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INTERNAL TIDES IN THE GULF OF MAINE

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BACKGROUND

The Gulf of Maine and the Bay of Fundy form a basin which is semi-enclosed by the relatively shallow Georges Bank. The Gulf of Maine system is connected to the North Atlantic Ocean mainly through the Northeast Channel and the Great South Channel (Figure 1). The Northeast Channel, with a sill depth of about 230 m, is flanked by the smaller Browns Bank to the northeast and the larger Georges Bank with a nominal depth of 60 m to the southwest. The Great South Channel with a sill depth of about 80 meters separates the southwestern end of Georges Bank from Cape Cod and Nantucket Shoals. The three major basins within the gulf, namely Wilkinson Basin and Jordan Basin, with maximum depths of about 300m, and the 370m deep Georges Basin. The basins are separated by sills with typical depths of about 200 meters.

The geometry of the Gulf of Maine/Bay of Fundy system is the crucial factor in the amplified tidal response of the Gulf system. The characteristic or resonant period of the Gulf system is very near to the frequency of the semidiurnal tide (Garrett, 1972) which is forced by the tides in the North Atlantic. Thus the semidiurnal tidal response of the Gulf is amplified, while the diurnal tidal response is not. The M2 semidiurnal harmonic constituent amplitude in the Gulf is four times greater than the next larges semidiurnal constituent, i.e., N2 (Wright, 1986). The near-standing semidiurnal tidal wave response of the Gulf system ranges from about 40 cm along the seaward edge of Georges Bank to about 15 meters at the head of the Bay of Fundy.

The amplitudes and phases of tidal currents associated with the Gulf surface tide tend to be depth-independent (i.e., barotropic) except in the lowest part of the water column where friction is important. There is considerable lateral spatial structure of barotropic tidal currents because of the complex bathymetry of the Gulf (see Brown, 1984). Throughout much of the interior Gulf, the tidal currents are a relatively week O(10 cm/s). However, in regions of steep bathymetry, such as the north flank of Georges Bank, relatively stronger barotropic tidal currents O(50 cm/s) are oriented across-isobath (Moody et al., 1984). Tidal currents in the Bay of Fundy are even stronger.

Internal or baroclinic tidal currents are generated by the interaction of the barotropic tidal currents and steep bathymetry in the presence of stratification. This interaction generates both a highly nonlinear internal solitary wave once every tidal cycle as well as a more regular internal tidal wave. The internal tidal wave appears to be generated continuously at depth along the north flank of Georges Bank and propagates toward the interior Gulf. Apparently, the internal solitary waves are generated as a lee wave associated with the incoming (i.e., flood) barotropic tidal current over the north flank of Georges Bank (Loder Brickman, 19??). When the flood tidal current begins to ebb, a solitary wave propagates toward the bank. As the solitary wave of isopycnal depression (or elevation) propagates away from a generation region, it can evolve into a packet of multiple depressions (Osborne and Burch, 1980). Internal wave packets also propagate away from Georges Bank (La Violette et al., 199), as seen in the Space Shuttle photographs of the sea surface. These propagating internal wave packets are detected from space by the sea surface texture changes associated with the internal solitary wave surface flow convergence (ripples) and divergence (slicks) patterns (Figure 2; Sawyer, 19??).

Marsden (1986) observed internal tides on the north flank of Georges Bank with moored current meters located at depths of 30, 40, and 75 meters in about 200 m of water (see Figure 3). He found that 98% of the current spectral energy density in the semidiurnal frequency band was contained in the mode in which the across-isobath component was largest. Phase differences in the currents at adjacent levels indicated a downward energy propagation at the mooring site; consistent with the rays pattern emanating from the top of the slope. Horizontal wave length and phase speed were estimated to be 20 to 30 km and 0.40 to 0.70 m/s, respectively

As part of a Gulf-scale UNH study of the Gulf of Maine during 1986-87 (Brown and Irish, 1992, 1993) water property and circulation variability measurements--showing strong semidiurnal tidal influence--were made in Georges Basin. This paper describes those observations and their relation to the known internal tidal generation zone on the Bank. An analysis of the inferred isopycnal displacement time series will be presented. The Garrett and Munk (1972) model adapted for semidiurnal frequencies is used to estimate the internal tidal velocity fields associated with the inferred isopycnal displacement fields.

<u>Observations</u>

During the August 1968 to September 1987 Gulf of Maine study, a series of five "seasonal" hydrographic surveys were conducted. This study focuses on the stratified time period between mid-August and mid-September, 1986. Twenty mid-August CTD casts from Georges Basin (see Figure 1) were averaged to create a basin-averaged density profile (Figure 4). The robust stratification during this time period supported a strong internal tidal signal.

During the 1986-87 study moorings were also deployed in Georges Basin, Wilkinson Basin, Jordan Basin, and the Northeast Channel. This study focuses on the Georges Basin observations which were made at 42° 32.4'N, 67° 15.2'W (Figure 2). Temperature and conductivity sensor pairs on the Georges Basin mooring were located at 50m intervals between a depth of 20 meters down to 270 meters (Figure 3). In addition, there was a bottom pressure/temperature instrument at 323m. The uninterrupted series of hourly measurements of temperature, salinity and bottom pressure (Brown and Irish, 1992) were obtained for the duration of the study. This analysis will focus on the Georges Basin mooring observations between 12 August through 12 September 1986.

Temperature and salinity measurements were used to compute a density time series. The time-averaged density values at the depths of the sensor pairs are shown in Figure 4. The structure of the density profiles--derived from the hydrography and time series --are very similar, indicating that the gross water property structure and hence the stability did not vary much over the time period of interest.

Analysis

The moored density time series were high-pass filtered so as to severely attenuate the variability with periods longer than 36 hours. A set of 17 selected isopycnal displacement time series were derived by way of a linear interpolation between the high-pass filtered density series (see Wallinga and Brown, 2003, for more details). A short segment of a subset of the isopycnal displacement time series (Figure 5) clearly shows correlation at different depth throughout the water column, particularly at semidiurnal frequencies. The statistics of the full suite of isopycnal displacements are presented in Table 1.

Spectral analyses were performed on both sets of isopycnal displacement time series for the summer season.

Energy density and variance preserving spectra (Figure 6) show that about 76% of the isopycnal displacement energy at all depths is in the semidiurnal frequency band (0.0759 - 0.0848 cph). Nonlinearities in the waveform are thought to be responsible for the lesser energy peaks of the higher harmonics. These results show that the semidiurnal frequency internal tide is dominant in Georges Basin. A harmonic analysis was performed on the isopycnal displacement time series.

The dominance of the correlated semidiurnal frequency variability of the water column is reflected in a time-domain empirical orthogonal function (T-EOF) analysis results in a first mode that explains about three fourths (74.8%) of the total variance. The mode-1 T-EOF structure has an amplitude maximum at 188 m depth with minimas at the surface and the bottom (Table 3); consistent with dynamical mode-1 characteristics. The mode-1 T-EOF amplitude time series (Figure 7) is clearly a semidiurnal signal. This mode is highly correlated (0.87) with the local barotropic pressure and lags it by about 0.8 hours.

A harmonic analysis of the isopycnal displacement series (Table 3) shows that about 60% of the total isopycnal displacement variance is explained by M2 internal tidal response. The M2 amplitudes have a maximum at 188 m and phases that are within +/- 15 degrees of a depth constant value of about 90 degrees G. The latter is the first-order structure of a classic dynamical mode-1 internal tide. Still, there is an approximate 30-degree phase increase from the surface to about 144 m depth. This phase structure indicated a slight downward internal wave phase velocity and an upward group or energy propagation velocity in this part of the water column.

The results of a frequency-domain EOF analysis of the isopycnal displacement field are consistent with the above results. Perhaps it is not surprising that the mode-1 amplitude and phase structures (Figure 8; Table 3) are nearly identical to those of the M2 harmonic amplitudes and phases. Mode-1 explains 94% of the variance in the semidiurnal frequency band of interest and 57% of the overall variance (Table 2).

Mode-1 Internal Tides

The horizontal internal tidal currents in Georges Basin were modeled using the vertical displacement observations, the buoyancy frequency profile based on the basin-wide CTD observation (Figure 4) and the approximate depth-averaged phase from the harmonic analysis (101 degrees G). The model first-model semidirunal internal tide has a horizontal wavelength of 59.3 km and a phase speed of 132.5 1.0 cm/s. Given that the distance between the hypothesized generation region on Georges Bank north flank and the Georges Basin mooring is 38.7 km, it would take 8.08 hours (234 degrees phase lag) for a model internal tidal wave to reach the UNH mooring. This implies that the UNH mooring is more than one half (0.65) model internal wavelengths from the assumed generation region.

The free parameter (C1) in the model formulation was set in accordance with the maximum amplitude of the observed vertical displacement. Figure 9 shows the model velocity and displacement amplitude structure based on Georges Basin parameters. The observed maximum amplitude of roughly 14.2 meters was located at a depth of 145 meters. The model amplitude maximum at a depth of 121 meters and was set to the observed maximum value of 14.2 m. The model M2 internal tidal current hodographs in Figure 10 which is roughly (4 cm/s) twice as large as the along-isobath velocity. The kinematics of the model M2 internal tide in Georges Basin (Figure 11) are those of a classic flat bottom ocean mode one internal gravity wave.

Model/Observations Comparison

The maximum in the observed isopycnal displacement depth of about 180 m (145 m?), in contrast to the model maxima at 121 meters. The difference in the two depths was thought to be explained by the non-isotropic internal wave energy transmission associated with the complex bathymetry. To explore this possibility, an energy ray pattern was constructed for the region. The ray trace was calculated such that the ray paths coincided with the observed phase structure at the mooring. This enabled us to trace back the rays to the assumed generation zone. The ray trace pattern (Figure 3) shows that the upward-propagating wave energy would be expected mainly in the depth range of approximately 70 to 220 meters.

Near the bank, our ray pattern is qualitatively inconsistent with that of Marsden (1986). Marsden (1986) showed downward ray orientations at his mooring.

Figures

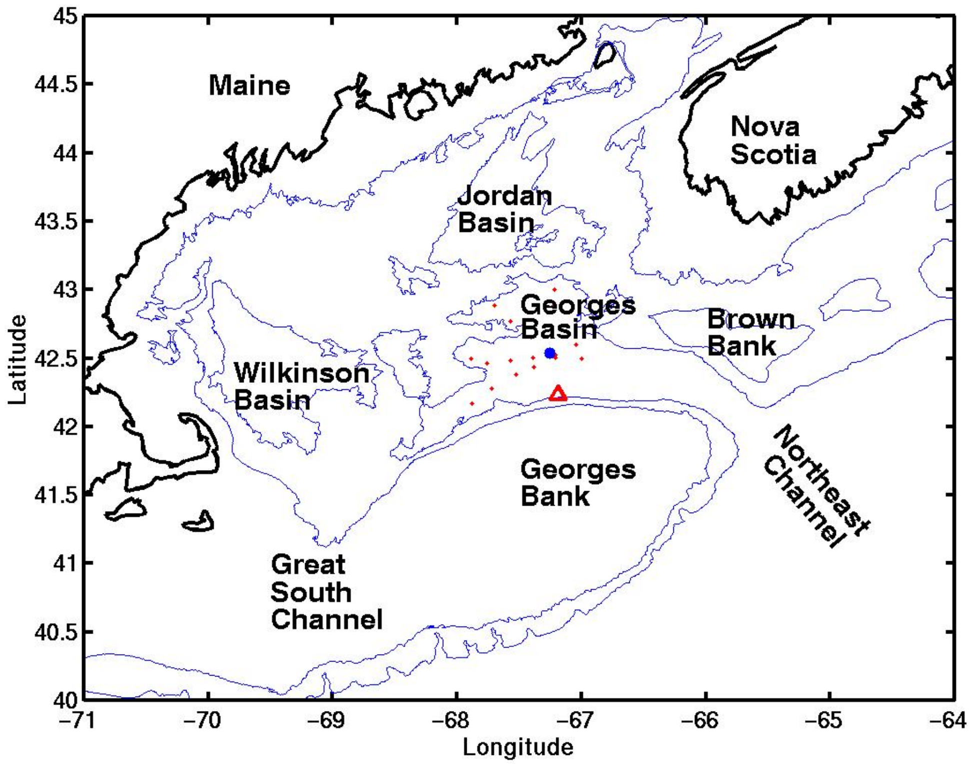

Figure 1. A bathymetric map of the Gulf of Maine. The 200 meter isobaths define the major basins of the Gulf including Georges Basin--the site of observations described here are shown. The UNH mooring site (circle) within Georges Basin and the Marsden (1986) mooring site (triangle) are located. The CTD casts (dots) used to calculate the basin-averaged density profile are also located.

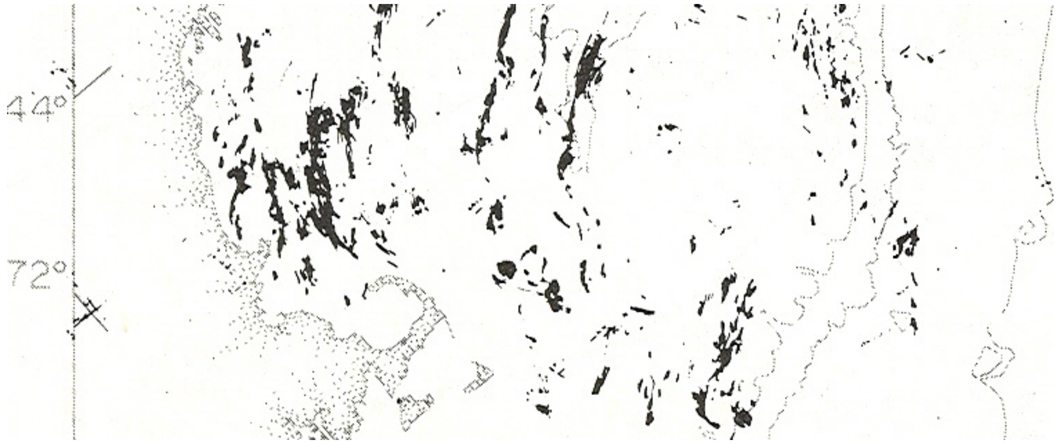

Figure 2. (from Sawyer) Tracings of internal-wave slicks superposed on bathymetric chart. The slicks were detected on images made by the Landsat satellites in the summers of 1972-1974.

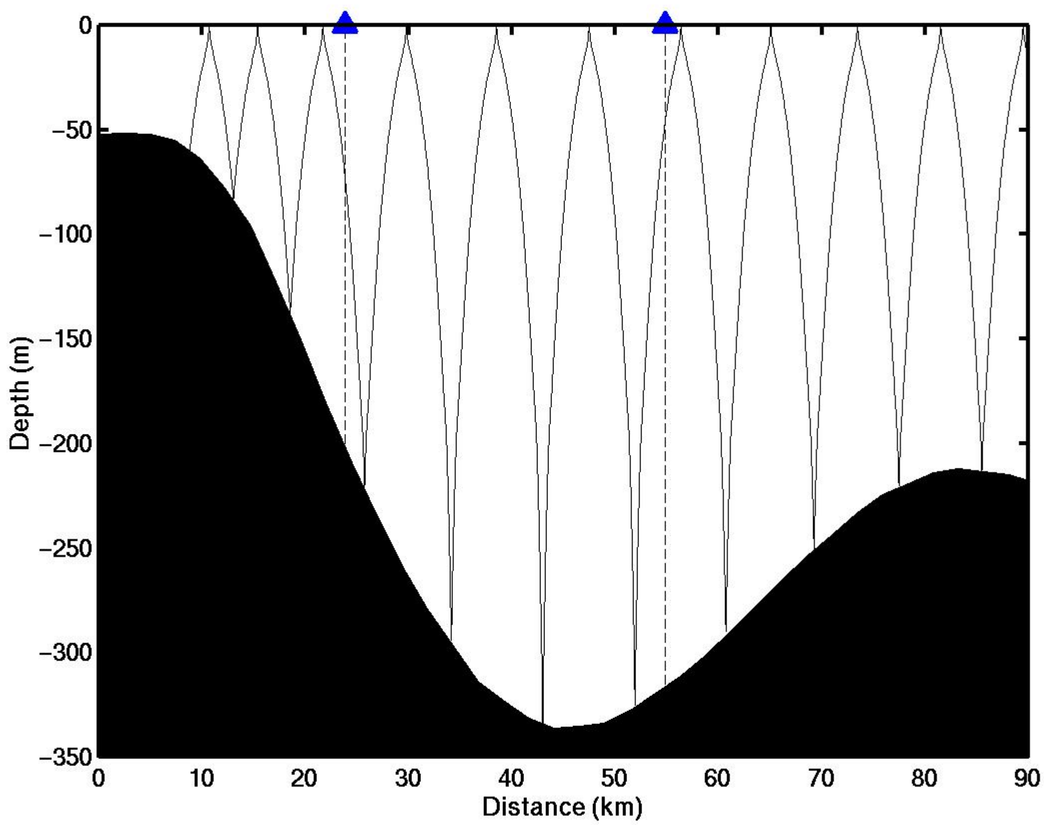

Figure 3. The location of the Marsden (1986) (MS) and the Brown and Irish mooring locations relative to the bathymetry, the depths of the temperature and salinity sensors on the GB mooring are indicated. The rays indicate the pathways of M2 internal tidal wave energy, given the August basin-averaged density profile (see Figure 5).

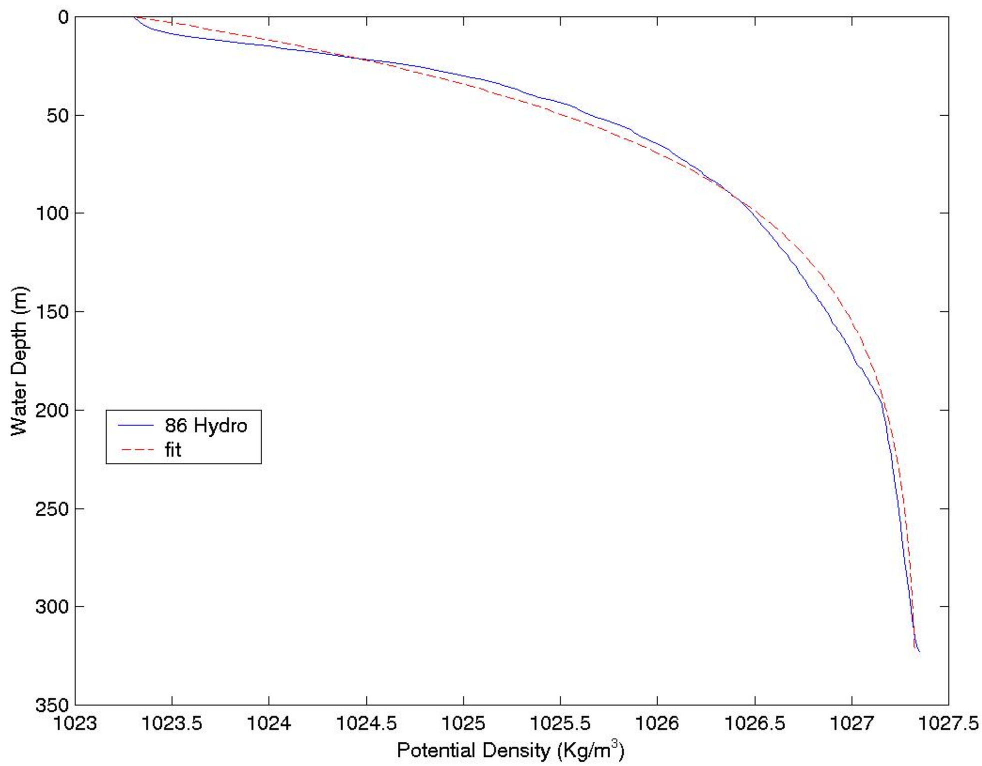

Figure 4. Time- and space-averaged density profiles in Georges Basin during August-September 9186. The dashed line is a spline fit to the averaged moored results. The solid line is the basin-averaged density profile from CTD casts at stations shown in Figure 1.

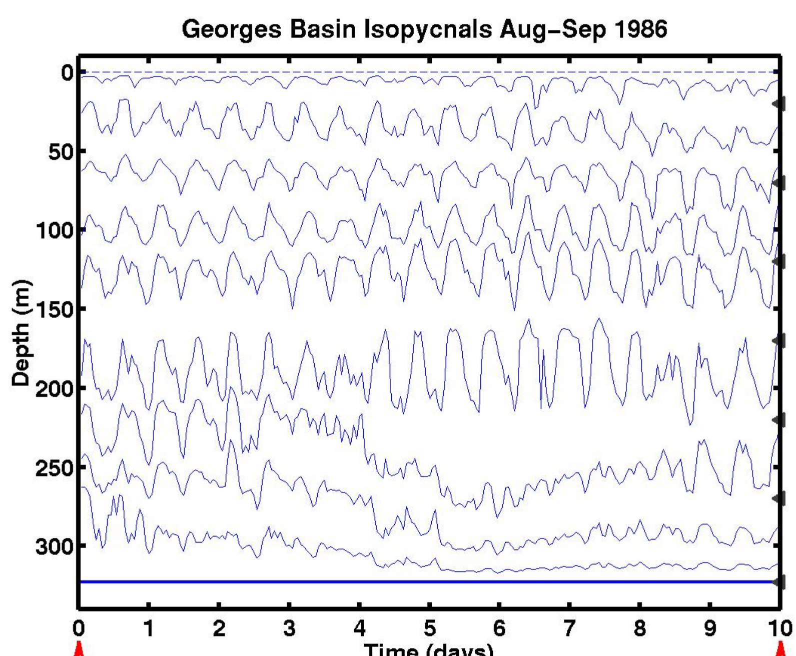

Figure 5. Isopycnal depth time series for a few days in August 1986 (bottom pressure, dashed dot). The depths of the temperature/salinity sensors are indicated by the carets.

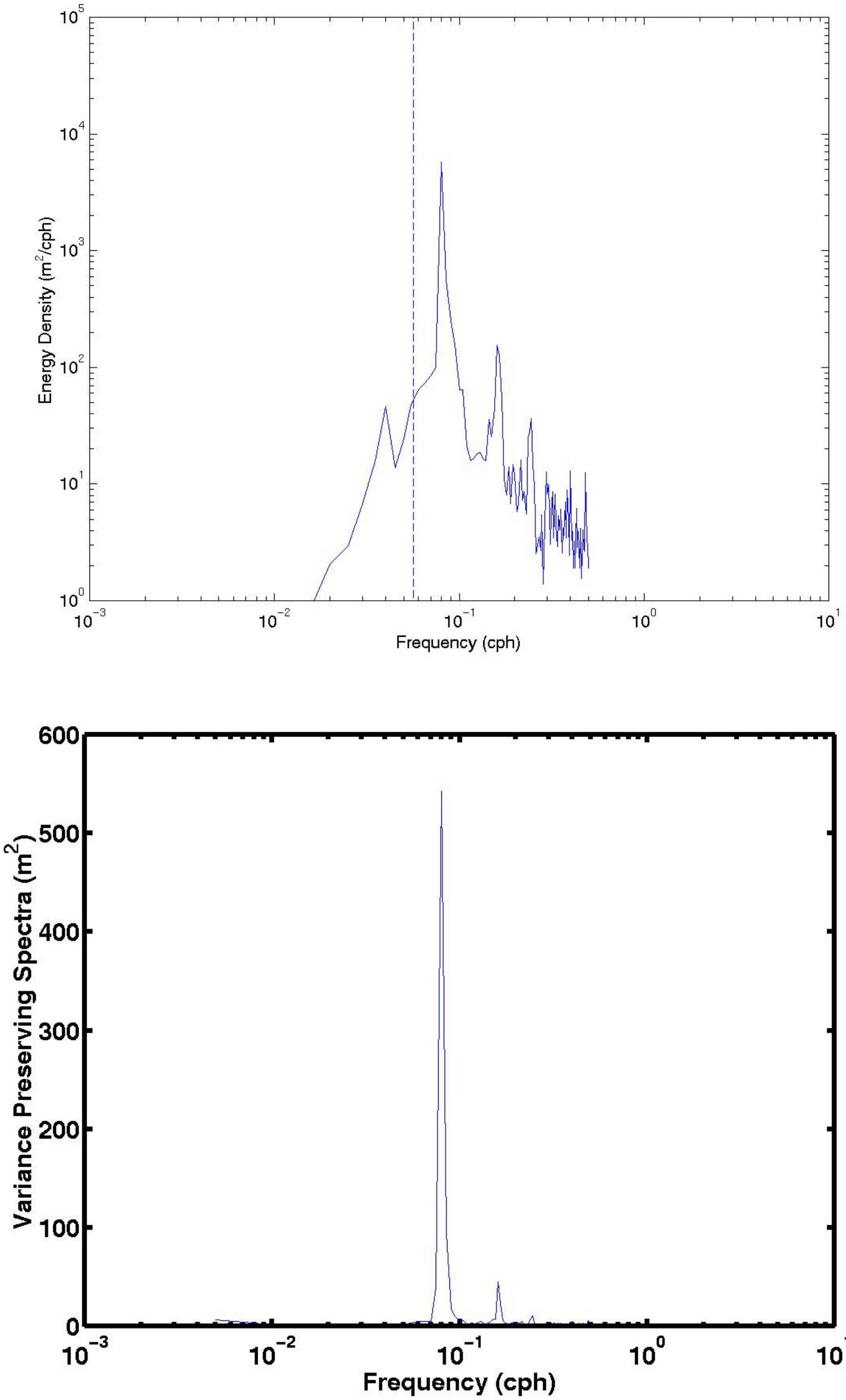

Figure 6. (a) Spectral energy density estimate for the average isopycnal displacement time series (see text). The spike at the semidiurnal frequency suggests the relation between the external and internal tide in the region. (b) The variance-preserving form of the spectra shows that most of the variance is in the semidiurnal frequency band.

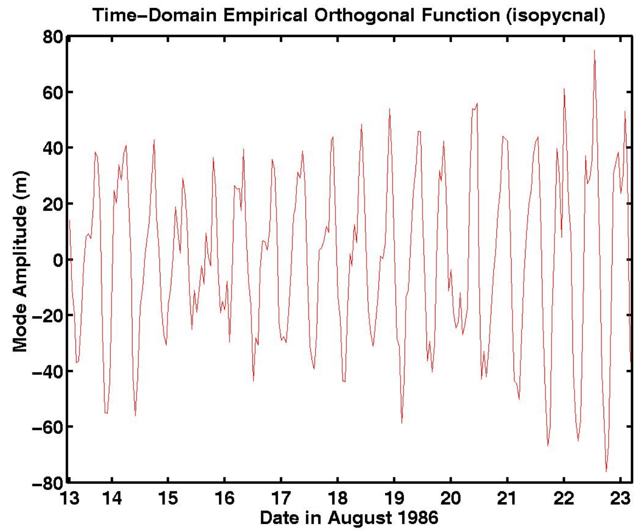

Figure 7. A segment of the mode-1 time-domain empirical orthogonal function (T-EOF) amplitude time series for Georges Basin isopycnal displacements. The dominance of semidiurnal variability is obvious.

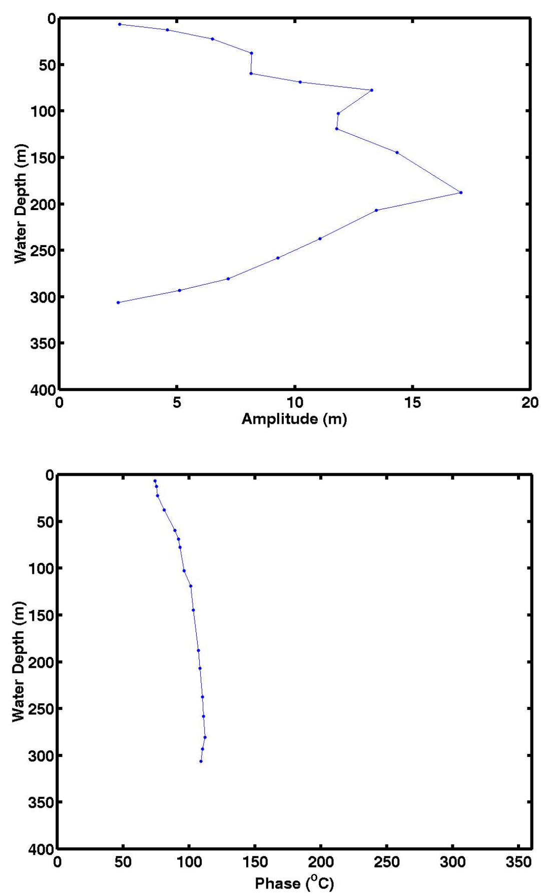

Figure 8. The first-mode empirical orthogonal function (EOF) in the [12 hour]-1 frequency band. The isopycnal displacement equivalent sinusodial amplitude and Greenwich epoch phases are presented. (a) The amplitude structure shows a general mid-depth maxima. (b) The phase structure is very nearly that of a classic mode-1 internal tide. Its depth-averaged phase is 100 degrees G.

Figure 9. The model first-mode M_2 internal tidal wave field in Georges Basin. (a) the horizontal longitudinal (solid) and transverse (dashed) velocity structure; (b) vertical velocity structure; and (c) vertical displacement structure.

Figure 10. Hodograph of the model internal tidal horizontal velocities. Maximum surface velocities are 4 cm/s. The deeper water velocities taper off to order 1 cm/s.

Figure 11. Kinematics of a classic mode-1 M2 internal tidal wave propagating from left (south) to right. Three isopycnals and the corresponding northward currents vectors for one tidal period. The convergence and divergence zones occur at the same time intervals. There is a 180-degree phase shift at the first e-folding depth scale of 121 m.

Figure 12. The first-mode empirical orthogonal function in the [12 hour]-1 frequency band of the residual or non-model isopycnal displacement time series (see text). The first-order phase structure with a 180-degree phase shift at 130 m depth, is that of a dynamical second mode with (a) a mid-depth maxima at the 162 m depth and (b) a downward phase propagation below 130 m.

Table 1. Summary statistics of the selected set of isopycnals at the Georges Basin mooring site.

Depths of Isopycnals

Isopycnal Sigma-t	Mean Depth (m)	Maximum Depth (m)	Minimum Depth (m)	Std. Dev. (m)
23.50	0.0	0.0	0.0	0.0
23.70	6.3	23.2	2.6	2.9
23.90	12.3	27.3	5.2	4.6
24.30	22.3	35.8	10.3	5.9
24.90	37.5	66.2	18.1	7.1
25.70	59.4	94.1	43.1	6.8
26.00	69.0	103.3	52.2	8.8
26.20	77.3	110.3	58.3	11.0
26.60	102.7	135.7	71.9	10.0
26.80	119.0	167.4	95.2	10.6
26.90	144.8	194.1	114.3	12.7
27.20	187.9	227.2	158.7	15.4
27.24	206.8	245.5	165.5	13.3
27.28	237.6	308.3	202.9	11.8
27.30	258.2	311.6	219.2	9.9
27.32	280.3	315.0	252.0	8.3
27.33	293.1	316.7	258.9	6.7
27.34	306.4	318.3	265.3	4.3
27.35	323.0	323.0	323.0	0.0

Table 2. A partition of the isopycnal displacement variance (ζ^2) in Georges Basin. Note that the M_2 semidiurnal internal tide clearly dominates in the period band between 1 and 36 hours. (From a harmonic analysis with a large bandwidth than the rest of the analyses.)

	ζ^2	ζ	%
	(m^2)	(m)	Total ζ^2
Total	1514.303	38.914	100.0
Mode-1 T-EOF	1132.662	33.655	74.5
SEMIDIURNAL BAND*	1049.271	32.390	69.3
M2 TIDES	911.384	30.189	60.2
SEMIDIURNAL BAND	921.661	30.359	60.9
SD Mode-1 T-EOF	866.361	29.43	57.2

Table 3. The structure of the isopycnal displacement series in terms of (a) the M_2 harmonic amplitude and Greenwich epoch; (b) the semidiurnal band mode-1 frequency domain empirical orthogonal function (F-EOF) in terms of sinusoidal equivalent amplitude and Greenwich epoch phase; and (c) the model time domain empirical orthogonal function (T-EOF) in terms of sea.

Isopycnal	Mean	Harmonic Constants		Mode-1 F-EOF		T-EOF	
				Sin. Equ.	Phase	Mode-1	Mode-2
sigma-t	Depth	Amp	Phase	Amp		Amp	Amp
	(m)	(m)	(deg G)	(m)	(deg G)	(m)	23.5
0	-	-	-	-	-	-	-
23.7	6.3	2.79+/-0.15		74+/-3	2.56	74	2.25
23.9	12.3	5.00+/-0.17		75+/-2	4.58	75	4.07
24.3	22.3	7.08+/-0.20		76+/-1	6.51	76	5.91
24.9	37.5	8.74+/-0.30		82+/-2	8.15	81	7.96
25.70	59.4	8.58+/-0.18		91+/-1	8.13	89	8.53
26.00	69.0	10.66+/-0.21		94+/-1	10.22	92	10.95
26.20	77.3	13.84+/-0.24		95+/-1	13.26	93	14.03
26.60	102.7	12.21+|/-0.29		99+/-1	11.85	96	13.10
26.80	119.0	11.76+/-0.34		103+/-1	11.77	101	13.68
26.90	144.8	14.36+/-0.37		104+/-1	14.34	103	16.73
27.20	187.9	17.23+/-0.53		108+/-2	17.06	107	20.36
27.24	206.8	13.14+/-0.72		107+/-3	13.46	108	16.57
27.28	237.6	11.37+/-1.03		107+/-5	11.07	110	13.87
27.30	258.2	9.78+/-0.98		107+/-5	9.28	111	10.99
27.32	280.3	7.62+/-0.78		108+/-5	7.17	112	8.21
27.33	293.1	5.53 +/-0.65		107+/-6	5.11	110	6.07
27.34	306.4	2.83+/-0.42		106+/-8	2.50	109	3.21
BP	323.0	0.816+/-0.001		77+/-0.1			