On the Linear Relationship between Loop Current Retreat Latitude and Eddy Separation Period

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(Manuscript received 3 September 2009, in final form 19 August 2010)

ABSTRACT

A linear correlation exists between the retreat latitude of the Loop Current following eddy separation and the subsequent eddy separation period. This empirical relationship was first identified in satellite altimeter-derived Loop Current metrics. In this paper, a simple vorticity model of the Loop Current is used to provide a semitheoretical basis for this relationship. After suitable scaling approximations, the theory predicts that the LC separation period is a linear function of retreat latitude, which agrees well with altimeter-derived empirical results. Specifically, the predicted slope and *y* intercept agree to within 9% and 2%, respectively, with the altimetry-derived values.

1. Introduction

The main source of water for the Gulf of Mexico is the Yucatan Current, which enters through the Yucatan Channel from the Caribbean Sea and forms, within the Gulf, an anticyclonic retroflection or ''loop'' current known as the Loop Current (LC). The Yucatan Current is a baroclinic jet with the bulk of the transport above 800 m (Sheinbaum et al. 2002) flowing along the eastern coast of the Yucatan Peninsula at speeds of 1 to 2 m s^{-1} (Badan et al. 2005) before it enters the Gulf to form the LC. Unlike the Yucatan Current, which is confined to a nearly fixed geographic position, the LC can intrude far into the Gulf, reaching on average to 26.2°N and a maximum of 28°N in the north–south direction and 85.8°W and a maximum of 92°W in the east–west direction based on altimeter-derived LC metrics (Leben 2005). During each intrusion cycle, the LC sheds a large warm core eddy that ranges in diameter from 300 to 400 km; after separating from the LC the eddy moves westward at speeds of 1–8 km day^{-1} (Elliot 1982; Vukovich and Crissman 1986; Vukovich 2007). These eddies are commonly referred to as LC eddies (LCEs). Separation, therefore, refers to the detachment and ultimate separation of an LCE into the western Gulf away from the LC. The LC retracts by an amount equal to the diameter of the eddy that has been shed, but in no instance has it been observed to retreat southward of 24°N (Leben 2005). These large intrusions and rapid retreats are a unique time-dependent characteristic of LC dynamics.

The time between eddy separation events is commonly called the eddy separation period and ranges from 0.5 to 18.5 months (Vukovich 1995, 2007; Sturges and Leben 2000; Leben 2005). Eddy separation is irregular, but not chaotic (Lugo-Fernández 2007). While the cause of eddy separation remains largely unexplained, we do know that the baroclinic Yucatan Current inflow (Hurlburt and Thompson 1980) and the associated vorticity and transport fluctuations affect eddy shedding (Candela et al. 2002; Oey et al. 2003; Lugo-Fernández and Badan 2007). Pichevin and Nof (1997) proposed that eddy separation results from a northward current entering an ocean and turning eastward, because of vorticity conservation, in order to balance the momentum of the system. Another proposed mechanism for

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DOI: 10.1175/2010JPO4354.1

eddy separation is the shearing of the LC by cyclonic eddies that have been generated by the interaction of the current with topography (Cochrane 1972; Zavala-Hidalgo et al. 2003; Schmitz 2005; Chérubin et al. 2006). A comprehensive theory capable of predicting the highly variable eddy separation periods exhibited by individual LC intrusion events has not been found.

Leben (2005) reported a correlation between the retreat latitude of LC after eddy separation and the eddy separation period (see his Fig. 5). This author found that for retreat latitudes ≥26°N there is a strong linear relationship, but for retreat latitudes <26°N there is more scatter. In spite of the scatter, the correlation between the retreat latitude and eddy separation period was −0.83 for 16 events. Leben (2005) hypothesized that this linear relationship reflects the sensitivity of LC intrusion to the initial condition set at the time of eddy separation.

The main objectives of this study are to provide a semitheoretical justification for the observed relationship between retreat latitude and separation period and to verify the functional form of the relationship. A simple statistical model based on the observed relationship could provide a forecast tool for predicting the period of LC intrusion and eddy separation from LC retreat. The ability to accurately predict the time scale of LC intrusion and eddy separation has large practical implications for offshore oil and gas activities in the Gulf of Mexico, scientific investigations, navigation, and hurricane forecasting (Lewis et al. 1991; Shay and Uhlhorn 2006).

2. Derivation

Derivation of the relationship between the LC retreat and the subsequent eddy separation period follows the semiempirical model developed by Lugo-Fernández and Badan (2007). These authors employ vorticity and mass conservation to show that the separation period T is directly proportional to the LC's circulation change between its retracted and extended positions [see their Eq. (11)]. Then, by assuming a generalized but reasonable shape and velocity distribution around the edges of the LC and estimating the LC's circulation directly, Lugo-Fernández and Badan (2007) obtained an expression for T as

$$T \geq \frac{2\pi H}{Q_0(f_0 + \zeta_0)}\left[f_0 Wb + \frac{\beta W b^2}{2} - V_i(2b + W)\right], \qquad (1)$$

where b is the length of the LC from 24°N, W is the width, and H is its thickness (both assumed constant). Also, f_0 is the Coriolis parameter at 22°N, and β is the meridional variation of f_0; Q_0 is the amplitude of a variable deep outflow into the Caribbean Sea through the Yucatan Channel; ζ_0 is the relative vorticity, also at 22°N; and V_i is the maximum velocity of the LC in the Yucatan Channel. Equation (1) represents a balance between the vorticity accumulation in the LC and the advection of vorticity through the Yucatan Channel to the Caribbean in the lower layer. The deep return flow to the Caribbean provides the volume conservation required by the LC intrusion into the Gulf.

Equation (1) was derived assuming that the LC always retreats to $y = 0$ (latitude 24°N). In this study we relaxed this requirement and allowed the LC to retreat to an initial position y_i approximately greater than or equal to zero and evaluated the respective integrals from y_i to a final y_n such that $y_n - y_i = b$ for each cycle. This has little effect on Eq. (1), except that b is now interpreted as the total distance from y_i to y_n along the north–south axis and not just its northern extent from the origin. An implicit assumption in this derivation is that the LC velocity is directed northward at y_i, which is a reasonable assumption. Extracting b from the square brackets reduces Eq. (1) to

$$T \geq \frac{2\pi Hb}{Q_0(f_0 + \zeta_0)}\left[f_0 W + \frac{\beta W b}{2} - V_i\left(2 + \frac{W}{b}\right)\right]. \qquad (2)$$

Equation (2) can be approximated by

$$T \geq \frac{2\pi Hb}{Q_0(f_0 + \zeta_0)}(f_0 W - V_i 2), \qquad (3)$$

for values of $W = 210$ km, $V_i \sim 1.5$ m s^{-1}, and $f_0 = 5.378 \times 10^{-5}$ s^{-1} since the middle term in Eq. (2) is at least $O(10^{-1})$ whereas the other two terms are $O(1)$ or larger. This result is compatible with the fact that the beta term is small by assumption (Pedlosky 1998). Additionally, since $b \geq W$, the term W/b is smaller than 2 at all times and so was neglected. Substituting $b = y_n - y_i = R\Delta\theta$ in Eq. (3), where R is the earth's radius and $\Delta\theta$ is the latitude change between the starting and final positions, yields

$$T \geq \frac{2\pi HR\Delta\theta}{Q_0(f_0 + \zeta_0)}(f_0 W - V_i 2). \qquad (4)$$

Equation (4) shows that to first order, the eddy separation period is a function of the latitude change. Further simplification can be achieved by noting that $\Delta\theta$ equals $(\theta_n - \theta_s)$ where θ_n is the northward latitude and θ_s is the southern or initial latitude. The northward extension of the LC is constrained by the geometry of the Gulf of Mexico and the conservation of potential vorticity to approximately 28°N, as shown in plate 2 and Fig. 2 of Leben (2005). Setting $\theta_n \approx 28°\text{N} = k$, and assuming a priori an equality, Eq. (4) can be expressed as

$$T = -m\theta_s + \kappa, \tag{5}$$

where m, in units of seconds per degree, is given by

$$m = \frac{2\pi^2 HR}{Q_0(f_0 + \zeta_0)180}(f_0 W - V_i 2) \quad \text{and} \quad \kappa = mk. \tag{6}$$

Equation (5) suggests that the separation period is linearly and negatively correlated with θ_s or the latitude from which the LC starts its northward intrusion. Since θ_s is equivalent to the retreat latitude of the LC after eddy separation, one obtains a linear functional relationship comparable to the linear correlation reported in Leben (2005). Equation (5) will be tested as part of the data analysis.

At this point, two aspects of Eq. (1) need to be discussed. First, we assumed that H and W are constants. The justification for this assumption comes from observations and theoretical considerations: 1) Sheinbaum et al. (2002) show that $H \sim 800$ m and is set by the channel depth off Miami; 2) observations in the LC confirm the two-layer approximation with an interface close to 800 m (Inoue et al. 2008; Welsh et al. 2009); and 3) analysis of hydrographic data in the Gulf also indicates that $H \approx 800$ m (Sturges 2005). The constancy of W, about twice the width of the Yucatan Channel, is also set by the geometrical constraint on the LC (Leben 2005; Vukovich 2007) and velocity cross sections through the LC that show a width of ~200 km (Nowlin and Hubertz 1972). The second aspect is whether Eq. (1) is a lower bound (Lugo-Fernández and Badan 2007). An examination of Eq. (11) in Lugo-Fernández and Badan (2007) shows that it is the amplitude of a sinusoidal variation, and as such is not a lower bound. Second, a comparison of the observed separation periods and the predictions of Eq. (11) [see Fig. 5 in Lugo-Fernández and Badan (2007)] reveals that this equation tends to overestimate T in general, which suggests again that it is not a lower bound.

3. Data and methods

We use an extension of the Leben (2005) database of eddy separation periods T and retreat latitudes θ_s that incorporates separation events up to March 2009 to analyze and evaluate the semiempirical relation derived in the previous section. The updated database (Table 1) contains 25 LC separation events with altimeter-derived separation periods between September 1993 and March 2009. The θ_s and T of the LC were estimated using the 17-cm sea surface height contour to track the LC as described in Leben (2005). Because both variables, T and θ_s, have measurement and estimation errors associated with the altimetric LC tracking, we apply a model II linear regression (Laws 1997) to estimate the regression parameters. This approach uses two linear regressions on the dataset; T versus θ_s and θ_s versus T with slopes m_T and m_θ, respectively. Then we estimate a new slope m_N given by the reciprocal of m_θ. The final slope estimate is the geometric average of m_T and m_N and the final y intercept is an average of the two intercepts. The ranges spanned by the two regression estimates give a conservative estimate for the error bounds on the slope and y intercept (Laws 1997). Errors of the slope and y intercept were estimated as

$$\delta m = \frac{\hat{m}}{2}\left(\frac{\delta m_T}{|\hat{m}_T|} + \frac{\delta m_\theta}{|\hat{m}_\theta|}\right), \tag{7}$$

where

$$m_T = \hat{m}_T + \delta m_T \quad \text{and}$$

$$m_\theta = \hat{m}_\theta + \delta m_\theta$$

TABLE 1. Updated information on eddy separation period and retreat latitude from the Colorado Center for Astrodynamics Research (CCAR) altimetry data between September 1993 to March 2009.

No.	Industry name	Date	Separation period (days)	Previous retreat lat (°)	Maximum intrusion lat (°)
1	Whopper	11 Jul 93	—	—	—
2	Xtra	10 Sep 93	61	27.001	27.3
3	Yucatan	27 Aug 94	351	26.460	27.7
4	Zapp	18 Apr 95	234	26.148	28.0
5	Aggie	08 Sep 95	143	26.787	27.2
6	Biloxi	14 Mar 96	188	25.655	27.3
7	Creole	13 Oct 96	213	26.249	26.7
8	El Dorado	30 Sep 97	352	24.591	27.5
9	Fourchon	22 Mar 98	173	25.484	27.6
10	Juggernaut	02 Oct 99	559	24.698	27.9
11	Millennium	10 Apr 01	556	24.872	27.7
12	O/N	21 Sep 01	164	25.761	27.6
13	Pelagic	28 Feb 02	160	26.488	27.3
14	Quick	14 Mar 02	14	27.283	27.5
15	Sargassum	05 Aug 03	509	24.705	28.2
16	Titanic	31 Dec 03	148	26.670	27.2
17	Ulysses	24 Aug 04	237	25.958	27.9
18	Vortex	13 Sep 05	385	25.111	28.2
19	Walker	06 Feb 06	146	26.738	27.5
20	Xtreme	18 Apr 06	71	27.534	27.6
21	Yankee	29 Sep 06	164	26.522	28.0
22	Zorro	03 Jun 07	247	25.641	28.4
23	Albert	16 Nov 07	166	26.251	27.5
24	Brazos	06 Mar 08	111	26.237	27.2
25	Cameron	30 Jun 08	116	26.266	26.8
26	Darwin	05 Mar 09	248	25.988	—

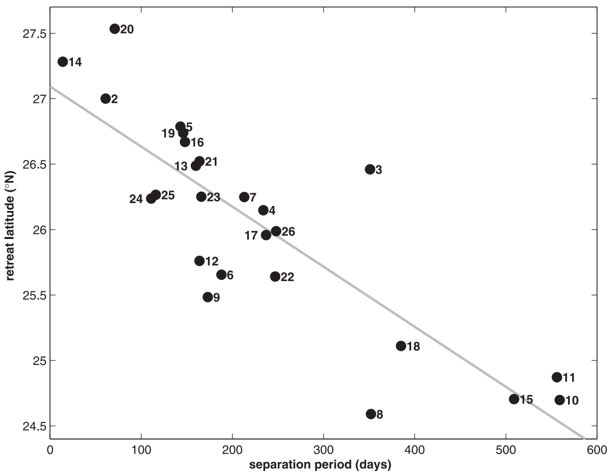

FIG. 1. Correlation between separation period T and retreat latitude θ_s for the Loop Current based on altimetry observations from September 1993 to March 2009. The correlation between θ_s and T is −0.84 and the linear fit has an R^2 of 0.70.

represent the respective best slope and standard error estimates from the regressions. For the y-intercept b the error estimate is

$$\delta b = \frac{\hat{b}}{2}\left(\frac{\delta b_T}{|\hat{b}_T|} + \frac{\delta b_\theta}{|\hat{b}_\theta|}\right), \tag{8}$$

where

$$b_T = \hat{b}_T + \delta b_T \quad \text{and}$$

$$b_\theta = \hat{b}_\theta + \delta b_\theta$$

represent the respective best y intercept and standard error estimates from the regressions.

4. Results

Figure 1 shows θ_s versus T for the 25 separation events observed from 1993 to 2009, which updates Fig. 5 from Leben (2005). First, observe that the new data display a clear linear trend also and include events around $\theta_s \sim$ 25°N that were absent in Leben (2005). The correlation between θ_s versus T is −0.84, comparable to that in Leben (2005). Thus, the assumptions and the equality sign in Eq. (5) are supported by the data.

We compare the altimeter-derived results to the semiempirical relationship for the slope given in Eq. (6), which requires the evaluation of three free parameters, V_i, ζ_0, and Q_0. Following Lugo-Fernández and Badan (2007), we use $V_i = 1.5$ m s^{-1} and $\zeta_0 = 6 \times 10^{-7}$ s^{-1}, which were estimated from observations of the LC in the Yucatan Channel. Our estimate of Q_0 was improved to reduce its uncertainty since m is sensitive to this parameter. To obtain an improved Q_0 estimate, we employed the low-pass deep transport time series at Yucatan Channel (Candela et al. 2003) shown in the upper panel of Fig. 2. The time series is integrated to calculate the transport anomaly V' in units of Sv (Sv ≡ 10^6 m^3 s^{-1}) days as

$$V'(t) = \int_0^t T'(t)\,dt.$$

This integration further low-passes the time series to emphasize the dominant long-period signal in the transport. The integrated transport is shown in the lower panel of Fig. 2. Next, we assume that V' is periodic with period P

$$V' = A_{V'} F_{\text{periodic}}\left(\frac{t}{P}\right)$$

so that

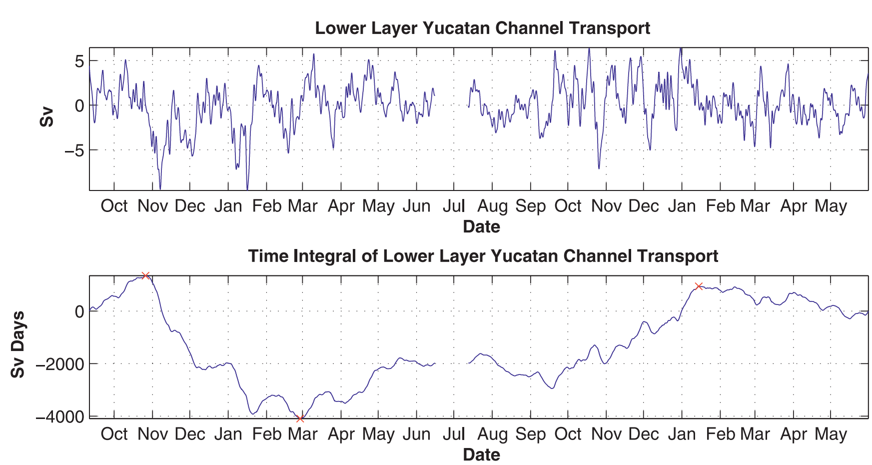

FIG. 2. (top) Lower-layer transport in the Yucatan Channel and (bottom) its integrated transport anomaly from 10 Sep 1999 through 31 May 2001. Data from Candela et al. (2003).

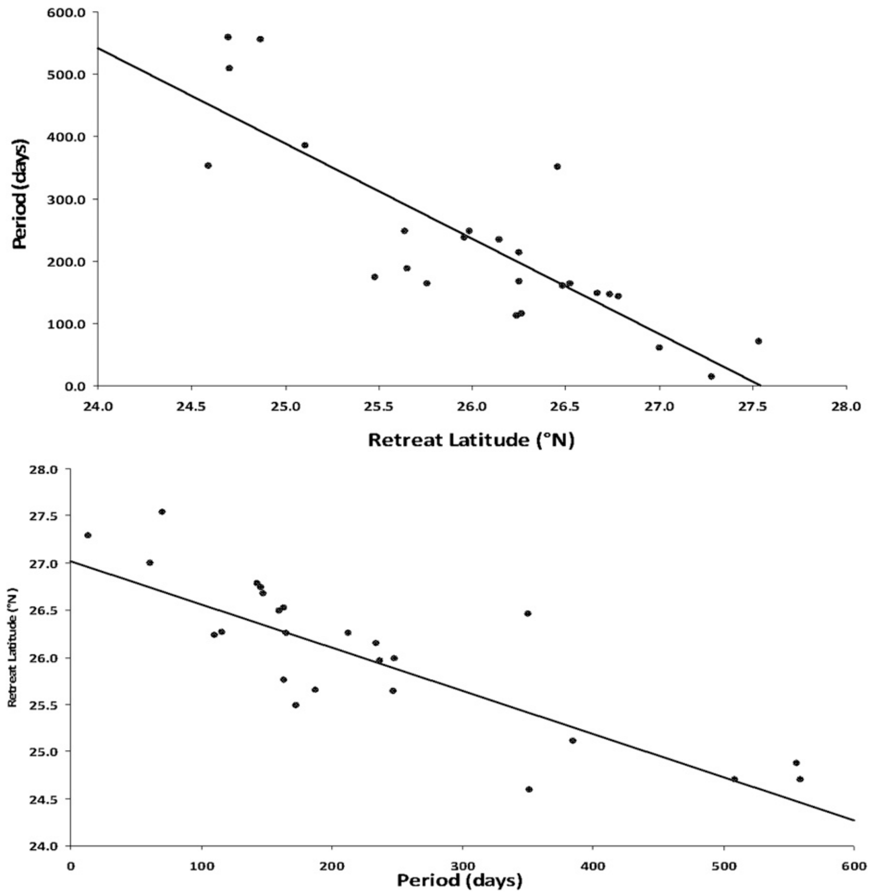

FIG. 3. Regressions of (top) eddy separation period T vs retreat latitude θ_s and (bottom) θ_s vs T using the CCAR altimetry data in Table 1.

$$\frac{dV'}{dt} = \frac{A_{V'}}{P}F'_{\text{periodic}}\left(\frac{t}{P}\right) = Q_0 F'_{\text{periodic}}\left(\frac{t}{P}\right),$$

where

$$Q_0 = \frac{A_{V'}}{P}.$$

From Fig. 2 we evaluate $A_{V'}$ and P as

$$A_{V'} = \frac{1}{2}[0.5 \times (\text{max}_1 + \text{max}_2) - \text{min}] = 2620 \text{ Sv days},$$

$$P = t_{\text{max}_2} - t_{\text{max}_1} = 446 \text{ days},$$

so

$$Q_0 = \frac{A_{V'}}{P} = 5.9 \text{ Sv}.$$

Note that this value is 1.1 Sv less than the visual estimate used in Lugo-Fernández and Badan (2007). Substituting this estimate of Q_0 in Eq. (6) we find that $m = -168° \text{ day}^{-1}$ after converting seconds to days.

Plots of T versus θ_s and θ_s versus T were constructed with the data in Table 1 (Fig. 3). Note that values T and θ_s (upper panel of Fig. 3) are anticorrelated, as predicted by Eq. (5). The slopes obtained from the regression equations are $m_T = -153° \text{ day}^{-1}$ and $m_\theta = -218° \text{ day}^{-1}$ (see Table 2). The geometric mean slope estimate is $-183° \text{ day}^{-1}$. The slope from Eq. (6), $-168° \text{ day}^{-1}$, is in very good agreement with the estimated geometric mean slope estimate, $-183° \text{ day}^{-1}$. The y intercept estimated from the regressions equals 27.3° versus the 28° assumed in deriving

TABLE 2. Regression results for T vs θ_s and θ_s vs T for the CCAR data. The asterisk (*) indicates the geometric mean.

Variable	Slope (days per deg)	y intercept (°N)
T vs θ_s	−153	27.5
θ_s vs T	−218	27.0
Mean	−186*	27.3

Eq. (5). Note, also, that the maximum observed intrusion latitude is 28.4° (Table 1), which is a little bit larger than our initial assumed value. The error estimates for the slope are $\pm 25°$ day^{-1}and $\pm 2°$ for the y intercept. The agreement between the altimeter-derived results and the semiempirical relationship regression parameters is very good, with discrepancies of 9% and 2% for the slope and y intercept, respectively. Based on the error estimates, the regression parameters are statistically significant.

5. Discussion and conclusions

First, we point out that Eq. (1) represents an integration over an LC intrusion cycle and that each cycle is independent of the previous cycle; thus, we can apply Eq. (1) to each individual cycle. The independence of the LC cycle from previous cycles reflects the short-term memory of the LC system, which was discussed in more detail in Lugo-Fernández (2007). As a result, each intrusion cycle is a unique event; nevertheless, the fundamental balance of vorticity and mass conservation represented by Eq. (1) still holds. Second, the deceptively simple Eq. (5) warrants a physical interpretation. To start, κ represents the constraint imposed by the Gulf's geometry on the northward intrusion of the LC. The slope represents the effects of the conditions at the Yucatan Channel on the LC motion and vorticity conservation. The slope also accounts for the dependence of the LC on the initial conditions as hypothesized by Leben (2005). Third, the estimated slope and y intercept from the semiempirical theory are in good agreement with the linear regression values based on the altimeter-derived LC metrics, with respectively 9% and 2% discrepancies between the estimated and regression derived values. The agreement between theory and observations suggests that this linear relationship is a fundamental physical property of the LC and arises from a straightforward conservation of mass and vorticity and the geometrical constraint imposed by the Gulf's deepwater basin. Finally, the correlation between T and θ_s (upper panel of Fig. 3) provides the recommended forecasting tool for LC eddy separation in the Gulf of Mexico.

Physically, the mechanism embodied in this work is as follows. During an intrusion cycle, the Loop Current penetrates northward into the Gulf, displacing water and gaining anticyclonic vorticity, until halted by the northern Gulf continental slope. Simultaneously, the displaced water forces flow back into the Caribbean Sea through the Yucatan Channel and under the Loop Current. This outflow advects anticyclonic vorticity out of the Gulf. Thus, the time scale is determined by the balance between accumulation of vorticity in the Gulf and outflow of vorticity from the Gulf. Since the final state is imposed by the geometry of the Gulf, the intrusion cycle depends primarily on the initial state of the Loop or its southern retreat position.

Acknowledgments. A. Lugo-Fernández appreciates the support of the U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), Gulf of Mexico Region during the preparation of this manuscript. R. Leben acknowledges support from BOEMRE Contract M08PC20043 to Science Applications International Corp. and from NASA Ocean Surface Topography Mission Science Team Grant NNX08AR60G. The opinions expressed by the authors are their own and do not necessarily reflect the opinion or policy of the U.S. Government. Thanks to two anonymous reviewers whose comments and suggestions helped to improve this work.

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