Causation of Large-Amplitude Coastal Seiches on the Caribbean Coast of Puerto Rico*

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ABSTRACT

Sea-level oscillations at supertidal frequency with amplitudes of the order of the mean tidal range have been reported from the Caribbean coast of Puerto Rico. Analysis of a 10-year time series of digital tide data from Magueyes Island, Puerto Rico, demonstrates that sea-level variance at the fundamental normal mode (seiche) frequency of the shelf has a pronounced fortnightly distribution with a maximum occurring 6–7 days after new and full moon. The sieche variance also shows a bimodal seasonal distribution with an inverse relationship to easterly wind stress.

It is argued that the seiches are excited by internal waves generated by strong tides in the southeastern Caribbean. Support is provided by airborne radar imagery showing sea-surface patterns suggesting the presence of internal waves near the southern Aves Ridge, and by the results of two field experiments, carried out during times when large-amplitude seiches were expected, to search for evidence of internal wave forcing near the shelf break. During the first experiment, large negative-amplitude, pulse-like internal waves were recorded 6 km seaward of the shelf break during a period of strong seiche activity. Such pulses were not observed during the second experiment. However, high-frequency temperature variance 2.3 km seaward of the shelf break, possibly resulting from internal surf, increased with depth and reached a maximum 6–7 days following new moon, again suggesting the presence of internal waves.

The 10-year time series analysis shows that large tides are necessary, but not sufficient, to generate high seiche activity. This is supported by the two field experiments; during the first, large-amplitude seiches occurred as expected, while during the second experiment they did not. We suggest that this behavior is related to variations in stratification which in turn alter the energy transfer from tides to seiches.

1. Introduction

Coastal waters typically oscillate at the resonant normal mode frequencies—generally in the range of 0.5 to 5 cycles per hour—characteristic of a specific harbor, bay or shelf (Defant 1961). Such standing waves, or seiches, are usually small in amplitude compared to local tides, but on occasion attain heights of the same order as the local tidal range. The excitation of large-amplitude seiches or "tsunamis" by seismic disturbances has received a great deal of attention (e.g., Van Dorn 1984). However, over the past century, reports from around the world have described the local occurrence—often along the coasts of marginal seas—of unexpected large-amplitude seiches that seem to have no relationship to seismic disturbances (e.g., Credner 1888; Honda et al. 1908; Fontseré 1934; Nakano and Unoki 1962; Tintoré et al. 1988). These seiches usually have a pronounced seasonal distribution and often occur when the wind is still and the seas calm. Such waves are generally considered to be the result of atmospheric forcing, and they are often categorized together as "meterological tsunamis" (Defant 1961). However, despite the many studies of their possible meteorological forcing, no successful schemes have yet emerged for predicting these large-amplitude aseismic seiches.

In this paper, we examine the characteristics and causation of large-amplitude seiches along the Caribbean coast of Puerto Rico. These waves were first reported by Harris (1907), who observed them on tide records from Guanica Harbor (Fig. 1) and who ascribed them to meteorological forcing. In a preliminary

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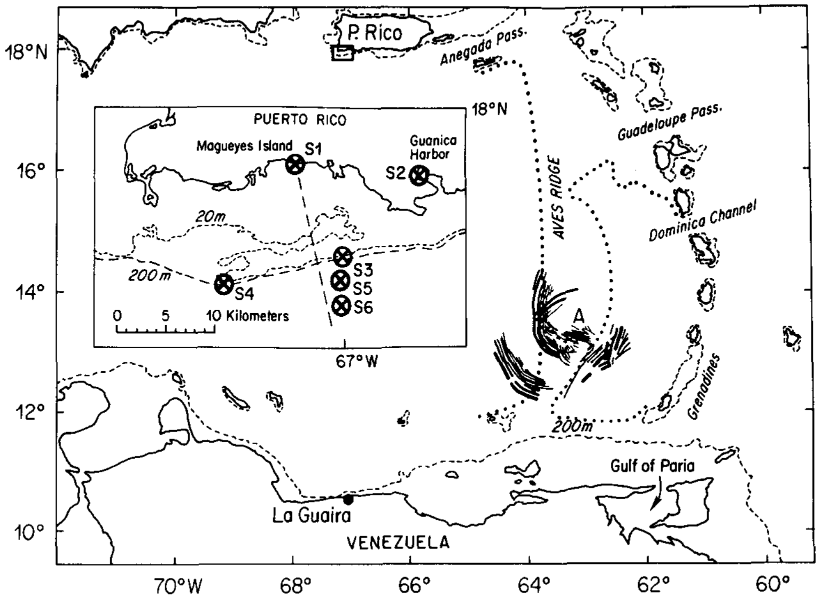

FIG. 1. Eastern Caribbean Sea with insert showing study area at the southwestern corner of Puerto Rico. S1 and S2 designate locations of Magueyes Island and Guanica Harbor tide stations; S3 and S4, two shelf-edge current meter stations; and S5 and S6, a thermistor station and an XBT station. Sea-surface patterns observed on airborne radar images and interpreted as surface expressions of internal waves are shown in the vicinity of the southern end of Aves Ridge. The letter *A* marks the location of a seamount that rises to within 400 m of the surface. Dashed line extending offshore from S1 depicts location of profile line shown in Fig. 2. Dashed bathymetric contour is the 200 m line; dotted contour is the approximate 2000 m line.

report, Giese et al. (1982) made the suggestion, based primarily on a study of analog tide records from nearby Magueyes Island (Fig. 1), that the seiches are excited by deep-sea internal waves generated by barotropic tides in the southeastern Caribbean Sea. Observations presented in this paper support that preliminary conclusion, but they also show that large tides do not guarantee that large seiches will follow. Some other factor(s) must be involved in the generation of large-amplitude seiches.

The paper is organized as follows. Evidence is presented in section 2 for the relationship between tides and seiche activity based on Fourier analysis of a ten-year time series of digital tide records from Magueyes Island, Puerto Rico. Possible locations for internal wave generation in the southeastern Caribbean are discussed in section 3, while seasonal variations in seiche activity are described in section 4. The results from two field experiments carried out in an attempt to test the hypothesis of tide-generated internal-wave excitation of seiches are presented in section 5, followed by some discussion in section 6. A companion paper (Chapman and Giese 1990) provides a theoretical basis for seiche excitation by internal waves.

2. Relationship between seiche activity and tides

Western Puerto Rico is separated from the Caribbean basin by a narrow shelf and steep island slope (Fig. 1). The shelf width varies from 3 to 10 km with emergent reefs along the inner margin. Water depth averages about 20 m at the shelf break. The island slope is very steep; depths of 200 m are generally found within 0.5 km of the shelf edge, and 1000 m depths within 5 km of the shelf break. Figure 2 shows a profile of the shelf and slope offshore of Magueyes Island. Merian's formula for open basin oscillations (Murty 1977) gives the fundamental resonant period, T, of the shelf as

$$T = 4L/(gd)^{1/2}$$

where L is the shelf width, d the shelf depth (assumed to be uniform), and g the gravitational acceleration. For a section normal to the shelf break and passing through Magueyes Island, $L \approx 10^4$ m and $d \approx 18$ m (mean depth), giving $T \approx 50$ minutes.

Approximately 50-minute sea-level oscillations are commonly observed on Magueyes Island tide records, and they sometimes attain heights in excess of the mean (diurnal) tidal range of 21 cm (Giese et al. 1982). In order to examine the time variation in relative seiche energy, six-minute tide data from Magueyes Island were obtained from the National Ocean Service (NOS) for the period beginning 1 January 1976 and ending 29 April 1986. Despite several gaps in the series, there are data for 3337 days. For each day, the time series was Fourier transformed and the daily variance spectrum computed.

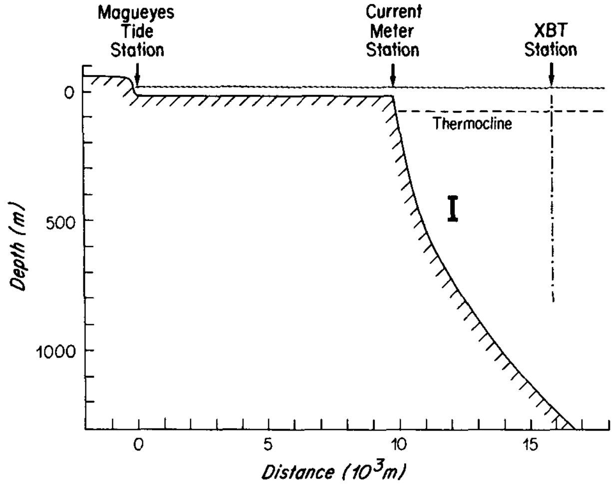

FIG. 2. Shelf and slope south of Magueyes Island, Puerto Rico. The current meter station (S3 on Fig. 1) was used in both field experiments, the XBT station (S6) in the first experiment, and the thermistor chain (the large **I** between them; S5) in the second experiment.

The spectrum for 28 June 1982 (part of a particularly active period discussed in section 5) is presented in Fig. 3. In preparing this figure, values near the maximum at 1.2 cph ($T = 50$ min) were plotted for each basic frequency bandwidth of 0.042 cph to emphasize the narrow resonant response at the normal mode period. For the subsequent figures, however, the "daily seiche variance" was calculated by grouping four basic bandwidths, i.e., the value used was the total variance over a frequency band of 1.20 ± 0.08 cph. The supertidal frequency spectral peak was almost always found in this range, supporting the conclusion that these oscillations are indeed seiches.

Figure 4 presents the fortnightly variation in average daily seiche variance following new and full moon, and shows a pronounced maximum 6–7 days after syzygy, strongly suggesting semidiurnal tidal forcing. The semidiurnal tidal influence is also evident in Fig. 5 which shows the distribution of seiche variance on the seventh day after syzygy in relation to the difference in time (days) between the preceding syzygy and perigee. Maximum seiche activity follows perigean spring tides ($|P - S| = 0$).

As reported in Giese et al. (1982), this relationship to the semidiurnal tide was initially surprising because the semidiurnal tide is very weak at this station. Magueyes Island is located close to the Caribbean M_2 and S_2 amphidromes; the M_2 and S_2 harmonic constituent amplitudes, 0.70 and 0.76 cm respectively, are an order of magnitude smaller than the K_1 and O_1 amplitudes, 7.92 and 5.36 cm (Zetler and Cummings 1972). However, while it seemed unlikely that the seiches were forced directly by the local semidiurnal tide, the possibility of indirect tidal forcing did seem feasible. Giese et al. (1982) found evidence of internal wave activity at the shelf edge off Magueyes Island in the form of large temperature perturbations within the thermocline about one week following syzygy. They suggested that these perturbations may have been generated by the preceding spring tides along the southeastern margin of the Caribbean where the semidiurnal tide reaches its greatest range (Kjerfve 1981).

As an initial test of the hypothesis that the Magueyes Island seiches are forced by semidiurnal tides in the southeastern Caribbean, we have plotted daily seiche variance for each day during every October of the 1976–86 Magueyes Island tide data versus tidal range in the southeastern Caribbean 6 days earlier (Fig. 6; note the logarithmic ordinate scale). While only small seiches follow small tidal ranges, large tidal ranges in the southeastern Caribbean can be followed by large-amplitude seiches at Puerto Rico. The increase in maximum seiche activity following larger range tides is remarkable. A doubling of the tidal range can be accompanied by an increase in maximum seiche activity of two orders of magnitude! We interpret these results to indicate two important points. First, since only low level seiche activity follows small tidal ranges, seismic and meteorological forces do not appear to be important for the production of large seiches at Puerto Rico. If they were, one would expect to see at least some periods of large seiche activity following low tidal

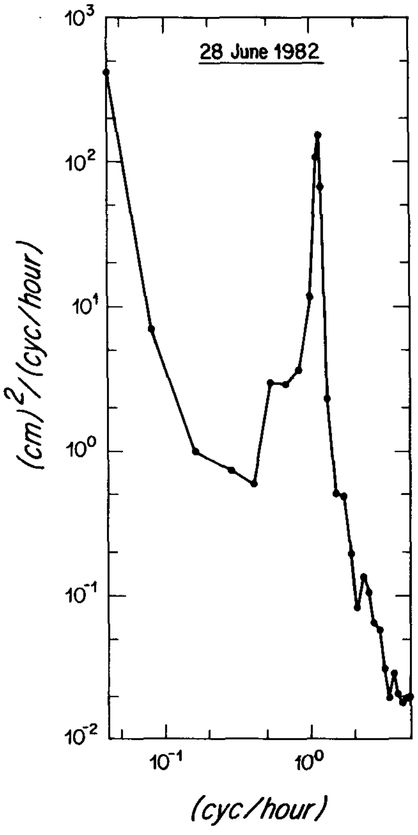

FIG. 3. Variance spectrum for Magueyes Island tide record for 28 June 1982. Peak at 1.2 cph indicates resonant shelf oscillations.

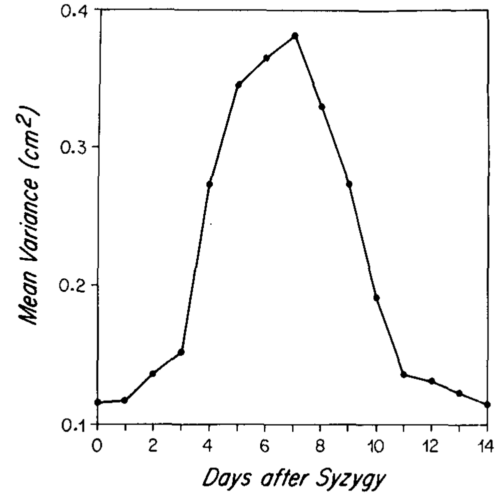

FIG. 4. Fortnightly distribution of sea-level variance at seiche frequency for Magueyes Island based on a 10-year time series. Variance maximum occurs about one week after syzygy, i.e. new and full moon.

ranges in the southeastern Caribbean. Second, large-range tides appear to be necessary for the occurrence of large-amplitude seiches. However, large-range tides alone are not sufficient to produce large-amplitude seiches. That is, small-amplitude seiches can follow large tides, so some other additional factor(s) must be involved in the seiche generation.

3. Location of internal wave generation in the southeastern Caribbean

Some evidence of internal wave generation in the southeastern Caribbean Sea can be seen on airborne radar imagery. These images sometimes show large-scale, banded, sea-surface patterns similar in form to those identified at other locations as being the surface expression of internal wave packets generated by tidal currents passing over large, shallow bathymetric features (e.g., Apel et al. 1975). An example of such bands is reproduced in Fig. 1 based on airborne radar images recorded on 10 August 1971; four days after full moon and two days after perigee.

The sea-surface patterns appear to be associated with seamounts that reach to within 400 m of the sea surface (U.S. Naval Oceanographic Office 1975) on the southern end of the Aves Ridge, some 650 km southeast of Puerto Rico (Fig. 1). One packet of waves appears to be traveling northwestward, away from a seamount toward Puerto Rico. Based on similar observations in the Sulu Sea (Apel et al. 1985), a possible scenario is that semidiurnal tidal currents passing over the seamounts form packets of internal solitary waves that propagate northwestward toward Puerto Rico, maintaining their form while traveling hundreds of kilometers.

To test this idea, we have estimated the travel time required for an internal solitary wave to reach Puerto Rico by using the phase speed computed for the lowest-mode, long, internal wave in a flat-bottom ocean. Taking a typical density profile offshore of Puerto Rico (Fig. 7), and assuming a deep-sea depth of 4000 m, the phase speed estimate is $c = 2.2$ m s^{-1} (using a program from Brink and Chapman 1987). Because solitary waves in fact travel faster than small-amplitude linear waves under otherwise identical conditions, this value provides a lower limit for the estimation of phase speed. Thus, an internal solitary wave would take 3.4 days, as an upper limit, to travel 650 km from the southern Aves Ridge to Puerto Rico. The age of the tide (phase inequality) for the closest tide station, Carupano, Venezuela, can be determined from the tidal harmonic constants given by Kjerfve (1981); $K°S_2 - K°M_2 = 25°$, giving a tidal age of 1.1 days. Adding this to the estimated travel time leads to a maximum expected delay of 4.5 days after syzygy. By comparison, the observed mean lag between maximum seiche activity and syzygy is in the range of 6–7 days (Fig. 4), suggesting that the waves may actually be formed farther away, perhaps over the Venezuela–Trinidad shelf where the tides are considerably stronger. This suggests that the patterns shown in Fig. 1 may represent scattering, rather than the generation, of the internal waves as they pass over the southern Aves Ridge.

4. Seasonal variations in seiche activity

The 1976–86 Magueyes Island tide data described in section 2 were also used to examine seasonal variations in seiche variance, revealing a pronounced bi-

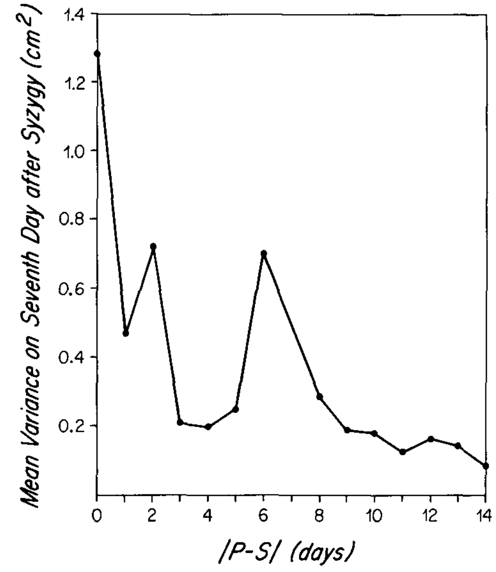

FIG. 5. Mean variance at seiche frequency on seventh day after syzygy in relation to absolute difference in time (days) between that syzygy and the nearest perigee ($|P - S|$). Seven days after perigean new or full moon ($|P - S| = 0$), the mean variance is about ten times the value of the variance seven days after an apogean new or full moon ($|P - S| = 14$).

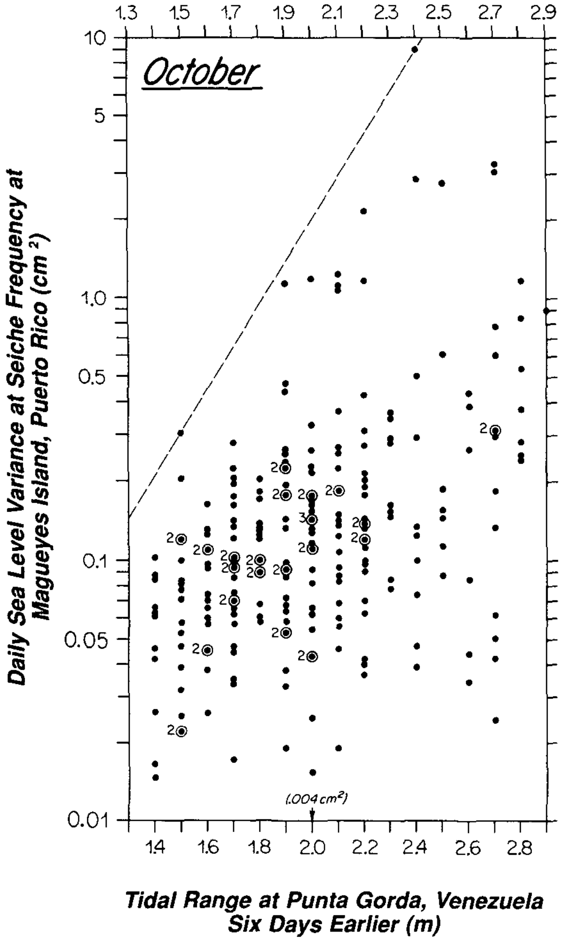

FIG. 6. Daily sea-level variance at seiche frequency at Magueyes Island during October plotted against the daily maximum tidal range at Punta Gorda, Venezuela (in the Gulf of Paria) six days earlier. Circled dots accompanied by numbers designate multiple occurrences. Dashed line is an attempt to designate qualitatively the upper boundary of observed seiche variance.

modal pattern (Fig. 8a) with maximum activity during the spring (May–June) and fall (September–November). Figure 8b presents the relative monthly variation in meridional sea-surface slope upward from south to north across the Caribbean Sea at 67°W. This figure is based on monthly mean sea-level data from La Guaira, Venezuela (Fig. 1), and Magueyes Island for the years 1957–61, 1963 and 1964. Figure 8c shows the monthly averaged zonal wind stress for a 1°box centered about 75 km southeast of Magueyes Island at 17.5°N, 66.5°W (Harrison 1989).

The patterns shown in Figs. 8a–c are similar, particularly the first two, suggesting the possibility that seiche activity is related to variations in the depth of the surface mixed layer or the strength of the Caribbean current, or both. Easterly winds produce a westward surface stress and a northward Ekman transport, which in turn, causes a deeper mixed layer along the north boundary of the Caribbean and a shallower one at the south boundary (Gordon 1967). Accordingly, the meridional sea-surface slope should provide an index to variations in the transport of the Caribbean current as well as the depth of the mixed layer at the northern boundary of the sea, e.g., along the shelf edge south of Puerto Rico. This suggests that seiche activity is enhanced when the current is weaker and/or the mixed layer is shallower (smaller meridional sea-surface slope), and that seiche activity is reduced when the current is stronger and/or the mixed layer is deeper (increased sea-surface slope).

5. Field experiments

Taking advantage of the distinct patterns of seiche activity, two field experiments were planned to coincide with periods of maximum expected seiche activity. Their purpose was to document the occurrence of the expected activity in the form of sea-level oscillations at the coast and cross-shelf currents at the shelf edge. In addition, attempts were made to record the arrival of internal waves seaward of the shelf edge.

The first experiment, which took place between 26 June and 1 July 1982 was timed to follow the perigean new moon of 21 June 1982. Sea-level measurements at six-minute intervals were recorded at Magueyes Island and at Guanica Harbor (Fig. 1) using Fisher-Porter type digital recorders. Seiches occurred at both stations almost continuously throughout the study period, with maximum activity occurring between 28 and

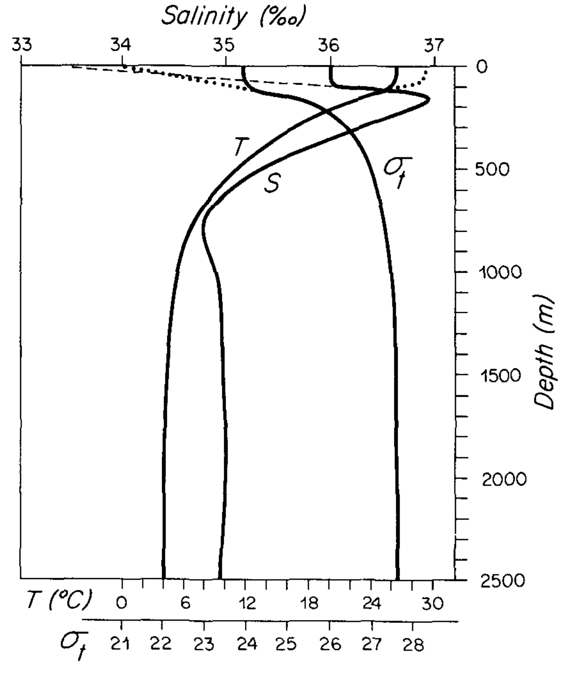

FIG. 7. Temperature, salinity and density (σ_t) profiles for a station offshore of Magueyes Island at 17°40′N, 67°00′W. Solid lines give values for late winter through early spring; dotted lines give values for late summer through early fall. Data from Fancher (1972).

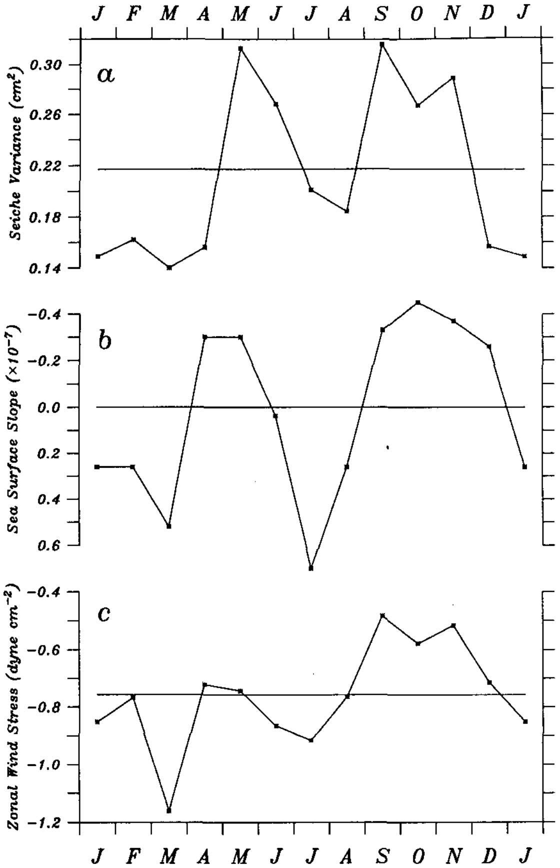

FIG. 8. (a) Monthly mean sea-level variance at seiche frequency from Magueyes Island tide records, January 1976 through April 1986. (b) Monthly anomaly in Caribbean sea-surface slope upward between Magueyes Island, Puerto Rico, and La Guaira, Venezuela. Mean sea levels were calculated for each station from monthly means for seven years, 1957–61 and 1963–64. Mean monthly anomalies were first calculated for each station, then the monthly anomaly for La Guaira was subtracted from that for Magueyes Island. These differences divided by the distance between the two stations yield the monthly sea-surface slope anomalies. (c) Monthly variation in zonal wind stress for a 1° box centered at 17.5°N, 66.5°W (south of Puerto Rico) based on a 125-year period (Harrison, 1989). Strongest easterly winds (largest negative values) occur in January, March and June–July; weakest easterly winds occur in April–May and September–November.

30 June (Fig. 9). The largest single oscillation at Magueyes Island occurred on 28 June and was 23 cm high as compared to the tidal range for that day of 12 cm. The oscillations had a mean period of about 51 minutes at Magueyes Island, while at Guanica Harbor the mean period was about 45 minutes.

Between 28 June and 1 July, currents were recorded at 2-minute intervals at the shelf edge station S3 (Fig. 1) using an ENDECO Type 174 current meter. The instrument was attached at a depth of 12 m to a subsurface mooring in 21 m of water. Current speeds varied from 0 to 18 cm s^{-1} and alternated direction from offshore to onshore (Fig. 10). The dashed-line in the upper panel in Fig. 10 is the velocity which would be expected if the sea-level variations were due solely to a fundamental mode coastal seiche. Thus, the relationship between shelf-edge current speed and phase, and Magueyes Island sea-level oscillations, is clearly consistent with a fundamental mode coastal seiche.

A search for internal wave activity was carried out by the deployment of expendable bathythermographs at 20-min intervals in 1200 m of water (station S6, Fig. 1). The series began at 1300 LST 28 June and ended at 0600 LST 29 June. The results reveal two negative-amplitude internal wave pulses and a zone of temperature inversion at a depth of 600 m (Fig. 11). The first wave was recorded at 1800 LST 28 June and was accompanied by a maximum isotherm displacement of about 100 m. The second wave, with a maximum displacement of about 75 m, was recorded at 0300 LST 29 June. Surface water cooling occurred in conjunction with the internal wave activity but also at times when waves were not recorded. It is likely that other internal waves passed the station during the study period but were not recorded because of the 20-minute spacing of the XBT casts. Such unrecorded waves may account for the other surface cooling events. We surmise that the temperature inversions at 600 m were produced by internal surf (Emery and Gunnerson 1973) resulting from waves breaking as they approached the steep submarine slope.

The second field experiment took place between 26 September and 7 October 1984 and was designed to record the vigorous seiche activity expected to follow the perigean new moon of 25 September. Three taut-wire current meter moorings, one with a thermistor string, and a tide recorder were used for the measurements. A deep mooring was placed at a depth of 722 m on the slope approximately 2.3 km south of the shelf break (station S5, Fig. 1). An Aanderaa RCM 4 current meter was attached at a depth of 383 m with an Aanderaa TR 2 temperature profile recorder and 100 m-long thermistor string from 384 to 484 m. The other

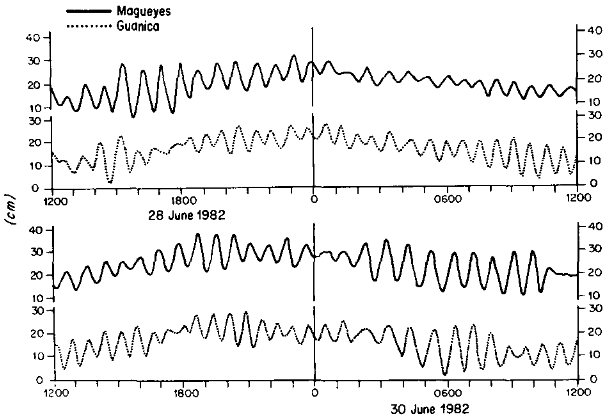

FIG. 9. Tide records from Magueyes Island and Guanica Harbor during the first field experiment in June 1982. Maximum seiche height exceeds the tidal range at both stations.

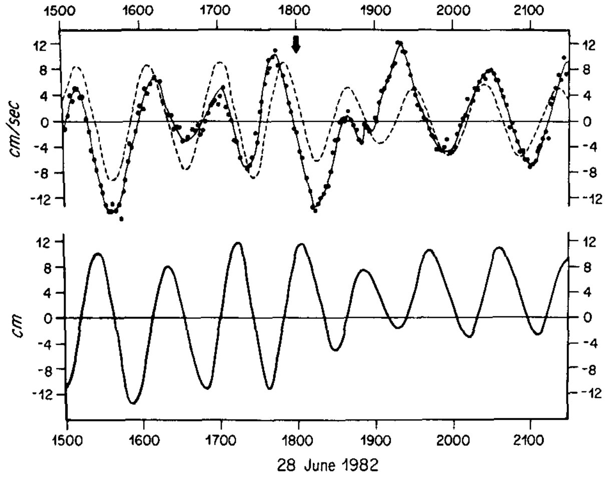

FIG. 10. Magueyes Island tide record (bottom), expected cross-shelf currents at the shelf edge assuming that the sea-level oscillations are due solely to seiche motions (dashed line, top), and observed cross-shelf currents at the shelf edge (dots and solid line fitted by eye, top). Positive currents are directed onshore. The arrow marks the time that an internal wave pulse wave was observed at the XBT station.

two moorings were placed at the shelf break and each carried an Aanderaa RCM 4 current meter. One was located north of the deep mooring in 21 m of water—station S3, the same location as the current meter station for the first experiment. The other was placed 12 km farther west along the shelf edge in 23 m of water (station S4, Fig. 1). The instruments on all three moorings were set for a 2-minute sampling interval. The tide recorder used in this study was the same NOS instrument on Magueyes Island that had been used in the first experiment.

Coastal sea-level and shelf-edge current observations made during this experiment indicate that the expected large-amplitude seiches did *not* occur. The offshore data are more difficult to interpret. While there is no evidence of discrete, clearly defined internal waves in either the deep thermistor or current meter data, the temperature records display increasing fine-structure during the first week, reaching a maximum during 1–3 October, after which the fine-structure decreases. This effect clearly increases with depth; at the lowest thermistor (484 m) the maximum short-term temperature variations are approximately 1°C, and they are most pronounced at about midnight (local time) on 1 October.

In order to quantify this observation, we calculated the daily total temperature variance at periods between 18 and 180 min at each of the five thermistors. The results, smoothed using a 3-day running mean, are presented in Fig. 12a. While details of the distributions vary between the thermistors, there is a trend toward increasing variance with depth and increasing variance in time, from 27 September (2 days following new moon) to October 1 or 2 (6 and 7 days following new moon). Similar temporal patterns are evident in the distributions of the variance at 50 min of the cross-shelf current data from the two shelf-break stations, and of the sea-surface data from Magueyes Island (Figs. 12b,c).

It is likely that the increasing temperature fine structure at the offshore station resulted from increasing turbulence due to dissipation of incoming internal waves, as has been observed by Sandstrom et al. (1989) at the continental shelf break off Nova Scotia. Increasing turbulence with depth is consistent with the observation, from the first experiment, of internal surf at about 600 m. The increase in turbulence through time to a maximum 6–7 days after new moon, and the absence of clearly defined internal waves in the temperature data, suggests that the expected internal waves arrived, but broke in water deeper than our offshore station. Since we have no previous data with which to compare these, we do not know if the expected seiche activity did not occur because of relatively low internal wave energy, or because of unresolved factors controlling the baroclinic–barotropic coupling.

6. Discussion

The results of this study confirm the conclusion of R. A. Harris (1907) concerning the nature of high-frequency sea-level oscillations along the south coast of Puerto Rico. The match between predicted and observed wave period at Magueyes Island, the match between expected and observed shelf-break currents, and the observations of similar activity patterns at Magueyes Island and Guanica Harbor, each with its distinct periodicity, demonstrate that individual shelf and bay sections of the island's Caribbean coast are separately excited and that each oscillates at its resonant

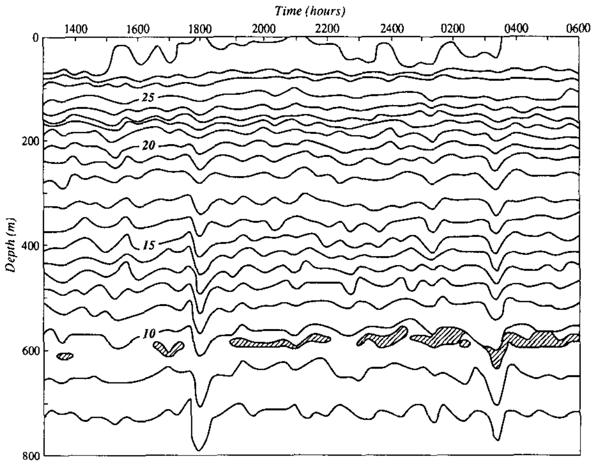

FIG. 11. Depth of isotherms at XBT station as determined by measurements made at 20 min intervals between 1300 LST 28 June and 0600 LST 29 June 1982. Negative-amplitude internal wave pulses were revealed by the casts at 1800 and 0320 LST. Shaded areas at about 600 m represent temperature inversions which may have been caused by waves breaking at that depth.

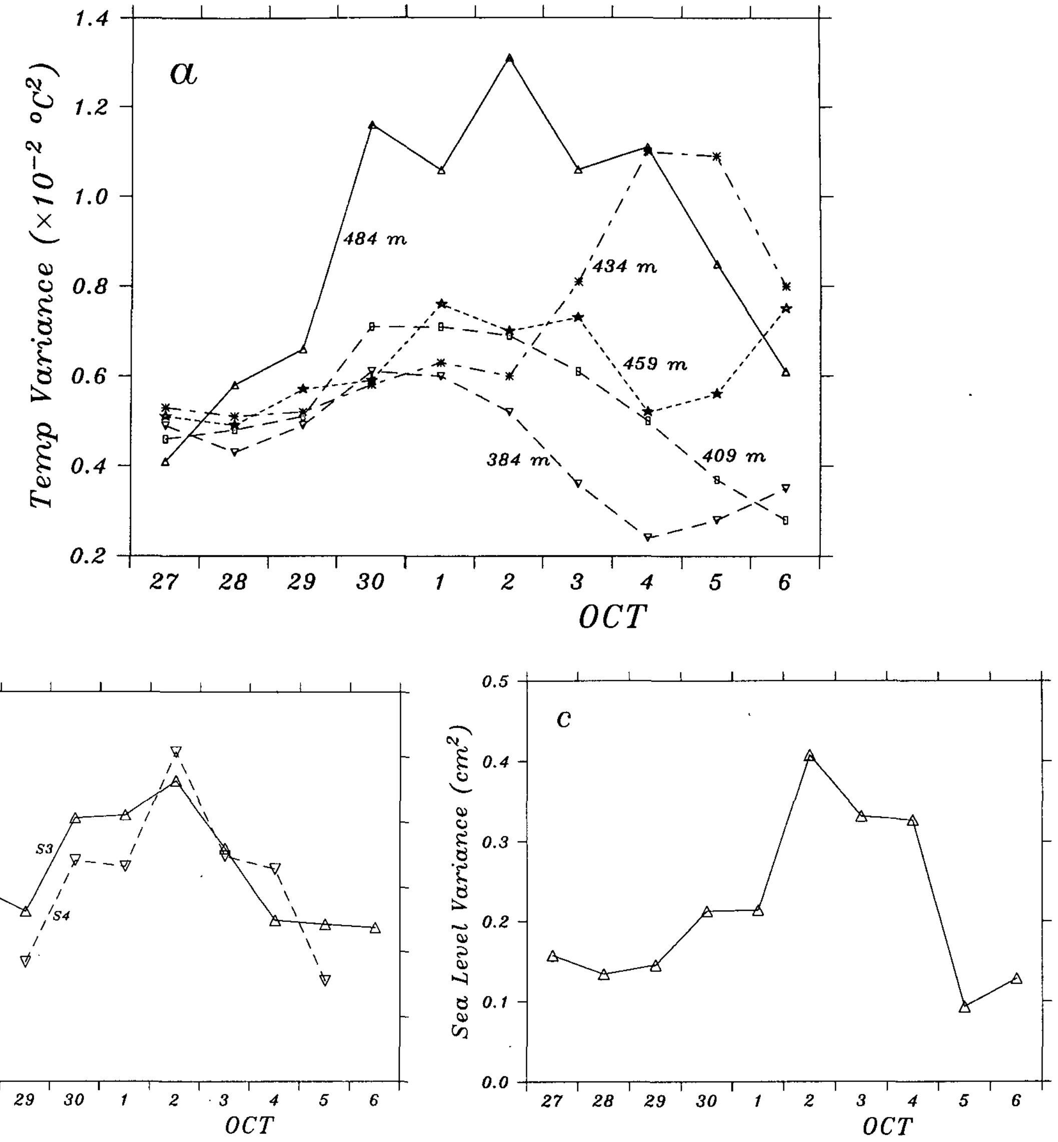

FIG. 12. (a) Three-day running means of daily mean temperature variance at periods ranging from 18 to 180 min recorded at 5 thermistors (station S5, Fig. 1). Depth is shown at each curve. The greatest variance occurs at the deepest thermistor (484 m) with a maximum on 2 October, 7 days after new moon. (b) Three-day running mean of daily mean cross-shelf current variance at shelf break at a period of 50 min. Stations from Fig. 1 are shown at each curve. (c) Three-day running mean of daily mean sea level variance at Magueyes Island at a period of 50 min.

normal-mode frequency. However, it appears that the seiches are not meteorologically forced as Harris had suggested. The inverse relationship between wind speed and seiche activity (Fig. 8), and the absence of high seiche activity levels following small range tides in the southeastern Caribbean over a 10-year period (Fig. 6), both argue against meteorological forcing.

On the other hand, our observations do support the hypothesis of Giese et al. (1982) that these seiches are excited by deep-sea internal waves generated by barotropic tides in the southeastern Caribbean Sea. Such a mechanism is supported by the fortnightly seiche variance distribution, by the relationship between maximum seiche activity and perigee–syzygy alignment, and by the evidence for Caribbean tide-generated internal wave activity. Theoretical support for this hypothesis is provided in the companion paper by Chapman and Giese (1990).

Unfortunately, the scenario that we have presented is not the entire picture. The relationship between tidal range in the southeastern Caribbean and seiche activity at Puerto Rico indicates that large-range tides are a necessary, but not a sufficient condition for the generation of large-amplitude seiches. This point is illustrated for a long time period (10 years) by data presented in Fig. 6 and for a short time period (10 days) by the results of our 1984 field experiment.

The natural question is, what other factors and processes are involved in the production of large-amplitude seiches? Our comparison of seasonal variations in zonal wind stress, Caribbean sea-surface slope, and seiche activity (Fig. 8) suggests that either the depth of the mixed layer or the strength of the Caribbean current or both—through their influence on internal wave generation, propagation or coupling with shallow coastal waters—plays an important role in the transfer of energy from tides to seiches. Figure 8 also indicates that seiche activity increases during autumn when buoyant plumes of low salinity water from South American rivers may reach the south coast of Puerto Rico (Froelich et al. 1978; Müller-Karger et al. 1989). This relationship matches the dependency between density stratification and energy transfer from baroclinic to barotropic modes found by Chapman and Giese (1990), but we are unable to find a similar match between increased seiche activity in May and June, and density stratification. Despite such deficiencies in our understanding of the seiche excitation process, demonstration that large-amplitude seiches can derive their energy from the tide-producing forces, by way of tidal currents and internal waves, suggests the possibility of eventually predicting them.

It is also important to consider the global significance of this phenomenon. For example, the same mechanism appears to be responsible for harbor seiches at Puerto Princesa in the Philippines (Giese and Hollander 1987). There are many similarities between phenomena associated with seiche activity along the south coast of Puerto Rico and at Puerto Princesa: both sites are on the shores of marginal seas; seiche activity has a distinct seasonal distribution; and the seiches appear to be excited by deep-sea internal waves. Many other published reports have described large-amplitude seiches along the coasts of other marginal seas, e.g., the "rissagues" of the Balearic Sea of the western Mediterranean (Tintoré et al. 1988), the "seebären" of the Baltic Sea (Defant 1961), the "abiki" of the Sea of Japan (Hibiya and Kajiura 1982; Akamatsu 1982), and the Longkou Harbor seiches of the Gulf of Bohai (Wang et al. 1987). These waves, like those we have studied, have a pronounced seasonal distribution, and they may occur when the sea and wind are calm. We suggest that in these and other locations where large-amplitude aseismic seiches occur, a study of the fortnightly distribution of seiche activity may indicate a tide-generated internal-wave causation. This mechanism might also account for the "tidal ringing" of the sea near the Shetland Islands reported by Cartwright and Young (1974).

7. Summary

Analysis of a 10-year time series of digital tide data from Magueyes Island, Puerto Rico, demonstrates that sea-level variance at the fundamental normal-mode frequency of the shelf has a pronounced fortnightly distribution with a maximum occurring 6–7 days after new and full moon. Furthermore, fortnightly variance is maximum when the preceding new or full moon coincides with perigee, and minimum when they coincide with apogee. We interpret these results to indicate that the oscillations are coastal seiches, most likely excited by deep-sea tide-generated internal waves. Based on travel time estimates, the internal waves probably form southeast of the southern Aves Ridge.

Simultaneous measurements of coastal sea-surface and shelf-break current oscillations obtained during the first of two field experiments verify that the oscillations are coastal seiches. Measurements of temporal changes in the vertical temperature structure indicated, during the first experiment, patterns suggesting large-amplitude unbroken internal wave pulses approximately 6 km offshore of the shelf break, and during the second experiment, patterns suggesting internal surf at a distance of about 2.3 km from the shelf break. However, the expected levels of seiche activity did not occur during the second experiment, showing the importance of some as yet undetermined factor(s) involved in the seiche generation process.

We have noted a similarity between the seasonal patterns of seiche activity at Magueyes Island and seasonal patterns of Caribbean sea-surface slope, and we suggest that this relationship may indicate that either the depth of the mixed layer at the shelf break, or the strength of the Caribbean current, or both, plays an important role in the transfer of energy from tides to seiches. More detailed observations are required to elucidate the coupling processes.

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