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## JP5.18 Weibull Distribution for Global Surface Current Speeds Obtained from Satellite Altimetry

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### 1. Introduction

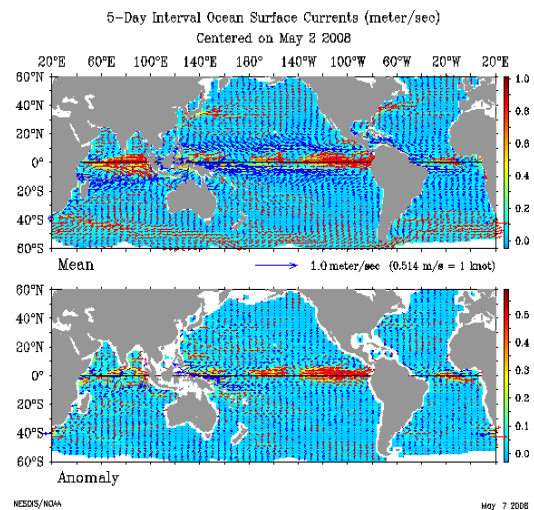
The world oceans contribute significantly to the global redistribution of heat necessary to maintain the earth's thermal equilibrium. Surface layer horizontal fluxes of momentum, heat, water mass and chemical constituents are typically nonlinear in the speed (Galanis et al. 2005; Lozano et al. 1996), so the space or time average flux is not generally equal to the flux that would be diagnosed from the averaged current speed. In fact, the average flux will generally depend on higher-order moments of the current speed, such as the standard deviation, skewness, and kurtosis. From both diagnostic and modeling perspectives, there is a need for parameterizations of the probability distribution function (PDF) of the current speed  $w$  (called  $w$ -PDF here).

Recent study on the equatorial Pacific (Chu 2008) showed that the  $w$ -PDF satisfies the two-parameter Weibull distribution in the upper layer (0 – 50 m) after analyzing the hourly Acoustic Doppler Current Profiler (ADCP) data (1990-2007) at all the six stations along during the Tropical Atmosphere Ocean (TAO) project. Question arises: Can such a result (e.g., the Weibull distribution for the equatorial Pacific surface current speeds) be extended to global oceans? To answer this question, we use the 5-day Ocean Surface Currents Analyses – Real-time (OSCAR) data to construct the observational  $w$ -PDF for the global ocean surface circulation. Special characteristics of the statistical parameters such as mean, standard deviation, skewness, and kurtosis will also be identified.

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### 2. The OSCAR Data

The OSCAR data are available for the world oceans from 60°N to 60°S on 1°×1° grid to a broad-based user community via a web-based interactive data selection interface on a time base with exactly 72 steps per year (about 5 day interval) starting from October 1992 (Fig. 1). The velocity is automatically computed from gridded fields of surface topography and wind derived on the base of the Ekman dynamics from satellite altimeter (JASON-1, GFO, ENVISAT) and scatterometer (QSCAT) vector wind data. See website: <http://www.oscar.noaa.gov/> for detailed information.



**Fig. 1. Global ocean surface current vectors (5-day mean and anomaly) derived from satellite altimeter and scatterometer data. The data can be downloaded from the website:**

<http://www.oscar.noaa.gov/>.

### 3. Stochastic Differential Equations for Surface Currents

Let  $(x, y)$  be the horizontal coordinates and  $z$  be the vertical coordinate. Vertically averaged horizontal velocity components  $(u, v)$  from the surface to a constant scale depth ( $h$ ) of surface mixed layer are given by (Chu 2008)

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

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

where

$$\Lambda_u \equiv fV_E + \frac{\tau_x}{\rho}, \quad \Lambda_v \equiv -fU_E + \frac{\tau_y}{\rho}, \quad (3)$$

represent the residual between the Ekman transport and surface wind stress. Here,  $K$  is the eddy viscosity;  $f$  is the Coriolis parameter;  $(\tau_x, \tau_y)$  are the surface wind stress components; and  $(U_E, V_E)$  are Ekman transports computed by

$$(U_E, V_E) = \int_{-h}^0 (\tilde{u} - u_g, \tilde{v} - v_g) dz, \quad (4)$$

where  $(\tilde{u}, \tilde{v})$  are the vertically varying horizontal velocity components; and  $(u_g, v_g)$  are the geostrophic velocity components. With absence of horizontal pressure gradient, e.g.,  $u_g = v_g = 0$ , Equations (1) and (2) reduce to the commonly used wind-forced slab model (Pollard and Millard 1970). For the sake of convenience, we assume that the residual between the Ekman transports  $(U_E, V_E)$  and surface wind stress does not depend on the horizontal current vector  $(u, v)$ . Away from the equator, this approximation is similar to a small Rossby number approximation (Gill 1982). If the forcing  $(\Lambda_u, \Lambda_v)$  is fluctuating around some mean value,

$$\begin{aligned} \Lambda_u(t) &= \langle \Lambda_u \rangle + \dot{W}_1(t)h\Sigma, \\ \Lambda_v(t) &= \langle \Lambda_v \rangle + \dot{W}_2(t)h\Sigma, \end{aligned} \quad (5)$$

where the angle brackets represent ensemble mean and the fluctuations are taken to be isotropic and white in time:

$$\langle \dot{W}_i(t_1) \dot{W}_j(t_2) \rangle = \delta_{ij} \delta(t_1 - t_2), \quad (6)$$

with a strength that is represented by  $\Sigma$ . Note that the Ekman transport is determined by the surface wind stress for time-independent case, and therefore the ensemble mean values of  $(\Lambda_u, \Lambda_v)$  are zero,

$$\langle \Lambda_u \rangle = 0, \quad \langle \Lambda_v \rangle = 0. \quad (7)$$

Substitution of (5)-(7) into (1) and (2) gives

$$\frac{\partial u}{\partial t} = -\frac{K}{h^2} u + \dot{W}_1(t)\Sigma, \quad (8)$$

$$\frac{\partial v}{\partial t} = -\frac{K}{h^2} v + \dot{W}_2(t)\Sigma, \quad (9)$$

which is a set of stochastic differential equations for the surface current vector. The joint PDF of  $(u, v)$  satisfies the Fokker-Planck equation,

$$\begin{aligned} \frac{\partial p}{\partial t} &= \left( \frac{\Sigma^2}{2} \right) \left( \frac{\partial^2 p}{\partial u^2} + \frac{\partial^2 p}{\partial v^2} \right) \\ &+ \frac{\partial}{\partial u} \left[ \left( \frac{K}{h^2} u \right) p \right] + \frac{\partial}{\partial v} \left[ \left( \frac{K}{h^2} v \right) p \right], \end{aligned} \quad (10)$$

which is a linear second-order partial differential equation with the depth scale ( $h$ ) taken as a constant. Transforming from the orthogonal coordinates  $(u, v)$  to the polar coordinates  $(w, \varphi)$  respectively the current speed and direction,

$$u = w \cos \varphi, \quad v = w \sin \varphi. \quad (11)$$

The joint PDF of  $(u, v)$  is transformed into the joint PDF of  $(w, \varphi)$ ,

$$\begin{aligned} p(u, v) du dv &= p(u, v) w dw d\varphi \\ &= \tilde{p}(w, \varphi) dw d\varphi. \end{aligned} \quad (12)$$

Integration of (12) over the angle  $\varphi$  from 0 to  $2\pi$  yields the marginal PDF for the current speed alone,

$$p(w) = \int_0^{2\pi} \tilde{p}(w, \varphi) d\varphi. \quad (13)$$

For a constant eddy viscosity ( $K$ ) at  $z = -h$ , the steady state solution of equation (10) is given by

$$p(u, v) = A \exp \left[ -\frac{K}{\Sigma^2 h^2} (u^2 + v^2) \right], \quad (14)$$

where  $A$  is a normalization constant. Substitution of (14) into (12) and use of (13) yield the Rayleigh distribution

$$p(w) = \frac{2w}{a^2} \exp \left[ -\left( \frac{w}{a} \right)^2 \right], \quad a \equiv \frac{\Sigma h}{\sqrt{K}}, \quad (15)$$

with the scale parameter  $a$ . The basic postulation of constant  $K$  may not be met always at the upper ocean. Hence we require a model that can meet the twin objectives of (a) accommodating Rayleigh distribution whenever the basic hypothesis (constant  $K$ ) that justifies it is satisfied and (b) fitting data under more general conditions. This requirement is supposed to be satisfied by the Weibull probability density function,

$$p(w) = \frac{b}{a} \left( \frac{w}{a} \right)^{b-1} \exp \left[ -\left( \frac{w}{a} \right)^b \right], \quad (16)$$

where the parameters  $a$  and  $b$  denote the scale and shape of the distribution. This distribution has been recently used in investigating the ocean model predictability (Ivanov and Chu, 2007a,b).

#### 4. Parameters of the Weibull Distribution

The four parameters (mean, standard deviation, skewness, and kurtosis) of the Weibull distribution are calculated by (Johnson et al. 1994),

$$\text{mean}(w) = a\Gamma\left(1 + \frac{1}{b}\right), \quad (17)$$

$$\text{std}(w) = a\left[\Gamma\left(1 + \frac{2}{b}\right) - \Gamma^2\left(1 + \frac{1}{b}\right)\right]^{1/2}, \quad (18)$$

where  $\Gamma$  is the gamma function. The parameters  $a$  and  $b$  can be inverted (Monahan 2006) from (17) and (18),

$$b = \left[\frac{\text{mean}(w)}{\text{std}(w)}\right]^{1.086}, \quad a = \frac{\text{mean}(w)}{\Gamma(1 + 1/b)}. \quad (19)$$

The skewness and kurtosis are computed by

$$\begin{aligned} \text{skew}(w) &= \frac{\Gamma\left(1 + \frac{3}{b}\right) - 3\Gamma\left(1 + \frac{1}{b}\right)\Gamma\left(1 + \frac{2}{b}\right) + 2\Gamma^3\left(1 + \frac{1}{b}\right)}{\left[\Gamma\left(1 + \frac{2}{b}\right) - \Gamma^2\left(1 + \frac{1}{b}\right)\right]^{3/2}} \\ & \quad (20) \end{aligned}$$

$$\begin{aligned} \text{kurt}(w) &= \frac{\Gamma\left(1 + \frac{4}{b}\right) - 4\Gamma\left(1 + \frac{1}{b}\right)\Gamma\left(1 + \frac{3}{b}\right)}{\left[\Gamma\left(1 + \frac{2}{b}\right) - \Gamma^2\left(1 + \frac{1}{b}\right)\right]^2} \\ &+ \frac{6\Gamma^2\left(1 + \frac{1}{b}\right)\Gamma\left(1 + \frac{2}{b}\right) - 3\Gamma^4\left(1 + \frac{1}{b}\right)}{\left[\Gamma\left(1 + \frac{2}{b}\right) - \Gamma^2\left(1 + \frac{1}{b}\right)\right]^2} - 3, \\ & \quad (21) \end{aligned}$$

which depend on the parameter  $b$  only [see (20) and (21)] for the Weibull distribution. The relationship between the kurtosis and skewness can be determined from (20) and (21).

## 5. Observational $w$ -PDF

The data depicted in Section 2 are used to investigate the statistical features of the global surface current speeds ( $w$ ). The four parameters (mean, standard deviation, skewness, and kurtosis) can also be calculated from the observational data ( $w$ )

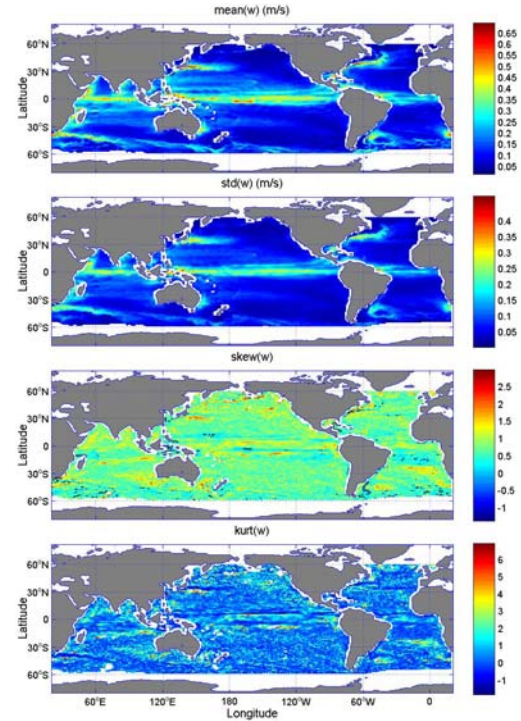
$$\text{mean}(w) = \frac{1}{N} \sum_{i=1}^N w_i,$$

$$\text{std}(w) = \sqrt{\text{mean}[w - \text{mean}(w)]^2},$$

$$\text{skew}(w) = \frac{\text{mean}\{[w - \text{mean}(w)]^3\}}{\text{std}^3(w)},$$

$$\text{kurt}(w) = \frac{\text{mean}\{[w - \text{mean}(w)]^4\}}{\text{std}^4(w)} - 3,$$

for the each grid point. The mean, standard deviation, skewness, and kurtosis fields of  $w$  estimated from the OSCAR data are displayed in Fig. 2. Large values of  $\text{mean}(w)$  occur in the western boundaries such as in the Gulf Stream, Kuroshio, and Somali Current, Malvinas Current and; secondary maxima in the equatorial zones especially in the western and central equatorial Pacific. Minima of  $\text{mean}(w)$  occur in the subtropical horse latitudes. The standard deviation of  $w$  is also large near the western boundaries and in the equatorial zones. In general,  $w$  is positively skewed in the most part of the global oceans and negatively skewed in the equatorial zones and Southern Ocean. The kurtosis field is much noisier than those of  $\text{mean}(w)$ ,  $\text{std}(w)$ , or  $\text{skew}(w)$ .



**Fig. 2.** First four parameters of the surface current speeds calculated from the OSCAR data (1992-2008).

The Weibull parameters ( $a$ ,  $b$ ) were calculated from  $\text{mean}(w)$  and  $\text{std}(w)$ . The distribution of the parameter  $a$  over the global oceans (Fig. 3a) is quite close to the distribution of  $\text{mean}(w)$ , i.e., with large values in western boundaries and equatorial zone. The distribution of the Weibull parameter  $b$  is shown in Fig. 3b. Thus, a four-parameter dataset has been established each location. The scatter diagrams were drawn for global oceans during all or different time periods.

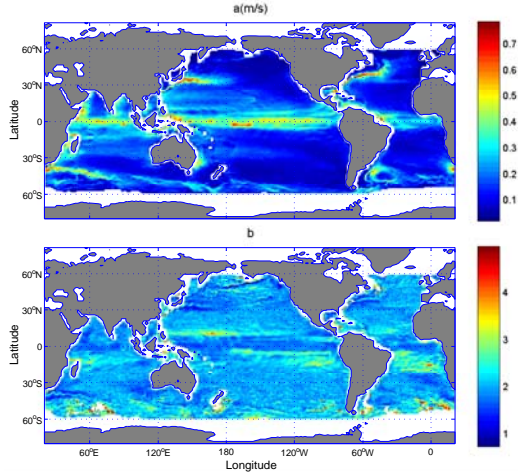


Fig. 3. Same as in Fig. 2, but for Weibull parameters ( $a$ ,  $b$ ).

The relationships between  $\text{skew}(w)$  and  $\text{mean}(w)/\text{std}(w)$  (representing the parameter  $b$ ) and between the  $\text{kurt}(w)$  and the  $\text{skew}(w)$  may be used to identify the fitness of the Weibull distribution for observational  $w$ -PDFs. The solid curve on these figures shows the relationship for a Weibull variable. Fig. 4 shows the kernel density estimates of joint PDFs of  $\text{mean}(w)/\text{std}(w)$  versus  $\text{skew}(w)$  and  $\text{kurt}(w)$  versus  $\text{skew}(w)$  for January (left panels) and July (right panels) OSCAR data from 1992 to 2008. Fig. 5 shows the similar items from the OSCAR data during (a) 1993-1997 (b) 1998-2002, and (c) 2003-2007. The contour intervals are logarithmically spaced. The thick black line is the theoretical curve for a Weibull variable.

For the observational surface current speeds ( $w$ ), the  $\text{skew}(w)$  is evidently a concave function of the ratio  $\text{mean}(w)/\text{std}(w)$  (the same as the Weibull distribution), such that the theoretical function is positive for small values of this ratio and negative for large values. However, for the core of the kernel with the joint probability higher than 0.32,  $\text{mean}(w)/\text{std}(w)$  is always less than 2.2 and  $\text{skew}(w)$  is always positive (Fig. 4, upper panes). Similarly, the

relationship between  $\text{skew}(w)$  and  $\text{kurt}(w)$  in the observations is similar to that for a Weibull variable (Fig. 4, lower panels) with smaller kurtosis. These features are almost the same between January (Fig. 4a) and July (Fig. 4b), and among three time periods: 1993-1997 (Fig. 5a), 1998-2002 (Fig. 5b), and 2003-2007 (Fig. 5c).

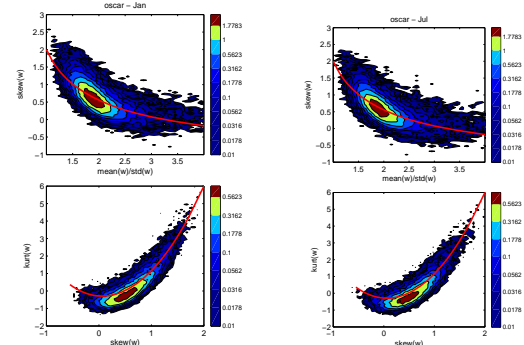


Fig. 4. Kernel density estimates of joint PDFs of (top)  $\text{mean}(w)/\text{std}(w)$  and  $\text{skew}(w)$  and (bottom)  $\text{skew}(w)$  and  $\text{kurt}(w)$  for (a) January and (b) July OSCAR data from 1992 to 2008. The contour intervals are logarithmically spaced. The thick black line is the theoretical curve for a Weibull variable.

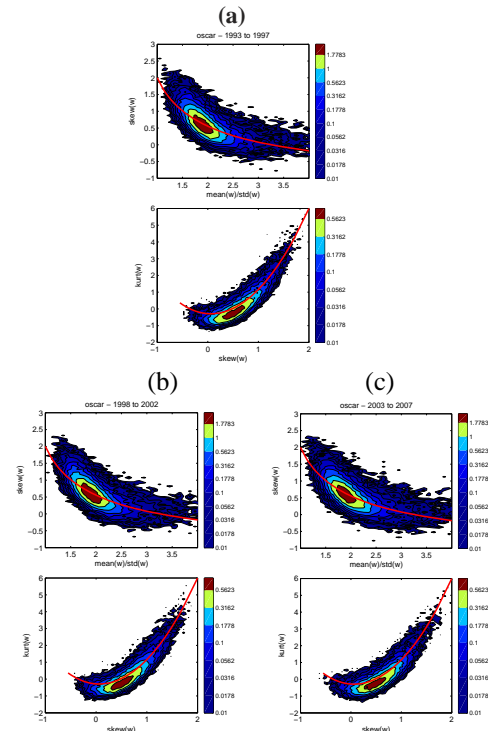


Fig. 5. Kernel density estimates of joint PDFs of (top)  $\text{mean}(w)/\text{std}(w)$  and  $\text{skew}(w)$  and (bottom)  $\text{skew}(w)$  and  $\text{kurt}(w)$  for the OSCAR data during (a) 1993-1997 (b) 1998-2002, and (c) 2003-2007. The contour intervals are logarithmically spaced. The thick black line is the theoretical curve for a Weibull variable.

The agreement between the moment relationships in the OSCAR data and those for a Weibull variable reinforces the conclusion that these data are Weibull to a good approximation.

## 6. Conclusions

This study has investigated the probability distribution function of the surface current speeds ( $w$ ), using long-term (1992-2008) 5 day "Ocean Surface Current Analyses – Real Time (OSCAR)" (OSCAR) data; and theoretically, using a stochastic model derived using upper boundary layer physics. The following results were obtained.

(1) probability distribution function of the global surface current speeds ( $w$ ) approximately satisfies the two-parameter Weibull distribution. In the upper ocean with a constant eddy viscosity  $K$ , the probability distribution function satisfies a linear second-order partial differential equation (i.e., the Fokker-Planck equation) with an analytical solution – the Rayleigh distribution (special case of the 2 parameter Weibull distribution).

(2) Four moments of  $w$  (mean, standard deviation, skewness, kurtosis) have been characterized. It was found that the relationships between  $\text{mean}(w)/\text{std}(w)$  and  $\text{skew}(w)$  and between  $\text{skew}(w)$  and  $\text{kurt}(w)$  from the data are in fairly well agreement with the theoretical Weibull distribution for the upper (0 - 50 m) tropical Pacific for the whole period. The OSCAR data also show that the ratio  $\text{mean}(w)/\text{std}(w)$  is generally less than 2.2 and the skewness is generally positive for the whole global oceans.

(3) The Weibull distribution provides a good empirical approximation to the PDF of global ocean surface current speeds with little seasonal and interannual variations. This may improve the representation of the horizontal fluxes that are at the heart of the coupled physical–biogeochemical dynamics of the marine system.

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