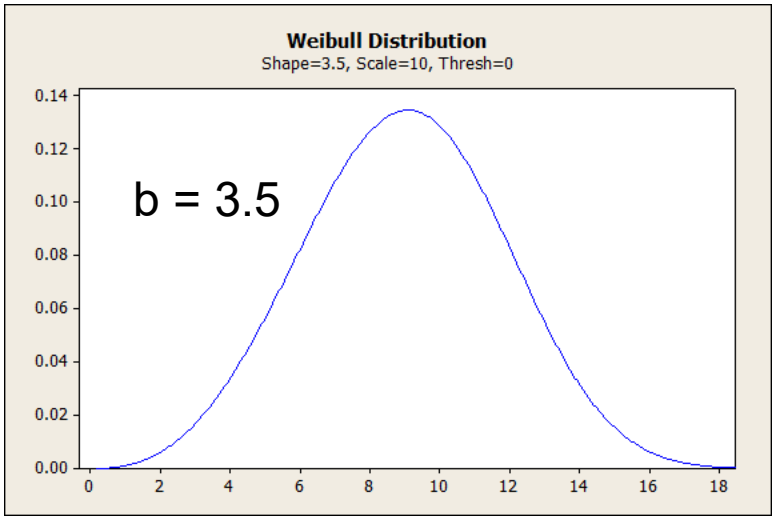


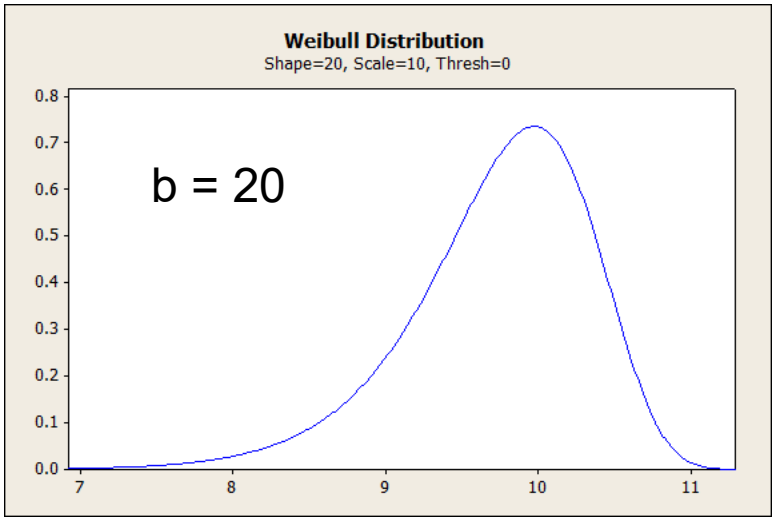
General Features

- Positive/Negative Skewness
- Kurtosis ≠ 3

Weibull Distribution – from Positive to Negative Skewness







$$p(w) = \frac{b}{a}\left(\frac{w}{a}\right)^{b-1} \exp\left[-\left(\frac{w}{a}\right)^{2}\right]$$

$a = 10$

Characteristics of the Weibull Distribution

$$b \simeq \left[\frac{\text{mean}(w)}{\text{std}(w)} \right]^{1.086}, \quad a = \frac{\text{mean}(w)}{\Gamma(1+1/b)}.$$

$$\text{skew}(w) = \frac{\Gamma\left(1+\frac{3}{b}\right) - 3\Gamma\left(1+\frac{1}{b}\right)\Gamma\left(1+\frac{2}{b}\right) + 2\Gamma^3\left(1+\frac{1}{b}\right)}{\left[\Gamma\left(1+\frac{2}{b}\right) - \Gamma^2\left(1+\frac{1}{b}\right)\right]^{3/2}}$$

$$\text{kurt}(w) = \frac{\Gamma\left(1+\frac{4}{b}\right) - 4\Gamma\left(1+\frac{1}{b}\right)\Gamma\left(1+\frac{3}{b}\right)}{\left[\Gamma\left(1+\frac{2}{b}\right) - \Gamma^2\left(1+\frac{1}{b}\right)\right]^2} + \frac{6\Gamma^2\left(1+\frac{1}{b}\right)\Gamma\left(1+\frac{2}{b}\right) - 3\Gamma^4\left(1+\frac{1}{b}\right)}{\left[\Gamma\left(1+\frac{2}{b}\right) - \Gamma^2\left(1+\frac{1}{b}\right)\right]^2} - 3$$

Γ → Gamma Function

Kurt ←→ Skew

- Since

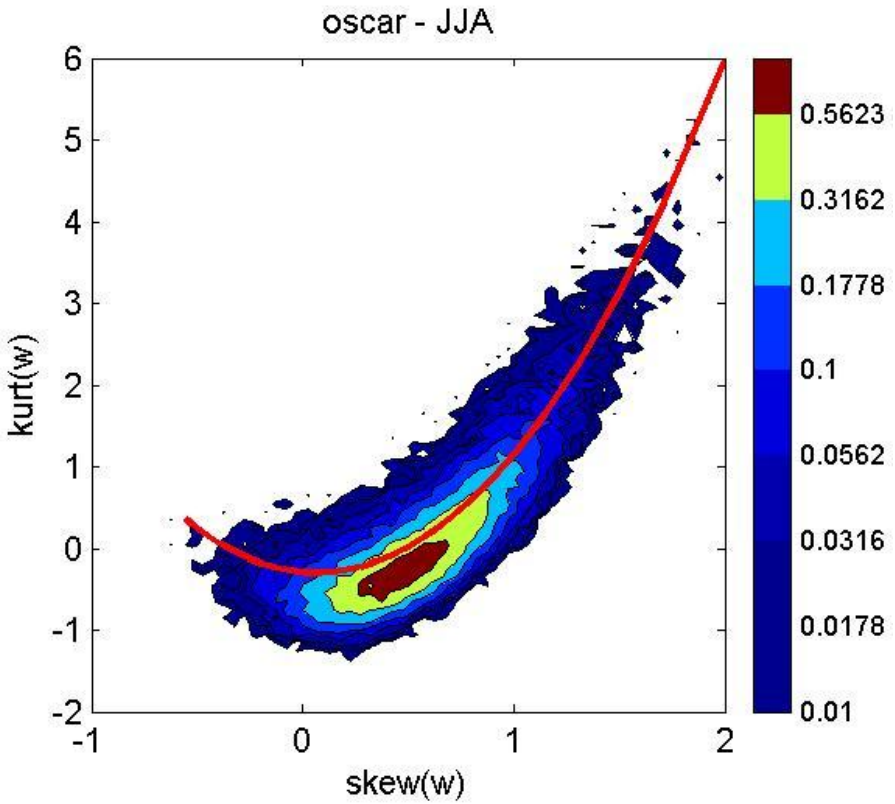
$$\text{Skew} = f_1(b), \quad \text{Kurt} = f_2(b)$$

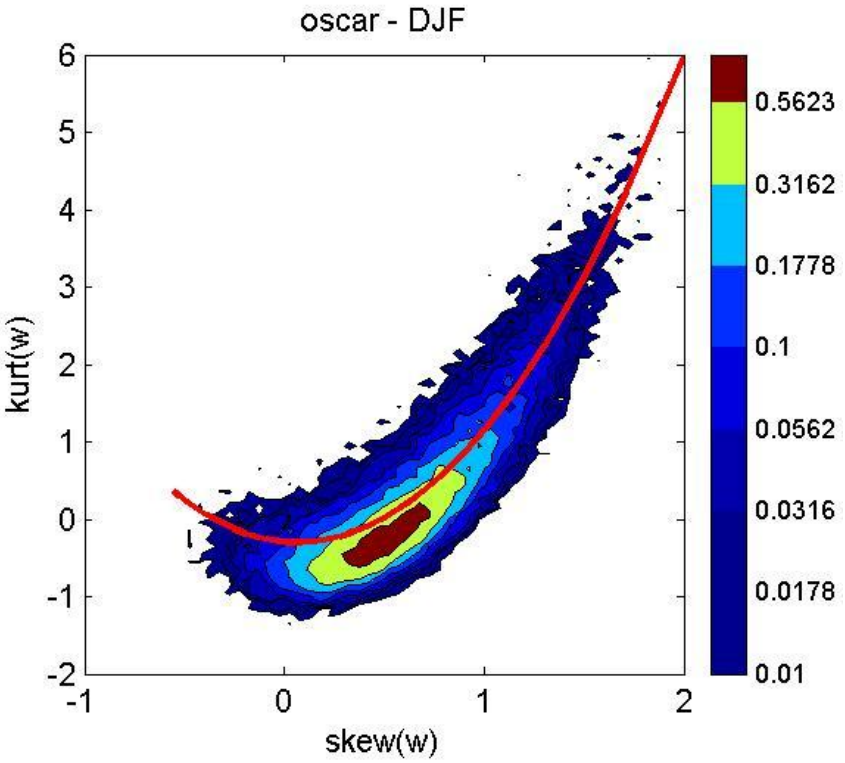
→

$$\text{Kurt} = F(\text{Skew})$$

Kernel Density Estimates of Joint PDFs of kurtosis and *skewness* Surface Current Speed

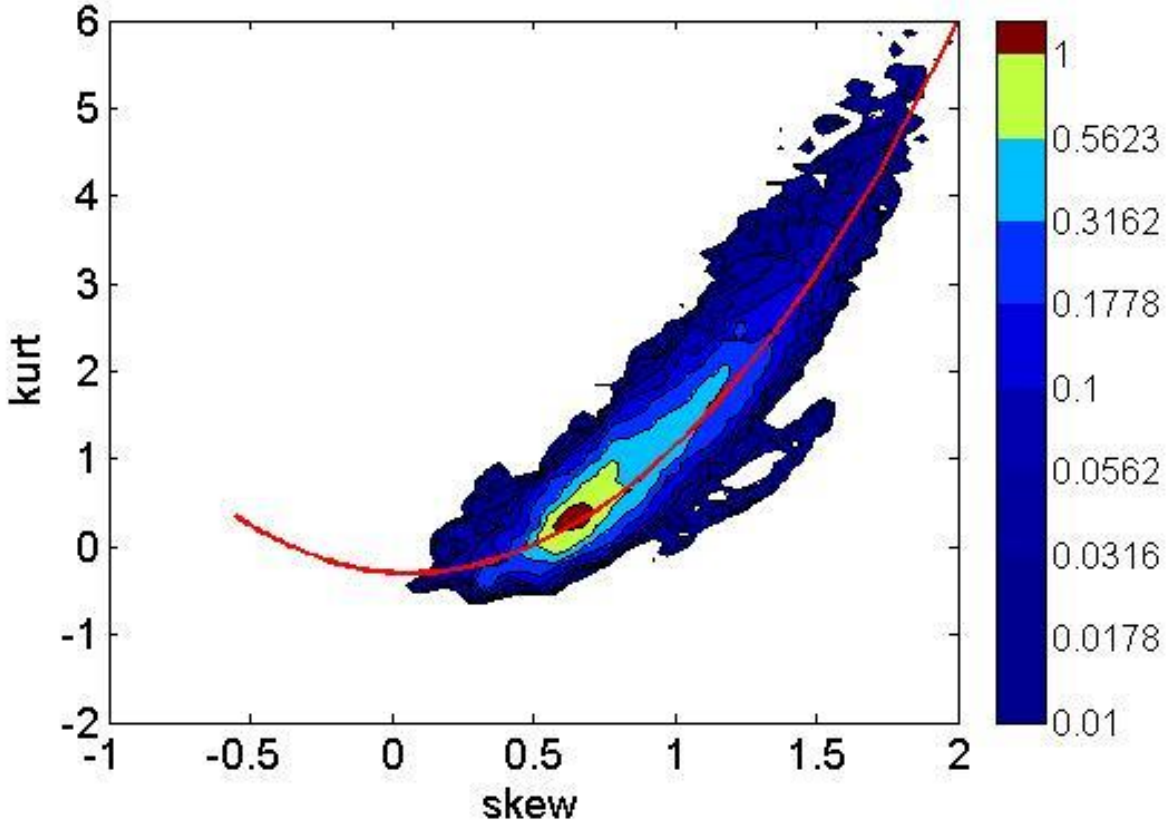
(Red Curve → Weibull Distribution)





Kernel Density Estimates of Joint PDF of Kurtosis and Skewness – Significant Wave Heights

(Red Curve → Weibull Distribution)



TAO Array

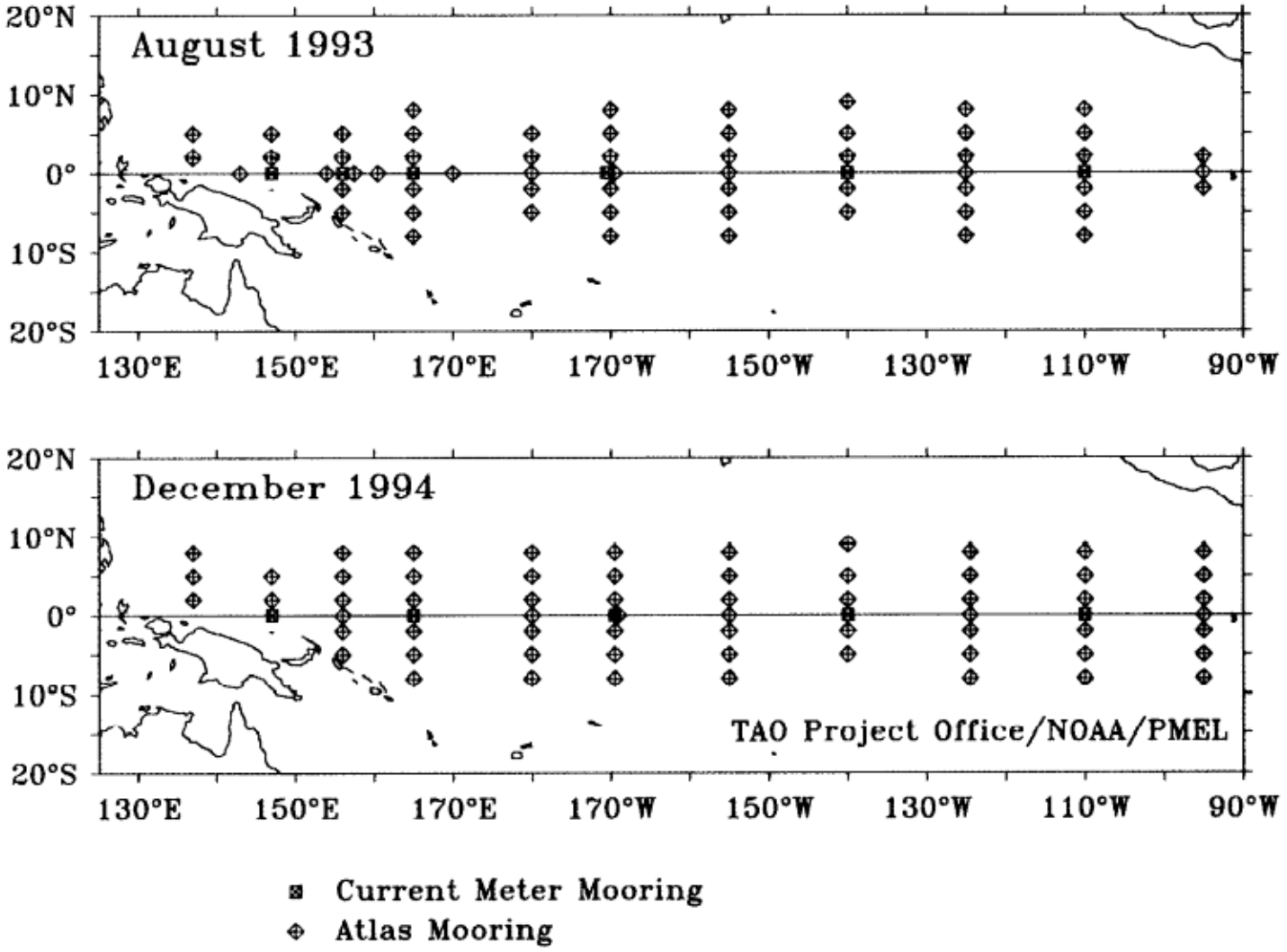


Fig. 1: The TOGA-TAO Array in August 1993 and in its final configuration December 1994. ATLAS moorings, ◇ and current-meter moorings, □.

0-50 m

Total

El Nino

La Nina

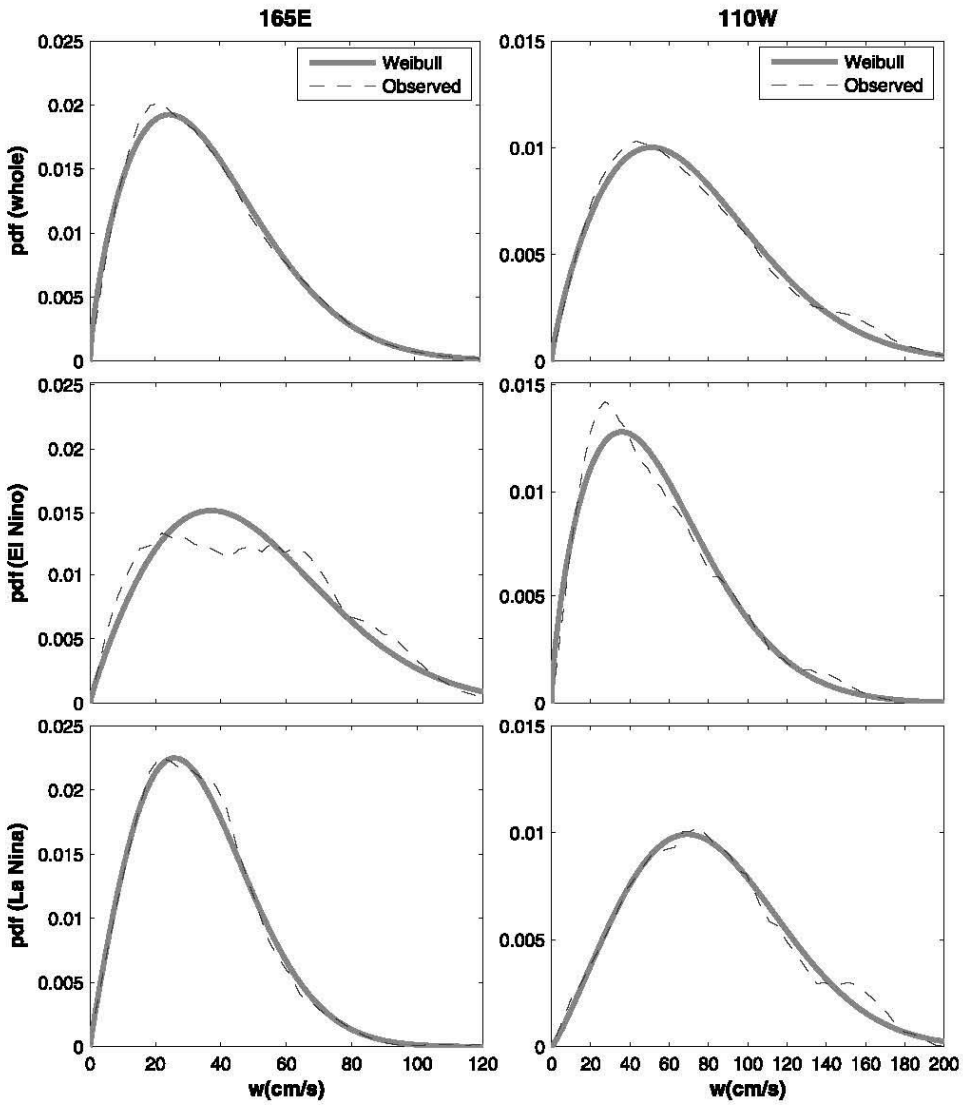


Figure 1. Comparison between observational *w*-PDFs (i.e., histogram, dashed curve) constructed from the T data and Weibull distributions (solid curve) for upper layer (0–50 m) along the equator at: (left) 165°E, and (ri with the upper panels for the whole period, the middle panels for the major El Nino events, and the lower pa major La Nina events.

Why is the Weibull Distribution ?

Stochastic Dynamics for the Ocean Surface Currents

Vertically Averaged Horizontal Velocity (u, v) within the Mixed Layer
-- Slab Model --

$$\frac{\partial u}{\partial t} = \frac{1}{h}\Lambda_u - \frac{K}{h^2}u \quad (1)$$

h → mixed layer depth

K → eddy viscosity

$$\frac{\partial v}{\partial t} = \frac{1}{h}\Lambda_v - \frac{K}{h^2}v \quad (2)$$

(τ_x, τ_y) → Surface wind stress

$$\Lambda_u \equiv fV_E + \frac{\tau_x}{\rho}, \quad \Lambda_v \equiv -fU_E + \frac{\tau_y}{\rho}$$

Ekman Transport (U_E, V_E)

$$(U_E, V_E) = \int_{-h}^{0} (\tilde{u} - u_g, \tilde{v} - v_g) dz,$$

$(\tilde{u}, \tilde{v})$ → Vertically Varying Velocity

(u_g, v_g) → geostrophic velocity

(u_g, v_g) = 0 → Eqs(1) (2) → Wind-forced Slab model

Ensemble Mean and Stochastic Fluctuations of the Forcing

- (1) Ensemble Mean → Ekman Transport is determined by the surface wind stress →

$$\langle \Lambda_u \rangle = 0, \quad \langle \Lambda_v \rangle = 0$$

- (2) Fluctuations (Σ → strength)

$$\Lambda_u(t) = \langle \Lambda_u \rangle + \dot{W}_1(t) h\Sigma, \quad \Lambda_v(t) = \langle \Lambda_v \rangle + \dot{W}_2(t) h\Sigma \quad (3)$$

$$\left\langle \dot{W}_i(t_1) \dot{W}_j(t_2) \right\rangle = \delta_{ij} \delta(t_1 - t_2)$$

Stochastic Dynamic System

Eq(3) → Eqs(1) (2)

$$\frac{\partial u}{\partial t} = -\frac{K}{h^2} u + \dot{W}_1(t)\Sigma \qquad (4)$$

$$\frac{\partial v}{\partial t} = -\frac{K}{h^2} v + \dot{W}_2(t)\Sigma \qquad (5)$$

Fokker-Planck Equation for PDF of (*u*, *v*)

$$\frac{\partial p}{\partial t} = \left(\frac{\Sigma^2}{2}\right)\left(\frac{\partial^2 p}{\partial u^2} + \frac{\partial^2 p}{\partial v^2}\right) + \frac{\partial}{\partial u}\left[\left(\frac{K}{h^2}u\right)p\right] + \frac{\partial}{\partial v}\left[\left(\frac{K}{h^2}v\right)p\right] \quad (6)$$

Polar Coordinate → $u = w\cos\varphi, \quad v = w\sin\varphi$

w → Current Speed

For Constant K → PDF of w → the Rayleigh Distribution

(Special Case of the Weibull Distribution)

$$p(w) = \frac{2w}{a^2} \exp\left[-\left(\frac{w}{a} \right)^2 \right], \quad a \equiv \frac{\Sigma h}{\sqrt{K}}$$

For Non-Constant *K* → Weibull Distribution

$$p(w) = \frac{b}{a}\left(\frac{w}{a}\right)^{b-1} \exp\left[-\left(\frac{w}{a}\right)^{2}\right]$$

$$\text{mean}(w) = a\Gamma\left(1+\frac{1}{b}\right)$$

$$\text{std}(w) = a\left[\Gamma\left(1+\frac{2}{b}\right) - \Gamma^{2}\left(1+\frac{1}{b}\right)\right]^{1/2}$$

Γ → Gamma Function

Summary

- The ***Weibull distribution*** provides a reasonable empirical approximation to the PDF of the near surface current speeds for the global oceans.

Part-2
Under Strong Tropical Cyclones

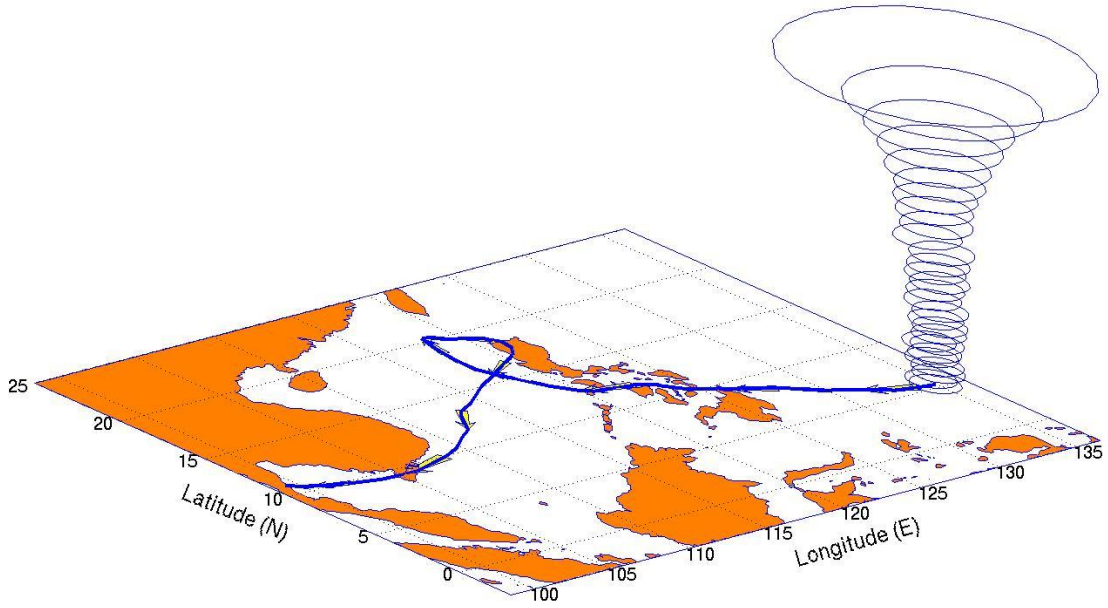
References

- Y.-C. Chang, P. C. Chu, R.-S. Tseng, G.-Y. Chen, and L. R. Centurioni, 2013: Strong observed currents under Super Typhoon Ma-on. Journal of Physical Oceanography (in revision).

- Chang, Y.-C., G.-Y. Chen, R.-S. Tseng, L. R. Centurioni, and P. C. Chu, 2013: Observed near-surface flows under all tropical cyclone intensity levels using drifters in the northwestern Pacific. *Journal of Geophysical Research*, **118**, 1-11, doi:10.1002/jgrc.20187.

- 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. *Journal of Geophysical Research*, 117, C11026, doi:10.1029/2012JC007996

What are upper ocean's currents under category-5 (super) typhoons ?

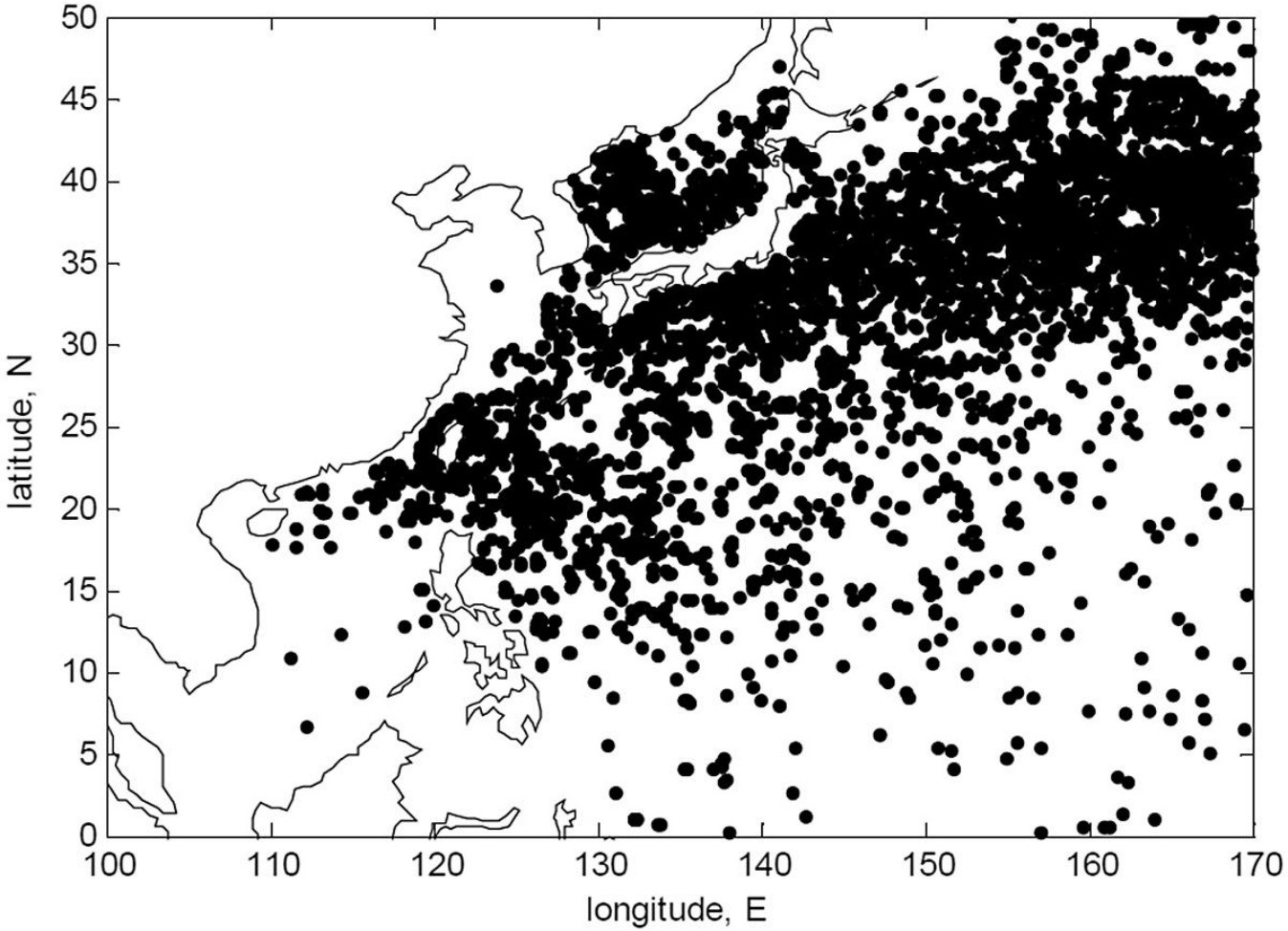


Surface Velocity Program (SVP) Drifter

SVP-SB
(SVP Drifter with Barometer and Salinity Sensors)

- 16" (41cm) Ø Surface Float
- 36"Ø (91cm) Ø x 7 Section Holey Sock Drogue
- Seabird SBE 37 SI Salinity Sensor w/ Temp
- Optional: Honeywell (HPB or IPT) Pressure Sensor
- Optional: 2nd Sea Surface Temperature Sensor
- Optional: EZ-Access Surface Float
- Telemetry Options: Iridium SBD, Argos II/III



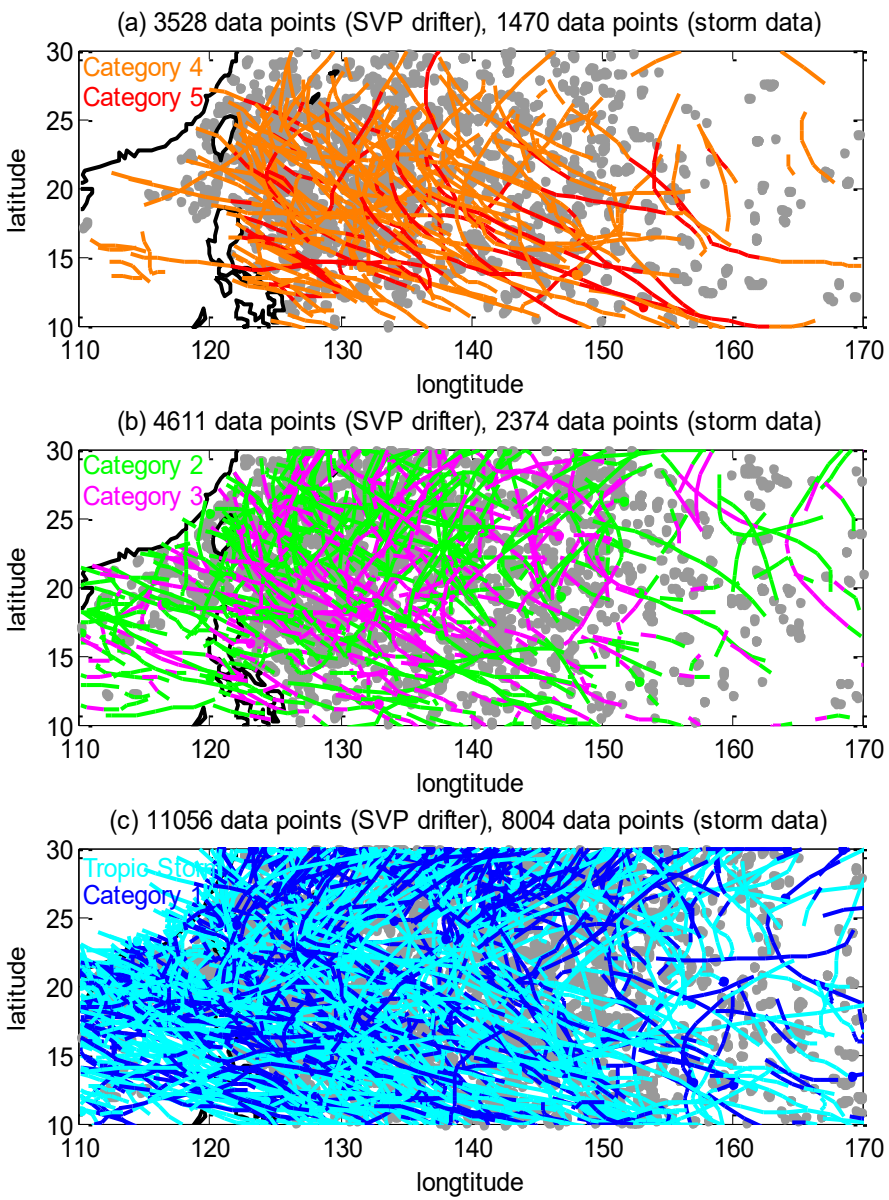


Global Surface Velocity Program (SVP) Drifters in the northwestern Pacific (100–170E, 0–50N) under high wind speeds (20–50 m/s) during 1999–2009.

Category 4-5

Category 2-3

Category 1



TTCs' tracks and data points of NOAA/AOML SVP drifters (gray dots) in the northwestern Pacific during 1985~2009

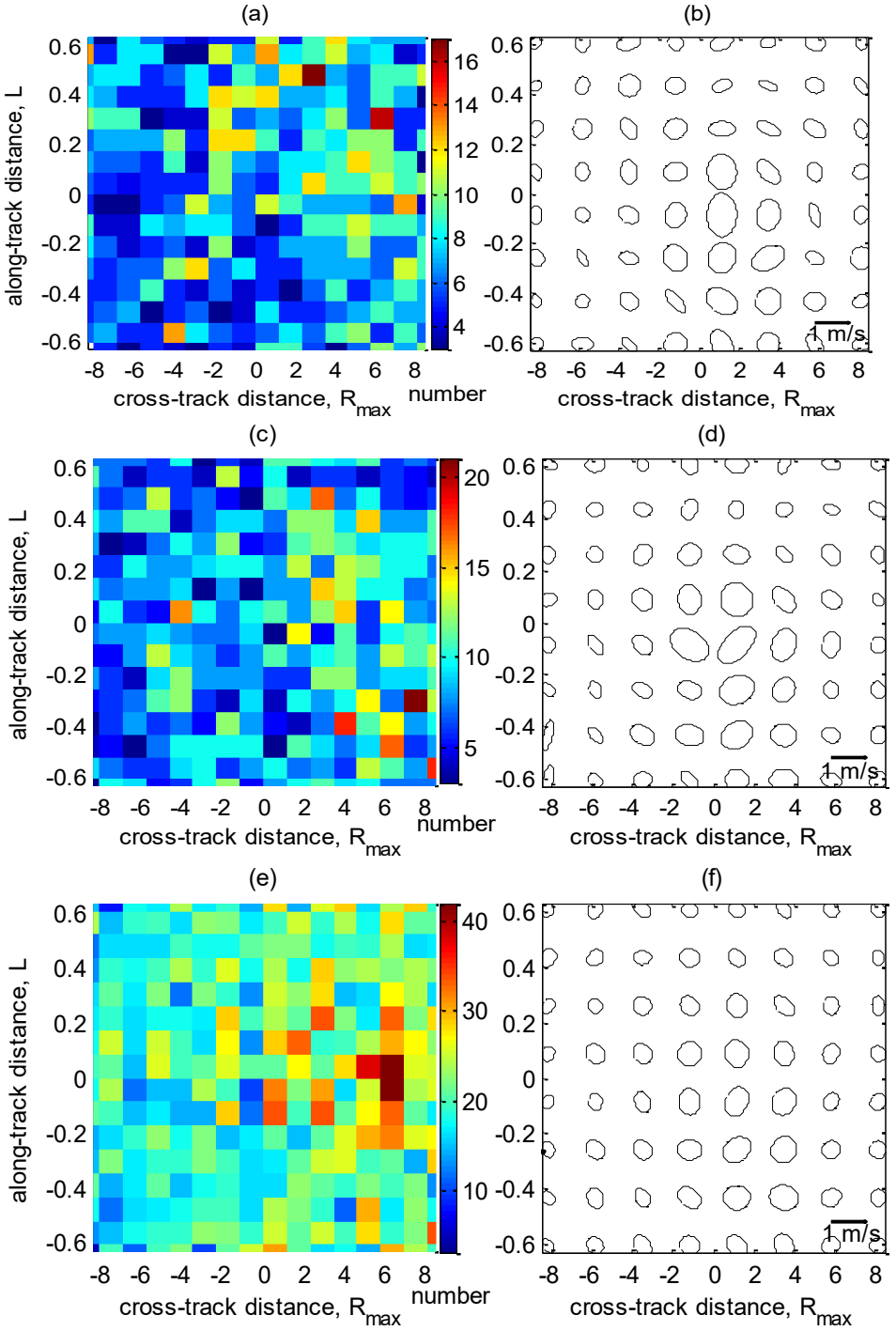
Numbers of data point

Standard error ellipses ($m\ s^{-1}$)

Category 4-5

Category 2-3

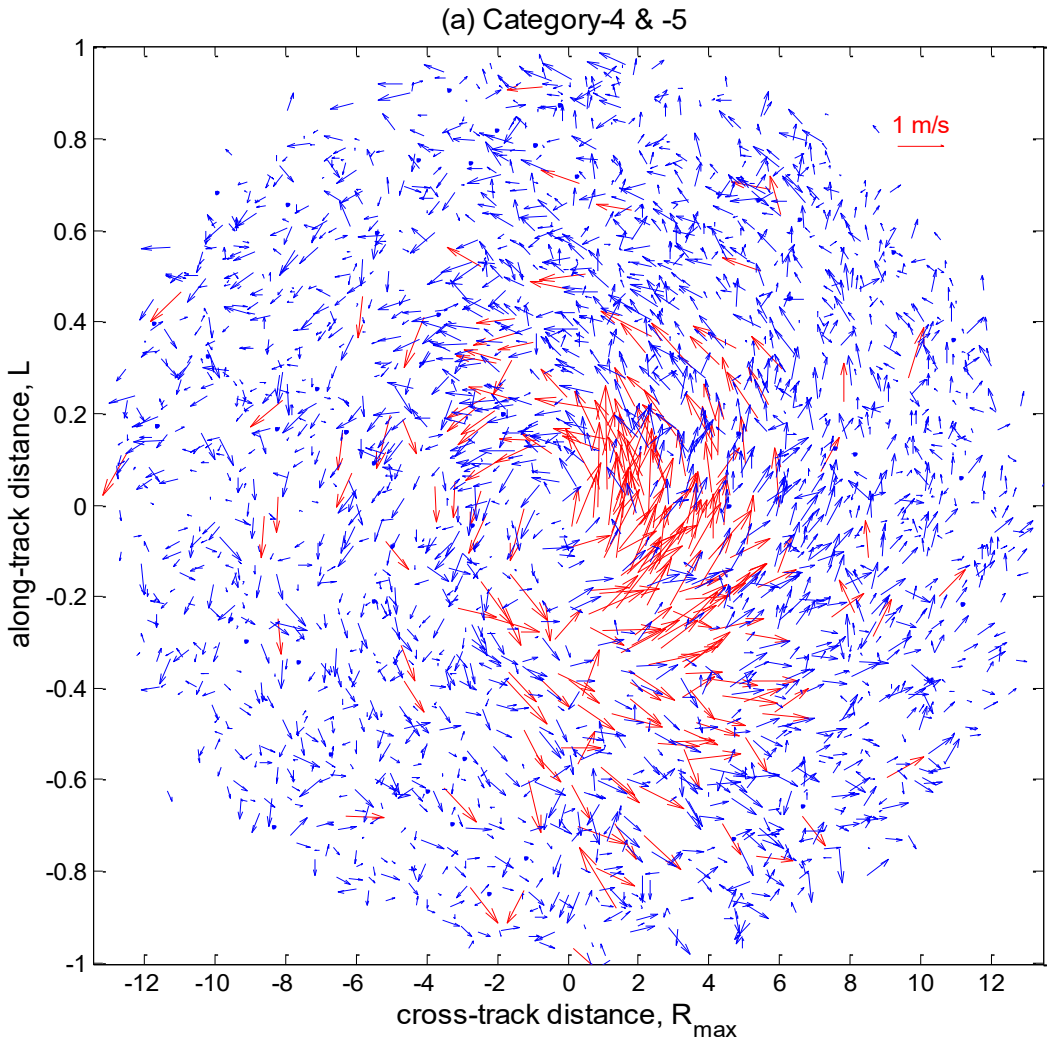
Category 1



Along-track Distance (L)
260-700 km

30 km < Rmax < 60 km

Red Arrows → Current
Speed > 0.8 m/s

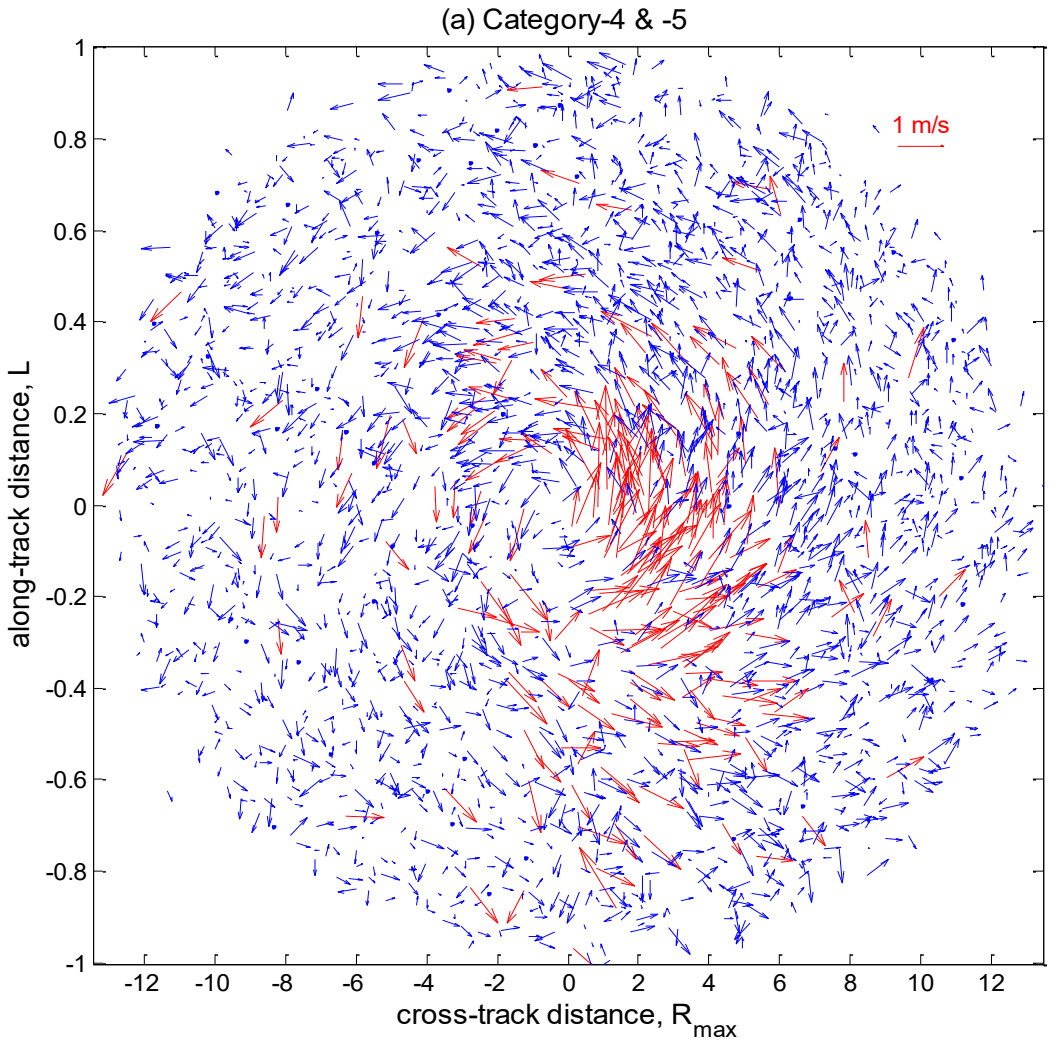


Storm center of category-4 and -5 (2654 data points) TCs versus observed current vectors (m s^{-1}) after removing background flow along all TCs' tracks (Chang et. al 2013 JGR)

Along-track Distance (L)
260-700 km

30 km < Rmax < 60 km

Red Arrows → Current
Speed > 0.8 m/s

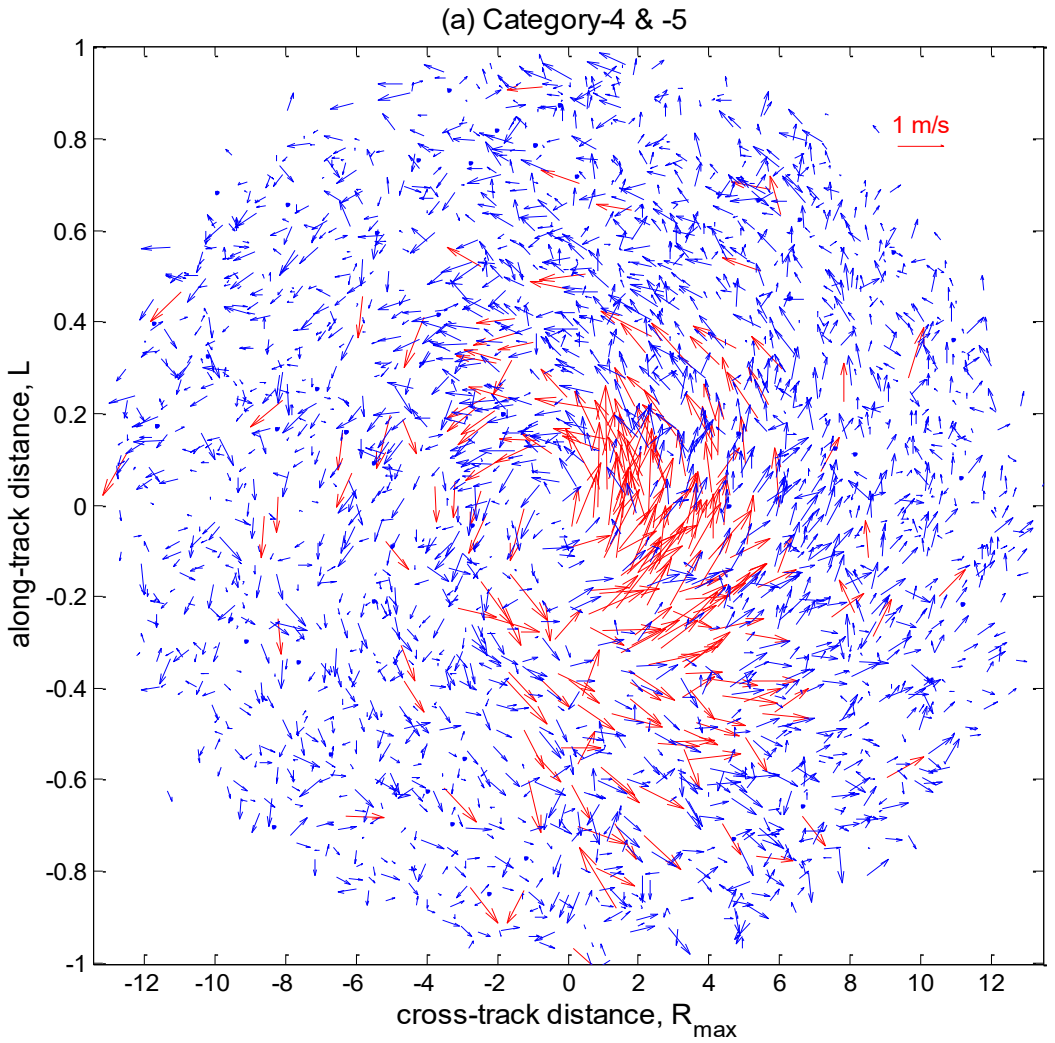


Storm center of category-2 and -3 (3353 data points) TCs versus observed current vectors (m s^{-1}) after removing background flow along all TCs' tracks (Chang et al. 2013 JGR)

Along-track Distance (L)
260-700 km

30 km < Rmax < 60 km

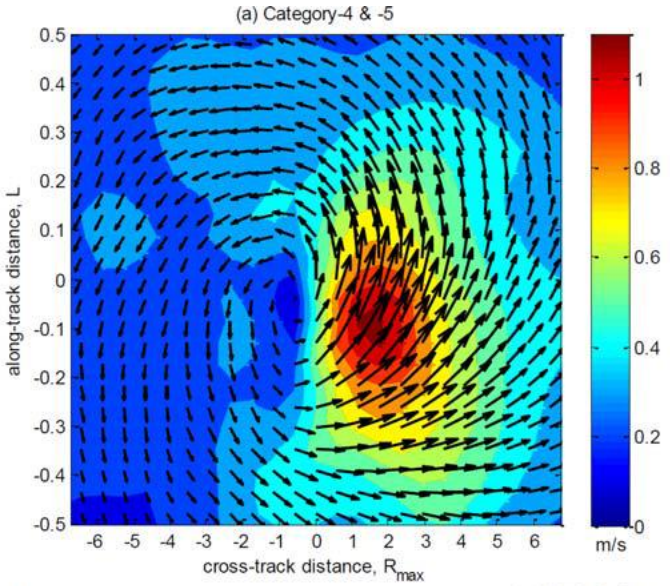
Red Arrows → Current
Speed > 0.8 m/s



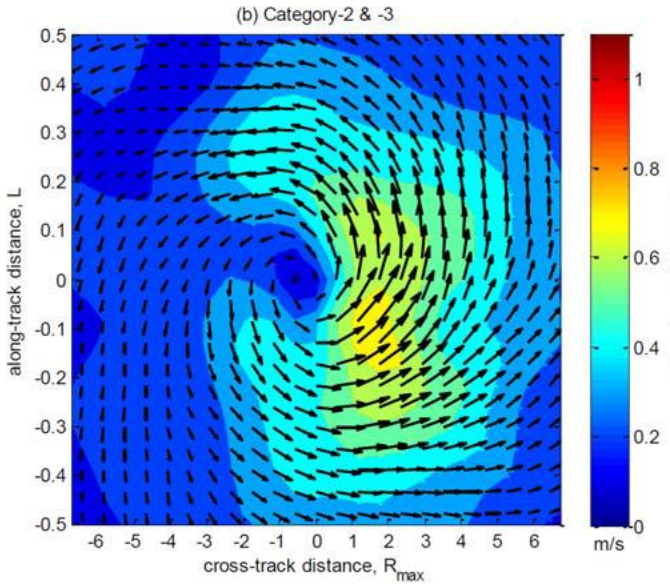
Storm center of category-1 TCs and tropical storms (7997 data points) versus observed current vectors (m s^{-1}) after removing background flow along all TCs' tracks (Chang et. al 2013 JGR)

Mean Currents

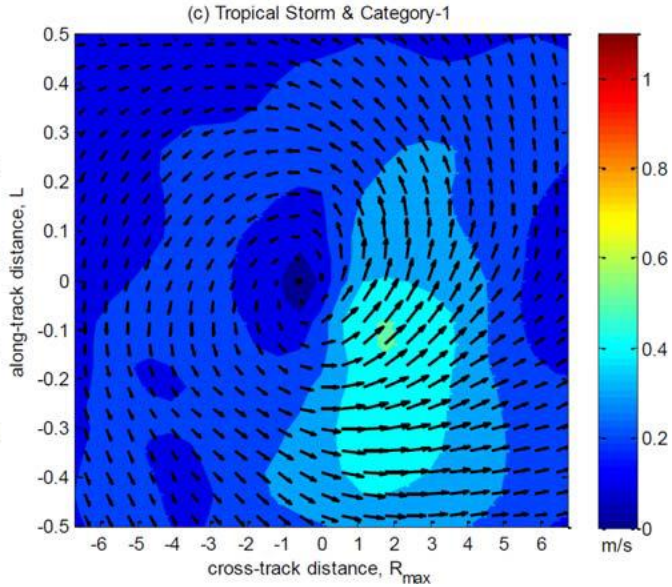
Category 4-5



Category 2-3



Category 1



U_h increases →

Wind-driven current decreases

Froude Number

Froude Number $F_r = U_h / c_1$

$$c_1^2 = g \frac{(\rho_2 - \rho_1) h_1 h_2}{\rho_2 (h_1 + h_2)}$$

h_1 is 18˚C isotherm depth

$h_2 = 1000\ m - h_1$

NODC-WOA

↓

C_1 ~2.88 m/s

U_h → TC ‘s Translation Speed

C_1 → *Phase Speed of First Baroclinic Mode (Upper Ocean)*

Ocean Response to TCs (depending on Froude number)

Fr < 1 ($U_h < c_1$) Barotropic (Upwelling)

Fr > 1 ($U_h > c_1$) Near Inertial (currents in the wake)

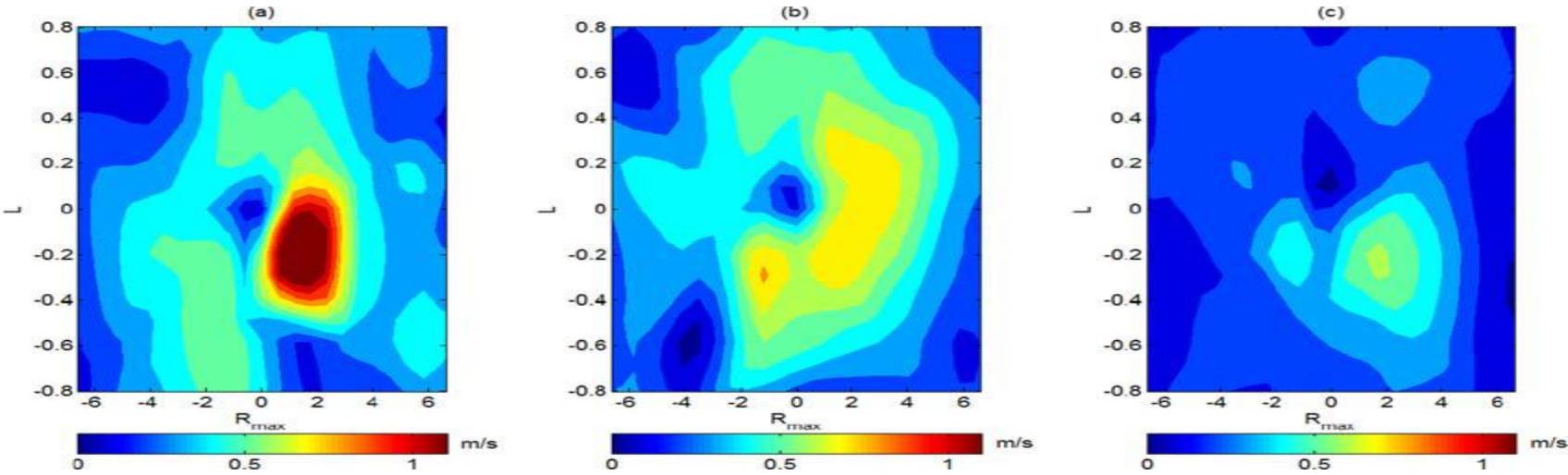
Chang and Anthes (1978); Chang (1985); Ginis and Sutyrin (1995)

Rate of occurrence of three F_r ranges in the three storm groups

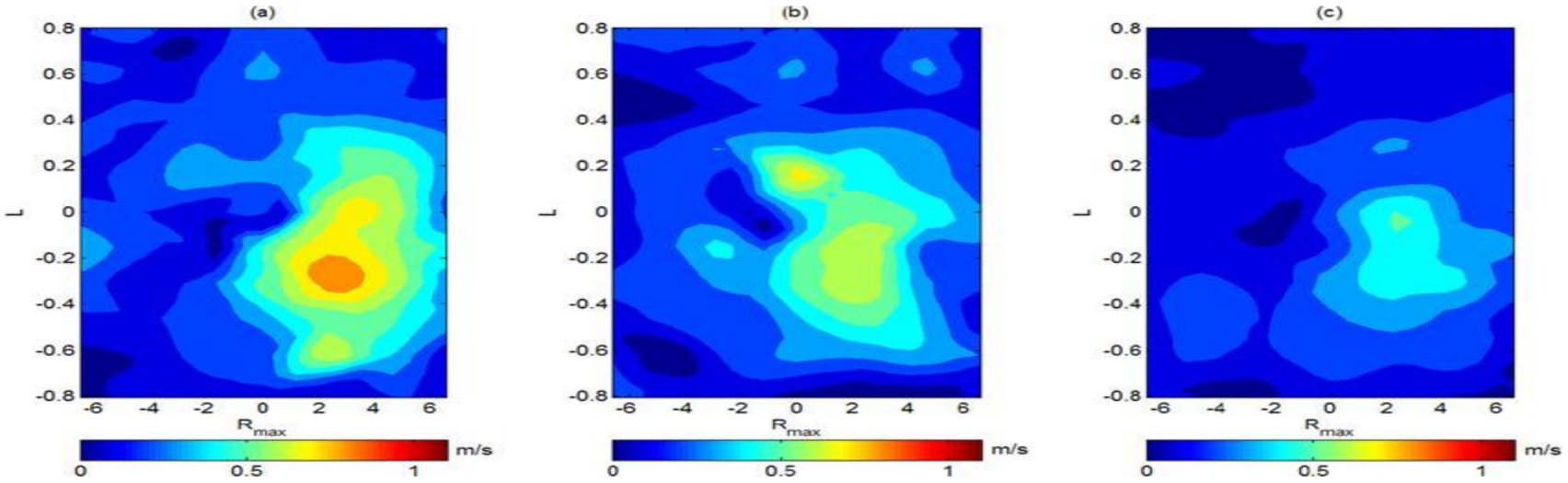
	moving speed	category -4 & -5	category -2 & -3	category-1 & tropical storm
F_r <1	slow	18%	28%	23%
1≦F_r<2	fast	53%	45%	48%
F_r≧2	fastest	29%	27%	29%

Dependence of Current Speed on Fr

Fr <1



Fr>2



Modeling → Scaled TC Wind-Driven Current Speed U_s (Price 1983)

$$U_s = \frac{\tau R_{max}}{h U_h} \qquad \tau = \rho_{air} C_d W^2$$

U_h increases → U_s decreases

W → Wind speed at 10 m height

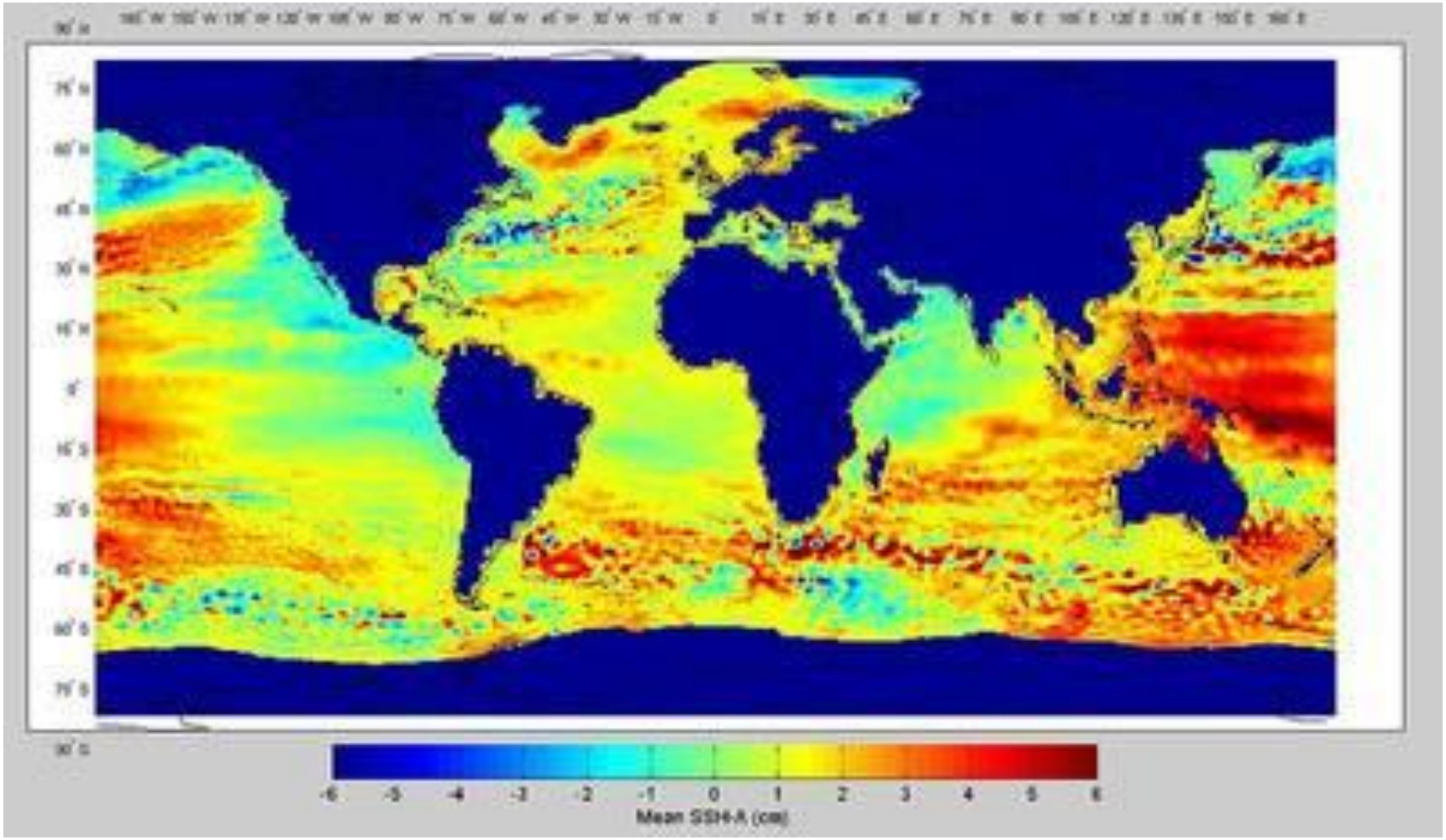
$$U_{ageo} = U_{obs} - U_{geo}$$

Wind Forcing → U_{ageo}

Archiving Validation and Interpretation of Satellite data in Oceanography (AVISO)

↓

U_{geo}



Global (1/3°×1/3° horizontal resolution) absolute sea surface Height from AVISO (http://icdc.zmaw.de/ssh_aviso.html?&L=1)

Observed wind-driven velocity U_{ageo} from drifter and the scaled wind-driven velocity U_s.

parameter	Category 4 & 5	Category 2 & 3	Category 1 & TS
W	60 m s^{-1}	45 m s^{-1}	30 m s^{-1}
τ	6.6 N m^{-2}	4.3 N m^{-2}	2.2 N m^{-2}
U_s	1.2 m s^{-1}	0.8 m s^{-1}	0.4 m s^{-1}
U_{ageo}	1.1 m s^{-1}	0.7 m s^{-1}	0.5 m s^{-1}

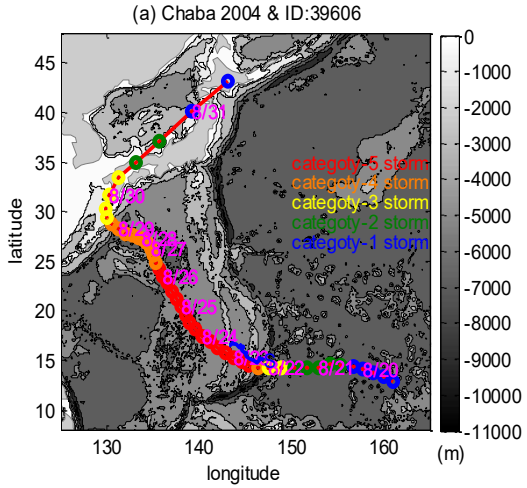
Three category-5 typhoons

- Chaba (2004)
- Maon (2004)
- Saomai (2006)

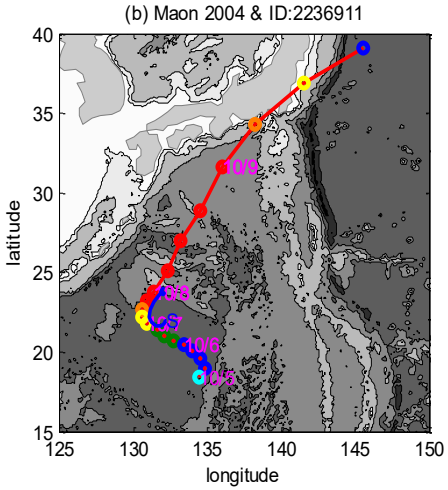
Information of three super typhoons (Chaba, Maon, and Saomai)

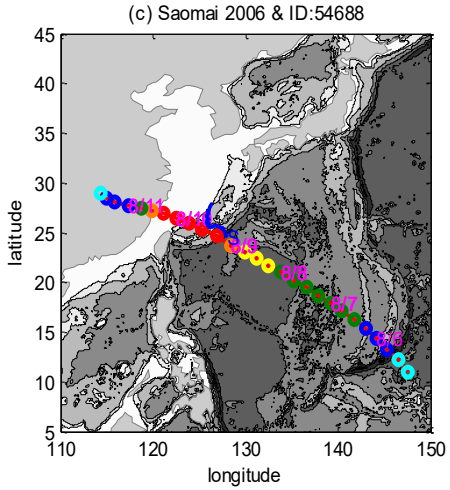
Storm's name	Chaba 2004	Maon 2004	Saomai 2006
Time as a super typhoon	1200 22 Aug – 0600 26 Aug	1800 07 Oct – 0000 09 Oct	0600 09 Aug – 0600 10 Aug
Minimum sea level pressure (mbar)	879	898	898
U_h (m s^{-1}) as a super typhoon	4.1 – 5.2 (slow moving)	2.9 – 15.4	7.0 – 8.7 (fast moving)
Drifter's ID	39606	2236911	54688
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

Chaba
Aug 2004



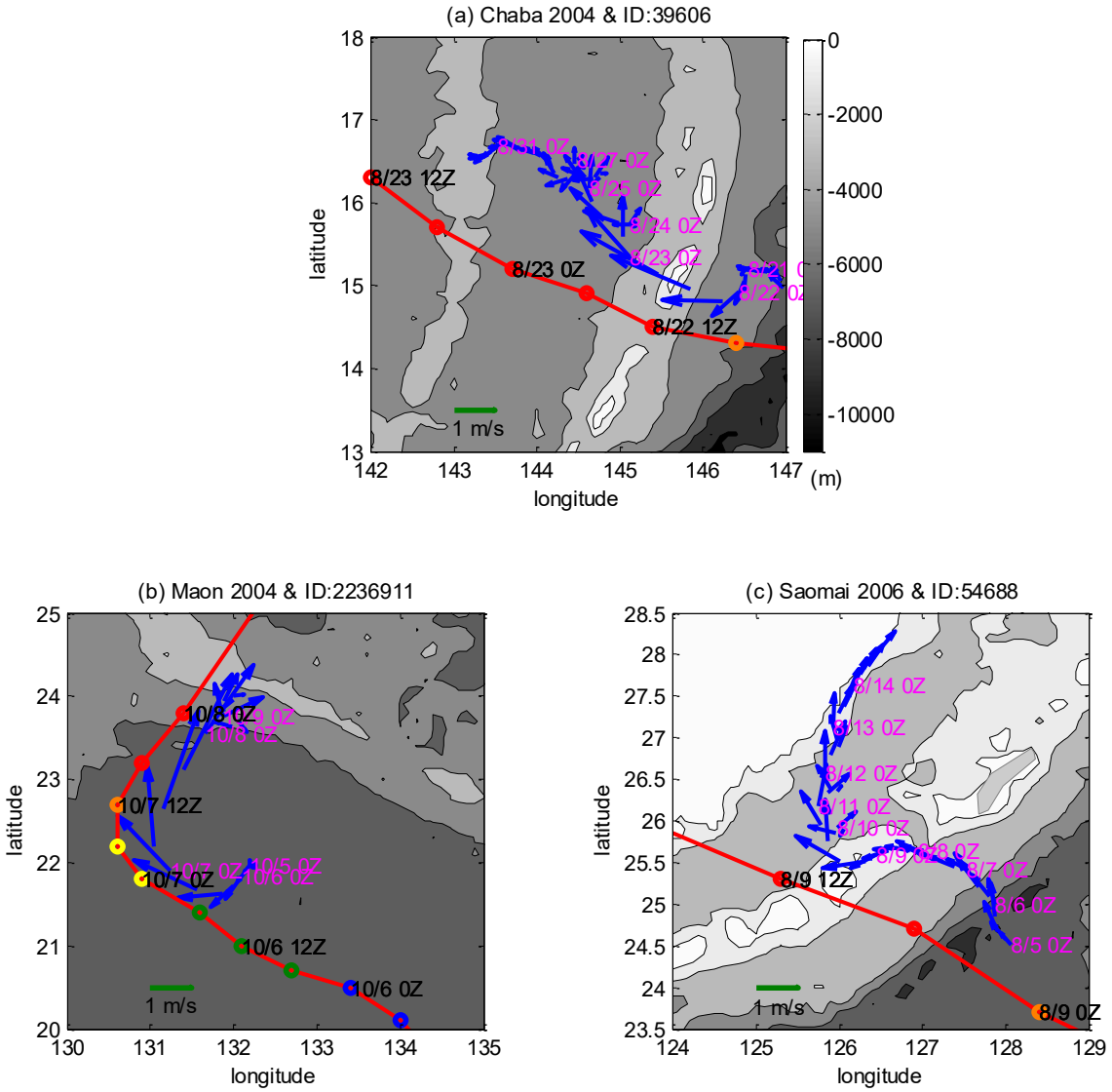
Ma-on
Oct 2004





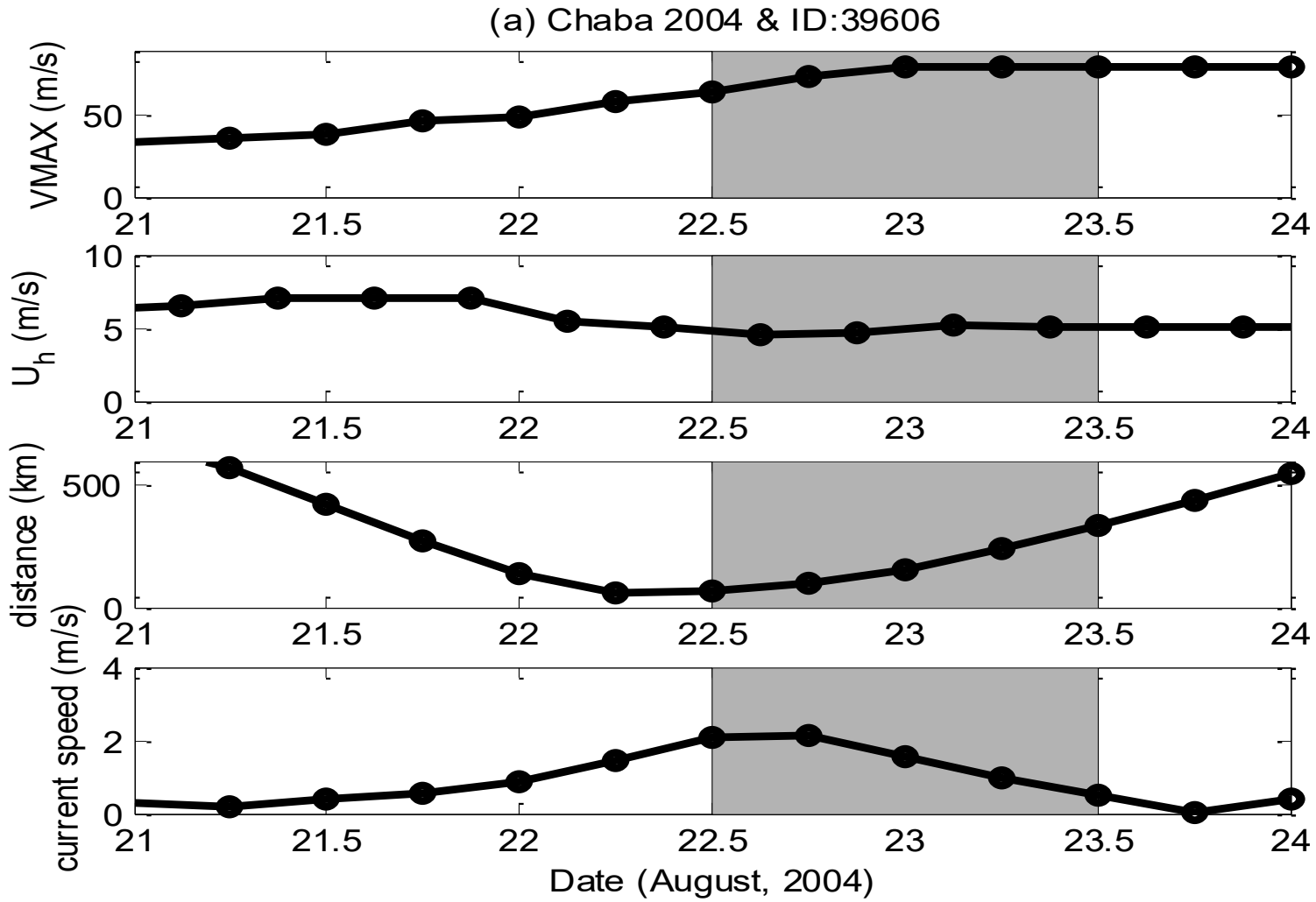
Saomai
Aug 2006

Three Tracks of three super typhoons (red curve) and three SVP drifters (magenta curve) [(a)39606, (b)2236911, (c)54688] with 6-hr time interval with the storm's intensities by color circles



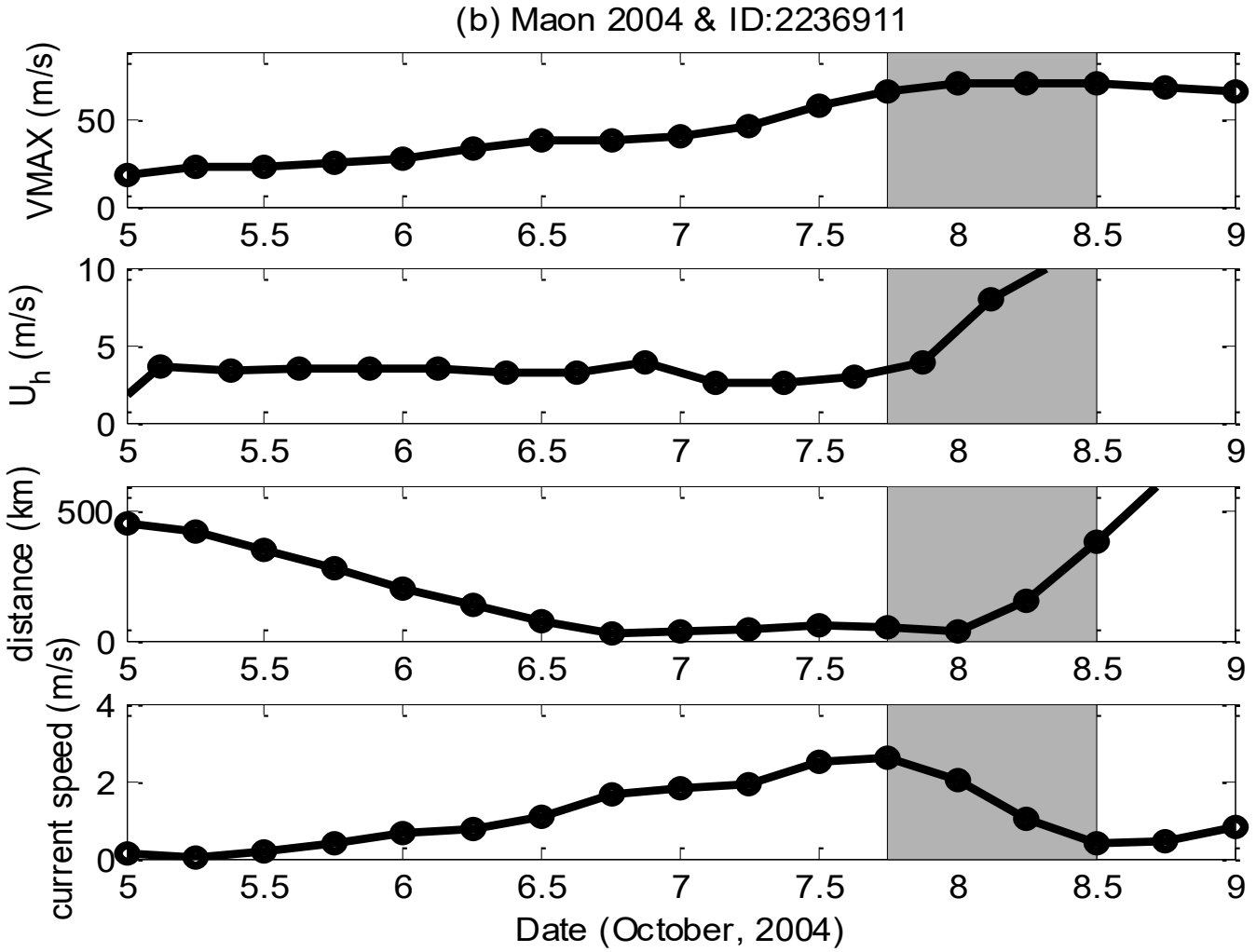
Three storm's paths and observed current vectors, both in 6-hourly interval

Chaba
Aug
2004



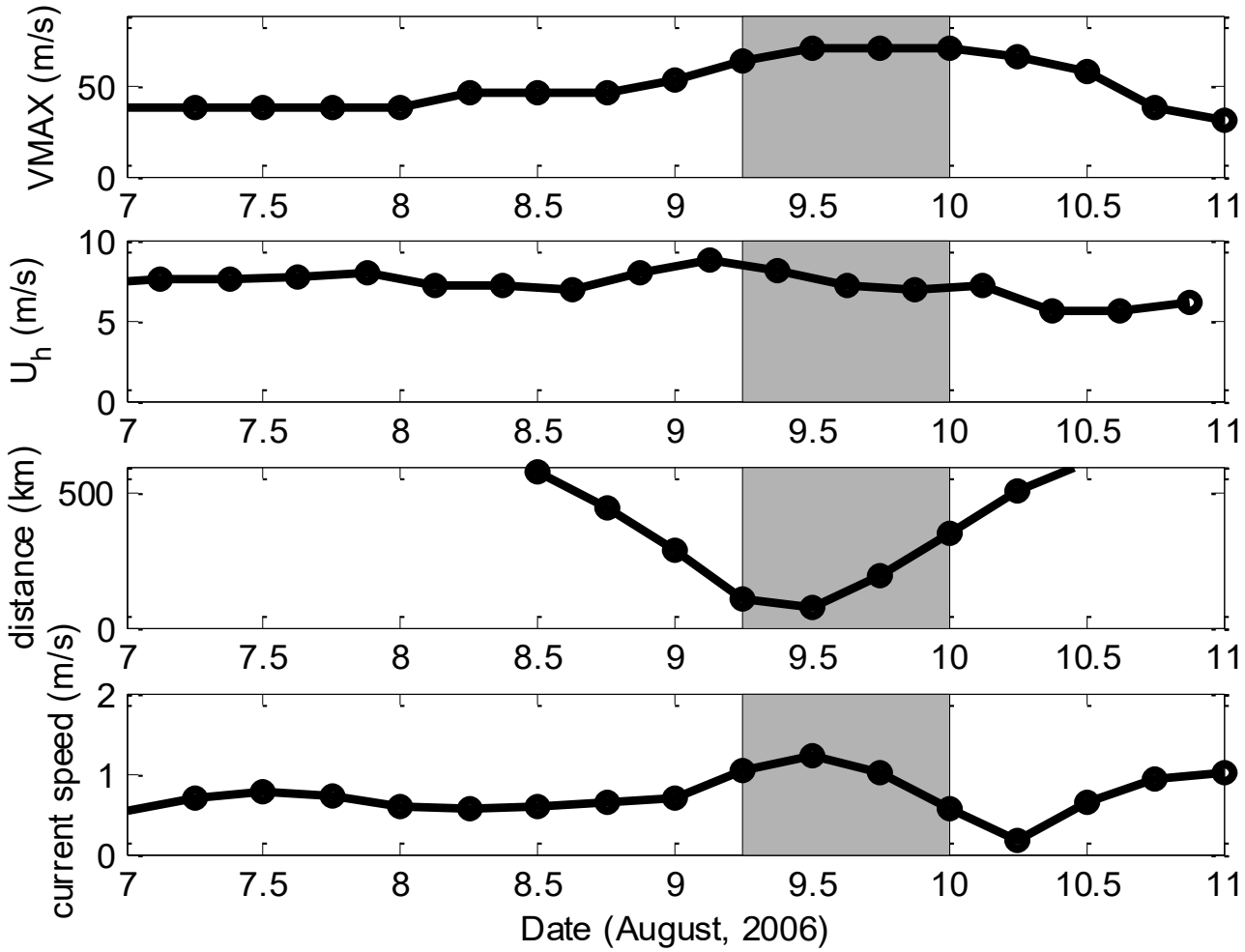
Time evolution of VMAX, U_h, D, and Uobs .
Shadings denote → the drifter was under a super typhoon and affected by the typhoon (D<400 km).

Maona
Oct
2004

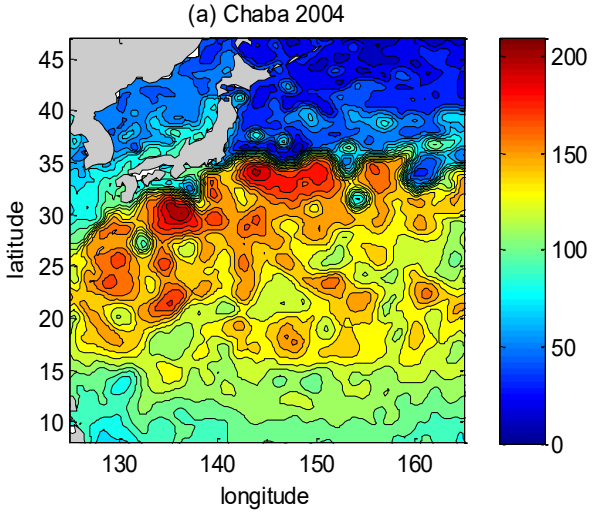


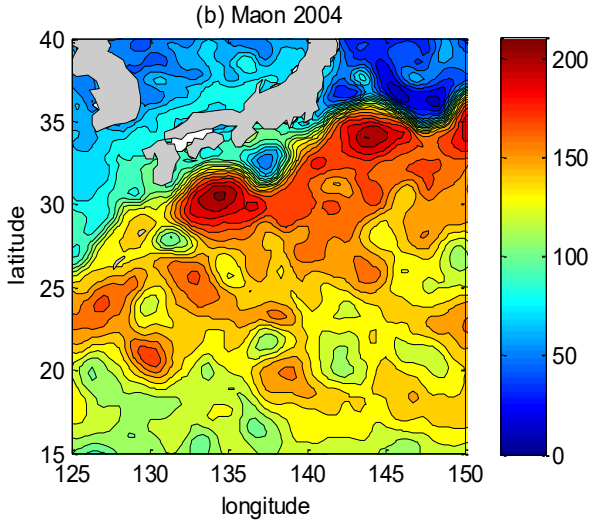
Time evolution of VMAX, U_h, D, and *U*obs .
Shadings denote → the drifter was under a super typhoon and affected by the typhoon (D<400 km).

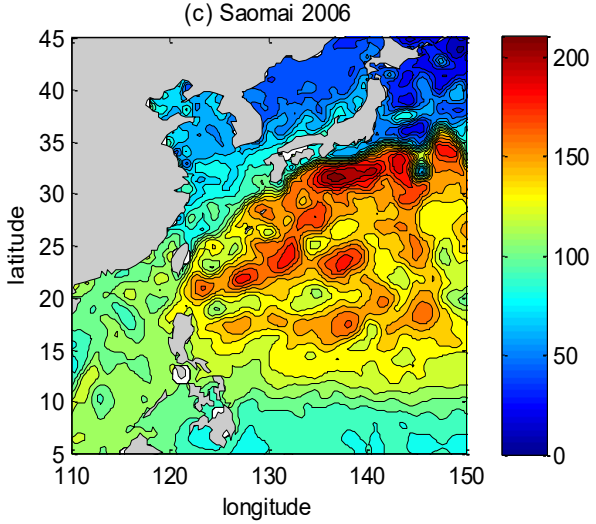
Saomai
Aug
2006



Time evolution of VMAX, U_h, D, and Uobs .
Shadings denote → the drifter was under a super typhoon and affected by the typhoon (D<400 km).



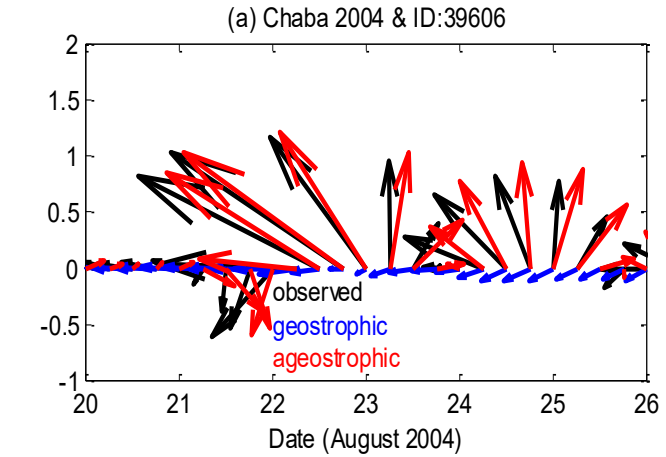


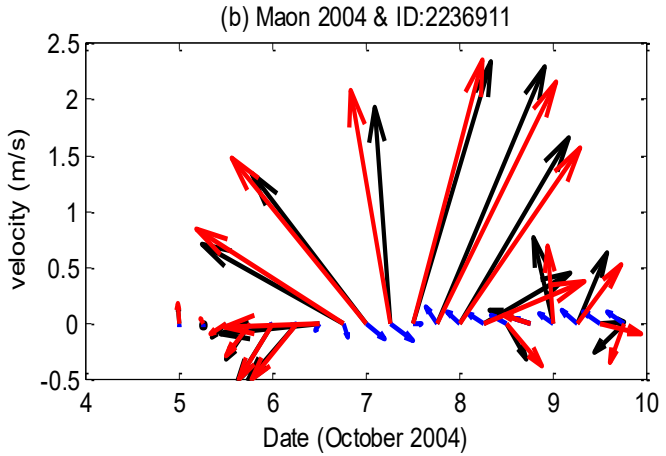


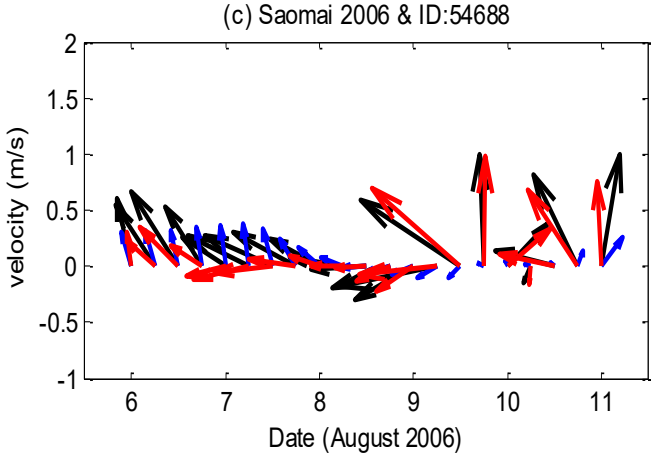
Gridded sea surface heights (Maps of absolute dynamic topography) from AVISO (units: cm) during (a) Chaba, (b) Maon, and (c) Saomai.

Observed (black arrows)
geostrophic (blue arrows)
ageostrophic (red arrows)
current vectors during

(a) Chaba
(b) Maon
(c) Saomai



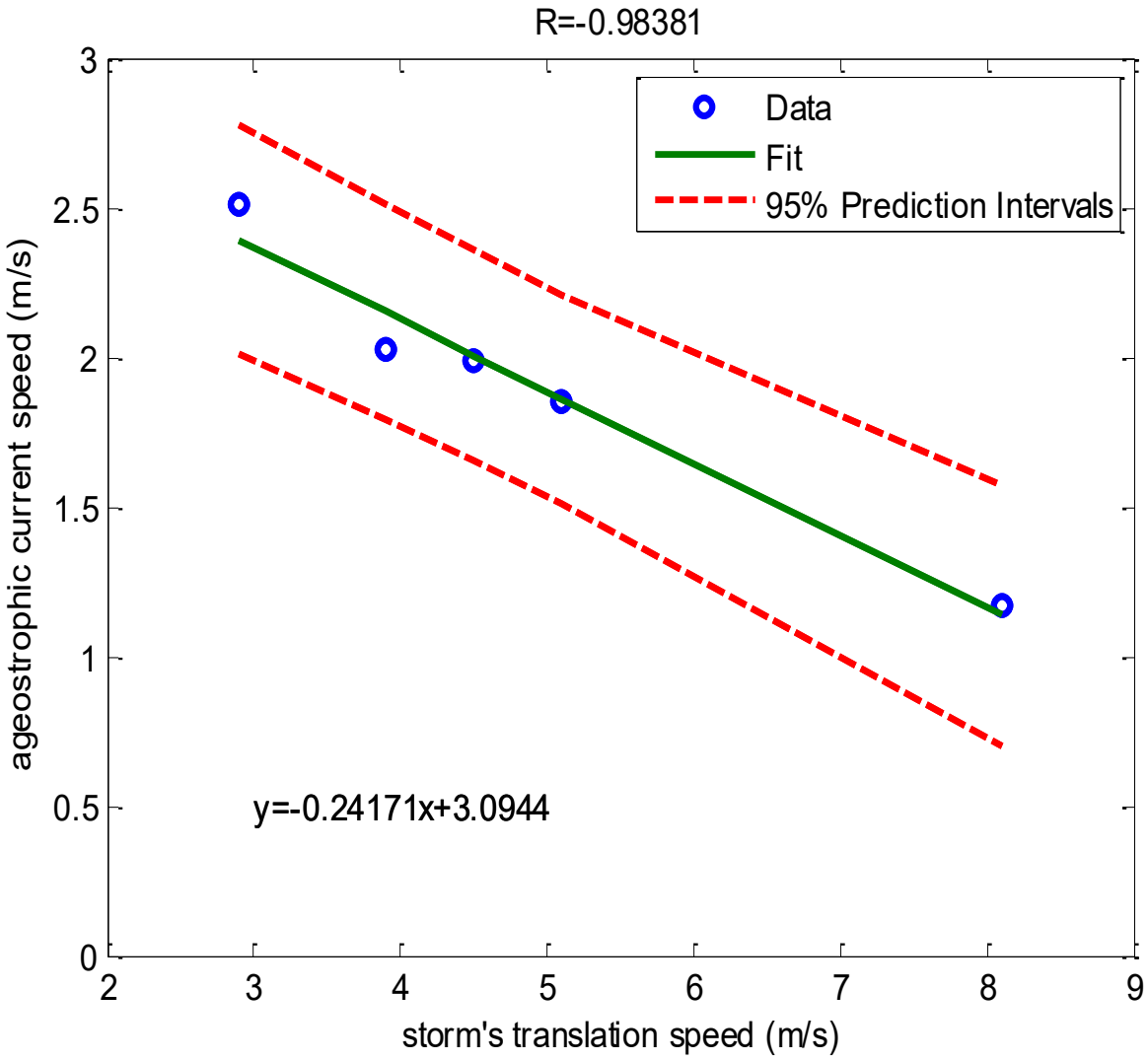




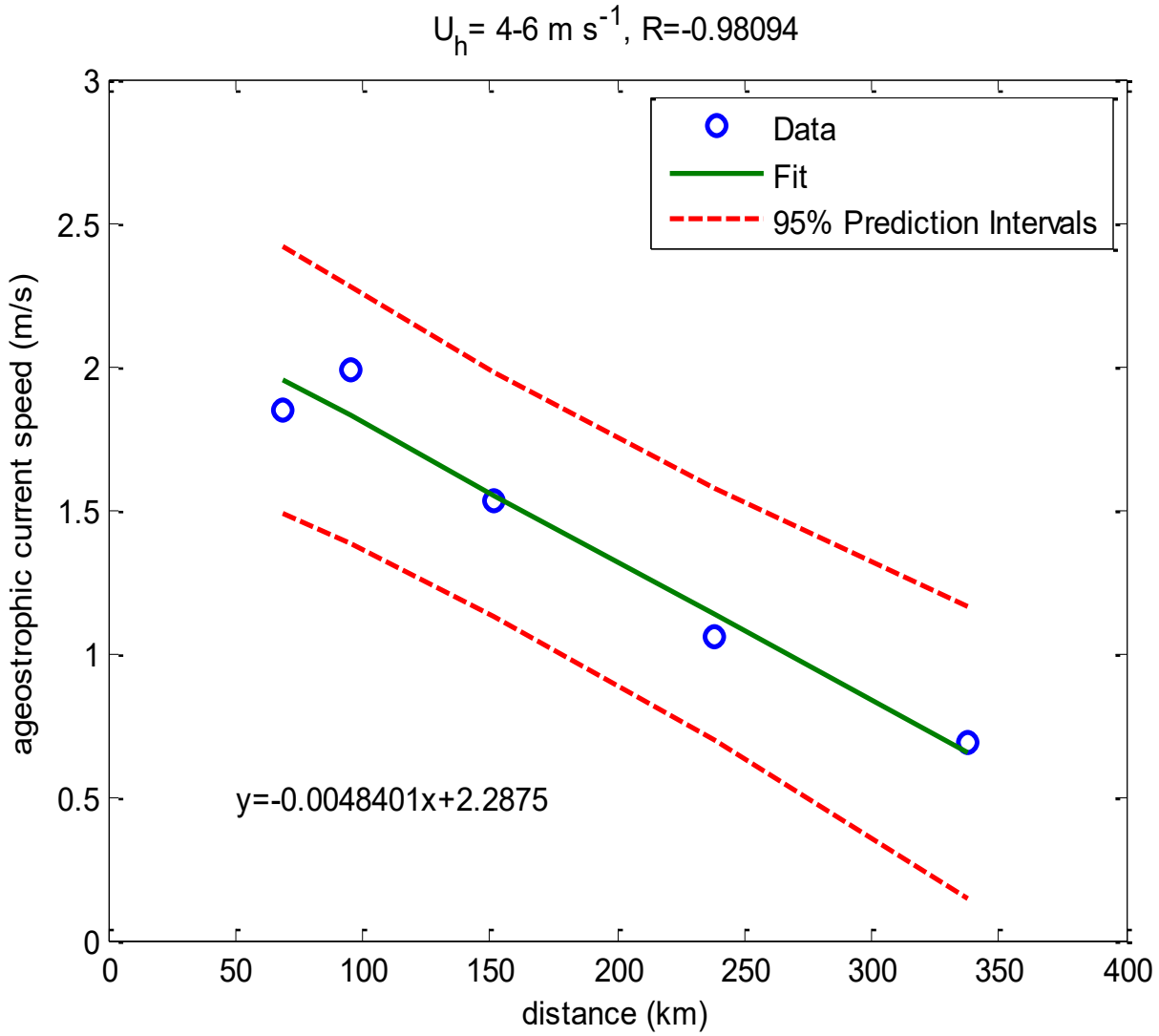
Name & ID	Time	Scale	U_h (m s^{-1})	D (km)	U_{obs} (m s^{-1})	U_{ageo} (m s^{-1})
Chaba & 39606	1200 22 Aug	Category 5	5.1	69	2.1	1.9
	1800 22 Aug	Category 5	4.5	95	2.1	2.0
	0000 23 Aug	Category 5	4.7	152	1.6	1.5
	0600 23 Aug	Category 5	5.2	238	1.0	1.1
	1200 23 Aug	Category 5	5.0	338	0.5	0.7

Name & ID	Time	Scale	U_h (m s^{-1})	D (km)	U_{obs} (m s^{-1})	U_{ageo} (m s^{-1})
Maon & 2236911	1800 7 Oct	Category 5	2.9	52	2.6	2.5
	0000 8 Oct	Category 5	3.9	38	2.0	2.0
	0600 8 Oct	Category 5	7.9	153	1.0	1.1
	1200 8 Oct	Category 5	10.6	382	0.4	0.5

Name & ID	Time	Scale	U_h (m s^{-1})	D (km)	U_{obs} (m s^{-1})	U_{ageo} (m s^{-1})
Saomai & 54688	0600 9 Aug	Category 5	8.7	108	1.1	0.8
	1200 9 Aug	Category 5	8.1	74	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



$$U_{ageo} = -0.242U_h + 3.09 \quad (2.9 \text{ m s}^{-1} \leqq U_h \leqq 8.1 \text{ m s}^{-1})$$



U_{ageo} = -0.0048D+ 2.29 (69 km$\leqq D \leqq$338 km)

Summary

- (1) High-speed currents → 2.6 m/s
- (2) Two types of upper ocean response are verified.
- (3) Modeling → Scale of TC wind-driven current ← is verified.
- (4) Current speed decreases with increasing TC translation speed.
- (5) Current speed decreases with increasing distance to TC center.