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The Effect of Hyperpycnal Water on Tidal Exchange

Ned P. Smith

ABSTRACT

Current meter and hydrographic data from a tidal channel connecting the western side of Exuma Sound with the eastern margin of Great Bahama Bank are used to investigate the efficiency of tidal exchanges. The density of water leaving the bank is usually higher than the density of water arriving on the flood tide. Data from near the shelf break confirm that density currents cascade down the narrow shelf. Tidal period bursts of seaward-directed flow are recorded just above the bottom, and the net flow is seaward. Spikes appear in the plot of near-bottom density. Salinity is used as a tracer during two consecutive tidal cycles to show that 95 and 97.5% of the water entering the channel is from Exuma Sound, and not bank water associated with the previous ebb. Perturbation analysis is used to show that the time-varying salt transport, has a strong seasonal component that is directly related to the presence or absence of density currents.

Introduction

Strong gradients of temperature and especially salinity are common in estuarine and inner shelf waters. Salinity gradients form as a result of the juxtaposition of sea water and fresh water arriving as rainfall, freshwater runoff and groundwater seepage. With vertical mixing, horizontal salinity gradients arise from the different response of deep and shallow waters to spatially uniform freshwater gains and losses. In a similar way, horizontal temperature gradients can arise along a depth gradient because of the inverse response of the water column to spatially uniform sensible and latent heat fluxes. A relatively shallow water column will magnify the effect of a given heat gain or loss. Hydrographic time series from tidal channels connecting shelf and estuarine waters clearly demonstrate these gradients, as water of different salinity and temperature ebbs and floods past the study site.

The hydrography of waters surrounding the Exuma Cays of the Bahamas is unusual in the sense that continental runoff is negligible. Horizontal gradients of hydrographic variables arise solely as a result of differences in the local response to freshwater gains and losses and sensible and latent heat fluxes. While rainfall is spatially variable, especially in summer months, it is unlikely that spatial gradients in precipitation and evaporation are significant when averaged over time periods greater than a few weeks. The region experiences a pronounced net freshwater loss over the course of a year. Schmitt et al. [1989] reported a 175 cm annual excess of evaporation over precipitation (E-P). Seasonal variations in E-P include a winter maximum that is roughly four times the net loss characteristic of midsummer months. On average, Great Bahama Bank generates hyperpycnal water throughout the year, but especially in winter months, when E-P is greatest and when effects of lower water temperature reinforce effects of higher salinity.

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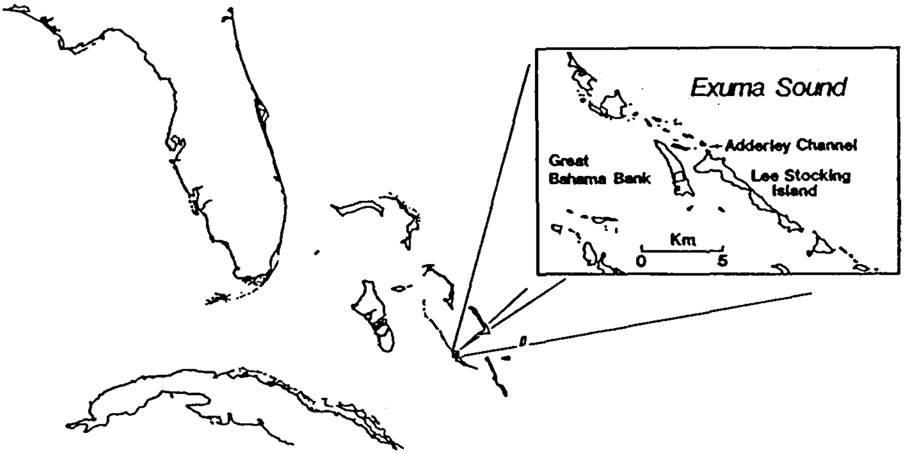

Figure 1. Map of the study area, showing Adderley Channel in the Exuma Cays along the western fringe of Exuma Sound. The two study sites are at the mouth of Adderley Channel and 0.2 km seaward, at the shelf break.

A series of field studies conducted from mid 1990 to mid 1992 [Pitts and Smith, 1993, 1994] investigated tidal exchanges in a region where deep-water and shallow-water environments are connected directly by tidal exchanges. The study area was between Exuma Sound and Great Bahama Bank (Figure 1) at the southern end of the Exuma Cays. Within one tidal excursion seaward of the Exuma Cays, water depths in Exuma Sound are on the order of 500 m; Great Bahama Bank extends for many tens of kilometers to the west with depths on the order of 3.5 m. The primary purpose of the field studies was to quantify long-term net transport through tidal channels serving as the connecting link between the bank and the sound.

Hydrographic data from Adderley Channel [Smith, 1995] exhibited great variability over complete tidal cycles. Relatively warm water left the bank on the ebb during summer months; cooler water was exported during winter months. High salinity water ebbed off the bank through much of the year, especially in late winter and early spring. Salinities as high as 40‰ were recorded at the end of the ebb cycle. High salinity water was virtually absent in the channel in late summer and early fall, when shoreward directed wind stress increased.

The purpose of this paper is to extend the earlier work by focusing on density and exploring the effect hyperpycnal water has on tidal exchanges at the mouth of the channel. It was hypothesized that hyperpycnal water recorded in the channel would cascade down the narrow shelf and over the wall, and thus not re-enter the tidal channel during the following flood cycle. To investigate density currents near the shelf edge, current and hydrographic data were recorded 0.5 m above the bottom, approximately 50 m from the top of a vertical wall that constitutes the shelf break. High-density water passing this study site is almost certainly lost to intermediate depths in Exuma Sound. Results confirm that hyperpycnal water descends the narrow shelf as a density current, increasing the effectiveness of tidal exchanges

Data

Data were obtained from two study sites. The first was near the mouth of Adderley Channel. The current meter was moored 2 m above the bottom in a water column that averaged 7 m deep. The study site was maintained from July 1, 1990 to June 30, 1991. Tidal conditions in the channel are summarized in Table 1 for the six principal constituents. M_2 tidal amplitudes at this location are 0.32 m and 0.67 m s^{-1}. The substantial phase lead of highest water level over strongest ebb speed indicates a predominantly standing wave pattern in the channel. The second study site was seaward of the mouth of the channel and about 50 m from the shelf break. The width of the shelf is on the order of 0.5 km. At the shelf study site, water depth was 25 m. The current meter was moored 0.5 m above the bottom, and the study site was maintained for an 84-day period of time from May 31 to August 22, 1992.

Table 1. Harmonic constants (amplitudes, η, in decibars or m s^{-1}, and local phase angles, κ, in degrees) of the principal tidal constituents calculated from current meter data and bottom pressures recorded in Adderley Channel. Positive current speeds represent ebb tide conditions.

	Tidal Constituent					
	M_2	S_2	N_2	K_1	O_1	P_1
A. Pressure						
1. η	0.32	0.05	0.08	0.09	0.07	0.03
2. κ	224	257	198	150	131	150
B. Current Speed						
1. η	0.67	0.11	0.15	0.06	0.05	0.02
2. κ	335	021	316	230	236	230

The current meter data and hydrographic data used in this study were provided by a General Oceanics Mark II recording inclinometer equipped with temperature and conductivity sensors. Temperature and conductivity were measured to accuracies of ±0.25°C and ±0.025 MS, respectively, according to instrument specifications. Conductivity, corrected for temperature, was converted to salinity [Perkin and Lewis, 1978], and density was calculated using the approach described by Millero and Poisson [1981]. Salinity was checked using measurements made at the study sites and in shelf waters unaffected by tidal exchanges. Salinity profiles were obtained using a Sea Bird Electronics Sea Cat Profiler.

Current speeds and directions from both study sites were decomposed into Cartesian coordinates; the along-channel component was used from the tidal channel station, and the across-shelf component was used from the shelf-break site.

Methods

Vertical current profiles made across the channel with a flow meter were combined with mid-channel current meter measurements to estimate volume transport for Adderley Channel [Smith, 1994]. Hydrographic data from the channel at the study site indicated that intense tidal mixing in the channel and wave mixing in Exuma Sound results in vertically and laterally homogeneous conditions at any given time. Using volume transport, in $m^3 s^{-1}$, and salinity, in kg m^{-3}, salt transport can be expressed in kg s^{-1}. Perturbation analysis can then be used to quantify the relative importance of the mean and tide-dominated time-varying components of the total transport through Adderley Channel. Decomposing the hourly volume transport, v_i, and salinity, s_i, into the annual mean and the deviation from the mean, the instantaneous salt transport is expanded into four terms:

$$s_i v_i = S V + s_i' V + S v_i' + s_i' v_i' \qquad (1)$$

where S and V are the annual mean salinity and along-channel volume transport, and s' and v' are the deviations from the annual mean in the i^{th} hour.

For determining the relative importance of mean and the time-varying transport, the annual mean of the s'v' term is usually calculated to make it comparable with the SV term. The right hand side of Equation (1) is immediately reduced to two terms, because the annual means of s' and v' are zero. Thus,

$$<s_i v_i> = S\ V + <s'\ v'>, \tag{2}$$

where the angle brackets represent the time average. Taking the average in this way, however, ignores useful information related to the temporal variability of the s'v' perturbation product. An alternate approach is to accumulate the s'v' terms and plot the cumulative net value as a function of time. For the m^{th} hour of the study, the cumulative salt transport is given by

$$T_m = \sum_{i=1}^{m} s'_i\, v'_i \tag{3}$$

The slope of the plot equals the $< s'\ v' >$ term in equation (2), but the deviations from the straight-line slope reveal seasonal variability, as well as fluctuations over shorter time scales.

Salinity recorded in a tidal channel can also be used as a tracer to estimate percentages of bank and shelf waters in a water sample--if the two end points of the mixture are known. If the salinities of unmixed bank and shelf water are S_b and S_s, respectively, and the salinity in the tidal channel is S_c, then the fraction of the tidal channel sample that originated in Exuma Sound, F_s, is given by

$$F_s = \frac{S_b - S_c}{S_b - S_s}. \tag{4}$$

Values of F_s will range from 0.0 to 1.0. Calculations assume that salinity recorded in the tidal channel is representative of the entire channel. In situ hydrographic data support this assumption, although temporary stratification has been reported [Wilson, 1991] immediately following slack water at the end of the ebb tide cycle. Relatively low density sound water initially floods in as a surface layer before the water column is homogenized by energetic tidal mixing.

Homogeneous Exuma Sound water occurs within one tidal excursion of the mouth of Adderley Channel as a result of a long-term net inflow through Adderley Channel [Smith, 1995]. Hydrographic gradients are common over Great Bahama Bank, however, and this makes it difficult to establish the value for S_b needed to evaluate equation (4). Nevertheless, at times relatively constant salinity water leaves the bank during much of the latter part of the ebb tide cycle. With values for both S_b and S_s, one can use hourly measurements of S_c to evaluate F_s. Using the current meter data to estimate the total volume of water entering the channel during the m^{th} hour of the flood tide, one can quantify the volume of Exuma Sound water as a fraction of the total. Summing over the entire flood tide cycle quantifies the efficiency of the exchange over the flood half of the tidal cycle, E_f:

$$E_f = \sum_{m=1}^{n} \frac{F_s V_m}{V_m}, \tag{5}$$

where V_m is the total volume of water entering the channel during the m^{th} hour of the flood tide.

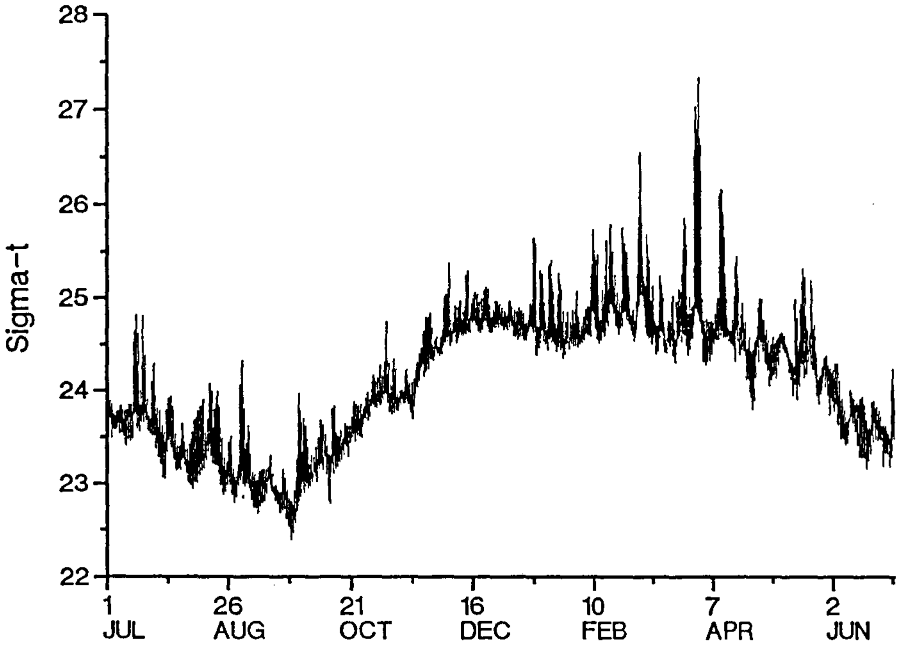

Figure 2. Sigma-t values calculated from conductivity and temperature measurements made at the mouth of Adderley Channel, July 1, 1990 through June 30, 1991.

Results

Figure 2 shows a time series of density in the form of sigma-t from the Adderly Channel study site obtained during the first study period. Superimposed onto the annual cycle and onto low-frequency variations over time scales on the order of 1-2 weeks are fluctuations associated with tidal exchanges. Tidal period deviations from the seasonal and low-frequency non-tidal variations occur in the form of transient "spikes" that increase sigma-t values by as much as two and a half units (2.5 kg m^{-3}). Density spikes are most prominent in late winter months and, to a lesser extent, in mid summer.

The relationship between density and along-channel flow in Adderly Channel is demonstrated in Figure 3, which contains time series of density and along-channel volume transport for a one-week period in early February, 1991. Ebb currents are defined to be positive. Careful comparison of the two curves shows that highest densities at the mouth of the channel coincide with slack water after the ebb. Density decreases quickly with the turn of the tide, and for much of the flood half of the tidal cycle density is low and relatively uniform. The asymmetry of the density plot over tidal cycles suggests that water entering on the flood tide is not the same water that left on the preceding ebb.

Current and hydrographic data from the shelf-break station provide information on the seaward movement of hyperpycnal water leaving Adderley Channel (Figure 4). A plot of sigma-t from the second field study shows decreasing values during the first month of the study. This represents the last of the late spring and early summer warming. Density spikes are less

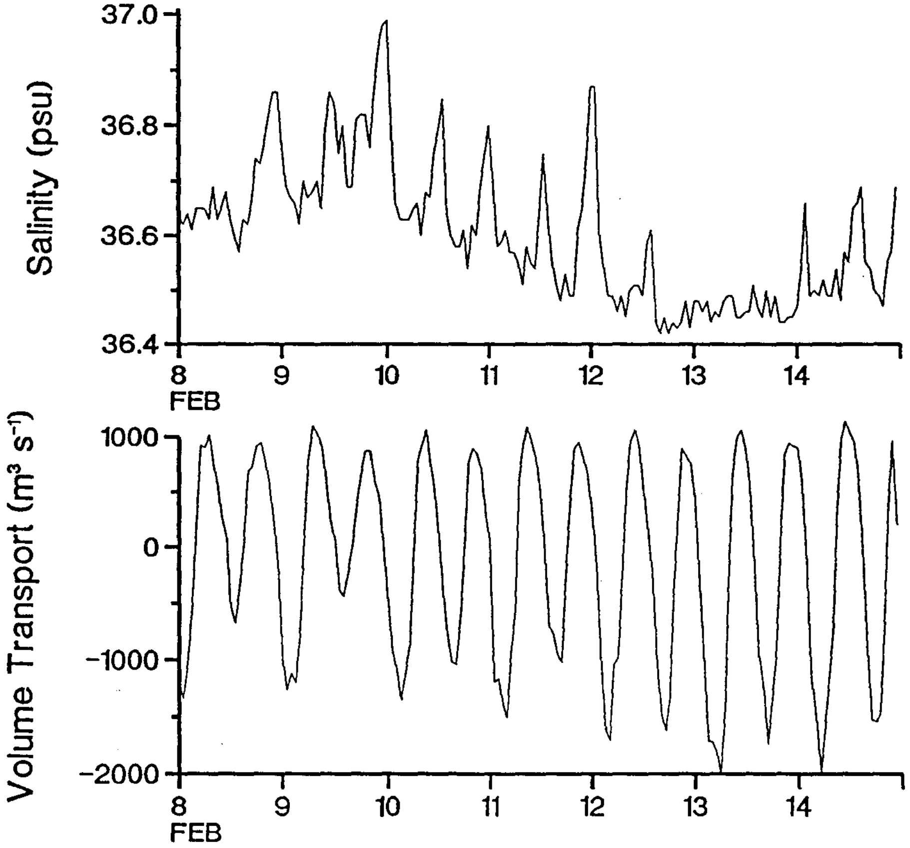

Figure 3. Composite of along-channel volume transport (m^3 s^{-1}) and salinity (psu) recorded at the mouth of Adderley Channel, February 8-14, 1991.

prominent, indicating that some vertical mixing occurs as hyperpycnal water cascades down the narrow shelf on the ebb tide. Nevertheless, transient spikes are evident, especially early and late in the study.

Figure 5 shows the across-shelf current component recorded at the shelf-break site during the same time period. Seaward flow is favored over landward flow as a result of density currents coming out of Adderley Channel. Weak flow into the channel occurs during the flood tide cycle, but for this time period the mean seaward and landward current speeds are +5.1 and -2.4 cm s^{-1}, respectively. Current meter data from Adderley Channel are not available for this time period, but the mean current speed during June, July and August of the 1990-1991 study was an inflow of about -6 cm s^{-1}. Thus it appears that the export of hyperpycnal water by density currents changes a flood-dominant condition in the channel into a locally ebb-dominant condition in near-bottom layers across the narrow shelf. Onshore winds characteristic of the study area may have contributed by encouraging a downwelling condition, but this would not occur at tidal periodicities.

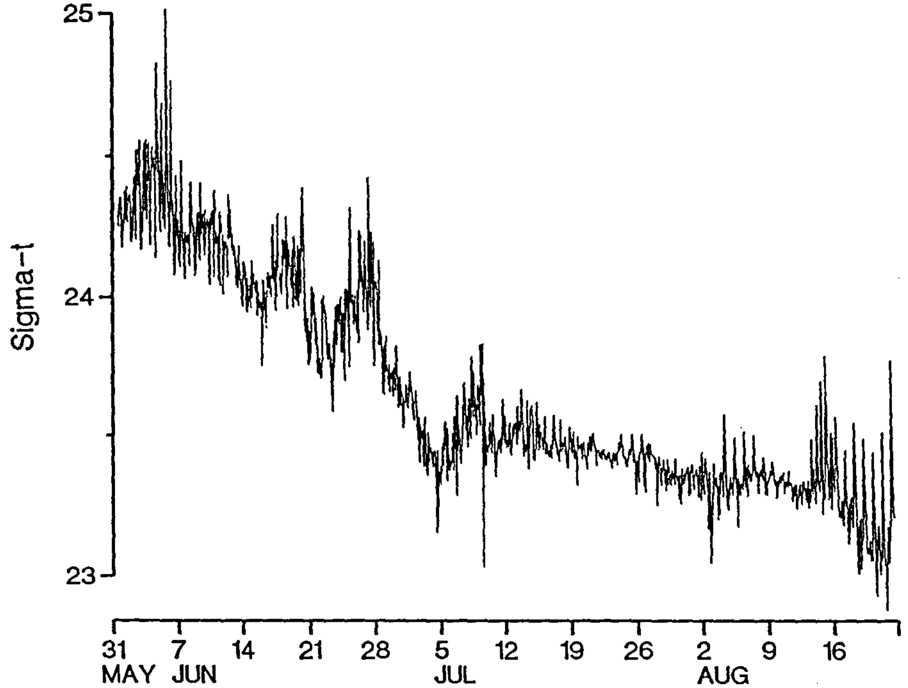

Figure 4. Sigma-t values calculated from conductivity and temperature measurements made 0.5 m above the bottom at the shelf-break study site, May 31 through August 22, 1992.

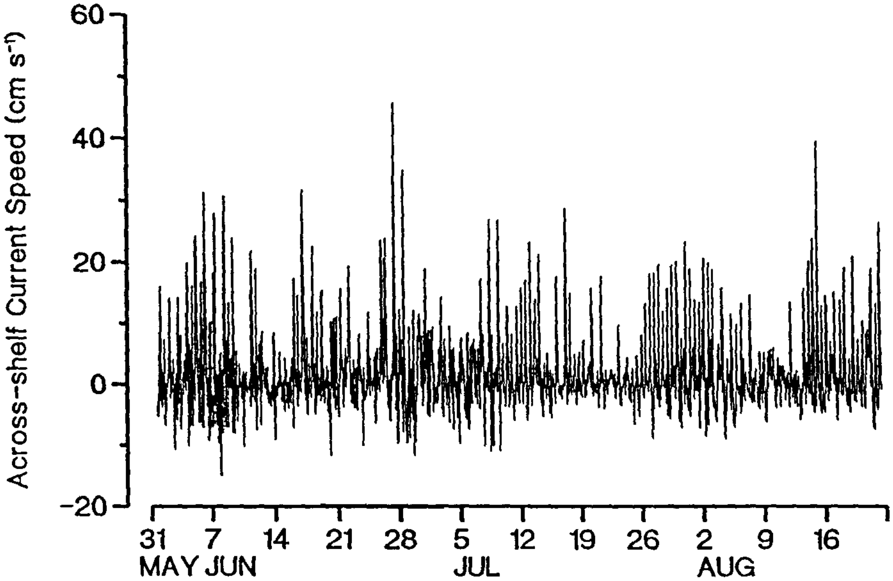

Figure 5. Across-shelf current speeds (cm s^{-1}) recorded 0.5 m above the at the bottom shelf-break study site, May 31 through August 22, 1992. Positive current speeds indicate seaward flow.

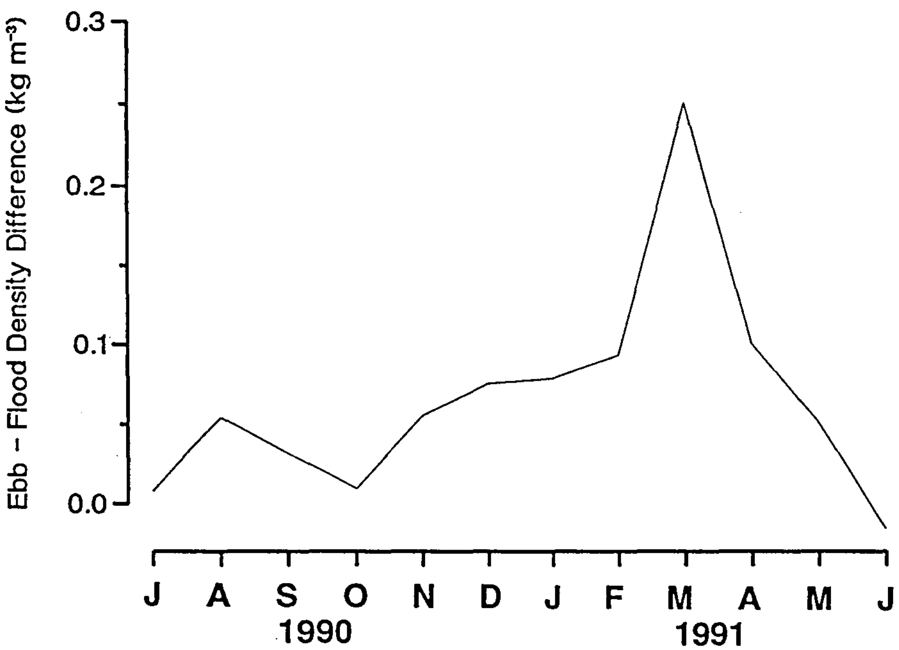

Figure 6. Monthly mean values of the difference between ebb tide densities and flood tide densities (in kg m^{-3}). Study months 1 through 12 refer to July 1990 through June 1990.

The annual variation in the export of hyperpycnal water is shown in Figure 6, which contains the monthly mean values of the differences between ebb and flood densities. On average, ebb densities are between 0.05 and 0.1 kg m^3 higher than flood densities. Greatest differences occur from February through April, when latent heat losses are greatest [Schmitt et al., 1989], when shallow bank waters are cooler, and when rainfall is at an annual minimum.

Salinity can be used as a tracer to quantify the percentage of shelf water in the channel. Combining this fraction with the hourly volume transport gives the transport of shelf water onto the bank. Equations (4) and (5) were used to quantify F_s for the two flood tide cycles on March 31, and to distinguish between Exuma Sound water entering the channel and bank water returning on the flood. Results suggest that 95% and 97.5% of the flood tide volume was Exuma Sound water not related to the previous ebb.

The role that density currents play in exporting salt from Great Bahama Bank on the ebb tide can be visualized by summing the perturbation products defined by equation (2). Results are shown in Figure 7. From the start of the record through late August, the s'v' values are predominantly positive, indicating a net export of salt, and the plot of cumulative values slopes upward. From early September through late December, the plot is essentially flat, indicating little net salt transport through the channel by tidal exchanges. During this same time period, sigma-t spikes are reduced relative to those recorded earlier and especially later in the study (Figure 2). In late February, sigma-t spikes increase in magnitude, the accumulation of exported salt increases correspondingly, and the slope of the curve in Figure 7 steepens. The similarity of the gross features of Figures 2 and 7 supports the logical assumption that hyperpycnal water leaving the bank on the ebb tide is lost to Exuma Sound via density currents, thereby enhancing the tidal exchange of water between the bank and the sound.

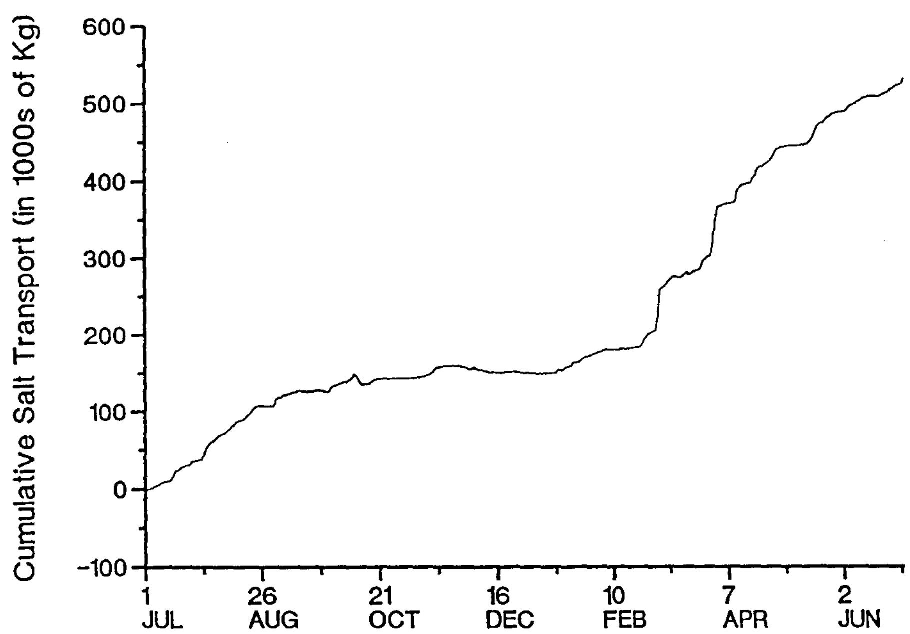

Figure 7. Cumulative salt transport, in thousands of kg, associated with the s'v' term in equation (2), July 1, 1990 through June 30, 1991. Positive accumulations indicate an export of salt from Adderley Channel.

Discussion

It is likely that there is a distinct seasonality in the existence and magnitude of density currents, and thus in the efficiency of tidal exchanges. The earlier Adderley Channel transport study [Smith, 1995] found that the tide-induced seaward mass transport was influenced partly by the differential response to seasonal heating in bank and sound waters, and partly by seasonally varying winds in the study area. During fall and early winter months, strong shoreward winds force Exuma Sound water onto the bank well beyond one tidal excursion. At those times, tidal exchanges move sound water back and forth through the channel, and hyperpycnal bank water is not exported to Exuma Sound. At times of relatively weak shoreward winds, nontidal inflow decreases. Longitudinal mixing by tidal currents brings hypersaline conditions to within one tidal excursion of the mouth of the channel, and density currents occur at the end of the ebb tide. Wind effects are alternately reduced and enhanced over seasonal time scales by sensible heat gains and losses that warm and cool bank water relative to sound water.

Data from near the shelf break show that density spikes are reduced somewhat due to mixing on the ebb tide. Nevertheless, density currents are sufficient to effect a long-term net transport into Exuma Sound. This occurs directly seaward of a channel that has an annual net inflow [Smith, 1995]. It follows that the net inflow must be fed from near-surface and intermediate layers over the inner shelf. Applications of these shelf transport patterns will not be pursued here, but the erosive effects of a seaward near-bottom volume transport should be significant as a mechanism for sediment transport. Similarly, the landward transport in near-surface layers, as well as the near-bottom seaward transport may be significant within the context of larval transport.

Data presented in this study focus on the effect that density currents have on the efficiency of tidal exchanges over the shelf. As noted above, however, this is the end product of a more complex series of cause-and-effect relationships. The presence or absence of density currents in shelf waters is a direct consequence of the availability of hyperpycnal water over the bank. That, in turn, is directly related to wind forcing in Exuma Sound. When strong, shoreward wind stress floods sound water onto the bank, hyperpycnal water retreats, density currents are temporarily absent in shelf waters, and tidal exchanges are temporarily less efficient.

A second effect of a quasi-steady export of hyperpycnal water should be noted in passing, although it lies outside the intended scope of this paper. The nearshore circulation along the western boundary of Exuma Sound is an unusually persistent south-to-north flow. Pitts and Smith [1994] have presented results that included mid-depth current measurements over a 402-day period of time from late October 1991 through late November 1992. During that time, the resultant current speed was just under 6 cm s^{-1}, and reversals in direction were infrequent and brief. The current meter record has not been decomposed into thermohaline and wind-driven components, but it is unlikely that wind forcing by itself would result in such a persistent south-to-north transport. Rather, it is postulated that the quasi-steady export of hyperpycnal water through Adderley Channel and other tidal channels along the Exuma Cays results in a band of high-density water along the western side of Exuma Sound. This would maintain a landward-directed baroclinic pressure gradient and force northward flow. The spatial and temporal characteristics of such a feature of the hydrography of Exuma Sound, as well as the impact it might have on the general circulation of Exuma Sound, are subjects for follow-up studies.

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