The role of advection in transporting nutrients to the Florida reef tract

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ABSTRACT

Near-bottom current meter and dissolved nutrient data are used to describe the advection of nutrients from the Florida Keys to the reef tract, where elevated nutrient concentrations have been shown to adversely affect reef corals. Results indicate a long-term across-shelf flow toward the reef tract that averaged 2 cm s\(^{-1}\) during the 13-month study. Combining the average flow rate with a representative dissolved inorganic nitrogen (DIN) concentration of 2.71 µM yields an average DIN transport rate of 55 µmole m\(^{-2}\) s\(^{-1}\) seaward past the study site. Low-frequency, nontidal across-shelf flow was toward the reef 80% of the time and a mean of 11 days was required to transport nutrients 8 km from the Keys to the reef tract (median = 4.7 d). M\(_2\) tidal currents transport nutrients seaward 0.38 km during the average ebb. Spectral analysis indicates no cause-and-effect relationship between across-shelf flow and the local wind field.

Keywords: Florida reef tract, Advection, Nutrient transport, Eutrophication

Introduction

The Florida reef tract is a relatively narrow band of fringing coral reef that lies 8-10 km off the Atlantic Ocean side of the Florida Keys. It is the largest and most important coral reef system that is part of the continental United States. Recently, there has been growing interest in circulation patterns in the region, particularly the exchange processes that occur between the reef tract and the waters surrounding the Keys. Some of this interest stems from concerns that corals may be suffering from eutrophication processes and could eventually be displaced by marine algaes (Lapointe and O’Connell 1990, Lapointe and Clark 1992). The data suggest that nutrient concentrations in waters surrounding the reefs, originating from anthropogenic and natural sources from the Keys and Florida Bay and moving to the reefs, may be increasing, allowing algae to become established in an otherwise nutrient-poor environment. Lapointe and Matzie (1996) have documented significant gradients of dissolved nitrogen and phosphorus from the Lower Keys to Looe Key Reef, historically the jewel of the Florida reef system.

The transport of water, and any substances dissolved or suspended in that water, between the Florida Keys and the Florida reef tract involves crossing Hawk Channel. This channel lies between and parallels the Keys and the reef tract, and it serves as the continental shelf on the Atlantic Ocean side of the Keys (Fig. 1). Hawk Channel extends approximately 240 km from Biscayne Bay to just west of Key West and it is typically 3-8 km wide and 5-15 m deep. A number of studies have described the tidal and wind-driven circulation of Hawk Channel (Lee 1986, Lapointe et al. 1992, Pitts 1994, 1997). These studies show that flow in Hawk Channel is dominated by low-frequency, along-channel motions that exhibit a seasonal cycle following changes in regional wind patterns. Tidal currents appear to be of secondary importance compared to the wind-driven flow.

Fig. 1. Map showing the study area in the Florida Keys. The dot shows the current meter site in Hawk Channel, the triangle represents the meteorological station on Sombrero Key, and the labels “P”, “PR” and “LK” show the locations where nutrient data were collected in Pine Channel, Patch Reefs and Looe Key, respectively. Label “B” shows the location of Bahia Honda Channel. The hatched line follows the 20 m isobath and also indicates the location of the reef tract.

This paper focuses on the across-shelf component of Hawk Channel circulation and integrates nutrient data to determine the role of advection in transporting nutrients from the lower Florida Keys to the reef tract. A 13-month time series of near-bottom current meter data from the middle of Hawk Channel near Looe Key Reef is used to quantify the tidal, low-frequency and long-term flow across Hawk Channel. Values of dissolved inorganic nitrogen (DIN) and total dissolved phosphorus (TDP) concentrations are incorporated to quantify the transport of these nutrients from the Keys to the reef tract. Also, wind data are used to determine the extent to which the local wind field drives the across-shelf flow.
Data and Methods

Current speeds and directions were recorded at a study site in the middle of Hawk Channel due south of Bahia Honda Key (24°36.40' N, 81°16.70' W) from July 2, 1992 to July 22, 1993 (Fig. 1). Data were recorded using a General Oceanics Model 6011 Mark-II inclinometer (accurate to ±1 cm s⁻¹ for speed and ±2° for direction) moored 4 m above the bottom in 13 m of water. Current speeds and directions were decomposed into along- and across-shelf components, then the hourly across-shelf components were converted to displacements by multiplying current speeds by the time interval they represent and accumulating the values. The time series of displacements was then plotted to characterize across-shelf flow past the study site over time scales ranging from days to months. Tidal components were quantified using a least squares harmonic analysis program (Schureman 1958). The tidal excursion, the horizontal distance a parcel of water is carried during an average half tidal cycle, was estimated from AT = 2πf, where A is the amplitude (in km hr⁻¹) of the principal tidal constituent (M₂) and T is the 12.42-hr periodicity of M₂. Note: along/across-shelf orientation was determined from a nautical chart of the study area. Chart bathymetry indicated a distinct 075-255° orientation of Hawk Channel, and the instrument was positioned over a flat mud bottom with no nearby topographic features (reefs, mud banks) that could steer currents.

Representative values for dissolved inorganic nitrogen and total dissolved phosphorus at the study site were obtained by averaging measurements made at three nearby sites (Lapointe and Matzie 1996). DIN measurements from patch reefs located 9.5 km west-northwest, or landward, of the study site were averaged with measurements made at Looe Key, 15 km southwest, or seaward, of the current meter (Fig. 1). TDP measurements from Pine Channel, located between Big Pine Key and Little Torch Key approximately 13 km from the current meter, were averaged with measurements from Looe Key. Nutrient measurements were obtained from these locations at approximately 1-wk intervals from April 27 to July 30, 1992. DIN and TDP parameters were used in this study for two reasons: 1) the majority of DIN was ammonium which is the nitrogen form most easily assimilated by marine algae, and 2) TDP includes dissolved inorganic phosphorus, the major phosphorus pool that supports macroalgae blooms in coastal waters of the Florida Keys (Lapointe 1989, Lapointe et al. 1994).

To quantify how long it takes nutrients to be transported from the Keys to the reef tract, a computer program was developed that calculates the time required for a parcel of water to travel 8 km (the width of the shelf at the study site) using the current meter data. Calculations were made using detided across-shelf current speeds that were obtained by subtracting the predicted tidal currents (Schureman 1958) from the observed currents. Displacement values were then accumulated from the beginning of the time series until a distance of +8 km (positive indicating seaward) was reached. At that point the time required to reach +8 km was recorded and the program repeated the process beginning with day-2 of the time series, and this process was repeated through the end of the time series. Results of the timed displacement analysis are presented as histogram plots.

Wind data recorded at a NOAA Coastal Marine Automated Network meteorological station on Sombrero Key (24°37.60' N, 81°06.60' W, Fig. 1) were obtained from the National Data Buoy Center to investigate the relationship between across-shelf flow and local wind stress. Wind speeds and directions were recorded at accuracies of ±1 m s⁻¹ and ±10°, respectively. The weather station is 17 km east of the study site. Speed and direction pairs were converted to wind stress vectors using the algorithm described by Wu (1980) for moderate wind speeds (1-20 m s⁻¹). Spectral analysis (Little and Shure 1988) was used to investigate the relationship between wind stress and across-shelf flow. To determine the wind stress components and periodicities for which across-shelf flow was most responsive, coherence spectra were calculated at 15° intervals of wind direction.

Results

Across-shelf flow

The cumulative net displacement of across-shelf current components (Fig. 2) indicates a long-term seaward flow past the study site that averaged 2 cm s⁻¹ during the 13-month study period (1 knot = 51 cm s⁻¹). There is a distinct seasonal signal as currents exhibit a quasi-steady seaward movement from the beginning of the study period to mid January and again from early April to the end of the study period. From mid January through mid April little net across-shelf motion occurred at the study site. Harmonic analysis indicates that tidal currents are relatively weak. The across-shelf amplitude of the M₂ constituent is only 2.7 cm s⁻¹. All other diurnal and semi-diurnal constituents have amplitudes less than 1 cm s⁻¹, which fall within the precision of the current meter. The across-shelf M₂ tidal excursion at the study site is 0.38 km. Thus, during any average ebb tide nutrients will be transported 0.38 km seaward across the middle of Hawk Channel.
Nutrient transport

Lapointe and Matzie’s (1996) measurements indicate average DIN concentrations at their Patch Reef and Looe Key sites of 2.56 µM ±0.79 and 2.86 µM ±0.77, respectively, between April 27 and July 30, 1992. A representative value for the Hawk Channel current meter station was taken to be the average of these two values, or 2.71 µM. Applying the long-term net across-shelf flow rate of +2 cm s⁻¹ to a cross-sectional area of 1 m² and combining the representative DIN concentration of 2.71 µM yields an average DIN transport rate of 55 µmoles m⁻² s⁻¹ seaward past the study site during the 385-day study period. The maximum across-shelf flow past the current meter, recorded on October 25, was 27.6 cm s⁻¹ seaward, which translates into a DIN transport rate of 748 µmoles m⁻² s⁻¹ toward the reef tract. Similarly, the average TDP concentrations obtained at Pine Channel and Looe Key were 0.174 µM ±0.054 and 0.149 µM ±0.071, respectively, between May 29 and July 9. Combining the +2 cm s⁻¹ long-term across-shelf flow rate with a representative TDP concentration of 0.161 µM yields an average seaward transport rate of TDP of 3.3 µmoles m⁻² s⁻¹. A maximum seaward TDP transport rate, using the 27.6 cm s⁻¹ current speeds recorded on October 25, was 44 µmoles m⁻² s⁻¹. Note that the nutrient concentrations observed by Lapointe and Matzie (1996) were well above threshold values noted for the demise of coral reefs by eutrophication. Studies by Tomascik and Sander (1985) and Bell (1992) indicate the onset of eutrophication on coral reefs at threshold values of 1.0 µM and 0.1 µM for DIN and TDP, respectively.

Timed Displacements

The results of the timed displacement analysis indicate that the average time required for water to be advected 8 km seaward across Hawk Channel was 11 days (median = 4.7 day, minimum = 18 hrs, maximum = 65 day). Fig. 3 (top) shows the frequency of occurrence of the time required to advect water seaward across the shelf from 0-65 days subdivided into 5-day increments. Over 50% of the calculations fall in the 0-5 day bin and indicate that a water parcel would have been transported 8 km seaward across the shelf in 5 days or less. Approximately 70% of the timings fall within the first two bins and indicate that transport across the middle of the channel would have occurred in 10 days or less. Fig. 3 (bottom) provides a closer look at the 0-5 day transport by expanding the first histogram bar from Fig. 3 (top) into half-day bins. This histogram shows a peak in the 1-2.5 day band with fewer timings falling in the 3-5 day bins.

A significant finding from the analysis was the fact that when using 1-day offsets the program output 379 timings using the 385-day time series. The importance of this is that the seaward across-shelf flow was strong enough and consistent enough, particularly near the end of the study, to provide almost as many output points from the program as there were days in the input time series. When the computer program was modified to investigate landward flow, only ten timings were output. That is, only ten times during the 13-month study did landward across-shelf displacement reach 8 km. Minimum and maximum landward travel times were 1.7 and 4.5 days, respectively (mean = 3 days).

Wind forcing

A plot of the wind stress recorded at Sombrero Reef from July 2, 1992 to July 22, 1993 (not shown) indicates that winds were primarily out of the eastern sector for most of the study period. There is some indication of a seasonal signal as wind stress is more northwestward during summer and early fall, but more southwestward during late fall and winter months. Results of the spectral analyses indicate no significant coherence between across-shelf currents and any of the 12 wind stress components over any time scale.
Fig. 3. Frequency of occurrence (%) of the time required for across-shelf currents to displace water 8 km seaward past the study site. The top histogram shows the results from the entire 385-day study period clumped into 5-day bins; the bottom histogram expands the first bar of the top histogram into half-day bins.

While the correlation coefficient (-0.116) between the across-shelf currents and the across-shelf component of wind stress is significant above the 99% confidence limit, the $r^2$ value of only 0.0135 indicates that this component of wind stress accounts for only about 1% of the total variance in the across-shelf currents. It should be noted that the currents were lagged 3 hrs relative to the wind to obtain the highest correlation coefficient. The correlation coefficient between across-shelf currents and along-shelf winds (-0.056, with a 1-hr lag) was also significant above the 99% confidence limit, but the small $r^2$ value (0.005) indicates little cause-and-effect relationship between this component of the wind and across-shelf currents. Further analysis indicates no statistically significant correlation between the seasonal signal observed in across-shelf flow and the seasonal signal in wind stress. While not of primary interest in this study, it is worth reporting here that the along-shelf currents were highly coherent with the along-shelf components of wind stress over all time scales between 2 and 27 days.

Discussion

The seaward across-shelf flow recorded in this study is similar to what has been observed at nearby Hawk Channel sites in other studies (Lapointe et al. 1992, Pitts 1994), and provides additional evidence that near-bottom shelf waters off the lower Florida Keys exhibit a seaward deflection toward the reef tract. The data presented here indicate that the across-shelf movement of water past the study site had a distinct seasonal signal; seaward from late spring to mid winter and highly variable during late winter and early spring months. This seasonal signal did not correlate with the seasonal signal in the wind pattern, but it roughly corresponds in time with the wet and dry seasons for this region. The quasi-steady seaward flow from May to November occurred during the region’s wet season, while relatively little net across-shelf motion was recorded during the December to April dry season. This seasonal pattern may be significant since nutrient concentrations in the waters surrounding the Keys are generally higher during the rainy season (Lapointe and Matzie 1996) when across-shelf transport to the reef tract is strongest.

The use of a single point measurement to estimate water movement across the shelf should be treated with caution for two reasons. First, data from nearby Keys tidal channels that connect the Gulf of Mexico with Atlantic shelf waters indicate that tidal currents play a much more important role closer to shore, especially near the mouths of channels (Smith 1994). Secondly, along the seaward edge of Hawk Channel near the reef tract, currents likely experience a greater degree of influence from the Florida Current. This influence results mainly from the passage of cyclonic gyres that develop off the Dry Tortugas and migrate eastward off the Lower Keys (Lee et al. 1992). Nevertheless, the flow pattern observed at the study site is probably representative of mid shelf conditions as it is consistent with patterns observed from other mid-shelf sites in the Lower Keys (Lapointe et al. 1992, Pitts 1994).

The apparent lack of any cause-and-effect relationship between across-shelf currents and wind stress contradicts results from an earlier circulation study from the same site (Pitts 1994). The previous study showed significant coherence between across-shelf currents and along-shelf wind stress at periodicities of 2.5-3 days, with a phase relationship suggesting a near-bottom return flow of shoreward-directed Ekman transport. An earlier study by Lee et al. (1992) showed that persistent westward winds produce downwelling in the deeper waters seaward of the reef tract along this section of the Keys, resulting in offshore flows in the lower Ekman layers. While Ekman dynamics probably play a comparatively minor role in the shallow, relatively sheltered waters of Hawk Channel, it is unclear why there was no significant relationship between along-shelf winds and across-shelf flow in the data presented here. A follow-up study from a Hawk Channel site off Key West (Pitts 1997) showed that across-shelf currents and across-shelf winds exhibited a consistent out-of-phase relationship during certain time periods, suggesting an upwind return flow of near-bottom currents. While the negative correlation coefficient from the results presented here suggests an inverse relationship between
across-shelf currents and across-shelf winds, the low $r^2$ value indicates a very weak association. The close coupling between along-shelf flow and wind forcing observed in this study is similar to what has been shown in previous studies (Pitts 1994, 1997).

An alternative to wind as the mechanism for forcing the observed seaward flow is the possibility that outflow from Florida Bay and the Gulf of Mexico into the Atlantic is responsible. Smith’s (1994, 1998, in review) studies have shown a long-term bay-to-Atlantic flow through virtually all of the major tidal channels between the middle and lower Florida Keys. Combining current meter and water level data with channel cross-sectional area measurements, Smith (1994) documented a quasi-steady nontidal outflow from the gulf of 620 m$^3$ s$^{-1}$ through Bahia Honda Channel, located just 5 km landward of this study’s Hawk Channel site. Outflow under Seven Mile Bridge, located 14 km to the northeast, is 454 m$^3$ s$^{-1}$ (Smith, in review). Work is in progress to determine whether or not the volumes exiting Florida Bay through these channels are enough to account for the seaward flow observed in Hawk Channel.

Calculation of the $M_2$ tidal excursion indicates that nutrients are carried 0.38 km toward the reef tract on the average ebb tide. The tidal excursion will increase or decrease as other semi-diurnal and diurnal tidal constituents cycle in and out of phase with $M_2$, producing spring and neap tide conditions. However, since most of the water that moves seaward on a given ebb tide will move approximately the same distance shoreward on the following flood, the value of tidal co-oscillations as a nutrient transport mechanism is determined by mixing characteristics and nutrient concentration gradients.

Another physical process that is responsible for transporting nutrients to the reef tract is turbulent diffusion. The importance of this process is governed by the frequency and size of turbulent eddies and the magnitude of the nutrient concentration gradients that exists across Hawk Channel. Smith and Pitts (1998) reported that diffusive transport plays a relatively minor role in transporting nutrients across Hawk Channel to the reef tract when compared to advective transport. Their results indicated that transport by turbulent diffusion is approximately an order of magnitude less than advective transport. However, like the measurements used in the study described here, results were based on current speeds and directions recorded at hourly intervals from which diffusion coefficients were determined for the intermediate and longer time scales. The importance of diffusion by smaller eddies could not be determined from hourly measurements, and these smaller, higher frequency eddies may be the most important for driving turbulent diffusion in the waters of Hawk Channel. Nevertheless, results from studies to date suggest that advection is the primary mechanism for transporting nutrients and other water-borne materials across the shelf to the Florida reef tract.

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References


Schuremen P (1958) Manual of harmonic analysis and


Smith NP (in review) Tidal, low-frequency and long-term mean transport through two tidal channels in the Florida Keys. Cont Shelf Res.

