NOTES AND CORRESPONDENCE

On Long-Term Net Flow over Great Bahama Bank*

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ABSTRACT

A 398-day time series of middepth current measurements is combined with available wind and bottom pressure measurements and historical salinity data to characterize long-term net flow patterns over Great Bahama Bank between the Tongue of the Ocean and Exuma Sound. The progressive vector diagram constructed from current measurements indicates a resultant flow of just over 2 cm s\(^{-1}\) toward 002°. Semidiurnal tides dominate the instantaneous current. A one-dimensional numerical model is used to investigate the local response to regional forcing. Results suggest that the long-term net flow is a response to the combined effect of wind-driven and density-driven flow toward the northwest, and a tide-induced residual current toward the east-southeast, aided by a quasi-steady barotropic pressure gradient toward the north-northeast. The slope of the sea surface is specified according to its ability to reproduce measurements. Under steady-state conditions, the model reproduces the middepth flow and indicates a vertically integrated resultant transport toward 004° at a rate of 0.097 m\(^3\) s\(^{-1}\).

1. Introduction

The carbonate banks of the Bahamas are extensive shallow water flats bounded by the Straits of Florida, Old Bahama Channel and the western side of the tropical North Atlantic Ocean. Embedded within the Bahamas are two semiclosed seas—Tongue of the Ocean and Exuma Sound. In terms of air-sea interaction, the banks serve as unbounded evaporation pans, generating hyperpycnal water during much of the year as a result of net latent and sensible heat losses. Schmitt et al. (1989) show that, on average, evaporation minus precipitation (E – P) in the vicinity of the Bahamas is approximately 175 cm. Weather data from Lee Stocking Island in the Exuma Cays (Fig. 1) indicate approximately 145 cm of evaporation versus 30 cm of precipitation during the one-year period from July 1990 through June 1991 (Pitts and Smith 1993). Seasonal variations in both evaporation and precipitation alternately increase and decrease E – P over the course of a year. Results of Schmitt et al. (1989) indicate that in winter months E – P increases to a rate of 225–250 cm yr\(^{-1}\), while in summer months E – P decreases to a rate of about 50 cm yr\(^{-1}\). Seasonal cooling, punctuated by occasional cold-air outbreaks (Roberts et al. 1982) increases the generation of hyperpycnal water during winter months.

A question directly related to the formation of high-density water involves the long-term net transport of this water toward either or both of the two semiclosed seas. It is hypothesized that the quasi-steady flux of hyperpycnal water could influence the baroclinic circulation of either the Tongue of the Ocean or Exuma Sound significantly. A study was conducted at a midbank site over a 13-month time period during 1992–1993 to investigate the long-term net movement of water over a part of Great Bahama Bank that lies between the Tongue of the Ocean and Exuma Sound. The purpose of this note is to document the long-term net displacement of water at the study site and to investigate the roles played by tides, wind forcing, and regional barotropic and baroclinic pressure gradients.

2. Data

The database consists of four parts: The first is a 398-day time series of hourly current speeds and directions recorded from 19 March 1992 to 21 April 1993. A General Oceanics Mark II solid state recording current meter was moored 2 m above the bottom in approximately 5 m of water on Great Bahama Bank. The study site (Fig. 1) was approximately halfway between Exuma Sound and Tongue of the Ocean, on a featureless and unvegetated coarse sand bottom. The second part is hourly bottom pressure readings from...
19 March to 17 September 1992, made with a Sea Data TDR-II pressure recorder. The third part is hourly wind observations recorded at a National Oceanic and Atmospheric Administration (NOAA) weather buoy moored at the northern end of Exuma Sound, approximately 85 km north of the study site. The wind record extended from 4 May 1992 to 30 April 1993. Finally, historical salinity data assembled by the U.S. Naval Oceanographic Office (1967) in Tongue of the Ocean and over Great Bahama Bank to the east helped characterize salinity gradients in the vicinity of the study site.

3. Methods

The long-term net flow past the current meter was quantified by the cumulative net displacement. Displacement is defined to be the product of the current component speed and the one-hour time interval that it represents. Net displacement is obtained by defining northward and eastward flow to be positive. By accumulating net displacement along the east–west and north–south axes, one obtains the well-known progressive vector diagram. A progressive vector diagram provides information only on the flow past the study site. In areas of insignificant bottom topographic variation, however, the pattern can be extrapolated in a spatial sense and used to infer regional flow patterns. In general, the resultant flow indicated by a progressive vector diagram should be accompanied by a measure of the persistence of that flow. The persistence of north–south and east–west component motion is quantified by the ratio of the resultant current speed to the mean current speed without regard to direction (Panofsky and Brier 1963).

Tidal components of the current record are obtained from multiple harmonic analyses of 29-day segments of the time series (Dennis and Long 1971), starting on the first of each month. Individual pairs of amplitudes and phase angles have been vector averaged, as suggested by Haurwitz and Cowley (1975), to obtain harmonic constants more representative of the entire time period. In the case of the bottom pressure data, the shorter record permitted eight analyses, with starting times offset by 20 days.

Long-term net transport (in m$^3$ s$^{-1}$) is quantified by the Eulerian transport $E$. According to Robinson (1983),

$$E = \frac{1}{T} \int_{t_0}^{t_0+T} \left[ \frac{1}{H + \eta} \int_{0}^{H+\eta} V(z, t) \, dz \right] \, dt,$$

where the total current $V(z, t)$ has east–west ($u$) and north–south ($v$) components, $T$ is the total study pe-
period, $H$ the mean water depth, and $\eta$ the time varying component of sea level. To investigate local transport as a response to regional forcing, a one-dimensional, five-layer model was used to reproduce the measured middepth flow and to quantify the vertically integrated volume transport at the study site in response to wind forcing, the density field, and the regional slope of the sea surface. Flow in the east–west and north–south directions was solved numerically over 30-second time steps from

$$\frac{\partial u}{\partial t} = -\alpha \frac{\partial p}{\partial x} + fu + \frac{\partial}{\partial z} \left[ K_x \frac{\partial u}{\partial z} \right] - F_x$$  \hspace{1cm} (2)$$

and

$$\frac{\partial v}{\partial t} = -\alpha \frac{\partial p}{\partial y} - fu + \frac{\partial}{\partial z} \left[ K_y \frac{\partial v}{\partial z} \right] - F_y$$  \hspace{1cm} (3)$$

where $\alpha$ is specific volume, $p$ pressure, $f$ the Coriolis parameter, $K$ the vertical eddy viscosity, and $F$ is a friction term that includes wind stress in layer 1 and quadratic bottom friction in layer 5. The model incorporated a parabolic vertical eddy viscosity coefficient (Bowden and Hamilton 1975). A roughness length of 0.2 cm was used to calculate bottom friction (Hathershaw and Langhorne 1988).

In this study, the tidal rise and fall in sea level and the time varying component of the barotropic pressure gradient are the net effect of three semidiurnal ($M_2$, $S_2$, and $N_2$) and three diurnal ($K_1$, $O_1$, and $P_1$) constituents. Tidal predictions (Schureman 1958) were used to simulate both water level and surface slope. Harmonic constants for water level were obtained from measurements (Table 1). The 100-cm mean layer thickness varied by approximately $\pm 10$ cm over each semidiurnal tidal cycle. Periodic variations in surface slope were used to represent barotropic tides moving across Great Bahama Bank. The amplitude, phase, and direction of propagation of each tidal constituent were selected according to how closely the harmonic constants calculated from simulated tidal currents matched those calculated from measurements. The direction of propagation was found to be approximately 80° (78°–82°) for all six tidal constituents. Once tuned, the model reproduced tidal amplitudes to within approximately 0.5 cm s$^{-1}$ and phase angles to within about 2°.

The long-term net transport was quantified by simulations made under steady-state conditions. To characterize wind forcing, buoy data were used to calculate a resultant mean wind stress of 0.422 dyn cm$^{-2}$ directed toward 266°. Wind stress was calculated according to Wu (1979). Baroclinic forcing was quantified in terms of the salinity gradient only; bank water was assumed to be isothermal. Historical data suggest that salinity averages about 36.6–36.8 psu in Tongue of the Ocean and salinity increases to well over 37 psu across Great Bahama Bank toward Exuma Sound throughout the year. In the vicinity of the study site, salinity gradients are on the order of 0.01 km$^{-1}$, and salinity decreases toward the southwest.

With tidal forcing, wind forcing, and baroclinic forcing specified by observations, the net flow simulated at the level of the current meter was two and a half times stronger than, and approximately 60° to the left of the resultant observed flow. The model was then run with a variety of specified barotropic pressure gradients to determine the regional sea level slope that would reproduce the observed quasi-steady middepth flow to the north.

Spectral analysis (Little and Schure 1988) was used to examine the relationship between middepth currents at the study site and wind stress, as estimated from the Exuma Sound buoy data. Both time series were decomposed into north–south and east–west components; wind stress vectors were decomposed into several intermediate components to determine the combination of current and wind direction that was most coherent. All time series were low-pass filtered using a 127-weight Lanczos filter with a half-power point at a period of 37 hours. Results relate winds and currents over timescales in excess of about two days.

### Table 1. Harmonic constants (amplitudes and local phase angles) of the principal tidal constituents at the study site. Amplitudes of the current and bottom pressure measurements are in cm s$^{-1}$ and decibars, respectively. Values are vector averages, as described in text.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>N-S</th>
<th>E-W</th>
<th>N-S</th>
<th>E-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>9.3</td>
<td>23.9</td>
<td>65.0</td>
<td>153.4</td>
</tr>
<tr>
<td>$S_2$</td>
<td>1.6</td>
<td>3.9</td>
<td>122.0</td>
<td>209.6</td>
</tr>
<tr>
<td>$N_2$</td>
<td>2.3</td>
<td>5.9</td>
<td>33.7</td>
<td>119.5</td>
</tr>
<tr>
<td>$K_1$</td>
<td>1.1</td>
<td>2.9</td>
<td>300.2</td>
<td>57.5</td>
</tr>
<tr>
<td>$O_1$</td>
<td>0.8</td>
<td>2.0</td>
<td>277.4</td>
<td>34.1</td>
</tr>
<tr>
<td>$P_1$</td>
<td>0.4</td>
<td>1.0</td>
<td>299.2</td>
<td>57.5</td>
</tr>
</tbody>
</table>

(a) Currents

(b) Pressure

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Table 2. Resultant speeds and directions for winds and currents measured from April 1992 through April 1993. Winds were measured in Exuma Sound, 85 km north-northeast of the study site over Great Bahama Bank.

<table>
<thead>
<tr>
<th>Month</th>
<th>Wind stress</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude (dyn cm⁻²)</td>
<td>Direction (deg)</td>
</tr>
<tr>
<td>Mar 1992</td>
<td>2.58*</td>
<td>000.2*</td>
</tr>
<tr>
<td>Apr</td>
<td>2.33</td>
<td>006.4</td>
</tr>
<tr>
<td>May</td>
<td>0.393b</td>
<td>249.5b</td>
</tr>
<tr>
<td>Jun</td>
<td>0.339</td>
<td>314.5</td>
</tr>
<tr>
<td>Jul</td>
<td>0.468</td>
<td>278.8</td>
</tr>
<tr>
<td>Aug</td>
<td>0.420</td>
<td>289.5</td>
</tr>
<tr>
<td>Sep</td>
<td>0.506</td>
<td>279.3</td>
</tr>
<tr>
<td>Oct</td>
<td>0.426</td>
<td>229.8</td>
</tr>
<tr>
<td>Nov</td>
<td>0.784</td>
<td>258.7</td>
</tr>
<tr>
<td>Dec</td>
<td>0.528</td>
<td>236.7</td>
</tr>
<tr>
<td>Jan 1993</td>
<td>0.610</td>
<td>281.2</td>
</tr>
<tr>
<td>Feb</td>
<td>0.257</td>
<td>246.9</td>
</tr>
<tr>
<td>Mar</td>
<td>0.367</td>
<td>281.8</td>
</tr>
<tr>
<td>Apr</td>
<td>0.354</td>
<td>253.3</td>
</tr>
</tbody>
</table>

* Current observations start: 19 March.
b Wind observations start: 4 May.
c Current observations end: 21 April.

The progressive vector diagram shows nicely the long-term net displacement but it is not well suited for describing temporal variability over timescales on the order of days to weeks. Figure 3 contains (a) the low-pass filtered east–west and (b) north–south current components plotted against time. Nontidal flow along the east–west axis is continually reversing over time.
scales of about a week and shows a subtle, very low-frequency fluctuation. Strongest eastward flow occurs in early May, early September, and again in early February. The north–south component also shows temporal variability over timescales of about a week, but values remain positive most of the time from late spring through late summer. North–south component fluctuations decrease noticeably in magnitude during summer months. The variability of north–south low-frequency motion is just over three times that of east–west low-frequency motion. The standard deviations of low-pass filtered north–south and east–west components are 4.6 and 1.4 cm s⁻¹, respectively.

Spectral analysis (results not shown) does not reveal a close coupling of low-pass filtered middepth currents and wind stress. North–south and east–west current components were paired with a variety of wind stress components. Highest coherence was found at periodicities of 4.5 and 6.5 days when north–south currents were combined with the 030°–210° component of the wind stress; coherence values were 0.4–0.5. It appears that either the winds at the buoy in northern Exuma Sound are not a good representation of winds at the study site or other processes not related to the surface wind field influence currents over these same timescales. A similar analysis involving only the first six months of the study indicates that wind forcing may be relatively more important during summer months. Over timescales of 2–5 days, coherence is 0.7–0.9 but only for north–south wind stress and north–south current components. Phase spectra show the expected phase lead of wind forcing, but the relationship is inconsistent and difficult to characterize. The transfer function in the 2–5-day band is on the order of 10–15 cm s⁻¹ per dyn cm⁻². Energy density spectra indicate that the amplitude of fluctuations in north–south wind stress in the 2–5-day band is on the order of 0.1 dyn cm⁻². Thus, wind forcing explains 20%–30% of the north–south variability appearing in the lower part of Fig. 3 during summer months.

Elliptical tidal rotations, appearing as relatively insignificant features in Fig. 2, dominate the instantaneous flow past the study site. Together with the tidal rise and fall in sea level, tidal currents provide a baseline component of the long-term net transport. Harmonic constants listed in Table 1 show that the M₂ constituent is dominant. The 88° phase lead of north–south flow over east–west flow, combined with the dominance of east–west components, indicates clockwise rotation with the major axis of the tidal ellipse nearly exactly in an east–west orientation. All six tidal constituents show similar, clockwise rotation. For the diurnal constituents, north–south components lead east–west components by about 117°.

Model simulations suggest that the observed long-term transport is the net result of buoyancy and wind forcing, acting more or less together, opposed by tidal forcing in combination with the barotropic pressure gradient. For baroclinic forcing alone, the salinity gradient of 0.01 km⁻¹ along a heading of 225° produces a middepth current of 0.4 cm s⁻¹ along a heading of 309°—the result of a steady baroclinic pressure gradient and a Coriolis deflection. The vertically integrated transport is 0.015 m³ s⁻¹ toward 308°. Westward-directed wind stress of 0.422 dyn cm⁻² with a Coriolis deflection produced a middepth current of 11.2 cm s⁻¹ along a heading of 319°, and a transport of 0.590 m³ s⁻¹ toward 315°. Tidal forcing alone resulted in a middepth current of 0.5 cm s⁻¹ toward 117° and a transport of 0.068 m³ s⁻¹. The time-varying barotropic pressure gradient, combined with a Coriolis deflection, closely approximated the observed tidal ellipses. When the model was run with wind, density, and tide forcing, the middepth flow was 5.2 cm s⁻¹ toward 298°—considerably faster and well to the left of the resultant speed and direction obtained from the current meter data. Only with the addition of a steady barotropic pressure gradient term did simulations match observations. When a regional sea level slope of 7.85 × 10⁻⁴ toward 019° was specified, the steady-state flow was 2.2 cm s⁻¹ along a heading of 002°, and the depth-averaged resultant transport was 0.097 m³ s⁻¹ along a heading of 004°.

5. Discussion

The breakdown of the long-term net transport into its individual components suggests that the observed slow northward flow is a result of nearly opposing forces: a tide-induced residual flow aided by the slope in the sea surface transporting water toward the east-southeast, opposed by a wind-driven and density-driven transport toward the northwest. In view of the approximately east–west orientation of the forcing, one might expect greater variability than observed in the east–west flow, as individual terms weaken and strengthen. The persistence of the east–west wind stress, however, is two orders of magnitude greater than that of the north–south wind stress. Apparently the other transport mechanisms vary little in time as well, at least in an east–west sense. As a result, north–south flow is more variable than east–west flow (Fig. 3).

The southwestward-directed baroclinic pressure gradient inferred from the historical database and, especially the north-northeastward-directed barotropic pressure gradient are, at best, tentative components of this study. No information is available to suggest how appropriate the historical salinity gradient might be to represent the density gradient during the time of the study. No information of any kind is available to justify the selection of a regional surface slope. Because the surface slope is specified according to its ability to reproduce observations, it undoubtedly compensates for errors in the density forcing term and in the wind forcing derived from the buoy data. To the extent that salinity gradients during the study period differed from
the historical mean and insofar as wind conditions differ between the buoy and the study site, the estimate of the surface slope will be contaminated by errors arising from these terms. One can use results of this study to postulate that the barotropic pressure gradient is significant, but a confirmation of the magnitude and direction requires a more thorough study.

It is unlikely that topographic steering is significant over Great Bahama Bank in the vicinity of the study area. In the absence of the highly elliptical east–west tidal oscillations, topographic steering could be a partial explanation for the persistent northward-directed resultant flow, and vice versa. But because these two co-existing features of the circulation are almost exactly perpendicular, topographic steering cannot be used to explain either one. In the absence of topographic steering, results from a single study site are more regionally representative.

The pattern that emerges, based on the progressive vector diagram and the calculations of persistence, is one of quasi-steady south to north nontidal flow with little east–west deviation, but with significant east–west tidal motion dominating the instantaneous flow. The northward-directed nontidal flow is not headed directly toward either Exuma Sound or Tongue of the Ocean, but barring significant deflections in the streamlines downstream of the study site, it appears that Exuma Sound receives the larger share of the high-density water generated in this part of Great Bahama Bank. Unpublished hydrographic data from Lee Stocking Island, 37 km southeast of the study site, has documented hyperpycnal water of as high as 1027 kg m$^{-3}$ leaving Great Bahama Bank on ebb tides between mid-December and mid-April. However, the impact this has on the circulation of Exuma Sound has not been investigated. A documentation of regional-scale circulation patterns, over Great Bahama Bank as well as in the adjacent semienclosed seas, are subjects for follow-up studies.

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REFERENCES


