GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19610, doi:10.1029/2009GL040028, 2009

West Florida Shelf mean circulation observed with long-term moorings

Robert H. Weisberg,[1] Yonggang Liu,[1] and Dennis A. Mayer[1]

Received 10 July 2009; revised 25 August 2009; accepted 8 September 2009; published 14 October 2009.

[1] The mean circulation on the West Florida Continental Shelf is described using long-term current measurements. Bounded by the Florida peninsula to the east and the Gulf of Mexico to the west, the West Florida Continental Shelf mean flow is oriented approximately along-isobath and southward. The mean velocity vectors veer systematically with depth, shoreward over shallow water and seaward over deeper water. This polarization change implies that the mean flow is upwelling over shallow water and downwelling seaward from the inner shelf. Such a well-organized, three-dimensional coastal ocean circulation pattern, revealed by an unprecedented set of observations, and explained on the basis of wind forcing and density field adjustment, has important implications for both fisheries and red tide occurrences.
Citation: Weisberg, R. H., Y. Liu, and D. A. Mayer (2009), West Florida Shelf mean circulation observed with long-term moorings, *Geophys. Res. Lett.*, *36*, L19610, doi:10.1029/2009GL040028.

1. Introduction

[2] The continental shelf, the transition region between the coastline and the deep ocean, is literally where society meets the sea. It is within this coastal ocean region where maritime commerce takes place, where commercial and recreational fisheries are situated, and where environmental concerns, such as harmful algae blooms [e.g., *Steidinger*, 1975; *Walsh et al.*, 2006], abound. Knowledge of the coastal ocean circulation is fundamental to the understanding and predicting coastal ocean property distributions and how these impact ecological processes because the circulation is what unites nutrients with light, thereby setting the stage for all trophic level interactions. Yet, the circulation is difficult to define. Driven by interactions that occur both between the shelf and the deep-ocean and the shelf and the estuaries, along with local forcings by winds and buoyancy fluxes, the coastal ocean circulation varies over a broad range of scales [*Boicourt et al.*, 1998]. Measurements of sufficient duration and spatial extent are necessary to distinguish among these different scales of motion and to estimate long-term means.

[3] Here we consider the mean circulation of the West Florida Continental Shelf (WFS), a broad, gently sloping region situated in the eastern Gulf of Mexico (Figure 1). Unlike many continental shelf regions (and the WFS before 1998), where moored measurements are limited to a few selected sites and are generally of short duration [e.g., *Niiler*, 1976; *Mitchum and Sturges*, 1982; *Marmorino*, 1983; *Weatherly and Thistle*, 1997; *Beardsley and Boicourt*, 1981], we are fortunate to have record lengths approaching, or exceeding, a decade. Such long records allow us to determine mean values with error estimates and hence to describe a spatially coherent pattern of mean flow. These add to similar descriptions for the central California coast [*Winant et al.*, 2003] and the Middle Atlantic Bight [*Lentz*, 2008].

[4] Our analyses are of velocity measurements made across nearly the entire water column with moored acoustic Doppler current profilers (ADCP). Initiated in 1993 with a single mooring deployed mid-shelf at the 47 m isobath [*Weisberg et al.*, 1996, 2000], multiple moorings were then deployed at several sites over a large portion of the WFS [*Liu and Weisberg*, 2005b, 2007; *Weisberg et al.*, 2005, 2009], and among these moored velocity time series, 12 records are longer than 3 years, 4 records are longer than 7 years and the 2 longest records (C11, C15) now exceed 10 years (Figure 1c).

[5] Statistical uncertainty of the mean velocity component μ is measured with the standard error ε, which is computed from $\varepsilon = \sigma/\sqrt{n}$, where σ is the standard deviation of the velocity component (low-pass filtered with a 36 hour cut-off) and n, the number of independent observations, is estimated as $n = T/\tau$, where T is the record length, and τ is the decorrelation time scale. With τ estimated to be $\sim$2–4 days, we use τ = 5 days as a conservative estimate for both velocity components at all moorings. This is consistent with estimates from other regions [e.g., *Beardsley and Boicourt*, 1981; *Lentz*, 2008].

2. Depth-Averaged Mean Flow Field

[6] The depth-averaged mean currents (from near surface to near bottom since the ADCPs do not sample the upper or lower 2 m, approximately) tend to orient along-isobath, and they are directed southward. This pattern is consistent across the entire shelf, with magnitudes varying from about 0.01 m s^{-1} at the 10 m isobath to 0.07 m s^{-1} at the 162 m isobath (Figure 1a). A weak, but discernable coastal jet with a relative maximum of $\sim$0.04 m s^{-1} appears between the 25 to 40 m isobaths, coinciding with the middle to outer portion of the inner shelf, defined here to be the region of interacting surface and bottom Ekman layers. This definition of the inner shelf [*Weisberg et al.*, 2001, 2005], for which the interactions occur through divergence, differs from that of overlapping surface and bottom Ekman layers [e.g., *Mitchum and Clarke*, 1986]. Thus (by virtue of stratification) the surface and bottom Ekman layers may be separated even within the inner shelf. The standard errors of the mean horizontal velocity vectors are less than 0.01 m s^{-1}, and less than their respective mean values, except at moorings C08 and C11. Hence all of the depth-averaged mean currents, with the exceptions of moorings C08 & C11, are statistically significant at the 67% confidence level (or higher), i.e., the mean flow field defined by Figure 1a is robust. These southward tending mean currents and the

[1]College of Marine Science, University of South Florida, St. Petersburg, Florida, USA.

0094-8276/09/2009GL040028$05.00

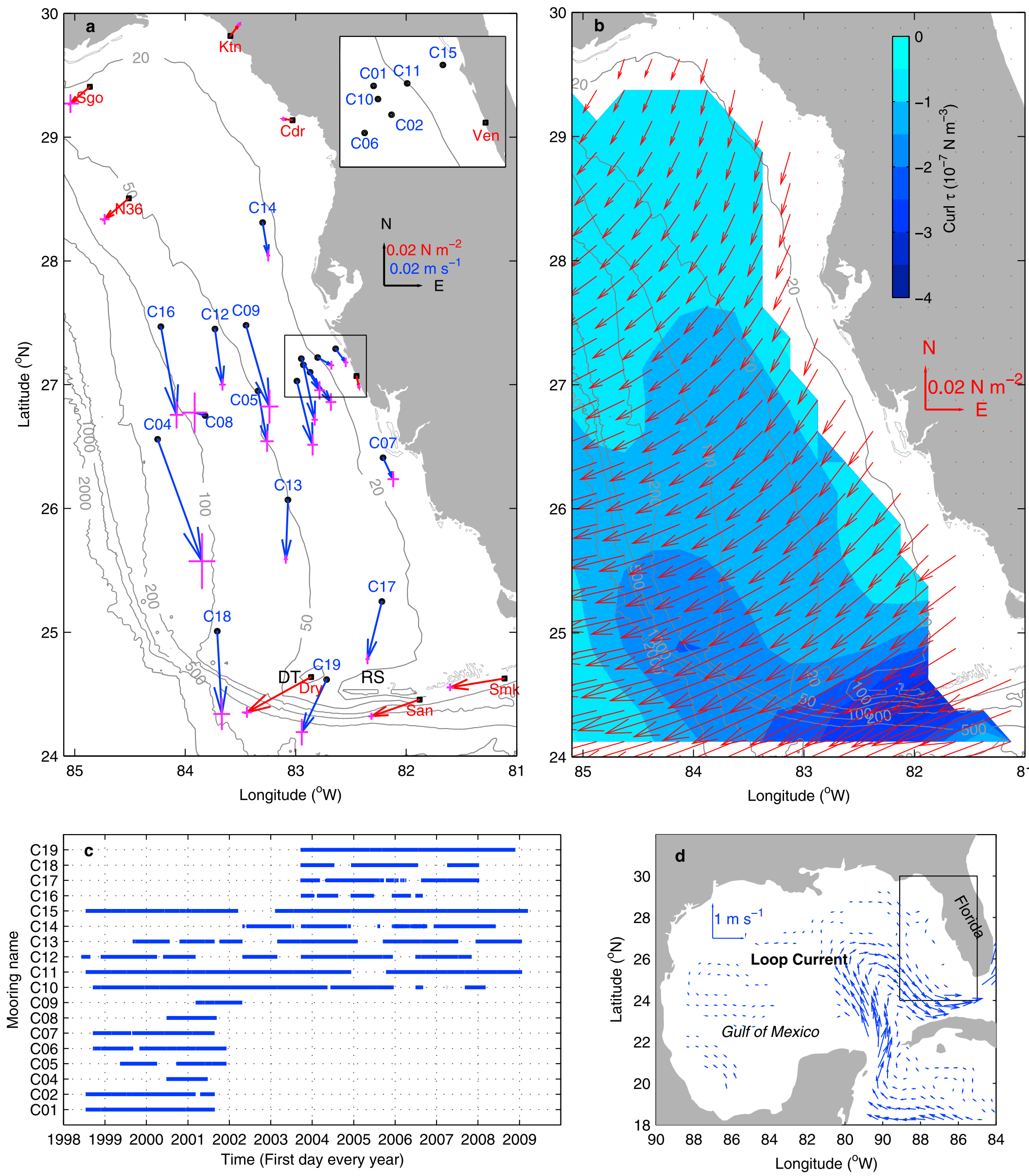

Figure 1. Mean winds and depth-averaged mean flows on the West Florida Shelf. (a) Depth-averaged mean current (blue) and wind stress (red) vectors. The standard errors ε of the mean values μ are shown as crosses ($\mu \pm \varepsilon$) at the arrow heads. Also shown on the maps are isobaths in meters. Wind data are downloaded from National Buoy Data Center, NOAA (http://www.ndbc.noaa.gov/). DT and RS designate Dry Tortugas and Rebecca Shoals, respectively. (b) Mean wind stress (τ) and curl τ from the Scatterometer Climatology of Ocean Winds [*Risien and Chelton*, 2008]. (c) Timeline of moored ADCP measurements. (d) Gulf of Mexico map showing mean Loop Current from the absolute surface geostrophic currents [*Rio and Hernandez*, 2004; also see *Alvera-Azcárate et al.*, 2009].

coastal jet are also consistent with inferences drawn from limited deployments of surface Lagrangian drifters [*Yang et al.*, 1999; *Ohlmann and Niiler*, 2005].

[7] The origin of the mean southward flow is related to both local forcing by the mean winds and deep-ocean forcing by the bounding Loop Current. The mean wind field (Figure 1b) obtained from analyses of satellite remotely sensed data [*Risien and Chelton*, 2008] is directed toward the southwest. Given that the along-shelf component of wind stress is the primary driving force for the inner shelf circulation [e.g., *Li and Weisberg*, 1999; *Weisberg et al.*, 2005] and that the across-shelf component provides a secondary effect through setting up a sea level gradient [e.g., *Li and Weisberg*, 1999; *Liu and Weisberg*, 2005a; *Fewings et al.*, 2008], these southwestward directed winds are upwelling favorable across the inner shelf. From north to south the mean winds increase in magnitude and turn offshore to become more easterly in the south, where sheltering by the Florida peninsula decreases. As a consequence of these systematic changes in magnitude and direction a negative wind stress curl is imparted (Figure 1b). This, along with the blocking effect of the Florida Keys, steers the circulation toward the west over the southern portion of the WFS. It also results in a downwelling influence by Ekman pumping.

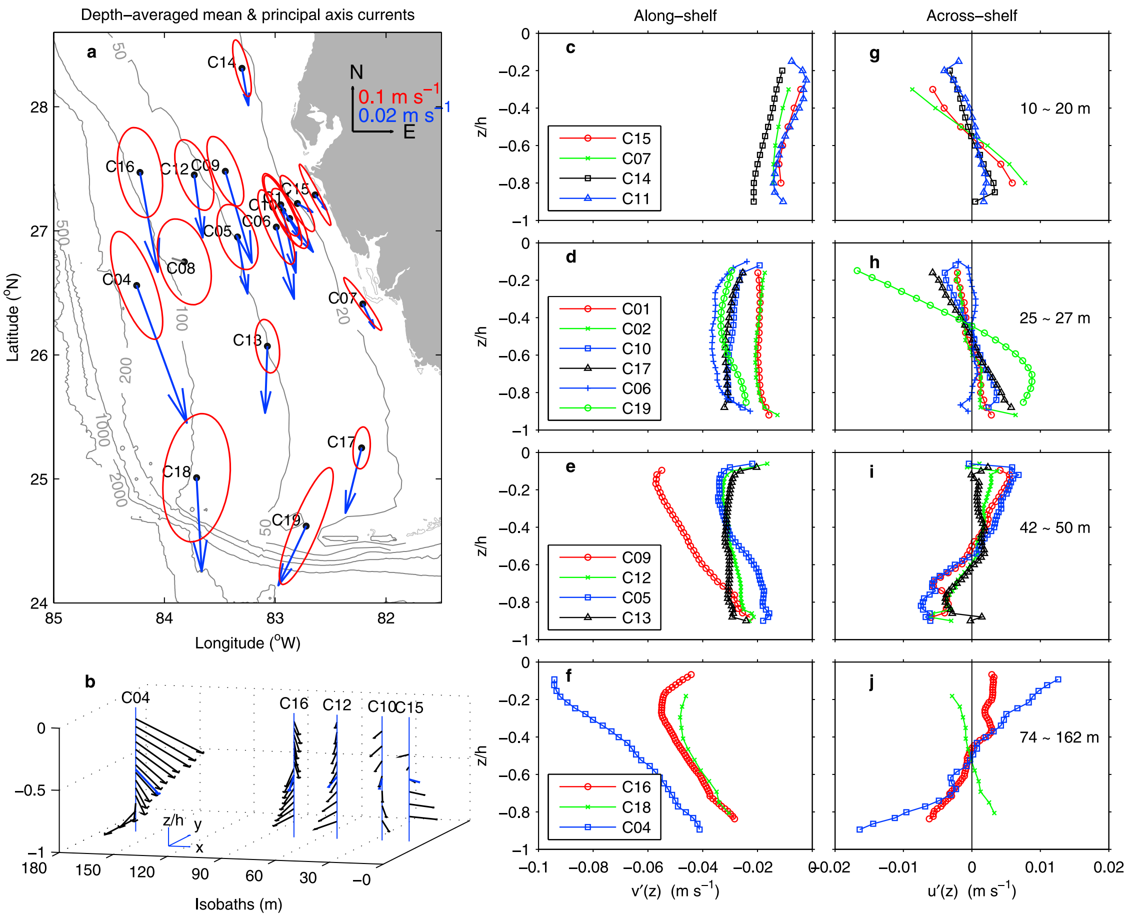

Figure 2. Zonation of mean horizontal velocity component profiles on the West Florida Shelf. (a) Depth-averaged mean velocity (arrows) and principal axes of variance (ellipses). (b) Three-dimensional view of mean velocity veering at selected sites. The depth-averaged velocities are shown as the blue arrows in the middle of the water column, where x and y are positive to the east and north, respectively. The vertical axis denotes the height normalized by the local water depth ($z/h = 0$, surface; $z/h = -1$, bottom). Mean (c–f) along- and (g–j) across-shelf velocity ($u' > 0$, onshore) profiles for different water depth zones: 10–20 m (Figures 2c and 2g), 25–27 m (Figures 2d and 2h), 42–50 m (Figures 2e and 2i), and 74–162 m (Figures 2f and 2j). Note that different scales are used for the vectors and the ellipses in Figure 2a and for u' and v' in Figures 2c–2j.

[8] The outer shelf is defined as the region within an internal Rossby radius of deformation from the shelf break (~30 km), where deep-ocean influences by the Loop Current (Figure 1d) are strongly evident [*He and Weisberg*, 2003]. With the Loop Current tending to impact the shelf break on average, the associated across-shelf pressure gradient there tends to support a southward circulation over the outer shelf. Hence, through a combination of outer shelf forcing by the Loop Current and mid to inner shelf forcing by winds we can account for the southward tending mean currents. Previous direct measurements of currents near the shelf break support this viewpoint [*Niiler*, 1976], and Loop Current intrusions and eddy shedding [e.g., *Huh et al.*, 1981; *Paluszkiewicz et al.*, 1983] contribute to increased current variability on the outer shelf.

3. Vertical Profiles of the Mean Along-Shelf and Across-Shelf Velocity Components

[9] The depth-averaged mean flow tends to be oriented along-isobath and aligned with the principal axis of the subtidal flow variability (Figure 2a). However, the principal axis direction, defined as the direction of maximum velocity variance at subtidal time scales, may differ from the temporal mean current direction for a number of reasons. For instance, at C08 & C11 the depth-averaged mean flow deviates substantially from the principal axis current direction, while the latter is still nearly along isobath. Since here we are examining mean flow structures, versus subtidal variability, the along-shelf direction is defined as the direction of the depth-averaged mean flow at each site. In that way the depth-averaged mean across-shelf flow is zero [*Lentz*, 2008].

[10] A zonation in the shelf-wide distribution of the mean currents is observed in both the along-shelf and the across-shelf components. For the along-shelf component the 10 m and 20 m isobath locations tend to have the smallest speeds, and these increase in magnitude with depth (Figure 2c). Thus we see values of 0.00 to 0.01 m s^{-1} near the surface and 0.01 to 0.02 m s^{-1} near the bottom over this innermost portion of the inner shelf. The along-shelf mean current speeds are larger at the 25 m to 40 m isobaths where they

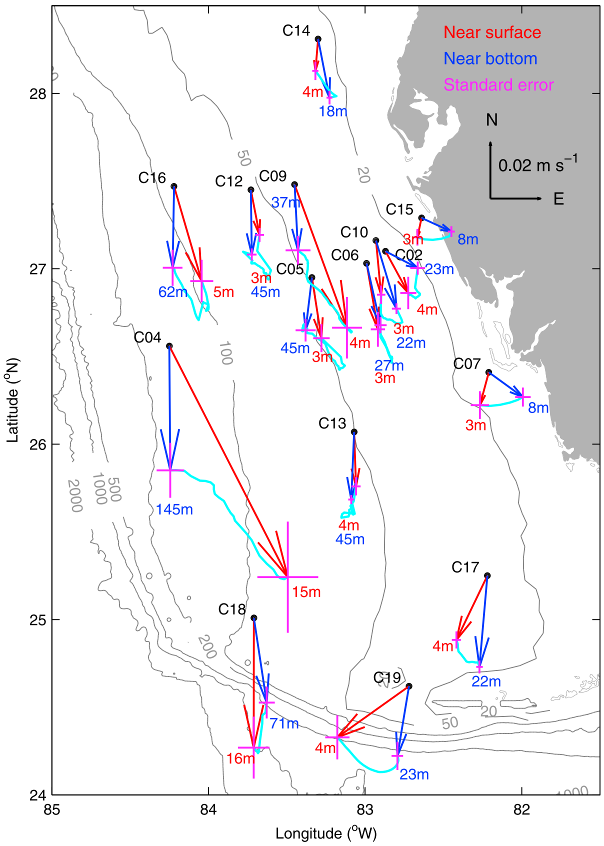

Figure 3. Zonation of mean horizontal velocity vector veering with depth on the West Florida Shelf. The mean velocity vector vertical profiles are shown as cyan lines connecting the arrowheads of the near-surface (red) and near-bottom (blue) velocity vectors. The standard errors ε of the mean values μ are shown as crosses ($\mu \pm \varepsilon$) at the arrow heads. Depths of near-surface and near-bottom levels are specified as red and blue numbers, respectively, for every mooring. Isobaths are in m.

tend to be more vertically uniform with depth at speeds of 0.02 to 0.04 m s^{-1} (Figure 2d). Farther offshore, but still within the definition of the inner shelf, we see along-shelf flows that decrease with depth (Figure 2e). Proceeding to the outer shelf locations we again see an increase in along-shelf mean speeds (Figure 2f). Thus the inner shelf exhibits a subtle local maximum (as seen in the Figure 1a vectors) and a change from vertically increasing to vertically decreasing currents seaward across this local maximum region.

[11] The two orthogonal velocity components are not unrelated, and the across-shelf component is equally interesting. Figures 2g–2j exhibit a two-layer structure in the across-shelf flow, whose sense changes around the 30 m to 40 m isobaths. Landward of this transition zone the near surface flow is directed offshore and the near bottom flow is directed onshore, whereas this directionality reverses seaward of the transition zone. Thus the transition zone, corresponding with the local maximum in the mean along-shelf component, is one of surface convergence and bottom divergence. A three dimensional perspective is provided in Figure 2b, where we see that the structural changes in the along-shelf and across-shelf velocity component distributions are manifest by the manner in which the velocity vectors veer with depth.

[12] In summary, the three-dimensional structure of the mean velocity vector field shows a change in the polarization of the velocity vector veering with depth when looking down from the surface. Landward of a transition region, centered at about the 30 m isobath, the mean velocity vectors veer to the left (shoreward) with increasing depth, whereas seaward of the transition region they veer to the right (seaward) (Figure 3). The transition region corresponds to a local maximum in southward directed, along-shelf flow. The veering results for the WFS are similar to that of a more limited Middle Atlantic Bight data set described by *Beardsley and Boicourt* [1981]. An extended Middle Atlantic Bight data set now shows a more complicated structure [*Lentz*, 2008], but neither of these shows the reversal in the across-shelf velocity component profiles as observed on the WFS.

[13] Exceptions to the above generalizations are at moorings C18 (Figure 2j), located at the shelf break in the south and mooring C19, also in the south and located in a channel that separates the Dry Tortugas from Rebecca Shoals. C18 is regularly impacted by the Loop Current and eddies, and C19 is indicative of the communication of water from the WFS to the adjacent Florida Current; hence both of these sites are unique.

4. Physics

[14] The data (because of the nonlinear eddy fluxes) are insufficient to evaluate the vorticity balance across the entire shelf. Heuristic arguments can nevertheless be advanced in explanation of the mean circulation findings, and resulting hypotheses can be tested for consistency. In the following discussions the coordinate directions (x, y, z) and the velocity components (u, v, w) are positive toward the east, north, and up, respectively.

[15] First, consider the inner portion of the inner shelf where the horizontal velocity vector turns toward the left (shoreward) when looking down from the surface, resulting in an up-isobath flow and upwelling out from the bottom Ekman layer. With w positive at depth, $\partial w/\partial z$ is negative across the water column, and from a vertical component of vorticity perspective this stretching of planetary vorticity filaments tends to balance the negative bottom stress torque that is imposed by the alongshore flow between its maximum at the center of the inner shelf and the coastline.

[16] As a consistency check we can compare w estimated independently from either the kinematic boundary condition, $w = u\partial h/\partial x$, where h is the water depth, or the curl of the bottom stress, $w = (1/\rho f)\mathrm{curl}\tau_b$, where ρ, f and τ_b are water density, Coriolis parameter, and bottom stress, respectively. The latter can be expressed as $w = (1/\rho f) r \Delta v/\Delta x$, where r is a resistance coefficient estimated as 5×10^{-4} ms^{-1} for the WFS (see the discussion in *Liu and Weisberg*, 2005a). These independent estimates on w overlap in the ranges of $3–8 \times 10^{-6}$ m s^{-1} and $5–10 \times 10^{-6}$ m s^{-1} demonstrating consistency for the hypothesis that the behavior of the mean flow field over the inner portion of the inner shelf is

governed by Ekman/geostrophic dynamics, i.e., winds drive a southward, upwelling favorable mean current.

[17] Next, consider the domain from the outer portion of the inner shelf to the outer shelf. There we require an additional concept because in the middle of the water column, away from the surface and bottom Ekman layers, the flow tends to be geostrophic. By combining the geostrophic velocity and the (isentropic) potential density equations we arrive at the following two equivalent forms:

$$w\frac{\partial\rho}{\partial z} = \frac{\rho_0 f}{g}\left(u\frac{\partial v}{\partial z} - v\frac{\partial u}{\partial z}\right) \quad (1)$$

or

$$w\frac{\partial\rho}{\partial z} = \frac{1}{\rho_0 f}\left(\frac{\partial\rho}{\partial x}\frac{\partial p}{\partial y} - \frac{\partial\rho}{\partial y}\frac{\partial p}{\partial x}\right) \quad (2)$$

where g is gravity and p is pressure. The first of these relates the vertical velocity component within the geostrophic interior with the vertical shear of the horizontal velocity components (thermal wind). The second shows that the geostrophic veering with depth is related to the baroclinic vector, $\nabla\rho \times \nabla p$. If isolines of density and pressure are collinear then there is no baroclinic torque and w is zero, whereas if these are at an angle the sign of w is determined by the sign of the baroclinic vector. Expressing the horizontal velocity vector in polar form: $u = V\cos\theta$, $v = V\sin\theta$, where V is the vector's magnitude and θ is its angle measured counterclockwise from east, differentiating with depth, and combining terms, results in:

$$w = -\frac{fV^2}{N^2}\frac{\partial\theta}{\partial z} \quad (3)$$

where N is the buoyancy frequency. With z positive upward, the clockwise veering with depth means that w is negative or downwelling across the geostrophic interior.

[18] As a consistency check we can compare w estimated independently from either equation (3) or the curl of the wind stress $w = (1/\rho f)\text{curl}\tau_w$. Either estimate results in a downwelling oriented w with magnitude of about 0.1 to 0.2×10^{-5} m s^{-1}. Thus seaward from the local maximum, the wind stress curl-induced downwelling from the surface Ekman layer is accommodated through the adjustment of the density field, i.e., geostrophic veering. A positive bottom stress torque (imposed by the mean along-shelf flow seaward from the local maximum) then accepts this downwelling into the bottom Ekman layer, completing the vertical circulation.

5. Summary and Implications

[19] Long time series of velocity show a coherent shelf-wide, mean circulation pattern for the WFS, with southward along-shelf currents. Organized about an inner shelf maximum in the along-shelf flow the polarization of the velocity vector veering with depth changes sign from onshore to offshore. This results in a mean upwelling over the inner portion of the inner shelf, versus a mean downwelling farther offshore. Blooms of the harmful algae, *K. brevis*, thought to originate offshore [*Steidinger*, 1975], are known to be advected toward the beach via the bottom Ekman layer [*Weisberg et al.*, 2009], and the commercial grouper fishery takes place (anecdotally) between the 40 m isobath and the shelf break. Is it coincidental that important elements of the phytoplankton and fisheries ecology show similarity with the long term mean circulation pattern, or might there be a causal relationship?

[20] **Acknowledgments.** The data used herein derive observations sustained over some 16 years, beginning with a USGS cooperative agreement and continuing under ONR, MMS, NOAA, and State of Florida support through programs or individual grants. Present support is by ONR grant N0014-05-1-0483 and NOAA grant NA06NOS4780246. USF Ocean Circulation staff are responsible for the success of the field program, specifically, R. Cole, J. Donovan, J. Law, and C. Merz. This is CPR contribution 5.

References

Alvera-Azcárate, A., A. Barth, and R. H. Weisberg (2009), The surface circulation of the Caribbean Sea and the Gulf of Mexico as inferred from satellite altimetry, *J. Phys. Oceanogr.*, *39*, 640–657, doi:10.1175/2008JPO3765.1.

Beardsley, R. C., and W. C. Boicourt (1981), On estuarine and continental shelf circulation in the Middle Atlantic Bight, in *Evolution of Physical Oceanography*, edited by B. A. Warren and C. Wunsch, pp. 198–233, MIT Press, Cambridge, Mass.

Boicourt, W. C., et al. (1998), Continental shelf of the southeastern United States and the Gulf of Mexico: In the shadow of the western boundary current, in *The Sea*, edited by A. R. Robinson and K. H. Brink, pp. 135–181, John Wiley, New York.

Fewings, M., S. J. Lentz, and J. Fredericks (2008), Observations of cross-shelf flow driven by cross-shelf winds on the inner continental shelf, *J. Phys. Oceanogr.*, *38*, 2358–2378, doi:10.1175/2008JPO3990.1.

He, R., and R. H. Weisberg (2003), A Loop Current intrusion case study on the West Florida Shelf, *J. Phys. Oceanogr.*, *33*, 465–477, doi:10.1175/1520-0485(2003)033<0465:ALCICS>2.0.CO;2.

Huh, O., W. J. Wiseman, and L. Rouse (1981), Intrusion of Loop Current onto the West Florida Continental Shelf, *J. Geophys. Res.*, *86*, 4186–4192, doi:10.1029/JC086iC05p04186.

Lentz, S. J. (2008), Observations and a model of the mean circulation over the Middle Atlantic Bight continental shelf, *J. Phys. Oceanogr.*, *38*, 1203–1221, doi:10.1175/2007JPO3768.1.

Li, Z., and R. H. Weisberg (1999), West Florida Continental Shelf response to upwelling favorable wind forcing: 2. Dynamics, *J. Geophys. Res.*, *104*, 23,427–23,442, doi:10.1029/1999JC900205.

Liu, Y., and R. H. Weisberg (2005a), Momentum balance diagnoses for the West Florida Shelf, *Cont. Shelf Res.*, *25*, 2054–2074, doi:10.1016/j.csr.2005.03.004.

Liu, Y., and R. H. Weisberg (2005b), Patterns of ocean current variability on the West Florida Shelf using the self-organizing map, *J. Geophys. Res.*, *110*, C06003, doi:10.1029/2004JC002786.

Liu, Y., and R. H. Weisberg (2007), Ocean currents and sea surface heights estimated across the West Florida Shelf, *J. Phys. Oceanogr.*, *37*, 1697–1713, doi:10.1175/JPO3083.1.

Marmorino, G. O. (1983), Variability of current, temperature, and bottom pressure across the West Florida Continental Shelf, winter, 1981–1982, *J. Geophys. Res.*, *88*, 4439–4457, doi:10.1029/JC088iC07p04439.

Mitchum, G. T., and A. J. Clarke (1986), The frictional nearshore response to forcing by synoptic scale winds, *J. Phys. Oceanogr.*, *16*, 934–946, doi:10.1175/1520-0485(1986)016<0934:TFNRTF>2.0.CO;2.

Mitchum, G. T., and A. Sturges (1982), Wind-driven currents on the West Florida Shelf, *J. Phys. Oceanogr.*, *12*, 1310–1317, doi:10.1175/1520-0485(1982)012<1310:WDCOTW>2.0.CO;2.

Niiler, P. P. (1976), Observations of low-frequency currents on the West Florida Continental Shelf, *Mem. Soc. R. Sci. Liege*, *6*, 331–358.

Ohlmann, J. C., and P. P. Niiler (2005), Circulation over the continental shelf in the northern Gulf of Mexico, *Prog. Oceanogr.*, *64*, 45–81, doi:10.1016/j.pocean.2005.02.001.

Paluszkiewicz, T., L. P. Atkinson, E. S. Posmentier, and C. R. McClain (1983), Observations of a Loop Current frontal eddy intrusion onto the West Florida Shelf, *J. Geophys. Res.*, *88*, 9639–9651, doi:10.1029/JC088iC14p09639.

Rio, M.-H., and F. Hernandez (2004), A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, *J. Geophys. Res.*, *109*, C12032, doi:10.1029/2003JC002226.

Risien, C. M., and D. B. Chelton (2008), A global climatology of surface wind and wind stress fields from eight years of QuikSCAT scatterometer data, *J. Phys. Oceanogr.*, *38*, 2379–2413, doi:10.1175/2008JPO3881.1.
Steidinger, K. A. (1975), Implications of dinoflagellate life cycles on initiation of *Gymnodinium breve* red tides, *Environ. Lett.*, *9*, 129–139, doi:10.1080/00139307509435842.
Walsh, J. J., et al. (2006), Red tides in the Gulf of Mexico: where, when, and why?, *J. Geophys. Res.*, *111*, C11003, doi:10.1029/2004JC002813.
Weatherly, G. L., and D. Thistle (1997), On the wintertime currents in the Florida Big Bend region, *Cont. Shelf Res.*, *17*, 1297–1319, doi:10.1016/S0278-4343(97)00018-6.
Weisberg, R. H., B. D. Black, and H. Yang (1996), Seasonal modulation of the West Florida Continental Shelf circulation, *Geophys. Res. Lett.*, *23*, 2247–2250, doi:10.1029/96GL02184.
Weisberg, R. H., B. D. Black, and Z. Li (2000), An upwelling case study on Florida's west coast, *J. Geophys. Res.*, *105*, 11,459–11,469, doi:10.1029/2000JC900006.
Weisberg, R. H., Z. Li, and K. Muller-Karger (2001), West Florida Shelf response to local wind forcing: April 1998, *J. Geophys. Res.*, *106*, 31,239–31,262, doi:10.1029/2000JC000529.
Weisberg, R. H., et al. (2005), West Florida shelf circulation on synoptic, seasonal, and inter-annual time scales, in *Circulation in the Gulf of Mexico*, *Geophys. Monogr. Ser.*, vol. 161, edited by W. Sturges and A. Lugo-Fernandez, pp. 325–347, AGU, Washington, D. C.
Weisberg, R. H., et al. (2009), A coordinated coastal ocean observing and modeling system for the West Florida Continental Shelf, *Harmful Algae*, *8*, 585–598, doi:10.1016/j.hal.2008.11.003.
Winant, C. D., E. P. Dever, and M. C. Hendershott (2003), Characteristic patterns of shelf circulation at the boundary between central and southern California, *J. Geophys. Res.*, *108*(C2), 3021, doi:10.1029/2001JC001302.
Yang, H., et al. (1999), Lagrangian circulation and forbidden zone on the West Florida Shelf, *Cont. Shelf Res.*, *19*, 1221–1245, doi:10.1016/S0278-4343(99)00021-7.

Y. Liu, D. A. Mayer, and R. H. Weisberg, College of Marine Science, University of South Florida, St. Petersburg, FL 33701, USA. (weisberg@marine.usf.edu; yliu18@gmail.com)