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NOTES AND CORRESPONDENCE

Observations of Shallow-Water Transport and Shear in Western Florida Bay*

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ABSTRACT

Acoustic Doppler profiler (ADP) data are used to describe depth-integrated transport and vertical shear at two study sites along the open western boundary of Florida Bay. During a 404-day study period, transport was into the bay at the northern study site, where the depth-averaged 3.2 m. Transport at the southern study site, where the depth averaged 2.0 m, was out of the bay during a 266-day time period. A comparison of flow in the top and bottom layers of the ADP profile at the northern study site reveals patterns that are very different from each other, and very different from the depth-integrated transport. Nontidal flow in the surface layer is nearly consistently out of the bay and highly correlated with wind forcing. East–west near-bottom flow is inversely correlated with the rise and fall of water level in northwest Florida Bay. Nontidal east–west flow in the bottom layer is negligible, suggesting a near balance between westward directed wind stress and eastward directed barotropic pressure gradients maintained by the setdown of water level in the bay. At the southern study site, near-bottom flow is similar to near-surface flow, and both are similar to depth-integrated transport. At both locations, the instantaneous directional shear from near-surface to near-bottom levels is less than 1° on average. Also, at both study sites, vertically integrated cumulative net transport can be approximated using current observations from a single level within the water column. Only at the southern study site, however, can the cumulative net displacement at any level be approximated by extrapolating vertically from mid-depth observations. Roughness lengths calculated from ADP profiles are concentrated below 1 cm but highly variable, and ADP profiles are not well suited for estimating bottom roughness.

1. Introduction

Florida Bay is a shallow coastal lagoon lying at the southern tip of the Florida Peninsula (Fig. 1). Taking the 81°05′W meridian as the open western boundary, the surface area of the bay is approximately 2220 km^2. The average depth of the bay is just over 1 m. The interior of the bay comprises many small subbasins with depths of about 2 m, but there are extensive seagrass-covered or unvegetated banks where water depths are less than 0.5 m. Occasionally, bank tops are exposed by some combination of low seasonal sea level, low tide, and the wind-induced setdown of water level.

Recent studies have defined some components of the regional circulation. Field studies have documented a net inflow through the northern and central parts of the western boundary, and a net outflow through the southern part (Smith 2000). Flow patterns through the interior of Florida Bay are poorly understood, although information is emerging through a combination of observational and modeling studies. Tides seem to be the principal driving force in the western and southern parts of the bay; throughout the bay, wind forcing produces a low-frequency variability over timescales on the order of several days and longer (Wang et al. 1994; Wang 1998). Wang (1998) tracked surface drifters moving eastward through the bay and leaving through Long Key Channel over time periods of 5–10 days, depending on wind conditions. Wind forcing is into the western quadrant for much of the year, and the west-to-east movement of water into, through, and out of Florida Bay is in an upwind direction. A net outflow has been observed through the major tidal channels that connect the southeastern and southern sides of Florida Bay with shelf waters on the Atlantic side of the Florida Keys (Smith 1994, 1998).

A recent field study by the Army Corps of Engineers, Waterways Experiment Station (Pratt and Smith 1999), included acoustic Doppler profilers (ADPs) to measure flow at two locations along the western boundary of the bay. The ADPs were near study sites that had been occupied earlier with single current meters moored just be-

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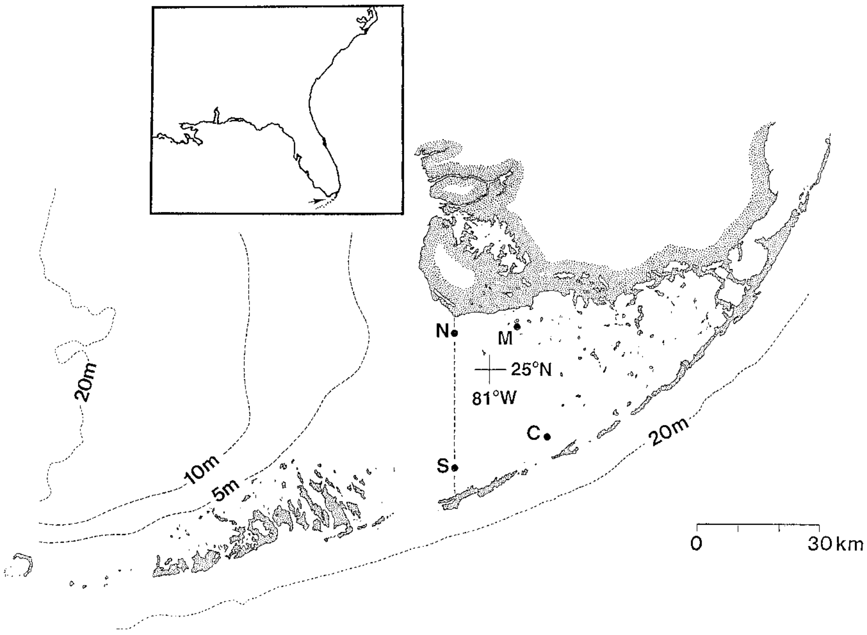

FIG. 1. Map showing stations N and S along the open western boundary of Florida Bay, the C-MAN weather station (indicated by C) and the water level recorder at Murray Key (M). Insert shows the study area at the southern tip of the Florida Peninsula.

low mid depth in 2–3 m of water (Smith and Pitts 1995). The ADP database provides an opportunity to examine vertical current structure in considerable detail. The purpose of this note is to describe the vertical structure of the flow at two shallow-water study sites along the western boundary of Florida Bay. A primary objective is to determine whether current measurements from a single, mid-depth level can be substituted for current profiles to calculate surface-to-bottom, two-dimensional transport at these study sites. A secondary objective is to determine whether current profile data are suitable for estimating bottom roughness coefficients.

2. Data

The study area is the 81°05′W meridian, which is often taken to represent the western boundary of Florida Bay. The distance from East Cape, at the tip of the Florida Peninsula, south to Marathon in the Florida Keys is 45 km, and the mean water depth is 3.0 m. Tidal amplitudes calculated from both current meter and water level records decrease from north to south (Smith 1997).

SonTek Acoustic Doppler Profilers were installed at stations N (25°04.996′N) and S (24°46.992′N) in Fig. 1. Station N was 3.5 km south of East Cape and 2.7 km west-northwest of First National Bank. Station S was in a relatively open area. The nearest shallow water was a group of small banks 7.4 km east of the study site. The time series from station N was 404 days long, from 14 March 1996 to 22 April 1997. Because of gaps in the record at station S, a 266-day time period from 14 March to 5 December 1996 was selected for analysis. Mean depths at the northern and southern study sites were 3.2 and 2.0 m, respectively. Currents were recorded hourly in 2–12 layers, according to the mean water depth and the tidal and nontidal rise and fall in sea level. Layers were 29 cm thick, and the lowest layer was 69–98 cm above the bottom. The accuracy of the current speeds is ± 0.5 cm s^{-1}, or 1% of the speed above 50 cm s^{-1}. The directional accuracy is approximately $\pm 2°$ (D. Slocum 1999, personal communication). Bottom pressures recorded by the ADP indicate water levels to the nearest 10 cm.

Wind data were recorded hourly at a Coastal-Marine Automated Network (C-MAN) weather station in Florida Bay (“C” in Fig. 1), 35 km from station N and 23 km from station S. Wind speeds and directions were recorded to the nearest 0.1 m s^{-1} and 1°, respectively. Air temperature, used to calculate air density, was recorded to the nearest 0.1°C.

A National Park Service Marine Monitoring Network water level recorder at Murray Key (“M” in Fig. 1) provided information on the low-frequency nontidal water level variations in the northwest corner of the bay. The availability of water level defined the start and end times of a 65-day study (3 October to 6 December 1996) designed to investigate the interrelationship of wind forcing, water level and the movement of water into or out of the bay past station N. Water levels were recorded hourly to the nearest 0.3 cm.

3. Methodology

Vertically integrated transport (in m^2 s^{-1}) quantifies the two-dimensional transport at each study site. When

ADP data are used, transport is calculated for east–west and north–south current components, then combined to obtain the transport vector. For each layer, transport is given by the product of the current component, the time interval it represents, and the layer thickness. The current measured in the top layer is extrapolated upward when the pressure sensor indicates that a partial layer exists above the last measurement. A logarithmic current profile is assumed from the bottom to the base of the first layer. Cumulative net transport is calculated by plotting transport vectors head-to-tail.

Progressive vector diagrams (PVDs) are used to compare near-surface and near-bottom flow over the long timescales considered here. PVDs are constructed by plotting current vectors head-to-tail, but the tidal and low-frequency expansion and contraction of the water column are not incorporated into the calculations. The vector connecting the starting and ending points, divided by the number of hours represented by the plot, quantifies the Eulerian resultant flow.

East–west transport components from station N were used with wind stress calculated from C-MAN observations (Wu 1980) and water level records from northwest Florida Bay to investigate inflow and outflow as a response to wind forcing and the setup or setdown of bay water levels. Low-pass filtering of all time series (Groves 1955) focused this part of the study on nontidal processes occurring over time scales in excess of about two days. The "D39" filter has a half-power point at a period of 55 hours. At periods of 33 and 130 hours, 10% and 90% of the input variance survives the filtering process. Spectral analysis of wind stress components included coherence and phase spectra (Little and Schure 1988). Coherence levels were used to identify wind conditions most favorable for bay–shelf exchanges, and the timescales over which wind forcing is most important.

The suitability of single-level current measurements for estimating vertically integrated transport was tested by extrapolating measurements from the second level in the profile (97 to 126 cm above the bottom) downward to the bottom and upward to a time-varying surface height, then comparing the result with transport obtained from profile measurements. The second level was selected because it was similar to the height above the bottom at which current meters have been moored in previous studies (Smith and Pitts 1995). No directional shear was incorporated into the calculations. Assuming a logarithmic profile, vertically integrated transport is given by

$$T_L = \frac{u_*}{k}\left[Z \ln\frac{Z}{z_o} - (Z - z_o)\right], \tag{1}$$

where u_* is the friction velocity, k is the von Kármán constant, Z is the total water depth, and z_o is the roughness length (Smith 1994). A z_o value of 0.5 cm was used in all the calculations. Roughness elements at station N were shell fragments, sand waves with amplitudes of 10–15 cm and occasional sponges and soft corals. The bottom at station S was covered by *Syringodium filiforme,* a seagrass that grows to a height of 30–40 cm.

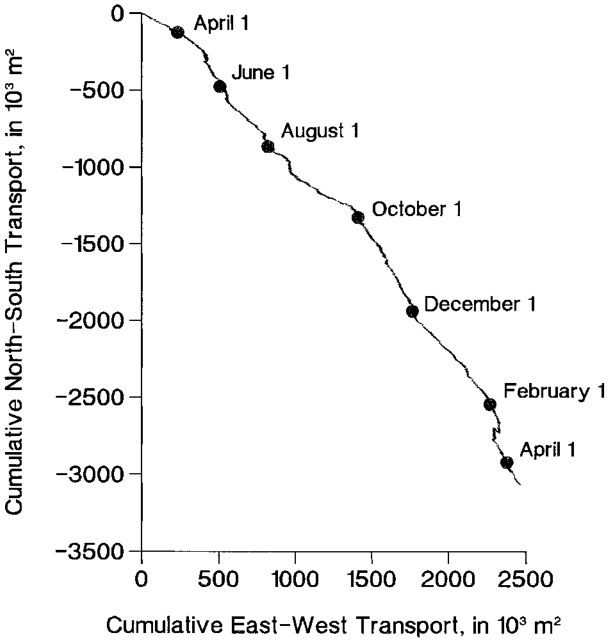

FIG. 2. Two-dimensional, vertically integrated cumulative net transport past station N, 14 Mar 1996–22 Apr 1997.

Similarity of the flow at near-surface and near-bottom levels in the water column was quantified in two ways. Linear regression of near-surface and near-bottom currents provided serial correlation coefficients for east–west and north–south components individually. Second, the complex correlation coefficient (Kundu 1976) compared the surface current vector with the near-bottom current vector. The phase angle of the complex correlation coefficient quantified the mean counterclockwise deflection of the near-bottom flow relative to the near-surface flow. The complex correlation coefficient was used also to quantify the similarity and deflection of currents measured in the second level of the ADP profile relative to the vertically integrated transport.

4. Results

a. Northern station

The depth-integrated cumulative transport of water past station N calculated from ADP data is shown in Fig. 2. The pattern indicates a quasi-steady southeastward transport of water, into Florida Bay. The 3.94 × 10^6 m^2 total transport during the 404-day study period reduces to a resultant transport of 0.113 m^2 s^{-1} along a heading of 141°. The east–west component of the total, which is the transport across the western boundary, is an inflow of 0.07 m^2 s^{-1}.

Figure 3 contains the PVDs for currents recorded in

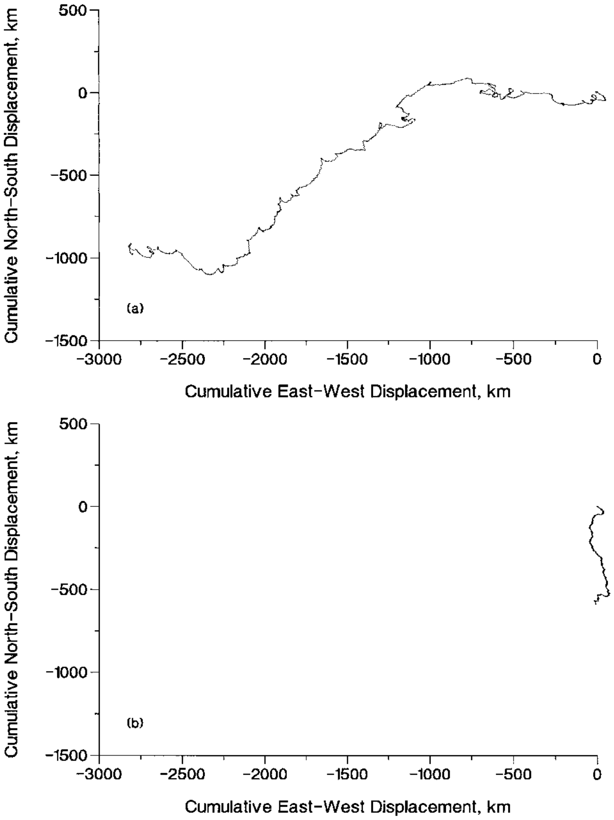

FIG. 3. Progressive vector diagrams calculated from (a) near-surface and (b) near-bottom current measurements at station N, 14 Mar 1996–22 Apr 1997.

the top and bottom levels at station N. The curves have been plotted using the same scales for east–west and north–south displacement to facilitate a comparison of near-surface and near-bottom flow. The resultant flow in the surface layer is 7.9 cm s^{-1} toward 251°. The curve comprises three parts. From the start of the record through mid July, the net flow is generally westward. From mid July through mid February, the resultant flow is southwestward, then from mid February through the end of the study the resultant flow is west-northwestward. The PVD constructed from current vectors at the bottom of the ADP profile is quite different in appearance. The resultant flow is southward and greatly reduced in magnitude relative to that at the surface. The resultant speed and direction are 1.6 cm s^{-1} and 183°. Because of topographic features north and east of Station N, it is likely that the southward displacement is a result of curvature in the trajectory of water flooding and ebbing past the study site. The resultant speed and direction for layer 2 (not shown), 1.6 cm s^{-1} and 179°, are similar to values found for the bottom layer.

The PVDs are not representative of the degree of similarity in the instantaneous current, which is dominated by the ebb and flood of the tide. Using both the serial, r_s, and complex, r_c, correlation coefficients to quantify the similarity of the instantaneous flow in near-surface and near-bottom levels, results indicate strong vertical coupling. For the east–west and north–south components, r_s values are $+0.91$ and $+0.63$, respectively. The r_c value is $+0.85$, and the phase angle of the complex correlation coefficient is 0.6°, which is within the accuracy of the ADP.

To test the suitability of mid-depth current meter data for estimating surface-to-bottom transport, speed and direction data from the second level of the ADP profile were used in (1), and results were paired with the two-dimensional transport calculated from the profile. An r_c value of 0.98, together with a 0.3° mean counterclockwise deflection of the vertically integrated transport vector relative to the level 2 current vector support the use of single-level current observations for calculating two-dimensional transport.

The cumulative net transport calculated from water level and profiles extrapolated from level 2 current observations was 3.92×10^6 m^2 at the end of the 404-day study, corresponding to a resultant transport of 0.112 m^2 s^{-1} along a heading of 134°. For station N, transport based on data from a level 2 underestimated profile-derived values by 0.5%, and the resultant direction was 7° to the left of the direction obtained from the ADP profiles.

The relationship of wind stress, water level and east–west flow at station N was examined by assembling data from an approximately two-month period from early October to early December. A series of coherence spectra (not shown) indicated that east–west flow at station N was most responsive to east–west wind stress. Low-pass filtered east–west wind stress, east–west surface and bottom layer current speeds from the ADP profile, and water level from Murray Key are shown in Fig. 4. Wind stress is highly correlated with flow in the top level of the ADP profile. The serial correlation coefficient is $+0.80$; spectral analysis indicates that the highest coherences (0.66–0.83) occur at periodicities in excess of 7 days and with virtually no phase difference. Wind stress is also highly correlated with water level fluctuations. The serial correlation coefficient is $+0.77$, and spectral analysis indicates that coherence varies from 0.79 to 0.88 over periodicities of 4–5 days, and again at periodicities greater than about 10 days. Phase differences are less than 20°.

Although it is clear that wind stress is moving water into and out of the northwest corner of the bay in the surface layer and affecting water level, the response of near-bottom flow to the setup and setdown of water level is poorly defined. The serial correlation coefficient is -0.16, indicating that a setdown of water level is associated with a near-bottom inflow. Spectral analysis indicates near-zero coherence over the longest timescales. The coupling is restricted to a single spectral peak at a period of 51 hours. The lag of near-bottom flow relative to low-frequency fluctuations in water level is about 8 hours. Time lagging the near-bottom flow

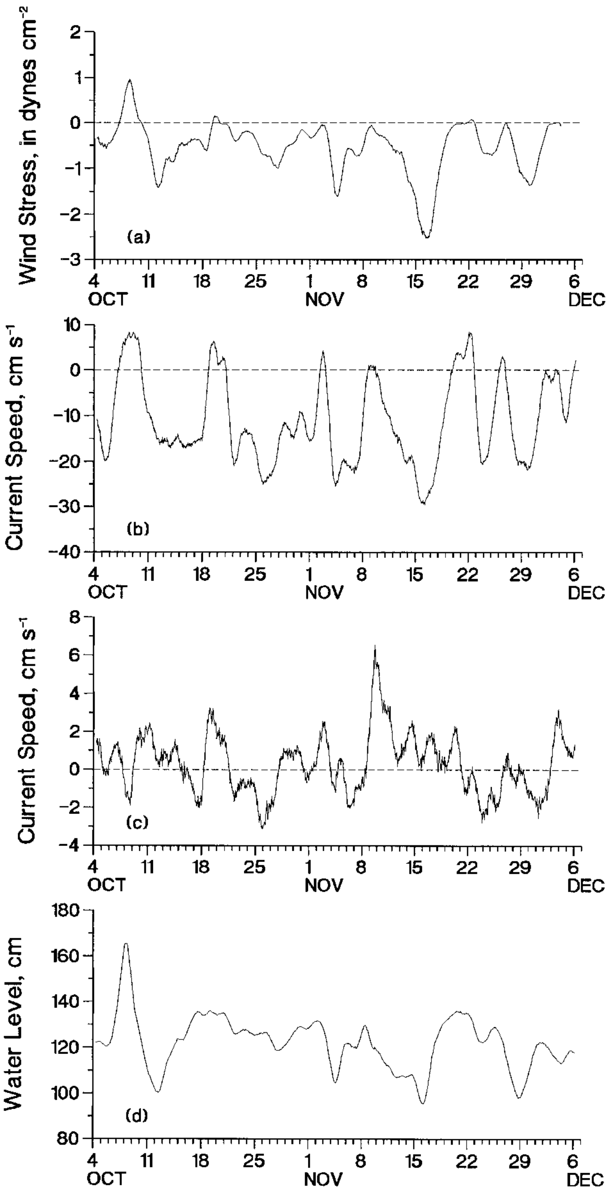

FIG. 4. Low-pass filtered (a) east–west wind stress calculated from observations made at the C-MAN weather station, (b) east–west near-surface current speed, and (c) near-bottom current speed from station N, and (d) water level from Murray Key.

time series by 8 hours, however, raises the serial correlation coefficient to only −0.17. While this is statistically significant at the 99% confidence level, the low correlation is an indication that the near-bottom flow at station N is a response to more than the rise and fall in water level in the northwest corner of Florida Bay. The water level record from Murray Key describes only part of the barotropic pressure gradient at station N.

b. Southern station

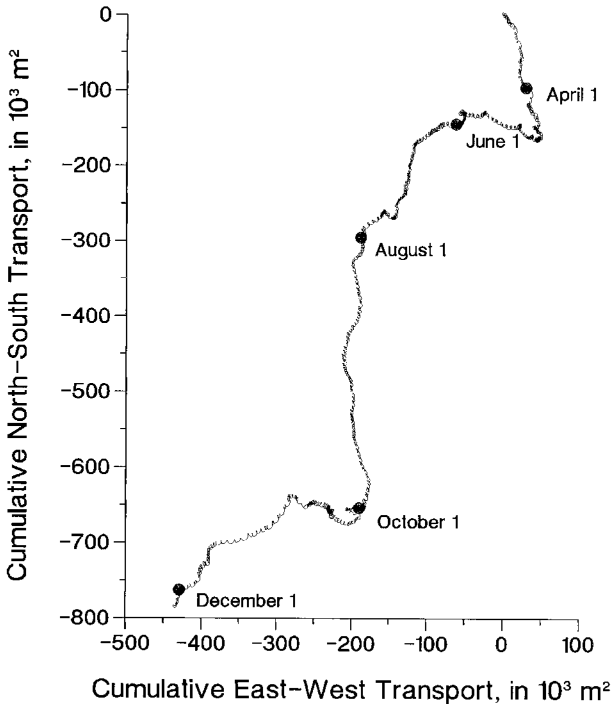

FIG. 5. Same as Fig. 2 but for station S, 14 Mar–5 Dec 1996.

Vertically integrated transport at station S during the shorter, 266-day study period is shown in Fig. 5. The pattern indicates an irregular movement of water toward 209°, but over shorter time scales nontidal transport is alternately into the southern and western quadrants. The 0.90×10^6 m^2 total cumulative transport represents a resultant transport of 0.039 m^2 s^{-1}. The east–west component is an outflow of −0.019 m^2 s^{-1}.

Fig. 6 shows the PVDs constructed from top-level and bottom-level currents recorded at station S. The noteworthy feature of the figure is the similarity of the two plots, and the similarity to the vertically integrated transport (Fig. 5). Both plots indicate resultant flow toward the southwest. The resultant direction is toward 237° at the top level and toward 239° at the bottom level. Resultant speeds in the top and bottom levels of the profile are 1.6 and 1.3 cm s^{-1}, respectively. Resultant flow through the second level of the ADP profile is 1.3 cm s^{-1} toward 239°. The r_s values calculated from near-surface and near-bottom east–west and north–south current components are +0.90 and +0.95, respectively. The r_c value calculated from near-surface and near-bottom layer current vectors is +0.94, and the phase angle is 0.4°.

The complex correlation coefficient calculated from level 2 current vectors and vertically integrated transport at station S is +0.96. This is slightly lower than the r_c value found at station N, but level 2 currents are nevertheless suitable for estimating two-dimensional transport. Using (1), the total transport over the entire study period is 0.81×10^6 m^2, which is about 10% less than the transport calculated from the ADP profiles. This may be due to larger wind effects recorded by the ADP in

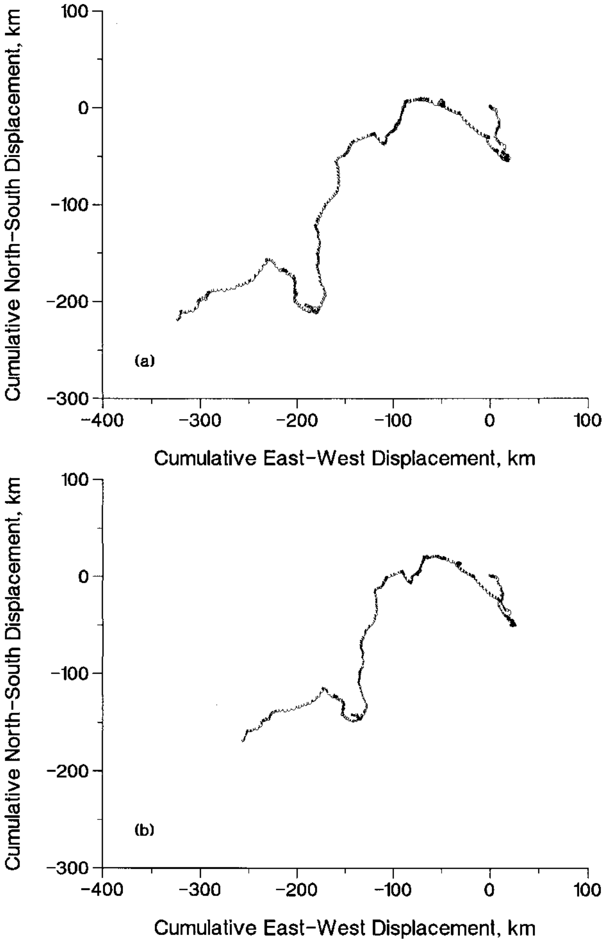

FIG. 6. Same as Fig. 3 but for station S, 14 Mar–5 Dec 1996.

near-surface layers, but not recorded by the current meter 1 m above the bottom. The direction of the cumulative net transport calculated from level 2 currents is 210°, which differs by only 1° from the direction obtained using ADP data.

c. Roughness length estimates

To quantify bottom roughness, current speeds were regressed against the natural log of the height above the bottom, and z_o was calculated as the y intercept of the regression line. Given the size of the roughness elements at station N, and in view of the empirically determined 30:1 ratio of the size of the roughness elements to the magnitude of the z_o value (Huschke 1959), values of 0.3–0.5 cm were expected. Because of the wide range of calculated values, results are not shown. At the station N, the number of z_o values in 0.1 cm bins decreased slowly for values up to 1.0 cm. Sixty-one percent of the values were broadly distributed between 0 and 1.0 cm, 19% were between 1 and 2 cm, and 9% were between 2 and 3 cm. Nearly 2% were greater than 10 cm. The broad peak of the histogram below a value of 1 cm made it impossible to identify a single representative value. Results were similar at station S, although it is not clear what roughness lengths should be expected in a seagrass meadow. Sixty-nine percent of the z_o values were less than 1.0 cm, and 20% were between 0.2 and 0.3 cm. Again, however, many values were unrealistically large. Fourteen percent were between 1 and 2 cm, and nearly 6% were between 2 and 3 cm. Over 5% of the z_o values were greater than 10 cm.

5. Discussion

Results from stations N and S show that while tide-dominated instantaneous current vectors in near-surface and near-bottom layers are similar, the resultant flow can be quite different over long timescales. At both study sites, average surface-to-bottom differences in the instantaneous current are primarily in speed. Differences in current direction are well within the accuracy of the ADP. Over long timescales, however, significant differences in both resultant speed and direction can appear as a result of subtle differences in the instantaneous flow. This is especially true at station N. While the local balance of forces could not be determined, the cumulative effect is to drive near-surface water west-southwestward and near-bottom water southward. At the more unbounded southern study site, current profiles indicate that even over the longest timescales the water column behaves very nearly as a single layer. Similarities and differences in flow throughout the water column and over long timescales have to be determined from time series of current profiles.

Results also demonstrate the significant differences that can exist between PVDs and cumulative net transport diagrams. At station N in particular, incorporating the tidal and low-frequency expansion and contraction of the water column rotates the resultant transport vector 42° counterclockwise from the heading of the PVD calculated from near-bottom currents, and 110° counterclockwise from the heading of the PVD calculated from near-surface currents. At station S, the counterclockwise rotation is less, but the transport vector is approximately 30° to the left of the near-surface and near-bottom PVDs.

Baroclinic pressure gradients, and thus their effect on current profiles cannot be estimated from the available database. Vertical stratification has not been reported at either location, but salinity maps (Wang 1998) indicate horizontal salinity gradients of as much as 1 psu km^{-1}. Time series of salinity from a study site midway between stations N and S indicate that salinity fluctuations at tidal periodicities are commonly on the order of 0.5 psu, and occasionally as much as 1.5 psu per half tidal cycle (Smith and Pitts 1995). The M_2 tidal excursion at that location is 3.9 km, indicating that horizontal salinity gradients are characteristically 0.1 to 0.3 psu km^{-1}. Thus, baroclinic pressure gradients may affect vertical current profiles, especially in near-bottom layers, just as wind effects may affect current profiles in near-surface layers.

Results from the two sites considered here support results from earlier studies conducted along the western boundary of Florida Bay, in which current meter data from a single level just below mid depth were used to estimate vertically-integrated transport (Smith and Pitts 1995). Conclusions drawn from the earlier work must be tempered, however, because results cannot necessarily be applied to near-surface and near-bottom layers individually. The availability of ADP profiles makes clear the limitations of single-level current measurements. If one is concerned with the transport of dissolved or suspended material that is uniformly distributed in the vertical, either ADP data or mid-depth current measurements may be satisfactory. If one is concerned specifically with transport in near-surface or near-bottom layers, however, current profiles may be necessary.

ADP profiles did not prove to be well suited for quantifying z_o values for use in (1), probably because the ADP did not make measurements within the lowest 69 cm of the water column, where vertical shear is greatest. Data from near-bottom levels are important in a linear regression if the y intercept on a ln$z$ axis is to be determined accurately. Nevertheless, results were generally consistent with what one would expect based on visual inspection of bottom roughness elements. Results were weakly supportive of the assumption that the current profile was logarithmic, but the z_o value used to calculate two-dimensional transport had to be based on observed bottom conditions rather than on measured current profiles.

The different flow patterns found for surface and bottom layers at station N are significant within the context of modeling Florida Bay circulation. Even in these shallow waters, over sufficiently long timescales, near-surface flow can be quite different from near-bottom flow. Thus, the decision to use a one- or multilayered model to simulate flow patterns may hinge on the distribution of dissolved or suspended material within the water column, and thus the need to understand transport specifically in near-surface or near-bottom layers. Results from western Florida Bay offer little guidance in this regard because they include both an example of large long-term differences in resultant flow (station N) and an example of small long-term differences (station S). A single-layer model would work well at either location for simulating the transport of material that is uniformly distributed through the water column. If dissolved or suspended material is concentrated in near-surface or near-bottom layers, however, a multilayered model would be needed at station N. Results suggest that it may be prudent to presuppose that vertical structure in the water column can be significant over long time scales until profile data are available to confirm that the water column acts as a single layer.

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