Low-Frequency Seiche in a Large Bay

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ABSTRACT
Short-term observations of sea surface elevations $\eta$ along the 10-m isobath and long-term observations inside and outside of a large bay (Monterey Bay, CA) were obtained to describe the nodal structure of the modes 0–3 seiches within the bay and the low-frequency (<346 cpd) seiche forcing mechanism. The measured nodal pattern validates previous numerical estimates associated with a northern amplitude bias, though variability exists across the modal frequency band, particularly for modes 0 and 1. Low-frequency oceanic $\eta$ white noise within seiche frequency bands (24–69 cpd) provides a continuous resonant forcing of the bay seiche with a $\eta^2$ (variance) amplification of 16–40 for the different modes. The temporal variation of the oceanic $\eta$ white noise is significantly correlated ($R^2 = 0.86$) at the 95% confidence interval with the bay seiche $\eta$ that varies seasonally. The oceanic $\eta$ white noise is hypothesized as being from low-frequency, free, infragravity waves that are forced by short waves.

1. Introduction
Seiche is the resonant response that develops in enclosed or semiclosed basins forming standing long waves with frequencies that typically range from 48 to 2880 cpd (periods 0.5–30 min). They are most common in small harbors (Okihiro et al. 1993; Okihiro and Guza 1996; among others), where the sea surface elevation $\eta$ in the harbor is amplified relative to the $\eta$ outside of the harbors. Okihiro and Guza (1996) measured $\eta$ inside and outside of the various harbors and found that the mode 0 (grave or Helmholtz mode) variance amplification could be as large as 200. Oscillations that occur at nonseiche periods are suppressed. The period of the seiche oscillation $T$ is dependent upon the basin shape (e.g., rectangular, semicircle), effective basin length $L$, and effective basin depth $h$. There are a number of simple geometric descriptions for different modes provided by Wilson et al. (1965). The period of motions required to force the seiche oscillation is the natural period of the seiche oscillation, which increases with the basin length.

Seiche is observed on large-scale basins with frequencies ranging between 16 and 72 cpd, such as Monterey (M) Bay, California (~38 km wide, ~23 km long). Breaker et al. (2010) set out to explain the origins of seiching oscillations in Monterey Bay through numerical modeling and a few single-point observations of $\eta$ within the bay. A detailed historical overview of the seiche investigations within the bay is provided. Most of the previous work has focused on field observations at the ends of the bay (i.e., Monterey and Santa Cruz) owing to the presence of long-term tidal stations (Wilson et al. 1965; O’Connor 1964; Raine 1967; Lynch 1970; Robinson 1969). Breaker et al. (2010) determined that the seiche excitation decays within a few cycles implying the system is moderately to strongly damped. Surprisingly, considering the damped nature of the bay, Breaker et al. (2010) found that the seiche oscillations were continuous in their response throughout the year. This continuous nature was a focal point of their research, with emphasis on the potential forcing mechanism(s) that could provide a year-round response in this relatively low-frequency band, which is required owing to the large size of the basin. A number of plausible mechanisms were suggested, but the exact mechanism remained undetermined. In the end, they hypothesized that many mechanisms may be responsible allowing for a continuous response. The goal herein is to build upon the foundation of Breaker et al. (2010) by explaining the
continuous forcing mechanism of the seiche. Breaker et al. (2010) suggested diurnal winds and tides that are continuous in the bay, but these mechanisms occur at frequencies much lower than the seiche frequencies. Here, we explore mechanisms that occur in the same frequency band.

The most appropriate method for evaluating the seiche forcing and response is by measuring $\eta$ inside and outside of the bay, similar to efforts described by Okihiro et al. (1993) and Okihiro and Guza (1996), and this is one of the missing pieces in the analysis by Breaker et al. (2010). In general, obtaining $\eta$ outside of a small harbor system is easier than outside a large bay owing to its relatively shallow depth and close proximity to the entrance. For Monterey Bay, this requires a sensor deployed far offshore in relatively deep water. Fortunately, as part of the National Oceanic and Atmospheric Administration (NOAA) tidal network (www.tidesandcurrents.noaa.gov), long-term $\eta$ are measured at the Monterey pier in Monterey, California, and the Oil Platform Harvest (OPH) station, California. The OPH station is unique as it is located approximately 13 km off the coast on an oil platform in 204-m water depth and 270 km south of the mouth of Monterey Bay (Fig. 1). Although not directly offshore of Monterey Bay, OPH is assumed to provide a reasonable measure of $\eta$ outside of the bay and away from coastal interference. The NOAA Monterey tidal station provides $\eta$ inside the bay. The amplification and forcing of the low-frequency seiche $\eta$ will be discussed using these two stations.

In addition, Breaker et al. (2010), through numerical modeling, confirmed the nodal structure ascertained by Wilson et al. (1965), who used numerical approximations to the one-dimensional equations of motion and continuity. Numerical results indicate a northern amplitude bias and a nodal structure that is asymmetric. However, there is limited synchronous field validation of the seiche nodal structure and amplitude asymmetry in the bay, so a short-term experiment was designed to measure the nodal structure with an array of pressure sensors deployed along the 10-m isobath in the bay.

2. Experiment

Sea surface elevation was obtained from 13 pressure sensors sampling at 1 Hz deployed along the 10-m water depth contour from Monterey to Santa Cruz for 11–18 October 2013 (Fig. 1). The straight-line distance between Santa Cruz and Monterey is 38 km. The location for each pressure sensor was chosen such that they were located at opposing antinodes for modes 0–3, as described from model results by Breaker et al. (2010). The amplification of the seiche is largest at the shoreline and decays seaward (Wilson et al. 1965). The 10-m isobath was chosen as the appropriate water depth for deployment, as it is located seaward of the surf zone but close enough to the shoreline to take advantage of shoreline amplification. In addition, 6-min $\eta$ obtained from the NOAA tidal stations at Monterey, California, for 2011/12 and Oil Platform Harvest, California...
number 9 411 406), for 2004–13 are analyzed to describe long-term seasonal trends. M represents the long-term observations of the bay seiche response, and OPH represents the long-term oceanic forcing outside of the bay.

3. Results

a. Short-term observations: Spatial structure

Auto- and cross-spectral estimates of $\eta$ were computed for the 13 stations using a 1.52-day Hamming window with 50% overlap resulting in 23 degrees of freedom (DOF) and 0.66-cpd frequency resolution (Figs. 2–3). The cross-spectral $\eta$ estimates are relative to $\eta$ measured at station 1 in the northern part of the bay (Fig. 1). Frequency bands of autospectral energy estimates are observed for the different seiche modes, based on the Breaker et al. (2010) suggestion: mode 0 is 24–28 cpd; mode 1 is 37.7–41.7 cpd; mode 2 is 50.7–54.7 cpd; and mode 3 is 64.9–68.9 cpd. The spectral estimates for the stations are subdivided into northern (solid lines, stations 1–6) and southern (dashed lines, stations 7–13) sections of the bay (Fig. 2).

For mode 0, the autospectral energy decreases from north to south (Fig. 2) highlighting the northern bias (Wilson et al. 1965; Breaker et al. 2010). There are several spectral peaks within the mode-0 frequency band and the transition between mode 0 and mode 1 is not obvious in the autospectral estimates. The mechanism responsible for the various peaks is unknown but may explain the differences in seiche periods found by previous investigators (Wilson et al. 1965; O’Connor 1964; Raines 1967; Lynch 1970; Robinson 1969; Breaker et al. 2010). The coincident (co)spectrum of the cross-spectral estimate defines the in-phase portion of the cross spectrum and highlights the transition between mode 0 and mode 1. When the cospectral values become negative for the southern stations for mode 1, it implies 180° out-of-phase standing wave response between the northern and southern antinodes (Fig. 3). Note the quadrature spectral estimates (not shown) are orders of magnitude smaller than the cospectral estimates, which also support the standing wave pattern. There is asymmetry in energy across the mode-1 frequency band that has both a northern and southern bias. For the northern antinode, the variance is larger at low frequencies within the mode-1 frequency band (Fig. 2), whereas variance is larger for the southern antinode at higher mode-1 frequencies. Energy is reduced in the mode-2 and mode-3 bands, and the sign of the cospectral estimates varies as

![Fig. 2. Autospectral estimates relative to station 1 at Santa Cruz for stations 1–13. (a) Stations located in the northern part of the bay and (b) stations located in the southern part of the bay. Gray shading represents 95% confidence intervals.](http://journals.ametsoc.org/doi/pdf/10.1175/JPO-D-14-0169.1)

![Fig. 3. Cospectral estimates relative to station 1 at Santa Cruz for stations 1–13. Stations located in the northern part of the bay are represented by solid lines, and stations located in the southern part of the bay are represented by dashed lines. Gray shading represents 95% confidence intervals.](http://journals.ametsoc.org/doi/pdf/10.1175/JPO-D-14-0169.1)
a function of station location within the standing wave nodal pattern. Wilson et al. (1965) suggested that the seiche pattern in the bay might be separated into two halves, owing to the presence of the Monterey Submarine Canyon. However, the data support a large-scale trend consistent with seiche patterns for the entire bay.

The spatial structure of the covariance $\sigma_{\eta_1,\eta_2}$ is computed by

$$\sigma_{\eta_1,\eta_2} = \sqrt{\text{real}(G_{\eta_1\eta_2})} \, df,$$

where $G_{\eta_1\eta_2}$ is the cospectral $\eta$ estimates (Fig. 3) at station 1 and station $X$ (1–13) within the seiche mode-0–3 frequency bands. The $\sigma_{\eta_1\eta_2}$ are compared against the model results by Breaker et al. (2010) (Fig. 4). The model variances are visually ascertained from Fig. 11 in Breaker et al. (2010), where the model results had a relatively coarse color scale resulting in a coarse variance resolution for comparisons. Negative values were assigned to alternating antinodes based on the sensor 1. The model estimates are an order of magnitude lower than the field observations. Regardless of the difference in magnitude, the nodal pattern and northern bias of the $\sigma_{\eta_1\eta_2}$ are similar to the model estimates.

b. Long-term observations: Continuous forcing

Autospectral estimates using a 25.6-h Hamming window with 50% overlap were computed for the same 2-yr (2011/12) records for M and OPH sea surface elevations resulting in 1370 degrees of freedom. There are significant energetic spectral peaks for the seiche modes in the M spectrum (Fig. 5a). Note that the 95% confidence interval is less than thickness of the lines in Fig. 5. The spectral energy between M and OPH is statistically independent for $f > 10$ cpd (Fig. 5a). The lowest-frequency spectral energy is associated with the tides and inertial motions (1.2 cpd for M) followed by a valley and then an increase for $f > 10$ cpd where the seiche energy for M occurs. The variance amplification, which is the M spectrum divided by the OPH spectrum, is approximately 16–40, where mode 2 is the largest (Fig. 5). In general, the grave, mode-0 amplification tends to be the largest. However, the nodal structure in the bay and the location of the M sensor results in the largest amplification for mode 2 (Breaker et al. 2010), whereas mode 0 is largest in the northern part of the bay.

The background spectral energy between modes, which is not related to seiche, is also elevated between OPH and M, with an amplification of approximately 10–100.
The shoaled energy goes as $h^{-1/2}$ (i.e., Green’s law), assuming a shallow-water wave. The shoaling factor for a depth of 208 (OPH) to 10 m (M) is $\sim 5$, consistent with the nonresonant white-noise amplification.

The standard deviation $\sigma$ of the total seiche is computed by

$$\sigma_{\text{seiche}} = \sqrt{\int G_{\eta\eta} \, df},$$

where $G_{\eta\eta}$ is the spectral energy integrated across all frequency bands (modes 0–3, 24–69 cpd) for both M and OPH. Running spectral estimates of $G_{\eta\eta}$ were computed every 12.8 h, using a 51.2-h total window with a 12.8-h hamming window with 50% overlap (Fig. 6a). There is a large spike around day 70, which is associated with the Japanese earthquake that occurred on 11 March 2011 (Figs. 6a,b). The magnitude 9.0 earthquake that occurred off the east coast of Japan induced a tsunami in the Pacific Ocean. There were a number of aftershocks that preceded the initial earthquake. The tsunami was observed in $\eta$ at OPH and M, both of which had an initial impulse that decayed over the next few days (Figs. 6b,c). The amplitude was larger in the bay. The temporal variation in amplitude is coincident at M and OPH (Fig. 6b), indicating the excitation and decay of the seiche are synchronous with the forcing outside of the bay, consistent with Breaker et al. (2010). The linear regression between $\sigma_{\text{ocean}}$ and $\sigma_{\text{bay}}$ results in a $R^2$ value of 0.86 with a slope of 3.5 (Fig. 6d) and is significantly correlated at the 95% confidence level. In summary, the ocean $\eta$ white noise at OPH is forcing the seiche within the bay.

Breaker et al. (2010) observed seasonal variability with seiche $\eta$ in the bay. To examine seasonal variability, the oceanic white-noise $\eta$ amplitude within the seiche frequency band is averaged per month from 2004 to 2013 at OPH ignoring the tsunami. A seasonal trend is observed at the 95% significant level (nonoverlapping confidence intervals between summer and winter in Fig. 6a). The amplitudes are largest in the winter months and decrease in the summer and early fall.

4. Discussion

These observations suggest that the low-frequency component of oceanic white noise is the source of the forcing for the seiche observed in Monterey Bay. Within the last decade, there has been an increase in efforts studying the origin of the long-period, small-amplitude oceanic sea surface oscillations and their behavior, which have been previously overlooked owing to the fact that their amplitude is $O$(mm). This increase in focus is related to understanding Earth’s continuous hum discovered by seismologists (Nawa et al. 1998). Initially, it was believed the hum was related to atmospheric pressure forcing with seasonal (Tanimoto and Um 1999) and annual (Nishida et al. 2000) variations. The current consensus is that the hum of Earth’s subaqueous crust is driven by free infragravity (IG) waves (Rhie and Romanowicz 2004; Webb 2007; Uchiyama and McWilliams 2008; among others). IG waves are forced by nonlinear
interactions between directionally spread, short waves (sea and swell) that occur in the 3456–12096-cpd frequency band (7–25-s periods) that radiate away from the coast and travel around the ocean basins (Herbers et al. 1994, 1995; among others). Based on these studies, it is plausible that small-amplitude, free IG waves in the seiche frequency bands are a component of oceanic white noise, and they are what is forcing the seiche in Monterey Bay and likely elsewhere.

Though there is agreement on the idea that free IG waves are a component of oceanic white noise, the question becomes what is the lower-frequency limit for these free IG motions in the open ocean. Nearshore scientists typically discuss IG motions in the 346–3456-cpd frequency band (Herbers et al. 1994, 1995; among others), which has been shown to be responsible for seiche in most small harbors, owing to their shorter basin length and shallower depths (Okihiro et al. 1993; Okihiro and Guza 1996). To examine sources of energy for Earth’s hum, Rhie and Romanowicz (2006) focused on 346–3456-cpd free IG waves. Webb (2007) considered lower frequencies in the ocean, looking at 86.4–864-cpd free IG waves, and Uchiyama and McWilliams (2008) evaluated free IG waves down to 8.64 cpd. The observations herein show that Monterey Bay is oscillating at 24–69 cpd, which is around the lower-frequency end for most studies but well within the band of interest as described by Uchiyama and McWilliams (2008).

Here, the low-frequency IG band is defined as 8.64–346 cpd, and the high-frequency IG band is defined as 346–3456 cpd. Uchiyama and McWilliams (2008) numerically modeled IG waves (>8.64 cpd), with emphasis on the low-frequency portion, and found that free IG waves are a mechanism that provides background oceanic $\eta$ white noise. The modeled free IG waves are on the order of millimeters in amplitude, consistent with observations (including observations at OPH). Herbers et al. (1995) evaluated the free and forced high-frequency IG waves at a number of sites, including OPH. Their measurements extended to a lower-frequency limit of 43.2 cpd, which is in the middle of the Monterey Bay seiche frequency band. They found that the high-frequency IG free waves represented most of the IG energy and were correlated with the short waves (Fig. 3 in Herbers et al. 1995). In addition, the low-frequency IG waves (considered as shelf waves in their paper) for OPH were also correlated with short waves, which they related to OPH as being located on narrow continental shelf. They also found small levels of spectral energy at OPH at both the low and high IG wave frequencies, which are consistent with measurements described here. It is hypothesized that these low-frequency motions are IG waves, which are either leaky or coastally trapped edge waves.

In the surf zone, MacMahan et al. (2010) found that surfzone motions within the low-frequency IG band produced vortical circulation patterns, where gravity was not the restoring force. This description was because most of the nonlinear short-wave interactions that force low-frequency IG motions reside in the nongravity restoring portion of the frequency–wavenumber spectrum. However, there is a narrow aperture at low wavenumbers within the gravity portion of the frequency–wavenumber spectrum that allows for the development of low-amplitude surface gravity waves, as described by Uchiyama and McWilliams (2008). The low-frequency IG sea surface elevations were considered negligible because the amplitude of these waves was so small, $O$(mm). However, these low-frequency IG waves are responsible for amplifying $\eta$ in Monterey Bay and likely in other bays worldwide.

Godin et al. (2013) described the oceanic $\eta$ white noise as diffusive, owing to the wide spatial distribution of free IG waves that form a noncoherent signal. Even though the free low-frequency IG motions travel across the ocean from various shorelines (Rhie and Romanowicz 2004; Uchiyama and McWilliams 2008), there is a spatial dependence, where the IG energy is higher closer to the source, which is the short-wave energy breaking at the shoreline (Uchiyama and McWilliams 2008). This relationship can be seen in the statistically significant seasonal trend in both the significant short-wave height $H_{\text{mo}}$ measured outside of Monterey Bay, which is averaged per month for 2004–13 (Fig. 7b), and in the oceanic white noise (Fig. 7a), where the subscript $\text{mo}$ represents significant wave height. The 12-month averaged linear square correlation $R^2$ between $H_{\text{mo}}$ and the oceanic white noise is 0.84, which is statistically significant at 95%. This does not account for the short-wave frequency–directional distribution in the nonlinear forcing of the oceanic white noise (Herbers et al. 1994; Uchiyama and McWilliams 2008).

In addition to the NOAA tidal network, there is the Deep-Ocean Assessment and Reporting Tsunami (DART) network, which records the bottom pressure signature of long waves every 15 min. The Nyquist frequency is 48 cpd, which is not ideal for analyzing the higher seiche modes found in Monterey Bay. However, DART buoy 46411 is located in 4259-m water depth, approximately 280 km from land and 520 km northwest of the mouth of Monterey Bay, and provides another deep-water estimate of the oceanic white noise for the seiche frequency band. The seasonal trends in $\sigma_{\text{DART}}$ seiche are consistent with OPH (Fig. 7a). However, the amplitude of $\sigma_{\text{OPH}}$ is higher by a factor of 2 because of shoaling.
(Fig. 7a) and may also be related to the truncation of the seiche frequency band. Surprisingly, the 12-month averaged $R^2$ value between DART and OPH is lower at 0.57, which is still statistically significant at 95%. It is believed that the difference in location and potential differences in local storms lower the $R^2$ value.

Another common hypothesis for the generation of oceanic white noise is atmospheric pressure perturbations. Atmospheric pressure perturbations are often suggested for forcing a multitude of low-frequency ocean motions, such as atmospheric-induced tsunamis (Monserrat et al. 2006), grave mode edge waves (Munk et al. 1964), background shelf energy (Munk et al. 1956), and seiche in Monterey Bay (Wilson et al. 1965). Barometric pressure measurements were obtained at M for 2004–13, which were converted to decibars (meters) assuming the density of seawater. The barometric pressure autospectrum (Fig. 5a, circles) is at least an order of magnitude smaller than the $h$ spectra at OPH and M. It is noted that $h$ at M and OPH were measured using an acoustic altimeter so that $h$ and atmospheric pressure are independent. There is a statistically significant seasonal trend in barometric pressure (Fig. 7a) consistent with trends in white noise at OPH ($R^2 = 0.77$). Barometric pressure fluctuations are not considered a significant forcing mechanism owing to their amplitude being an order of magnitude smaller.

5. Summary and conclusions

Owing to the continuous nature and low frequency of the seiche response in Monterey Bay, California, long-term sea surface elevations from NOAA tidal stations were evaluated to understand the resonant amplification of the bay seiche to external oceanic forcing and to elucidate the oceanic forcing mechanism. It was found that there was a significant correlation ($R^2 = 0.86$) between the oceanic $h$ and bay $h$, suggesting the oceanic forcing outside the bay is responsible for the seiche. The amplification is approximately 16–40 for modes 0–3, which is the same order of the grave mode (mode 0) amplification observed in small harbors (Okihiro and Guza 1996). The oceanic forcing oscillations within the seiche frequency band are considered oceanic white noise, which are often overlooked because the amplitudes are $O$(mm). These long-period, small-amplitude oscillations are hypothesized to be free low-frequency (8.64–346 cpd) infragravity waves (Uchiyama and McWilliams 2008) but for frequencies lower than typically described as infragravity (346–3456 cpd) waves (Herbers et al. 1995). There is a statistically significant seasonal trend in the ocean white noise correlated with increases in short-wave energy ($R^2 = 0.84$), which are largest in the winter months. The oceanic white noise is also correlated with atmospheric pressure perturbations ($R^2 = 0.77$), but the barometric pressure spectral energy is orders of magnitude lower.

Owing to the continuous nature of the seiche response in Monterey Bay, California, a short-term experiment was designed to measure the spatial patterns of the modes 0–3 oscillations guided by the modeling results by Breaker et al. (2010). The cospectral estimates for the array of sea surface elevations highlight the frequency bands for the different modes. The spectral energy...
across the modal frequency bands is not equal and indicates northern and southern bay differences. The nodal pattern of the measured covariance estimates was consistent with the modeled nodal pattern by Breaker et al. (2010).

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