APÉNDICE D

COASTAL SEICHES, INTERNAL TIDE GENERATION, AND DIAPYCNAL MIXING OFF PUERTO RICO
COASTAL SEICHEs, INTERNAL TIDE GENERATION, AND DIAPYCNAL MIXING OFF PUERTO RICO

Edwin Alfonso a,*, Jorge Capella a, Julio M. Morell a, José M. López a, Jorge E Corredor a, Ángel Dieppa a and Marvi Teixeira b

a Department of Marine Sciences, University of Puerto Rico, Mayagüez 00681, Puerto Rico.
bElectrical Engineering Department, Polytechnic University of Puerto Rico, Hato Rey, Puerto Rico.

Abstract

High vertical diffusivity values, $\kappa_d > 6 \times 10^{-3}$ m$^2$ s$^{-1}$, were measured between SEP-DEC 1997 and MAY-OCT 2000 in oceanic waters of the Mona Passage. These elevated diffusivities are associated with the presence of locally generated internal waves of semidiurnal frequency, with a reduction of the Richardson number at the base of the pycnocline, and with increased seiching activity over the southwest coast of Puerto Rico. The patterns of activity are strictly correlated with the lunar cycle and with changes in the stratification of the Caribbean Surface Water (CSW). Increases in the stratification of the water column are due to the influence of the Amazon and Orinoco Rivers. The development of a shallow pycnocline (thin mixed layer) increases the Brunt-Väisälä frequency and reduces the tidal beam slope. Under the proper astronomical forcing and vertical stratification conditions energy from the barotropic tide at or near the shelf break is transferred offshore towards the generation of internal tides and shoreward into the platform waters consequently increasing the coastal seiche activity. This work links a remote continental process such as the discharge of the Orinoco River to a coastal dynamic process in the northeastern Caribbean, such as the coastal seiches.

Keywords: Eddy diffusivity; Internal waves; Internal tides; Seiches; Solitons; CaTS; Caribbean Sea; Orinoco River; Puerto Rico; Mona Passage.

* Corresponding author. Tel.: + 1-787-832-4040, Ext. 3838; fax: + 1-787-265-5408.
E-mail addresses: ealfonso@rmocfis.uprm.edu (E. Alfonso), jcapella@rmocfis.uprm.edu (J. Capella), oceano@coqui.net (J. Morell), jo_lopez@rumac.uprm.edu (J. M. López), quimoceia@caribe.net (J. Corredor), adieppa@rmocfis.uprm.edu (A. Dieppa) and mteixeir@caribe.net (M. Teixeira).
Introduction

Internal waves of semidiurnal period, also known as the internal tide or baroclinic tide, are present in all oceans, including the Caribbean Sea (Roberts, 1975; Morozov, 1995; Giese, 1993; Giese et al., 1990). The internal tide is generated by the interaction of the barotropic tide (surface tide) with submarine topography. Barotropic tidal currents deflected by the submarine slopes cause a vertical displacement of the density interface that later is propagated along the interface.

The strength of the internal tide is a function of topographic conditions. A considerable vertical displacement of the stratified waters is required for the generation of the internal tide when the surface tide impinges on the submarine topography. For symmetric submarine mountains (Gaussian shaped), the internal tide is small because barotropic flow goes around it. In contrast, when the barotropic tide goes over a ridge, the barotropic flow is forced to cross the isobaths and generates an energetic internal tide (Holloway and Merrifield, 1999). Other important aspects are how closely aligned is the slope of the tidal beam ray relative to the topographic slope (Prinsenberg and Rattray, 1975; Prinsenberg et al., 1974; Baines, 1982), and the incidence angle of the barotropic tide (Guizien and Barthélémy, 1999).

The Caribbean Island Arc in the Atlantic and the Hawaiian Ridge in the Pacific are both ideal physical settings for the generation of internal waves (Morell et al., 1995; Bejarano, 1997; Giese et al., 1990; Neale, 1995). Passages between islands, submarine ridges, sudden changes in bottom depth and complex bathymetry normal to the barotropic flow characterize the offshore island chains. The HOME project (Hawaii Ocean Mixing Experiments) in the Hawaiian Archipelago is currently pursuing this line of research (Müller and Briscoe, 2000). The internal wave/internal tide field in the Eastern Caribbean is only known from sparse local observations and a coherent picture of the various generation foci is lacking. López
et al. (1981), Fornshell and Capella (1987); Neale (1995); and Bejarano (1997) have described the passage of internal waves through the Caribbean Sea. Morell et al., (1995) describes their impact over fish abundance, Sander (1981) looks at their potential as source of nutrient enrichment around the Caribbean Islands, while Giese et al. (1982); Giese (1983); Giese et al. (1990); and Teixeira (1999) focus on coastal seiche dynamics.

High frequency internal waves and solitary internal waves (~200m length) have been detected in the Southern Caribbean from airborne observations (Apel et al., 1975; Neale, 1995). Profiles of temperature, salinity and dissolved oxygen from waters south of Puerto Rico show a persistent internal wave field. Diurnal and semi-diurnal oscillations with amplitudes ranging between 10-100 m have been often observed through the use of BT/XBT and Hydro/CTD profiles and thermistor chain data (López et al., 1981; Fornshell and Capella, 1987).

During the late 1970’s Graham Giese found for the first time a direct relationship between coastal seiches and the astronomical tide using the water level record from Guanica Harbor, located on the southwest coast of Puerto Rico. Coastal seiches at Magueyes Island and Guanica Harbor with cause nearshore waters to rise and fall with a periodicity of 50 minutes and 45 minutes, respectively (Giese et al., 1990; Teixeira, 1999). Interest in this subject arose when based upon Palawan Island studies Giese (1983) suggested a strong tide impinging over the Aves Ridge as the probable generation mechanism for solitons arriving at the south coast of Puerto Rico. Giese et al. (1982) and Giese et al. (1990) further investigated the internal tide – soliton – coastal seiche relationship in the northeaster Caribbean.

A cause-effect relationship between coastal seiches and internal waves has been established for the Sulu Sea (Giese and Hollander, 1987; Giese et al., 1982) but the evidence is still inconclusive for the Puerto Rico seiches. Recent studies point to a local seiche generation mechanism (Teixeira and Capella, 2000). Seiche activity increases every 14 days and maximum activity occurs 6 to 7 days after syzygy (Giese et al., 1990; Giese et al., 1982; Teixeira, 1999). Teixeira and Capella (2000)
argue that increments in activity correspond to the lunar phase, lunar declination and lunar perigee cycles. Large internal tidal bores (breaking internal tidal waves) off the west coast of the United States generate nearshore upwelling at specific days in the lunar cycle (Pineda, 1995). These events produce surface temperature anomalies near moon quarters. It is striking the similitude with the seiches cycle reported by Giese et al. (1990) and Texeira and Capella (2000). Seiches and nearshore upwelling are both related to high internal tide activity and favorable astronomical conditions. This work could help to better understand the link between oceanic internal wave activity and coastal physical phenomena.

CTD profiles from the northern Mona Passage in a region locally known as El Pichincho (escarpment rising to a depth of 250 meters) revealed 45 meter oscillations in the isopycnal surface corresponding to $\sigma_t = 24$ kg m$^{-3}$ (Bejarano, 1997). This area is recognized as a region of high biological activity (Morell et al., 1995). Bejarano (1997) describes the wave as semidiurnal with a wavelength of 40 kilometers, the phase velocity was 0.89 m s$^{-1}$ and maximum speeds of 64 cm s$^{-1}$ and 23 cm s$^{-1}$, over and under the thermocline, respectively. Surface stress associated with the internal wave currents can modify the spectrum of the short waves generated by the wind and cause distinctive surface roughness patterns (Alpers, 1985) visible to remote sensors in the space. The changes in roughness cause Bragg scattering of microwave signals allowing an active sensor such as SAR (Synthetic Aperture Radar) to easily detect them. But visual photography of internal waves is possible from space if the satellite is located at position that sun glint can reveal their presence. Photos of Mona Passage taken by an astronaut (space shuttle mission STS-7, June 21 1983) shows the surface tracks associated with internal waves (Figure D. 1).

A strong correspondence between internal waves and vertical turbulent eddy diffusion has been established in previous studies. High values of the coefficient of vertical eddy diffusion and small local gradient Richardson numbers are associated with the generation and breaking of internal waves near the shelf break (Müller and
Briscoe, 1999; Müller and Briscoe, 2000). High diapycnal diffusivities ($\kappa_p$) have been observed along a turbulence band centered in the baroclinic energy beam ray coming from the shelf break (Lien and Gregg, 2001). The authors argue that the internal band had a width of 50 m and was formed by the breaking of internal waves in the shelf break. This mechanism has been proposed as the explanation for the apparent discrepancy between the observed vertical structure of the world oceans and measured values of vertical diffusivity (Müller and Briscoe, 2000).

In this paper we present evidence of a cause-effect relationship between turbulent vertical eddy diffusion, coastal seiches and internal tide generation off the south coast of Puerto Rico. Using CTD profiles and ADCP and tide data we obtained simultaneous measurements of the coefficient of vertical eddy diffusivity in offshore waters and of coastal seiche energy. These observations suggest a direct link between events of high vertical diffusivities in the Mona Passage and strong coastal seiching in the southwest of Puerto Rico. Also we provide evidence that this link is found in the local generation of internal waves along the insular slope. These processes are strongly modulated by astronomical conditions and by the degree of stratification of the offshore waters. A very particular scenario that distinguishes the northeastern Caribbean from the Hawaiian Ridge occurs from the modulation of local stratification, and of internal tide generation, off the south coast of Puerto Rico by a remote mesoscale phenomenon such as the discharge of the Orinoco River into the Caribbean Sea.

1. **Study Site**

This work is based upon data collected in Mona Passage and in oceanic waters off southwest Puerto Rico. Station **ADCP1** (*Acoustic Doppler Current Profiler 1*) was located about 10 nautical miles to the NNE of Mona Island (18° 17.478’ N, 67° 48.155’ W) in oceanic waters with a depth of 481 meters. The station is located in the central axis of the Mona Passage (Figure D. 2), in an area of low bottom relief. An RD Instruments 75 kH acoustic Doppler current meter was
deployed for four and a half months at this location. The station is located about six nautical miles to the SW of EL Pichincho (source of internal waves) and 32 nautical miles to the west of station InWaPE. Mona Passage allows the exchange of water masses between the Atlantic and the Caribbean. Vertical profiles of low frequency meridional transport show a two-layer baroclinic structure (Segura, 2000). The upper layer reaches a depth of 300 meters and consists of the following water masses: Caribbean Surface Water, Subtropical Underwater and the Sargasso Sea Water. These water masses generally cross the Mona Passage from the Atlantic Ocean to the Caribbean Sea. The lower layer consists of the upper reaches of the Tropical Atlantic Central Water moving from south to north across the Mona Passage. In Mona Passage the semidiurnal component (M2) of the barotropic tide propagates from north to south (Kjërve 1982) around an amphidromic system centered south of the island of St. Croix. The M2 component current ellipses in the Mona Passage showed anti-clockwise rotation and the principal axes are aligned along the channel axis (Rosario, 2000).

**InWaPE** (Internal Wave Productivity Estimates) station is located 2.4 nautical miles to the southwest of Punta Cadena (18° 16.6’ N, 67° 16.0’ W), in offshore waters with an estimated depth of 223 fathoms (401.4 m). The station is less than ¼ mile from the shelf break at a location where internal wave signatures have been observed from space (Figure D. 1). Spectra of current measurements of the shelf waters near InWaPE revealed coastal seiches with periods near 20 and 31 minutes (Alfonso, 1995).

**CaTS** (*Caribbean Time Series*) serial station is located in the north Caribbean Sea 22 nautical miles from the SW coast of Puerto Rico (17° 36.00’ N, 67° 00.00’ W), at a depth of 2880 m. Monthly measurements of biological, chemical, physical and bio-optical parameters have been conducted since 1995 while older occupations extend back to the early ‘70s. The station can be impacted by mesoscale phenomena such as eddies and by the discharge of the Orinoco River (Corredor and Morell, 2001). Internal waves with amplitudes of 20 m have been
detected at this location. The halocline oscillates throughout the year between 11 meters in the fall down to 106 meters in the spring (Corredor and Morell, 2001).

Water level records are from an Official NOAA tide station located at Magueyes Island. Station reference number is 9759110 (Latitude: 17° 58.3' N Longitude: 67° 2.8' W).
2. Methodology

An RD Instruments 75kHz Acoustic Doppler Current Profiler (ADCP) current meter was deployed four and a half months (May 24 - October 11, 2000) at station ADCP1. A total of 5035 records at 40 minutes intervals were taken with a 10 meter vertical bin resolution between 44 meters down to 444 meters. Measurements shallower than 44 meters were discarded due to contamination with the surface signal. At the beginning and end of the deployment CTD and XBT profiles were completed. The last 36 records of the ADCP (October 10, 2000) were simultaneous with a CTD-XBT cast time series. An SBE19 CTD was lowered down to 200 meters every hour for 12 hours and XBTs were launched between casts. Contours of temperature and density (sigma-t) were generated from these data. Another ADCP data set from a previous deployment (September 3- December 3 1997) for which concurrent CTD profiles were available was also used in our study. These measurements were made at a shorter time interval (dt=20 min) but preserved the 10-meter vertical resolution. The ADCP configuration is detailed below (Table D.1).

Current measurements were expressed as horizontal components U and V, which is naturally, aligned perpendicular and parallel to the principal axis of Mona Passage. From the ADCP and CTD data we calculated the velocity shear squared, \( S^2 = (\partial U/\partial z)^2 + (\partial V/\partial z)^2 \), the buoyancy frequency squared, \( N^2 = -(g/\rho_0)(\partial \rho /\partial z) \), and the local gradient Richardson number \( R_i = N^2 / S^2 \). CTD data allow us to calculate the Brunt-Väisälä frequency profile down to 144 meters. Vertical diffusivities were parameterized in terms of the Richardson number using the equations and parameters for tropical waters reported by Pacanowsky and Philander (1981).

The NOAA primary water level sensor is an air acoustic measurement device that registers water level every 6-minute with an accuracy of 3.05 mm. Water level data is continuously processed by NOAA and can be downloaded from \texttt{http://co-ops.nos.noaa.gov/}. Only water level data concurrent with the ADCP deployment
periods were processed. A digital band pass filter centered at 1.2 CPH was applied to isolate the 50-minute coastal seiche signal. A spectrogram was applied to the filtered data to show the distribution of the seiche energy during the sampling period.

3. Results and Discussion

Vertical mixing by shear instabilities occurs locally when the shear is larger than the stabilizing effect of the buoyancy gradient. Tendency for development of shear instability can be expressed in terms of the local gradient Richardson Number, \( \text{Ri}_G \).

\[
\text{Ri}_G = \frac{N^2}{gS^2} = \frac{N^2}{\left( \frac{\partial U}{\partial Z} \right)^2 + \left( \frac{\partial V}{\partial Z} \right)^2}
\]

where \( U \) and \( V \) are the components of horizontal velocity perpendicular and parallel to the central axis of Mona Passage, respectively. \( N \) is the buoyancy frequency or Brunt-Väisälä frequency. For small values of the Richardson number vertical mixing is enhanced. A small Richardson number occurs when the value of the Brunt-Väisälä frequency is small or for high values of vertical velocity shear. For Richardson numbers, \( \text{Ri} \), smaller than the critical value of \( \frac{1}{4} \), a stable stratified flow can become unstable by any small perturbation resulting in the development of Kelvin-Helmholtz instabilities (Thorpe, 1971; Thorpe, 1973). Internal waves can increase the vertical shear and reduce the Richardson number below the typical oceanic values (0.4-1.0) and below the critical value of \( \frac{1}{4} \) (New, 1988; New and Pingree, 1990).
The time evolution of the $Ri$ field at ADCP1, to a depth of 150 m, is presented in Figure D. 3. Even though values of the Richardson number smaller than $\frac{1}{4}$ are observed throughout the monitoring period, these become more common in August and October. At the end of September and during the first week of October the values are critical ($Ri < \frac{1}{4}$) at all depths.

The vertical eddy coefficient ($\zeta_d$) can be parameterized in terms of the Richardson number (Pacanowsky and Philander, 1981) by

$$v = \frac{v_0}{(1 + \alpha Ri)^n} + v_b$$

$$\kappa_d = \frac{v}{(1 + \alpha Ri)} + \kappa_b$$

where $\kappa$, is the eddy viscosity and $\kappa_b$ and $\kappa_b$ are the background values. For tropical waters Pacanowsky and Philander (1981) applied the following values: $n=2$, $\alpha=5$, $\kappa_0=100$ cm$^2$ s$^{-1}$, $\kappa_b=1.0$ cm$^2$ s$^{-1}$ and $\kappa_b=0.1$ cm$^2$ s$^{-1}$. Using these parameters and the values of $Ri$ shown on figure 3 we estimated the vertical eddy coefficients for the water column in Mona Passage between May and October 2000 (Figure D. 4). The computed coefficients ranged between $30 \times 10^{-4}$ and $50 \times 10^{-4}$ m$^2$s$^{-1}$. This last value is inside the range of high values observed for the seasonal thermocline (Peters et al., 1988). Recently, Morel et al. (2001) reported high vertical diffusivities up to $27 \times 10^{-3}$ m$^2$s$^{-1}$ (a mean of $5.3 \times 10^{-4}$) at several offshore locations around PR utilizing different data sources and a different parameterization for $\zeta_d$. These high vertical diffusivities suggest that intense vertical mixing occurs in the waters around Puerto Rico, including the Mona Passage. Between the last week of September and first two weeks of October the vertical eddy diffusivity is above $60 \times 10^{-4}$ m$^2$s$^{-1}$.

We visited station InWaPE and ADCP1, September 22 and October 10 2000, respectively and found a strong internal tide signal at both sites (Figure D. 5 and Figure D. 6). In ADCP1 the isopycnals form a sinusoidal pattern with peak to
valley heights of 25 m. Since on October 10 the vertical diffusivities ($\kappa_d$) reached values of $35 \times 10^{-4}$ m$^2$s$^{-1}$, we can assume that the internal wave field was a typical one on that date. A few days’ earlier values of over $70 \times 10^{-4}$ m$^2$s$^{-1}$ were observed which leads us to speculate that the internal wave activity was higher during that period. The relationship between elevated vertical diffusivities and internal tides has been extensively reported in the literature (Stigebrandt, 1979; Stigebrandt, 1999; New, 1988; New and Pingee, 1990; Gregg et al., 1999; Alford and Pinkel, 1999). Müller and Briscoe (1999, 2000) discuss the global impact of high vertical diffusivity values (low Richardson numbers) resulting from the generation and breaking of internal waves in the margin of islands or continents, a process often referred to as mixing along oceanic boundaries.

We visited station InWaPE on the first day of increased vertical mixing and found an internal tide with a maximum height of 25 m. In contrast to the ADCP1 observations, the temperature contours showed a square, rather than sinusoidal, waveform. The change in shape corresponds to its short distance from the shelf break, less than 0.5 km. Holloway et al. (1999) report on a similar internal waveform in waters of the Australian North West Shelf.

Figure D. 7 shows the correspondence between high vertical mixing in the Mona Passage and extreme coastal seiche activity on the southwestern PR shelf. Beginning in August and until the first week of October the more energetic seiches correspond in time to high values of the coefficient of vertical eddy diffusivity in the water column. The simultaneous occurrence of enhanced vertical mixing, of the internal tide, and of energetic seiches suggests a common denominator for these processes.

A strong barotropic current re-directed by the submarine slope can apply a strong push to the isopycnals and generate internal waves of larger amplitude. These large amplitude baroclinic waves increase the vertical shear, reduce the Richardson number over the critical value of $\frac{1}{4}$, and increase the vertical eddy diffusivity. In other words, barotropic energy is transformed into baroclinic internal
wave modes and is dissipated as turbulence. Our observations point to extreme seiche activity during specific astronomical conditions so the barotropic tide must be involved in the excitation of these oscillations. Being the normal mode of response of coastal waters seiches will feed on many types of forcing energy. Whether extreme coastal seiches on the southwestern PR shelf are excited directly by the barotropic tide, by the same mechanism involved in the generation of internal tides, or due to the arrival of internal waves at the shelf break is not clear.

Giese (Giese et al., 1982) first observed that extreme seiches occur over the southwestern PR shelf six days after the coincidence of syzygy and lunar perigee. This observation links maxima in the gravitational pull of shelf waters to the seiche excitation mechanism. Extending this idea we would expect that more energy to be available for seiche activity during the overlap of the following astronomical conditions: Syzygy, perigee, 18° lunar declination (Moon just over our zenith), perihelion and near equinoxes. We have defined a relative index of tidal force as a function of the overlap of all this events. This tidal force index (TDI) is defined it as:

$$ TDI = \frac{\left(FL + PL + DL\right) + \frac{1}{2.5} (PS + DS)}{3.8} $$

such that

$$ 0 < FL < 1 \quad 0 < PL < 1 \quad 0 < DL < 1 \quad 0 < PS < 1 \quad 0 < DS < 1 $$

where FL is the Lunar Phase, PL is the lunar perigee, DL is the lunar declination, PS represents the perihelion and DS is the solar declination. Each index goes from 0 (not favorable) to 1 (most favorable). For example, during perigee the value of PL equals 1 and during apogee the value of PL equals 0. The Sun’s indexes (PS and DS) are normalized by 2.5 as the tidal force exerted by the Sun is 2.5 times weaker than the Moon’s tidal force. All indexes are normalized by the maximum value of
their sum, 3.8. The final index $I$, is a relative index of the astronomical factors that result in greater tidal forces.

Figure D. 8 shows the tidal force index (TDI) oscillating with a fortnightly period that is modulated by lower frequency components. When TDI remained above a threshold value of 0.7 over a full fortnightly cycle the column average diffusivity reached over $70 \times 10^{-4} \text{ m}^2\text{s}^{-1}$ and the seiche activity was extreme and lasting. The TDI may be higher during any particular day but it is the local fortnightly minimum which must exceed the threshold criterion. So, an elevated low-range in the tidal force index sometimes results in the enhanced transfer of energy from the barotropic tide to coastal seiches and to the offshore internal tide field. However a high value of the index is necessary but not sufficient to explain the increases in vertical diffusivity, the local bathymetric slope and open-ocean stratification conditions must also be considered.

Figure D. 9 (top) shows periods during which large eddy diffusivities were calculated below a depth of 100 meters and that do not correspond to stronger seiche activity. We can see more energy in the seiche only if higher diffusivities occur above a depth of 80 meters. Figure D. 9 (bottom) shows the column-averaged diffusivities and now the significant peaks do coincide with seiche energy. Figure D. 10 provides a closer look at the events of enhanced seiche activity and intense mixing. During 1997 the eddy diffusivity peaks and the peaks of seiche energy coincided while during the same period of the year in 2000 we observed an elevated plateau in the diffusivites between the two peaks of seiche activity in September and October. Previous work in the Norwegian fjords by Stigebrandt (1976; 1979; 1999) has established a direct relationship between increases in baroclinic wave drag and the damping of seiches. Taking the same approach as these previous works we can interpret Figure D. 10b as follows: during the right astronomical forcing and stratification conditions energy from a common source either feeds coastal seiche activity or is dissipated as turbulence, therefore resulting in the inverse seiche-turbulence relationship shown in this figure. An initial increase in seiche activity is
followed several days later by 7-8 days of enhanced turbulent mixing, and a final seiching event.

Changes in the offshore stratification of the top 150 meters are the key to explaining why both the seiche and vertical mixing increase markedly between the end of August and first weeks of November. Giese et al. (1982), Giese et al. (1990), and Teixeira (1999) have reported increases in seiche activity on the south coast of Puerto Rico between September and November. Giese et al. (1990) and Gordon (1967) suggested that the depth of the mixed layer and/or the inclination of the Sea surface due to Ekman transport caused by westward wind stress are capable of seasonally modulating seiche activity. Brunt-Väisälä time series contours from the CaTS station reveal pronounced seasonal changes in the magnitude and in the vertical structure of the stratification (Figure D.11). This marked seasonality reflects the influence of the discharge of the Orinoco and Amazon Rivers and the variability in the wind regime near Puerto Rico. The influence of the Orinoco River over the waters of the Northeast Caribbean peaks between September and November (Corredor and Morell, 2001) and the stratification is stronger. High B-V values in April and May could be associated to the influence of old Amazon River water lenses that enter the Caribbean Sea from the Tropical Atlantic (Muller-Karger and Varela, 1990). These Amazon waters were dispersed to the east in the previous semester by the retroflection of the North Brazil Current (NBC) and now return west due to a stronger North Equatorial Current (NEC).

Under the influence of low-salinity, warm, waters and of weaker winds the mixed layer depth (MLD) south of Puerto Rico reaches its yearly minimum of ca. 30 meters in the fall. During this time of the year the MLD lies at approximately the same depth as the southern and western PR shelf break thus allowing the shallow pycnocline to act as a waveguide for internal waves generated in the Island margins. The shelf break is located at a depth of around 30 m and internal waves generated over it can propagate along the shallow pycnocline. The mechanisms that have been proposed for the generation of internal waves over abrupt topography (Prinsenberg
1974,1975; Baines, 1986) exhibit a certain degree of symmetry in the cross-slope direction so a certain amount of the radiated energy is expected to travel towards the insular shelf where it can feed the large-amplitude coastal seiches. The “favorable” stratification window is rather short as the shallow MLD may soon be destroyed by tropical cyclones. As winter approaches we observe a decrease in ML temperature an increase in salinity, stronger wind stress and the arrival of large northern swell, all of which contribute to a deepening of the MLD. In February and March the mixed layer is deeper in the Eastern Caribbean reaching depths of around 90 meters in the vicinity of PR (Corredor and Morell, 2001; Hernandez, 1999).

Morozov (1995), Muller and Bricoe (1999, 2000), and others have investigated the relationship between bottom slope, and the generation of internal tides from the barotropic tide. It is now widely recognized that this latitude-dependent process occurs worldwide and regional, as well as global, estimates of barotropic to baroclinic energy conversion have been produced. Because Puerto Rico is located in a relatively low latitude (18°N), small bathymetric slopes are conducive to the generation of the internal tide.

The slope of the tidal beam (the path along which the internal tide energy propagates) relative to the slope of topography is a critical parameter for the generation of the internal tide with most efficient generation resulting for near critical slopes (where characteristics are parallel to the topography). The equation for the characteristics is,

$$\frac{dz}{dx} = \pm \left( \frac{\sigma^2 - f^2}{N^2(z) - \sigma^2} \right)^{1/2}$$

(4)

where N is the Brunt-Väisälä frequency, \( \sigma \) is the frequency of the wave and \( f \) is the Coriolis parameter. For our latitude (18°N) and semidiurnal internal waves (T=12.4 h), \( \sigma \) and \( f \) have the following values 1.405 x 10^{-4} \text{ Rad s}^{-1} and 4.505 x 10^{-5} \text{ Rad. s}^{-1}, respectively. Because the Coriolis Parameter has such a low value, the slope is
small. For high BV frequencies the value of the slope is further reduced. Figure 12 shows the slope of the characteristics using the BV values from Figure D. 10. For example, under normal stratification conditions near Puerto Rico (N= 2.78 x 10^{-4} Rad. s^{-1}) the energy of the semidiurnal internal tide (σ=1.405 x 10^{-4} Rad. s^{-1}) will propagate as a tidal beam ray with a slope of 2.74°. For similar stratification conditions in the Bay of Biscay (40°N), the slope of the beam would be 21°. Submarine topographic slopes similar in magnitude to the tidal beam slope are potential sources of the internal tide. Gently sloping topography is easier to find than abrupt topography which leads us to speculate that the generation of the internal tide in low latitudes is a rather common phenomenon. Figure D. 12 shows that as we approach the month of October the tidal ray slope decreases therefore allowing the generation of the internal tide within the depth range of the seasonal pycnocline. In April and May the slopes are small but larger than ½ a degree. In December and February we need slopes larger than 5 degrees (white areas) and up to 40 degrees. Figure D. 13 (top) presents the average ray slope between depths of 22 and 62 meters for each month. It shows that the minimum critical slopes required for the generation of the internal tide are in April-May and in September-October. Giese (1990) found that the seasonal variation in seiche variance has a bi-modal distribution that shows maxima in May-June and September-November. This fact supports that maximum internal wave activity and maximum seiche activity are correlated. Critical slopes in April and May could be associated to the influence of old Amazon River water lenses that enter the Caribbean Sea from the Tropical Atlantic (Muller-Karger and Varela, 1990).

In October 2000 the slopes were at a minimum during our occupation of station ADCP1. Twelve CTD casts taken at this station allow us to average 12 profiles of the tidal beam ray slope (Figure D. 13, bottom) which ranged between 0.5 and 0.8 degrees. These slopes are critical for the generation of the internal tide. Figure D. 14 shows the distribution of bathymetric slopes with values equal to the tidal ray slopes. These areas represent possible generation zones of the internal tide.
at depths less than 200 m. The slopes that are normal to the barotropic flow can generate a stronger internal tide.

Kjërve (1981) describes the semidiurnal ($M_2$) amphidromic system centered south of St. Croix and west of Martinica. The co-phase lines rotate anti-clockwise around the amphidrome and as such the phase of the semidiurnal tide is expected to propagate from north to south around Puerto Rico and the Mona Passage. Current measurements in the Mona Passage confirm this statement (Rosario, 2000). In Figure D. 14 the critical slopes, red and blue areas, are numerous across the Mona Passage. Most are located at the shelf break of the Puerto Rico and Mona platforms but there are other scattered critical areas that could act as generation foci. Multiple generation areas could explain the complex patterns observed in Figure D. 1.

A larger number of areas with slopes smaller than one degree relative to slopes larger than 13° (Figure D. 14, bottom) facilitate the generation and dispersion of the internal tides. That fact could explain the increases in diapycnal mixing and in seiche energy between September and November. Ray slopes smaller than one degree in the first 60 m restrict the generation of the internal tide to areas near the shelf break. A transect along meridian 67° W shows that the shelf break is the more probable generation area (Figure D. 15). Summarizing in a few sentences, more stratification reduces the slope of the tidal beam allowing the internal tide to be generated near the shelf break in many areas. This condition increases the baroclinic wave energy and the vertical eddy mixing. At the same time more baroclinic energy is returned to barotropic energy in the form of coastal seiches.

We want to emphasize that during the period of stronger stratification (September-November) the tidal force index is higher too (Figure D. 16). For the last week of September and the first two weeks of October both the astronomical and stratification conditions are favorable. So it may be expect that during that part of the year the barotropic tide can dissipate more of its energy to the baroclinic modes. Figure D. 17 summarizes most of our above describe scenario; it represents
a conceptual model of how the energy available for turbulent mixing and coastal seiches can increase.
4. Conclusion

The combination of favorable astronomical and stratification conditions can increase the internal wave field. The stronger internal tides can increase diapycnal mixing and at the same time the energy transfer to barotropic coastal seiches is more effective. The right conditions match between September-November and in a lesser degree between April-May. This could explain the observed seasonal pattern of large seiche events in Magueyes Island reported in previous works. The degree of stratification around Puerto Rico is a direct function of the Orinoco River discharge into the Caribbean waters. The extreme seiche activity and stronger diapycnal mixing will occur only when strong stratification and astronomical conditions coincide.

This work reveals the fine interconnection between continental processes such as the Orinoco River discharge and the coastal dynamics processes around islands such as the coastal seiches. The strong stratification created by the Orinoco River prepare the best possible scenario for an increase of turbulent mixing and seiche activity.

The implications of these findings over the biological processes in the ocean and in the coast cannot be discarded. The internal waves by increasing turbulence can input more nutrients to the euphotic zone and increase the primary production. In other words is a source of new production. Also the internal wave currents can advect and compact the phytoplankton, forcing it to a variable light regime. In the south coast the seiche amplitude can be equal or greater than the diurnal tides. This could imply that the seiche could have a stronger influence over the local biology than the tide itself.
Acknowledgments:

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Stigebrandt, A., 1999. Baroclinic wave drag and Barotropic to baroclinic energy transfer at sills as evidenced by tidal retardation, seiche damping, and


List of Captions

Figure D. 1. Photo taken by the 7th shuttle mission (STS-7) in June 21 1983 near 1030 AM. It shows the Mona Passage (to the east is Puerto Rico west coast and in the center is Mona Island). From the east side of Mona Island up to Rincon’s peninsula is present a long bright strip that could be a surface signal of the internal tide. Inside this zone some brighter narrow strips cross each other. This wavelike fronts could be the surface signal of solitons locally generated. Photo courtesy of NASA.

Figure D. 2. Station ADCP1 is located 10 nautical miles to the NNE of Mona Island (18° 17.478’ N, 67° 48.155’ O), about 6 nautical miles SW of El Pichincho (generation area of internal waves) and 32 miles to the west of station InWaPE. This off shelf station is near the central axis of Mona Passage in a zone of low bottom relief with an estimated depth of 267 fathoms (481 m). CaTS (Caribbean Time Series) serial station is located about 22 nautical miles from the SW coast of Puerto Rico (17° 36.00’ N, 67° 00.00’ W), with a maximum depth of 2880 m. The map is a courtesy of Aurelio Mercado and Harry Justiniano.

Figure D. 3. Values of the Richardson Number from May 24th to October 11th 2000 in ADCP1 station. The shaded regions represent critical values of the Richardson Number, (\(Ri < \frac{1}{4}\)), a necessary conditions for the development of Kelvin-Helmholtz instabilities. On August critical values show more frequently and at the end of September and first week of October they are present in the whole water column.

Figure D. 4. We can see that the coefficient of vertical diffusivity, \(\kappa_d\), keeps between \(30 \times 10^{-4}\) and \(50 \times 10^{-4}\) m\(^2\) s\(^{-1}\). This last value is inside the range of highest observed open ocean diffusivities in the seasonal thermocline. This implies
that the Mona Passage is an intense mixing zone. Between October and September values are over $60 \times 10^{-4} \text{ m}^2\text{s}^{-1}$.

Figure D. 5. Sigma-t contours in ADCP1. The pycnocline is located around 40 m depth. The isopinclals over 60 m show a crest at 0845 and a trough at 1245. The crest-trough height is 10 m. The 24.6 and 24.3 kg m$^{-3}$ isopycnals show a crest at 0845 but the trough occurs later around 1600. The crest-trough height is 23-25 m. The isopycnals between 80 and 110 m depth show a crest at 1030 and a trough at 1600. The crest-trough height is 21-23 m.

Figure D. 6. Displacement of the isotherms (in particular the 29.0 C isotherm) showed a squared form internal wave. The wave differs from the one showed in figure 5 due to its interaction with the shelf. Between 0800 and 0930 the isotherm is around 32-34 m. After 0930 the isotherm descended abruptly down to 48 m. In 30 minutes descended about 14-16 m. The 29.0 C isotherm keeps between 47-49 m depth from 1000 until 1400. After 1430 the isotherm was abruptly displaced up to 24 meters (1500). Between 1530 and 1700 stayed in 28 m. To summarize the internal wave had a maximum height of 25 m.

Figure D. 7. This figure shows the simultaneous increase in the coastal seiche activity and in the vertical diffusivity. Vertical dashed lines delimit periods of more activity. Reduction in the Richardson number due to increase shear by internal waves facilitates the diapycnal diffusion. Extreme seiches coincided with increases in the vertical eddy coefficient and as consequence more turbulent mixing. The connection between both processes is that both are generated by internal waves.

Figure D. 8. Tidal force index, normalized seiche energy, vertical eddy diffusivity in the water column between 54 and 144 meters depth and its
average. At each side are the Brunt-Väisälä frequency profiles for the start and end of the sampling period. The time series starts on May 25\textsuperscript{th} and ends on October 11\textsuperscript{th} of 2000. The tidal force index shows a fortnightly cycle and starting in the year day 260 is above 0.7 and keeps over this value until year day 288. During this period the net tidal force is larger, the column averaged vertical diffusivities and the coastal seiches are extreme and persistent.

Figure D. 9. Tidal force index, normalized seiche energy, vertical eddy diffusivity in the water column between 54 and 144 meters depth and its average. At each side are the Brunt-Väisälä frequency profiles for the start and end of the sampling period. The time series starts on September 3\textsuperscript{rd} and ends on October 11\textsuperscript{th} of 2000. The figure shows periods of higher diffusivites below the 100 m depth that do not coincide with higher seiche activity but when the increase in vertical mixing is above 80 m both events coinced. The average column diffusivity is higher during major seiche activity.

Figure D. 10. A closer looks to the relationship between seiche activity and eddy diffusivity. Figure D. on top shows that the peaks in vertical diffusivity and seiche activity coincided. The other figure shows a plateau in vertical diffusivity delimited by the two peaks in seiche activity.

Figure D. 11. (Top) BV frequency contours between 0-1000 m in the CaTS station. (Bottom) Zoom of the First 200 meters. From August to November the BV values kept over 8 CPH in the top 60 meters.

Figure D. 12. Internal tide characteristics slope in CaTS station. Values less than 1\degree are common in the top 200 m. Between August and October slopes
smaller than 1° can reach 20 m depth. Between April and May slopes smaller the 1° can reach over the top 40 meters. White areas represent slopes higher than 5 degrees.

Figure D. 13. (Top) Average slope of the internal tides energy beam between 22 and 62 meters depth. May and April show the smaller slopes. (Bottom) Average slope profiles constructed from 12 individual profiles from ADCP1 station on the 10th October 2000.

Figure D. 14. (Top and middle) In the red and blue areas the topographic slope match the slope of the internal tides energy beam shown in the previous figures. They represent possible generation areas of the internal tide. If the barotropic flow is perpendicular to these areas the internal tide can be easily generated. (Bottom) Red and blue identify slopes between 13-15° in depths of 200 m and less. These regions are scarce.

Figure D. 15. A transect along meridian 67° W (between 17-18° N) shows that slopes smaller than 1 degree are confined to the platform and abyssal bottom. Very near the shelf break (lat. 17.9 N) the slope is adequate for the internal tide generation.

Figure D. 16. Tidal force index throughout the year. This index determines the degree of overlap in astronomical factors necessary to increment the tidal energy available for the barotropic and baroclinic tides.

Figure D. 17. The left frame shows typical conditions between January and March. During this time of the year the influence of the discharge of the Orinoco River (dark green area) in the northeastern Caribbean is minimum or non-existent. The seasonal pycnocline (continuos black line) is deepest than in
any other time of the year, the BV frequency values are small and the characteristic slopes are the steepest ($> 15^\circ$). All this factors limited the generation of internal tides to steeper slopes at deeper depths. Vertical diffusivity (red scattered zones) is higher along the tidal beam (dotted black line) but the energy is not effectively transferred to the shelf and the seiches are small. The right frame shows typical conditions present between August and November. Strong influence of the Orinoco River discharge over the stratification conditions, high values of BV frequency, and ray slopes smaller than 1$^\circ$. In these favorable conditions the internal tides can be generated near the shelf break and dramatically increase the vertical eddy mixing in the top 60 meters. The internal tide energy can be transferred easily to the shelf waters and increase dramatically the seiche activity. In both frames the astronomical conditions (Moon in quarters) are favorable to increment the internal wave activity but the Orinoco River makes the difference.
Figure 2
Richardson number, values $R_i < 0.25$

5/15/00  6/15/00  7/15/00  8/15/00  9/15/00

Figure D. 3
Figure D. 4

Vertical eddy diffusivity in ADCP1

Year day 2000

Depth (m)

May 15 Jun 15 Jul 15 Aug 15 Sep 15

$m^2 s^{-1}$

-0.006 -- 0.008
-0.005 -- 0.006
-0.0027 -- 0.005
1E-3 -- 0.0027
Sigma-t ($\sigma_t$ (kg m$^{-3}$)) in ADCP1 (10/OCT/2000)

Depth (m)

Hour (AST)

Figure D. 5
Figure D. 6

Temperature in InWaPE (22-September-2000)
Close Relationship between Seiche Energy and Diapycnal Mixing, K

Normalized seiche energy

Seiche in Magueyes I.

Year day 2000

Depth (m)

Coefficient of vertical eddy diffusion (Pacanowski and Philander 1981)

\( m^2 s^{-1} \)

-0.006 -- 0.008
-0.003 -- 0.006
1E-3 -- 0.003

Figure D. 7
Figure D. 8

Vertical eddy diffusion coefficient

Seiche Energy

Year day 2000

Brunt-Vaisalla Frequency (CPH)

Year day 2000

Column averaged diffusivity between 54 and 144 m depth

Year day 2000
Figure D. 9
Relationship between eddy diffusivity, \( K_v \) and Coastal Seiches

[Graph showing Seiche Energy and Column Averaged Eddy Diffusivity for Year day 1997]

Seiche Spectrogram (Magueyes I.)

[Graph showing Seiche Energy and Column Averaged Eddy Diffusivity for Year day 2000]

Figure D. 10
Figure D. 11

BV Frequency in CaTS throughout the year

BV Frequency in the top 200 m in CaTS station

Figure D. 11
Changes in Tidal ray slope in CaTS throughout the year

Figure D. 12
Figure D. 13

Slope of the Tidal Ray in ADCP1 (10/OCT/2000)

- Slope of the tidal ray (degrees)
- Month
- Depth (m)

Mean
**North-south slopes at depths < 200 m**

- **Critical slopes in red and blue degrees**
  - Red: 0.6 -- 0.8
  - Orange: 0.4 -- 0.6
  - Light orange: 0.2 -- 0.4
  - Light gray: 0 -- 0.2
  - Gray: -0.2 -- 0
  - Dark gray: -0.4 -- -0.2
  - Dark blue: -0.6 -- -0.4
  - Dark blue: -0.8 -- -0.6
  - Black: Shoreline

**East-west slopes at depths < 200 m**

- **Critical depths in red and blue degrees**
  - Red: 0.6 -- 0.8
  - Orange: 0.4 -- 0.6
  - Light orange: 0.2 -- 0.4
  - Light gray: 0 -- 0.2
  - Gray: -0.2 -- 0
  - Dark gray: -0.4 -- -0.2
  - Dark blue: -0.6 -- -0.4
  - Dark blue: -0.8 -- -0.6
  - Black: Shoreline

**North-south slopes at depths < 200 m**

- **Critical slope in red and blue degrees**
  - Red: 13 -- 15
  - Dark blue: -15 -- -13
  - Black: Shoreline

**Figure 14**
Slope (north-south, Py) and (east-west, Px) along meridian 67°W

Slope (north-south, Py) and (east-west, Px) above 100 m depth

Figure 15
Figure 16

Evolution of the tidal force index throughout the year

- Tidal Index
- Fourth diurnal Signal

Date (2000)
Figure 17
Table 1. Acoustic Current Doppler Profiler (ADCP) configuration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td><strong>1. ADCP CONFIGURATION.</strong></td>
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<td><strong>2. PREDICTIONS</strong></td>
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