os-2015-80 January 2, 2015

Continuous seiche in bays and harbors,

Park J., MacMahan J., Sweet W. and Kotun K.

Response to Reviewer #1.

We are grateful to the reviewer for their careful and critical review of the manuscript. The revised manuscript incorporating their comments results in a more accurate description of the problem, provides additional context for the reader, and improves the clarity of the presentation. In particular, the reviewers additional citations refute the assertion in the original manuscript that continuous seiche had not been clearly recognized in the literature, and we thank the reviewer for lending their expertise in correcting this error.

Please note that the reviewers comments are listed below, with our responses indented under each comment.

General Comments

Looking at data from only two countries does not help in coming to ’global’ conclusions. The authors do not seem to have made much effort to find any other data...

It would be preferable to have data from all around the globe, not solely the Pacific basin. However, the suggested mechanism of tidally-forced shelf-resonances is not basin, country or tide gauge specific, and good agreement between the estimated and observed resonances across varying shelf domains suggests that the underlying physics are robust and independent of observation specifics or location.

Regarding other data, significant effort was expended to obtain and process the presented data. While it is always desirable to have a preponderance of data and results, when clear and consistent results are obtained as here, one needs to consider the trade off of time and effort balanced by competing demands for one's time and the potential of diminishing returns in supporting the primary hypothesis. A conundrum that we all face at one time or another.

This should be understood in the context that this work is a follow-on to work in Monterey Bay wherein continuous seiche has been recognized for some time and well characterized. Larry Breaker wondered whether a global mechanism for continuous seiche could be identified, motivating the present work. As mentioned below, we examined 6 additional bays/harbors and found the tidally-forced shelf-resonance at each one. So out of 7 basins we have examined, we found the mechanism in each one. This was not a trivial undertaking in terms of time and effort. One is then faced with a decision as described above. Will a coastal basin be identified where this is not the case? The answer must surely be yes. Yet given the positive results to a simple, but apparently not widely-known hypothesis, it seems reasonable to publish the findings.

There is also confusion in the text on whether ’continuous’ or ’continuous-tidally forced’ seiches are being discussed.

> Thank you for this comment. We have modified the text to clarify the distinction.

The authors also make the claim that continuous seiching is a new observation (p. 2364) but that is not really true and I found the literature review inadequate and rather US-centric.

> As mentioned above, we are grateful for the literature suggested by the reviewer which clearly refutes the assertion of continuous seiche as only recently recognized. The paper has been rewritten including additional references suggested by the reviewer providing a more accurate description of the problem.

The paper by Wijeratne et al. (p.2363) is misrepresented. The main points in that paper are that the seiches on the east coast of Sri Lanka vary over a fortnight but are strongest at neaps due to it taking a week for the internal tides to travel from the Andaman Sea. Those on the west coast have no fortnightly modulation but rather a diurnal one.

> Thank you for this comment. Pertinent to our discussion we are interested in identifying recorded instances of continuous seiche, and their potential forcings. We believe that the observations in the original manuscript (pg 2363, 16-21) are justified in Wijeratne et al., so this is perhaps a matter of interpretation rather than misrepresentation.
>
> Considering the first sentence: “Wijeratne et al. (2010) observed that seiches with periods from 17 to 120 min were continuous persistent throughout the year at Trincomalee and Colombo, Sri Lanka, finding a strong fortnightly periodicity of seiche amplitude at Trincomalee, but no discernible seasonal variability at Colombo.” These are straightforward interpretations of the cited content, although it does seem a bit awkward and uninformative to discuss fortnightly periodicity and seasonal variability in the same sentence. The latter portion really serves no purpose to the argument or following discussions, and has been removed.
>
> The second sentence reads: “The fortnightly modulations of seiche energy were attributed to forcing by astronomical tides, while the overall seiche generating mechanisms were thought to include diurnal weather, tides and currents.” Here, we see the potential of a perceived inaccuracy as there is no distinction between astronomical tides and internal tides, of which the latter is primary issue/mechanism addressed by Wijeratne et al. We have changed this to remove any ambiguity.
>
> It is notable that Wijeratne et al. not only provide evidence of continuous seiche, but also attributed the 74 minute seiche at Colombo and the 54 minute period at Galle to tidally-forced shelf resonances (section 3.1, pg 5). They then investigated seiche amplitude variations suggesting that diurnal modulations along Western Sri Lanka could be weather forced. This view is consistent with the one we are suggesting, that tidally-forced shelf resonances are a primary contributor to continuous coastal seiche, while internal waves (which clearly can be a primary forcing), weather and other forcings serve to modulate seiche amplitudes if they are

sustained by shelf-resonance. Based on this, we have rewritten this section highlighting the recognition of continuous seiche and tidal shelf-resonance by Wijeratne et al.

The first sentence of section 1 could maybe refer to Airy's study of the seiche at Malta which I think is often said to be the first seiche to be identified in the ocean rather than a lake.

Thank you for the suggestion. It is good to have additional context/reference for the reader, and we have added the citation as recommended.

2363, 19 – Colombo

Corrected.

2364, 18-22 - this is an amusing sentence. Have the authors never looked at tide gauge charts? If they had they would have seen that most of them have high frequency signals superimposed on the tide, that are most easily spotted at the turning points, through which a pencil line had to be drawn in the old days prior to being digitised for tidal analysis. In some ways electronic data loggers have been a backward step.

While the intention was not to induce amusement, it is always nice to bring a bit of levity and enjoyment to the reader! We suppose the question of whether we have looked at tide gauge charts is essentially rhetorical, intended to emphasize the reviewers amusement. Surely the reviewer is not suggesting that in general high frequency signals superimposed on the tide are seiche.

Regarding the opinion that in some ways electronic data loggers have been a backward step, we work with 'old-school' tide observers who hold the same opinion, however, the current state-of-the art in water level measurement and dissemination is rather remarkable, so several steps forward. An interesting discussion to be held under a different forum.

2365, 6 - as mentioned, I find 6 examples in only 2 countries a bit limited for making global conclusions.

As discussed above, we believe that good agreement between the estimated and observed resonances across the varying shelf domains (island and coastal) suggests that the underlying physics are robust and independent of observation specifics or location. Since such shelf conditions exist around the globe, it does not seem an unreasonable suggestion.

Additionally, subsequent to the initial review of the article we also have identified a shelf-resonance in Biscayne Bay of the northern Atlantic. In short, out of the 7 harbors/bays examined, we have found shelf-resonance seiche at each location. It would be folly to assert that such forcing is truly 'global' in the context of being found at every coastal location on the globe, but it is supportive that at every location we have examined, it has been observed. Further, the mechanism is compelling simple and ubiquitous, and, the energy analysis at Monterey suggests it to be the viable candidate at that location whereas internal waves are not.

17 - it would be good to say in the text here where (which countries) these bays are. Also in the figure 1 caption or the reader has to struggle with the lats and lons and his geographical memory.

> We have clarified the locations.

2366, 14 - at Monterey and five other

> Changed.

18 - I can see what is claimed at Kahului. But I can't for Honolulu - that is just green (zero) around 0.2 min through the plot. Maybe you mean about 0.8 min?

> Thank you for the correction.

22 - 'A close examination'. Is the reader supposed to take this on trust? It is fundamental to a main claim of the paper. Are you referring to what comes much later in Figure 5? If so I would say so.

> This is not the same as the amplitude-modulated modes in Figure 5. If one looks at the Kahului spectrogram at 2 minute periods, there is an distinct sine-wave modulation of the resonance periods (frequencies) versus time, e.g. the resonances themselves are frequency-modulated. Since this was not clear to the reviewer, we have changed the text to specifically exemplify the 2 minute mode.

In Figure 2 the 'vertical bands associated with increased energy'. I think I would say that does not mean more percentage of energy above and below the main band but rather a stronger band overall and then it is an artefact of the colouring.

> Yes, the vertical bands are instances of increased overall energy, although not uniform increases across the spectrum as in the addition of white noise, but rather the canonical ocean wave spectrum under different sea states.

Also in Kahului, middle right of Figure 2 - the blue band at 0.2 min seems to have streaks that point to the bottom left. What are they?

> These are temporospatial energy signatures of swell-events, as mentioned in section 3 Continuous Modes.

p2366 - it would good to know what the tidal range is at these 6 places and the tidal form factors.

> We have added this information in the text and table 1.

2367, 12 - I would add ’identified in Figure 3’ after ’spectra’

Changed.

23-26 - there are many statements like this associating a peak in the spectra with some feature of the bay which you can’t possibly know for sure, without at least the use of a local model. Also p2369, 1 and many other places. And 2371, 6. 2372, 6.

If by a model the reviewer is referring to the basic physics of shallow-water wave propagation and wave resonance as outlined in lines 10-15, we agree. If the reviewer is suggesting that a numerical model is the only method to attribute observed water level resonances to spatial features of a bay or harbour, then we respectfully disagree. For example, in the United States the U. S. Army Corps of Engineers is responsible for harbor design, and has a long history of making such attributions based on observation and basic physical principles. For example, work from the early 1960's where numerical models are being vetted against observed modes that have been analytically attributed can be found here: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0684953

2368, 13 ’power spectra in Figure 3’

Added.

22 - affine? define?

We are referring to a mathematical affinity, a linear mapping between two states, which in this case is sensible in the discussion of dynamical (modal) behavior preservation. We believe that the typical OS reader is sufficiently mathematically erudite and familiar with the term.

2371, 6. What is a pier mode? Again these are plausible statements but you can’t know for sure.

A pier mode refers to a standing wave supported at one boundary by a pier structure extending into the water.

2372, 24-26 - so far you have considered just the 1-d dependence of a shelf mode and so its frequency. To write this sentence you must have an idea of its long-shelf dependence. What is it, in general terms? 2373, 1-4 ditto.

In general the along-shelf modulation is not something that we can consider without a numerical model, or a coherent set of along-shore water level observations. We were able to marginally address it at one location since we have a coherent set of measurements at Hawke and Poverty bays as discussed in section 4.9 Hawke and Poverty. Each coastal location can experience modulations of transverse shelf-waves by along-shore traveling modes (edge-waves), and of course, variable bathymetry will induce along-shore spatial dependence, and there are certain to be other influences from internal waves, atmospherics etc.

2373, 10 - I don't understand 'shelf mode amplitudes'. There are several modes per site, there is not a unique frequency as I understand it (as you mention later for combining the metamodes), so presumably this is the amplitude of several modes combined or a band?

> We apologize for the confusion. As stated in the manuscript "Fig. 5 plots time series of the shelf-mode amplitudes from the spectrograms shown in Fig. 2". So these are amplitudes over time of the single shelf-mode at each of the stations. Modes other than the shelf-mode are not included. Referring to an excellent paper suggested by the reviewer: Woodworth et al. (JGR 2005 doi:10.1029/2004JC002648), our Figure 5 is the same metric as their Figure 5 "timeseries of seiche amplitude". Pertinent differences are that our amplitudes are determined by spectral analysis, that we present shelf-mode seiche specific to multiple stations, and that we have determined a modal decomposition of the timeseries of seiche amplitude. We have rewritten this to clarify the issue.

I think Figure 5 is very nice and I would stop there. There are clearly fortnightly dependencies which are the object of the paper. I have a problem with the metamode text and onwards with the energetics. I get the general ideas but it is a bit vague what you are doing and for someone unfamiliar with EMD, for example, it won't mean much. Anyway you say later you don't understand the metamodes properly yourself. I would drop the later tables and figures in the paper and the energetics discussion of Section 6, and maybe use them for writing a more theoretical report in the future.

> We would like to clarify that the fortnightly modes are viewed as supporting evidence for the hypothesis that tidally-forced shelf-resonances can be a primary driver of continuous seiche. Sufficient energy is a fundamental criteria for any source attribution hypothesis, and addresses a very simple question: does the proposed forcing mechanism contain sufficient energy to drive and sustain the observed resonances? For example, internal waves in Monterey Bay (which are quite energetic) had been proposed as a prospective driver of observed seiche, but a simple kinematic analysis shows that this is not possible (Park & Sweet, 2015).
>
> Regarding the metamodes, as above, their fortnightly modulation provides compelling support for the primary hypothesis, and as far as we are aware, it is a novel concept in oceanographic analysis. We suggest that publication of this line of reasoning along with the questions it raises regarding metamode variability is consistent with scientific inquiry and may lead others to advance the state of knowledge. We therefore respectfully decline your suggestion to remove this material.

Section 7 - I think you will find many places where there is near-continuous seiching due to the ambient wind (the findings might not be published but that's a different issue). I would rewrite this to make it clearer you are looking at the tidal associations which are quite nice. Are any of the bays shallow enough to look at the change in frequency of the seiches with the tide? - Table 2 suggests not I guess.

> Please note that as suggested by Reviewer #2, this material now resides in a Discussion section. We have rewritten this material as noted to better relate the tidal hypothesis. Regarding the wind, as you point out it is difficult to conceive of it as a continuous forcing, rather a near-continuous one, and for that reason we do not consider it a candidate for continuous forcing.
>
> Pertinent to the change in frequency, please recall the earlier discussion regarding the 2 minute mode at Kahului, these are exactly as the reviewer suggests, and as noted in the manuscript this has been verified at Monterey (Park and Sweet 2015).

Table 2. Monterey depths - why are 3 listed (harbour, bay and shelf?). Please make it clearer. Others also.

> Thank you for this clarification. Yes, the different depths correspond to representative values over the horizontal dimensions of the respective mode. We have clarified this in the text and the table.

Table 3 caption last line - I would add the estimates are from the nearest peaks in Figure 3. Should the frequency from Merian's formula be the same as for a shelf wave equation solution for a flat shelf?

> Yes, estimates of mode periods from the PSD's are directly from the observed peaks, as marked with triangles in Figure 2. As for an equivalence between Merian's and a wave equation solution, the boundary conditions of the latter will admit multiple solutions that match Merian's simplified geometry estimate.

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Response to Reviewer #2.

> We are grateful to the reviewer for their careful and critical review of the manuscript. Please note that the reviewers comments are listed below, with our responses indented under each comment.

Paper Structure I think the paper structure could be significantly improved. The paper lacks of a method section that help the reader to understand how the analysis will support the main conclusions of the manuscript. Section 3 is a very short section that could be included in Section 2. Also, the authors should consider to discuss/present the results in terms of the bay geometry similarity in order to extend the conclusions of this work to other locations and hence re-organized the material presented in Section 4. Also, the paper lacks of a discussion sections to put in perspective the present findings with respect to previous studies at the same locations. Finally, the conclusions presents a summary and discussion of the paper and hence should be re-written and significantly shortened.

> Thank you for these suggestions to improve the presentation of the paper.
>
> With respect to Section 3 Continuous modes, although it was quite short we feel that it is a primary and distinguishing topic of the paper, and would prefer for it to remain a distinct section. Further, based on the suggestions of Reviewer #1, this section has been clarified.
>
> Section 4 is where we present the spectral analysis and subsequent identification of the shelf-modes, including section 4.2 which explicitly discusses the geometric/dynamic similarities between bays. Although it may be useful to discuss this at the end of section 4 after the individual bays have been analyzed, we feel that it is helpful to present this idea in the front matter, close to the introduction of figure 3 where the dynamic similarities are manifest in the spectra.
>
> Regarding the addition of a methods section, if it were to appear at the front it would be a terse description of the methods used since it seems a bit unwieldy to present in detail mode identification based on the dispersion relation/spectral analysis, the introduction of metamodes via EMD of modal time series, and the kinematic analysis of modal energy. Since the EMD/metamode analysis might be considered an atypical analysis technique it would warrant significant description that may seem laborious without reference to application/results. Nonetheless, we agree that additional description of these overall techniques and their objectives in the front-matter will benefit the clarity of the presentation and have modified the introduction accordingly.
>
> Finally, we have added a discussion section and rewritten the conclusion as suggested.

Resonance analysis
To my knowledge in order to identify resonance it is required the analysis of at least two signals obtained at different locations. These spatially separated signals should have: (i) a highly coherent variance in the water level, (ii) a phase relationship corresponding to a standing wave conditions (cross-spectra of the two signals) and (iii) an amplification of the water level at a given frequency. In order that resonance is demonstrated all of the above must be satisfied. Thus, I encourage the authors to present such analysis (i-iii) at those locations where data is available.

> Thank you for this interesting comment. We agree that a demonstrated amplification is the hallmark of resonance, and that appropriate phase and coherence will exist between the forcing and resonant waves, as well as between resonant waves themselves. We are not entirely clear if the reviewer is suggesting that the forcing (tidally-driven shelf-modes), or the bay/harbor modes themselves should be shown from the data to satisfy these conditions. We will try to address both.
>
> We recall that since resonance is a property of the system, not the forcing, it is not required for the forcing to be at a resonant frequency. Initiation of resonance requires input energy displacing the system from equilibrium, i.e. a pendulum. This is a central argument of the paper: a tidally-driven shelf-resonance, which is not a bay/harbor resonance, provides energy (water level elevation) which drives and sustains the natural bay/harbor resonances.
>
> Another hallmark of resonance is a highly tuned oscillation with a large Q-factor (signal-to-noise ratio) wherein the amplification is nearly singular in frequency. The shelf-resonances at Monterey and Hawke Bays are prime examples. In such cases it is difficult to conceive of geophysical processes that could produce such highly-tuned amplifications other than a structural resonance, and when one considers the close agreement between the physics and observations (now table 4), we suggest that a resonance is the most plausible explanation.
>
> Regarding both the shelf and bay/harbor modes at Monterey, the resonance structure was known for some time based on observations inside the Bay alone without cross-spectral analysis (e.g. Wilson et al. 1965).
>
> So another perspective would be that to 'identify resonance' requires observation of the resonant oscillation and appropriate physical system parameter matching, while attributing the forcing or internal wave structure of a resonance must satisfy the cross-spectral conditions noted by the reviewer.
>
> As noted by Munk the 'harbor paradox' allows for long-waves to be effectively amplified at the tide gauge. Evidence of this is presented in Figure 3 spectra at Honolulu with comparison of the harbor (black) and reef (red) energy at the shelf-resonance period, exhibiting amplification inside the harbor. So there are at least two stages of amplification for this shelf-mode, the mode itself on the shelf, and its amplification inside the bay/harbor. In any case, this is distinct from the natural resonances of the bay/harbor that are excited by the amplified shelf-mode. We are therefore unsure of the utility of demonstrating a coherent phase relationship outside/inside the harbor for the shelf-modes.
>
> The other possibility is demonstration of phase coherence of one of bay/harbor resonances itself across varying spatial locations in a bay/harbor. As noted by the reviewer this requires multiple

sensors within a bay/harbor, which unfortunately is not included in our data.

However, we can analyze the shelf-mode amplification and show that it is indeed a coherent wave between offshore and the tide gauge. A brief analysis as suggested by the reviewer follows below. As noted above, we are unsure if this adds significantly to the results other than as a verification of the harbor paradox since the shelf-mode is not a bay/harbor resonance. If it is felt that this is a constructive addition to the manuscript, we will be glad to add it.

At Honolulu the coherence and phase between the offshore (outside reef) and harbor gauges at the 27.1 minute shelf-mode are:
Phase : 0.1972 rad = 11.3 degrees
Coherence : 0.81, 0.84, 0.88 (lower 95%, Estimate, upper 95%)

Assuming a shallow water wave speed of sqrt(9.81*150) = 38.36 m/s, and noting that the cross-shore distance between the harbour and reef gauges is 1530 m, the propagation delay would be 1530 m / 38.36 m/s = 39.89 s. Temporally, the fraction of a resonance cycle of this propagation delay is 39.89 s / (27.1 * 60) s = 0.025. From the cross-spectral phase estimate the fraction of a cycle phase-delay is 11.3 deg / 360 deg = 0.031. Since there will be a reduction of the wave phase-speed as the wave shoals and encounters friction into shallower waters it is expected that the actual phase delay will be longer than that estimated from linear wave theory (38.89 s). This is consistent with the slight increase of phase-delay observed (cross-spectral data), and even without it, the first-order estimate (2.5%) is not widely different from the observed estimate (3.5%).

Reference

Wilson, B. W., Hendrickson, J. A., and Kilmer, R. E.: Feasibility study for a surge-action model of Monterey Harbor, California, Tech. Rep. 2–136, United States Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, 1965.

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Continuous seiche in bays and harbors

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Abstract. Seiches are often considered a transitory phenomenon wherein large amplitude water level oscillations are excited by a geophysical event, eventually dissipating some time after the event. However, continuous small–amplitude seiches have ~~recently~~ been recognized presenting a question as to the origin of continuous forcing. We examine 6 bays around the Pacific where continuous seiches are evident, and based on spectral, modal and kinematic analysis suggest that tidally–forced shelf–resonances are a primary driver of continuous seiches.

1 Introduction

It is long recognized that coastal water levels resonate. Resonances span the ocean as tides (Darwin, 1899) and bays as seiches ~~(Chrystal, 1906) .~~ (Airy, 1877; Chrystal, 1906) . Bays and harbors offer refuge from the open ocean by effectively decoupling wind waves and swell from an anchorage, although offshore waves are effective in driving resonant modes in the infragravity regime at periods of 30 s to 5 minutes (Okihiro and Guza, 1996; Thotagamuwage and Pattiaratchi, 2014) , and at periods between 5 minutes and 2 hours bays and harbors can act as efficient amplifiers (Miles and Munk, 1961) .

Tides expressed on coasts are significantly altered by coastline and bathymetry, for example, continental shelves modulate tidal amplitudes and dissipate tidal energy (Taylor, 1919) such that tidally–driven standing waves are a persistent feature on continental shelves (Webb, 1976; Clarke and Battisti, 1981). While tides are perpetual, seiches are often associated with transitory forcings and ~~are~~ considered equally transitory. A thorough review of seiches are provided by Rabinovich (2009) wherein forcing mechanisms are known to include tsunamis, seismic ground waves, weather, non–linear interactions of wind waves or swell, jet–like currents, and internal waves. Excepting strong currents and internal ~~waves~~tides, these forcings are episodic and consistent with ~~the~~ a perception that seiches are largely transitory phenomena. However, records of continuous seiche extend back to at least Cartwright and Young (1974) who identified continuous 28 minute seiche in Baltasound, Unst and Lerwick of the Shetland Islands over a 16 week period in 1972. Their source hypothesis consisted of long waves from the North Sea trapped as edge–waves along the island shelf, and they noted large seiche amplitude modulations from fast–moving meteorological fronts.

~~Giese et al. (1990)~~ Internal waves are known to influence seiches as demonstrated by Giese et al. (1990) who analyzed a 10 year time series of six minute data at Magueyes Island, Puerto Rico, noting distinct seasonal and fortnightly distributions of shelf–resonance and seiche amplitude suggesting that stratification and its influence on internal waves generated by barotropic tides are important components of the observed seiche variability. Subsequent work led Giese et al. (1993) to conclude that in locations where strong internal waves propagate to coastal regions, that seiche sustainment is possible, and to question "is this a general phenomenon to be expected wherever large coastal seiches are found, or is it specific to certain locations where large internal waves are known to occur?"

Golmen et al. (1994) studied a coastal embayment near the headland Stad in northwest Norway and identified a permanent seiche superimposed on the semi–diurnal tide concluding that tidal forcing was the only possible energy source of the observed oscillations. Continuing their exploration of internal waves and seiche, Giese et al. (1998) examined harbor seiches at Puerto Princesa in the Philippines finding that periods of enhanced seiche activity are produced by internal bores generated by arrival of internal wave soliton packets from the Sulu Sea. However, as one would expect from soliton excitation, their analysis suggests that these seiches are not continually present.

~~Breaker et al. (2008) noticed that seiches in Monterey Bay are continously present~~Woodworth et al. (2005) studied water levels at Port Stanley in the Falklands islands identifying continuously present 87 and 26 minute seiches with amplitudes of several centimeters. They also noted that amplitudes rise to the 10 cm level typically once or twice each month with no obvious seasonal dependence, and that these seiches have their maximum amplitudes nearly concurrently. Tidal spring-neap dependence was not observed, leading them to reject barotropic or internal tides as a cause, instead, they concluded that rapid changes in air pressure and local winds associated with troughs and fronts are likely driving these seiches.

Persistent seiche around the islands of Mauritius and Rodrigues was observed by Lowry et al. (2008) with distinct fortnightly and seasonal amplitude variations along the east and southeast coasts, but no fortnightly or seasonal variations along the west coast. Breaker et al. (2008) noticed continously present seiches in Monterey Bay, leading Breaker et al. (2010) to consider several possible forcing mechanisms (edge–waves, long period surface waves, sea breeze, internal waves, microseisms, and small–scale turbulence) and to question whether or not "the excitation is global in nature"~~such that continuous oscillations would be observed in other bays~~. Subsequent analysis by Park and Sweet (2015) confirmed continuous oscillations in Monterey Bay over a 17.8 year record, and presented kinematic analysis discounting potential forcings of internal waves and microseisms while suggesting that a persistent mesoscale gyre situated outside the Bay would be consistent with a jet–like forcing. However, jet–like currents are not a common feature along coastlines and could not be considered a global excitation of continuous oscillations.

Wijeratne et al. (2010) observed ~~that~~ seiches with periods from 17 to 120 minutes ~~were~~ persistent throughout the year at Trincomalee and Colombo, Sri Lanka, finding a strong fortnightly periodicity of seiche amplitude at Trincomalee on the east coast, but no ~~discernible seasonal variability at Columbo~~fortnightly modulation on the west coast, rather a diurnal one attributed to weather forcing. The fortnightly modulations ~~of seiche energy were attributed to forcing by astronomical tides , while the overall seiche generating mechanisms were thought to include diurnal weather, tides and currents~~were strongest at neaps due to it taking a week for internal tides to travel from the Andaman Sea. It is notable that Wijeratne et al. (2010) attributed the 74 minute seiche at Colombo and the 54 minute period at Galle to tidally–forced shelf–resonances.

Most recently, MacMahan (2015) analyzed 2 years of data (2011–2012) in Monterey Bay and Oil Platform Harvest, 270 km south of Monterey, concluding that low–frequency "oceanic white noise" within the seiche periods of 20 to 60 minutes ~~is directly and continuously forcing the~~ might continuously force bay modes. The oceanic noise was hypothesized to consist of low-frequency, free, infragravity waves forced by short waves, and that this noise was of O(mm) in amplitude. So while the term "noise" applies in context of a low amplitude background signal, and the qualifier "white" expresses a uniform spatial and wide range of temporal distributions, the underlying processes are coherent low–frequency infragravity waves. Based on a linear system transfer function between Platform Harvest and Monterey Bay water levels, he concluded that the bay amplifies this noise by factors of 16–40 resulting in coherent seiche. It was also suggested that the highest amplification, a factor of 40, is associated with the 27.4 minute mode, however, as discussed below and in agreement with Lynch (1970), we find that this is not a bay–mode, but a tidally–forced shelf–mode, and find an amplification factor (Q) of 12.9. Further, as discussed below, we find low–frequency infragravity waves may not have sufficient energy to drive the observed oscillations, but are likely a contributor to observed seiche amplitude variability.

~~It seems remarkable that , while tides and seiches have been studied for over a century, seiches have only recently been recognized as continually present, yet to the authors knowledge with exception of the work by MacMahan (2015) and Park and Sweet (2015) , the question posed by Breaker et al. (2010) has not been previously addressed~~The foregoing suggests that coastal seiche are not to be considered solely a transitory phenomena, yet it seems that continuous seiche is not as widely known as its transitive cousin. For example, Bellotti et al. (2012) recognized the importance of shelf and bay–modes to tsunami amplification, ~~yet~~ but considered them to be independent processes, and the comprehensive review by Rabinovich (2009) falls short of continuous seiche recognition by noting that "in harbours and bays with high Q-factors, seiches are observed almost continuously." ~~Perhaps~~

~~the lack of clear recognition of continuous seiche is partly due to the requirement for long term, digital records of coastal water levels capable of precisely resolving small amplitude, long period oscillations, while the episodically forced, large amplitude oscillations are readily apparent, and that such records have only become available in the last few decades.~~

~~Bays and harbors offer refuge from the open ocean by effectively decoupling wind waves from the bay or harbor, although offshore waves are effective in driving resonant modes of bays and harbors in the infragravity regime at periods of 30s to 5min (Okihiro and Guza, 1996; Thotagamuwage and Pattiaratchi, 2014). Even though bays and harbors can appear quiescent in relation to the sea, they can act as efficient amplifiers of long period waves with periods between 5 minutes and 2 hours (Miles and Munk, 1961), and if tidally–forced long period waves from shelf resonances are continuously present, there is potential to continuously excite bay and harbor resonances.~~

The focus of this paper is to present evidence in pursuit of the questions posed by Giese et al. (1993) and Breaker et al. (2010), namely, is there a continuous global excitation of seiche, and what is the source? We find that perpetual ~~bay oscillations~~ seiche are indeed present at six ~~bays~~harbors examined around the Pacific, suggesting that there is a global excitation~~, thereby negating the specific mesoscale gyre hypothesis of Park and Sweet (2015) at Monterey Bay~~. Spectral analysis of water levels ~~allows us to identify resonances from the shelf down to harbor and pier scales, and to identify the~~ identifies shelf–modes at each location as tidally–forced standing waves in agreement with Webb (1976) and Clarke and Battisti (1981)~~. Given the lack of plausible forcing mechanisms based on the analysis of Breaker et al. (2010) and Park and Sweet (2015), we suggest that long period shelf resonances~~, and identifies resonances down to harbor and pier scales.

Decomposition of shelf–resonance time series into intrinsic mode functions (IMFs) allows us to examine temporal characteristics of shelf–resonance in detail, leading to identification of fortnightly tidal signatures in the shelf–modes. An energy assessment of the available power from the shelf–modes as well as the power consumed to drive and sustain observed oscillations in Monterey Bay indicates that shelf–modes are indeed energetic enough to continually drive seiches. In terms of the query posed by Giese et al. (1993), we will suggest that their results are specific to locations where large internal waves are known to occur, and that long period shelf–resonances driven by tides ~~are a primary~~ might constitute a more general excitation of continuous bay and harbor modes~~, while internal waves and free infragravity waves are secondary contributors serving to modulate seiche amplitudes~~.

2 Locations and Data

We examine tide gauge water levels from six bay/harbors shown in figure 1 with the tide gauge location denoted with a star. Monterey Bay is located on the central California coast of North America, Hawke and Poverty Bays on the western coast of the North Island of New Zealand, Hilo resides on the western shore of the island of Hawaii, Kahului on the northern shore of the island of Maui, and Hononlulu on the southern shore of the island of Oahu. Tides at these stations can be characterized as mixed–semidiurnal with mean tidal ranges listed in table 1.

Three of the bays (Monterey, Hawke and Poverty) can be characterized as semi–elliptical open bays with length–to–width ratios of 1.9, 2.0 and 1.4 respectively. We therefore anticipate a degree of similarity between their resonance structures. Bays at Hilo and Kahului are also similar with a triangular or notched coastline, while Honolulu is an inland harbor of Mamala Bay.

Data for Hawke and Poverty bays at the Napier (NAPT) and Gisborne (GIST) tide gauges respectively are recorded at a sample interval of $\mathrm{T_s} = 1$ min, and are publicly available from Land Information of New Zealand (LINZ) at http://apps.linz.govt.nz/ftp/sea_level_data/. Data for Monterey and Hilo at a sample interval of 6 min are available from the National Oceanic and Atmospheric Administration (NOAA) tide gauges at http://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels. In addition to this publicly available data, we also analyze water level data from independent wave studies at Honolulu, Hilo and Monterey sampled at 1 s intervals. At Honolulu data was collected by Seabird 26+ wave and water level recorders using Paroscientific Digi–quartz pressure sensors at two locations, one collocated with the NOAA tide gauge inside the harbour, and the other at 157.865°W 21.288°N outside Honolulu harbor. At Monterey and Hilo data was recorded at 1 s intervals by WaterLog H–3611 microwave ranging sensors co–located with the NOAA tide gauges. Table ~~1~~ 2 lists the approximate bay and harbor dimensions along with the periods of record and sampling intervals.

3 Continuous Modes

~~Breaker et al. (2008) noticed that seiches in Monterey Bay was continuously present over 14 months in 2002 and 2003, motivating Breaker et al. (2010) to contribute a comprehensive review of Monterey Bay oscillations and to question whether such continuous oscillations were peculiar to the bay~~Continuous seiche over periods up to 17.8 years have been observed, but most studies are limited to periods less than a year, one or a few coastal locations, and a single geographic region. In figure 2 we present water level spectrograms at ~~five other bays~~ six locations around the Pacific basin where vertical bands are associated with seasonal or episodic wave energy, and horizontal bands indicate the presence of persistent oscillations. These long–period oscillations appear to have essentially invariant amplitudes suggesting that time varying processes such as weather or waves are not likely forcings. For example, inspection of the ~~Honolulu or~~ Kahului data at periods near 0.2 min (12 s) reveals time varying amplitudes from wind waves and swell, whereas the longer-period oscillations are essentially constant. We therefore have reason to suspect that there is a continuous global forcing of bay and harbor oscillations.

A close examination of modes at Kahului with periods between 1 and 5 minutes does reveal a time-dependent *frequency modulation*. The 2 minute mode is a good example where a distinct sinusoidal oscillation in period is found throughout the record. This behavior is also observed at Monterey (Park and Sweet, 2015), ~~and at Hilo ,~~ Hilo and Honolulu where high-resolution (1 Hz) data was available, but is not shown in figure 2. These modulations are coherent with the tides, and are a manifestation of changing boundary conditions (water depth, exposed coastline and spatial resonance boundaries) as water levels change with the tide.

4 Mode Identification

Spectrograms provide information regarding time dependence of energy, but are not well suited when detailed frequency resolution is desired. To identify resonances in the water level data we estimate power spectral densities with smoothed periodograms (Bloomfield, 1976) as shown in figure 3. The Monterey and Hilo estimates are composites of 6 min and 1 s data with periods longer than 12 min represented by spectra of the 6 min data. Horizontal arrows indicate the range of modes associated with their respective spatial domains as discussed below. Triangles mark the tidally–forced shelf–resonances, also discussed below.

To relate temporal modes with spatial scales we find solutions to the general dispersion relation $\omega^2 = g\,k\tanh(kd)$ where ω is the mode frequency obtained from power spectra in figure 3, k the wavenumber, and d the water depth which ~~are representative values over the~~ is a representative value from nautical charts over the horizontal dimensions of the respective mode wavelength in the bay or harbor~~from nautical charts~~. This provides estimates of the modal wavelength $\lambda = 2\pi/k$, which we list as $\lambda/2$ or $\lambda/4$ in table ~~2~~ 3 for all prominent modes. $\lambda/2$ corresponds to spatial modes between two fixed boundaries, for example between two opposing coasts of a bay as found in the longitudinal direction of the semi–elliptical bays, while $\lambda/4$ corresponds to one fixed and one open (free) boundary condition as found in a transverse mode where one boundary is a coast and the other the open sea, as is the case for the tidally–forced shelf–resonances.

For example, the 55.9 minute mode at Monterey and the 160–170 minute modes at Hawke correspond to longitudinal modes between the ends of the bays and are therefore delineated as closed–boundary $\lambda/2$ modes. The majority of the open–boundary condition modes correspond to transverse bay and shelf modes, however there are exceptions such as the 1 minute mode at Monterey and the 32 second mode at Honolulu which are open–boundary waves supported by open basins near the tide gauges as evidenced on harbor maps. We cannot assure that all entries in table ~~2~~ 3 are properly attributed as $\lambda/2$ or $\lambda/4$ modes, as we have not closely examined the physical boundary conditions of each mode.

4.1 Shelf Resonance

The period of a shallow water wave resonance supported by a fixed–free boundary condition is expressed in Merian's formula for an ideal open basin as $T = 4L/\sqrt{gd}$ where L is the shelf width corresponding to $\lambda/4$, and d the basin depth (Proudman, 1953). In addition to a shelf–mode standing wave based solely on geometric wave reinforcement, a shelf–resonance is dynamically supported when the shelf width is approximately equal to $g\alpha/(\omega^2 - f^2)$ where g is the gravitational acceleration, α the shelf slope, ω the frequency of oscillation and f the Coriolis parameter (Clarke and Battisti, 1981). Table ~~3~~ 4 lists solutions for shelf–mode period (inverse of frequency) for each of the bays where the shelf slope is approximated as the depth of the shelf break divided by the shelf width, and where the basin depth is taken as one half the shelf break depth. Also listed are modal periods deemed to represent the shelf–resonances obtained from the power spectra in figure 3. The agreement is reasonable given the simplistic formulations and crude spatial representations, and when viewed from the perspective of the apparently time invariant modal energy evident in the spectrograms and with recognition of tidal energy as a driver of shelf–resonances, suggests that tidally–forced shelf–resonances are continually present.

4.2 Dynamic Similarities

Topological similarities between Monterey and Hawke bays are striking, each a semi–elliptical open bay with aspect ratios of 2.0 and 1.9 respectively, although a factor of 2 different in horizontal scale. One might expect that these similarities would lead to affine dynamical behavior in terms of modal structure, although not the specific modal resonance periods, and that indeed appears to be the case as seen in figure 3. Both bays exhibit highly tuned resonances evidenced by high quality factors (Q) in the bay modes. The shelf–resonances of both bays, 27.4 min at Monterey and 105.8 min at Hawke, indicated with the triangle symbol in each plot, are exceptional examples of this, while the longer period modes (56 min at Monterey and 165 min at Hawke) correspond to longitudinal bay oscillations. The semi–elliptical topology of these bays is such that boundaries of the longitudinal modes are not parallel as in an ideal rectangular basin, but are crudely represented as semi–circular boundaries. The range of spatial scales between these boundaries is reflected in the longitudinal spectral peaks with broad frequency spans at the base and evidence of a series of closely spaced modes corresponding to a range of wavelengths. This is contrasted to the shelf–modes where the resonances are remarkably narrow indicating the narrow–range of spatial scales reflected in the relatively uniform widths of the shelves at Hawke and Monterey Bays.

Poverty Bay is the other semi–elliptical open bay and it exhibits the same generic modal structure. Although here, the bay modes are shorter in period due to the significantly smaller size, and the shelf–mode is the longest period mode. It is also evident here that the shelf–mode is mixed with other modes as it does not have a high Q–factor as found at Monterey and Hawke, although part of this difference could result from poorer trapping or more radiation or other energy loss associated with this mode.

Hilo and Kahului bays also share structural similarity, but lack the high degree of topological symmetry found in the semi–elliptical bays that support both longitudinal and transverse modes. As is the case for the semi–elliptical bays, the power spectra of these two bays are conspicuously similar with the substantial difference being the precise frequencies of their associated modes. Here, shelf–modes appear to dominate the water level variance, but rather than a set of discrete, high–Q shelf–resonances as found at Monterey and Hawke, they are energetic over a broad range of frequencies and spatial scales. This suggests that the shelves here are not well represented by a uniform width, but encompass a range of scales to the shelf break as evidenced in bathymetric data. In the following sections we examine specific resonance features at each of the bays.

4.3 Monterey

Monterey Bay seiche has been studied since at least the 1940's (Forston et al., 1949) with a comprehensive review provided by Breaker et al. (2010). The primary bay modes at the Monterey tide gauge have periods of 55.9, 36.7, 27.4, 21.8, 18.4 and 16.5 min, where the 55.9 min mode represents the fundamental longitudinal mode, while the 36.7 min harmonic is attributed to the primary transverse mode. We identify the 27.4 min mode as a shelf–resonance, also recognized by Lynch (1970), and consider it to be a potential continuous forcing of long period water level oscillations throughout the bay. The harbor modes (figure 3) have been associated with resonances between breakwaters, and are amplified by wave energy, whereas the bay modes are weakly–dependent on wave forcing (Park and Sweet, 2015).

4.4 Hawke

Hawke Bay is approximately 85 km long and 45 km wide with a rich set of modes at periods between 20 and 180 minutes. Modes at periods of 170.6, 167.1 and 160.1 min correspond to longitudinal oscillations, while the 105.8 min oscillation is identified as a shelf–resonance (table ~~2~~3).

4.5 Hilo

At Hilo we are afforded full spectral frequency coverage and find that pier modes have periods below 20 seconds corresponding to spatial scales less than 100 m. These modes are excited by waves and swell just as the harbor modes at Monterey. Harbor modes at periods of 3, 4 and 5.9 minutes correspond to standing waves within the breakwater and spatial scales of 1, 1.3, and 1.9 km respectively. The shelf offshore Hilo is not a uniform width, but transitions from less than 2 km just south of the bay to roughly 18 km along the northern edge with the spectra revealing a corresponding plateau at periods between 10 and 30 minutes with a rather broad shelf-resonance centered on a period of 30.9 minutes, qualitatively different from the high–Q shelf–resonances at Monterey and Hawke bays. This well known 30.9 minute mode at Hilo corresponds to a shelf–resonance on a shelf width of approximately 17 km.

4.6 Kahului

Oscillations at Kahului follow the same general structure as Hilo with wave and swell excited pier modes at periods less than 20 seconds, and within–harbor pier–breakwater modes at periods of 51 and 63 seconds. The primary harbor mode has peak energy at 188 seconds (3.1 minutes) corresponding to a $\lambda/2$ spatial scale of 1.1 km which is the dominant lateral dimension of the harbor.

An interesting feature of the Kahului power spectra is a low energy notch between periods of 120 and 160 seconds. This lack of energy corresponds to a lack of standing wave reflective boundaries at scales of $\lambda/2$ from 650 to 1000 m. Such low energy features are present in all spectra indicating spatial scales where standing waves are not supported. The dominant shelf–mode at Kahului has a period of 35.5 minutes, similar to that of Hilo.

4.7 Honolulu

At Honolulu we have the benefit of both short sample times ($\mathrm{T_s} = 1$ s) and two gauge locations, one inside the harbor and one on the reef outside the harbor. The offshore power spectrum is shown in red in figure 3 exemplifying an open ocean or coastal location dominated by wind waves and swell. The rejection of wind wave energy inside the harbor is impressive, revealing a set of pier–modes in the 8 to 20 second band supported by rectangular basins around the gauge. Modes with periods of 82 and 88 seconds correspond to waves with $\lambda/2$ of approximately 500 m, which is the fundamental dimension of the basin.

While the harbor is quite efficient in rejection of wind waves and swell, amplification of the shelf–mode and other long period resonances is a striking manifestation of the "harbor paradox" as noted by Miles and Munk (1961). Indeed, power spectra of the other harbors in figure 3 might suggest that they may be even more efficient amplifiers.

4.8 Poverty

Poverty Bay is a small–scale version of Hawke and Monterey bays with a similar resonance structure, however, the bay is small enough that the lowest frequency mode is not a longitudinal mode within the bay, but is the shelf–resonance at a period of 79 minutes. The 57.3 minute mode is not explicitly a Poverty Bay mode, but is a longitudinal mode of the open bay between Table Cape to the south and Gable End to the north, inside which Poverty Bay is inset. We also note that the 42.1 minute mode is a shelf edge–wave evident in both Hawke and Poverty bays as discussed below. The reader is referred to Bellotti et al. (2012) for a detailed numerical evaluation of Poverty Bay shelf and bay modes.

4.9 Hawke and Poverty

Hawke and Poverty bays are located approximately 35 km apart along the southeast coast of northern New Zealand. Concurrent 7 month records allow examination of cross–spectral statistics between the two locations, with power spectra presented in the upper panel of figure 4 and coherence in the lower panel plotted as the upper and lower 95% confidence intervals. Power spectra reveal that the two bays share shallow water tidal forcings at periods longer than 180 minutes, but are essentially independent in terms of major oscillation frequencies between 20 and 180 minutes. There are coincident spectral peaks near periods of 42 and 58 minutes, however the coherence of the 58 minute energy is low indicating that is likely independent between the two locations.

Coherence at the shallow water tidal periods (373, 288, 240, 199 min) is quite high and as expected has near zero phase shift (not shown). Shelf–modes with periods from 100 to 160 minutes also share coherence in the 0.5 range, which is sensible since they have quarter wavelengths that are as long, or longer than, the 35 km separation distance. The only other energy with coherence reliably above the 0.5 range is the 42 minute mode. This mode has a phase shift of -160°from Napier (Hawke Bay) to Gisborne (Poverty Bay) indicating a traveling wave moving from south to north along the coast, empirically validating the shelf edge–wave explanation inferred numerically by Bellotti et al. (2012).

5 Shelf–metamodes

Since tidally–forced shelf–modes are a plausible driver of seiches, we expect that tidal amplitude variance should be reflected in seiche amplitudes, a view consistent with the strong fortnightly modulation of seiche amplitude reported by Giese et al. (1990) and Wijeratne et al. (2010). To examine such a dependence figure 5 plots time series of ~~the~~ shelf–mode ~~amplitudes from the spectrograms shown in figure 2, along with temporal low–pass representations from superposition of the lowest frequency~~ amplitude at each station. Amplitudes are determined by shelf–mode power–spectral values versus time at each station. To examine the mean temporal behavior of shelf–modes we decompose the time series into intrinsic mode functions (IMFs) ~~of the shelf–mode amplitude time series computed~~ by empirical mode decomposition (EMD, Huang and Wu (2008)). The temporal low–pass response of the shelf–modes is shown in figure 5 by the thick lines which are a superposition of the lowest frequency intrinsic mode functions (IMFs). We term these IMFs of shelf–mode amplitudes as *metamodes*.

It is clear from figure 5 that shelf–modes are continually present at all stations, albeit with significant temporal variability. The ~~lowest frequency metamodes shown with the thick lines~~ metamodes reveal annual modulations in the long period records of Monterey and Hilo, and fortnightly cycles at Kahului and Honolulu.

To assess the relative contribution of individual shelf–mode IMFs (metamodes) to the total shelf–mode variance, we list the mean period in days (T) of each metamode Hilbert instantaneous frequency vector, and percent variance each metamode IMF contributes to the total variance in table ~~4~~5. We note that the fortnightly astronomical tidal constituents, the lunisolar synodic fortnightly ($\mathrm{M_{sf}}$) and lunisolar fortnightly ($\mathrm{M_f}$), have periods of 14.76 and 13.66 days respectively with IMFs closest to these periods highlighted in table ~~4~~ 5 and shown in figure 6, where we find at Monterey and Hilo that the fortnightly variance in shelf–mode amplitude is the dominant contribution, while at Kahului, Hawke and Poverty bays it is the second strongest metamode. At Honolulu and Kahului the bulk of the metamode variance is on sub–daily time scales, however, the fortnightly mode is the strongest of the modes at diurnal and longer scales, a relation that holds at all stations except Poverty Bay. We also note in figure 6 evidence of a seasonal dependence in metamode amplitude, and will correlate these IMFs with their corresponding fortnightly tidal IMFs below.

The foregoing indicates that fortnightly metamodes are present at all six stations suggesting that tidal forcing of shelf–modes is a likely driver. To assess an assumed linear dependence between fortnightly tidal forcing and metamodes, we compute IMFs on the tidal water level data and cross–correlate the resulting fortnightly tidal IMFs with the fortnightly metamodes. Correlations are computed over a sliding window of length 20 days with results shown in figure 7 where dashed red lines indicate the 95% significance threshold. An interesting feature is that while all stations exhibit near perfect correlation at times, they also episodically transition to near zero or statistically insignificant correlation. This suggests that the fortnightly modulation of tidally–driven shelf–resonances is also influenced by other factors, of which internal tide variability has previously been noted by Giese et al. (1990) and Wijeratne et al. (2010).

While there is significant temporal variability in the fortnightly tidal metamode correlations, it appears that the majority of the time correlations are quite high and significant above the 95% level. The IMF mode numbers and mean correlations statistics are listed in table ~~5~~ 6 where $\mathrm{T_R}\%$ is the percentage of time that the 95% significance threshold is exceeded, $\overline{\mathrm{R}}$ is the mean correlation of values above the 95% significance threshold, and $\overline{\mathrm{Lag}}$ the mean lag value of 95% significant correlations. Overall, these data suggest that correlations significant above the 95% level are present 76–87% of the time, and from a linear model perspective that fortnightly tidal oscillations account for 35–50% of the metamode variance.

6 Mode Energy

Knowledge of a mode's temporospatial characteristics allows estimation of the total energy sustained by the mode. Figure 3 indicates that Hilo, Kahului, Honolulu and Poverty bays are dominated by energy of the shelf–mode, while at Hawke and Monterey bays the shelf–mode is the second largest amplitude. We are therefore motivated to investigate modal energy in Monterey Bay to test our hypothesis that the shelf–mode is a potential driver of bay oscillations from a kinematic perspective.

We estimate the total potential energy to support a mode by assuming a raised–cosine profile of amplitude h either orthogonal to the shore for the transverse and shelf–modes, or parallel for the longitudinal modes. Multiplying this profile area ($\mathrm{A_M}$) by the alongshore extent of the mode ($\mathrm{L_A}$) gives the volume of water displaced: $\mathrm{V_M = L_A\,A_M}$ where we have neglected the influence of shoaling on the transverse modes as the wavelength is much longer than the shelf width. (This assumption is supported by the agreement between the shelf–mode spatial scales based on the observed shallow–water frequencies in table ~~3~~4.) The energy to move this volume is equivalent to the work performed to change the potential energy of the mass in the gravitational field $\mathrm{E_M} = \rho\,\mathrm{V_M\,h_M\,g}$, at an average power output of $\mathrm{P_{out} = E_M/T}$ where T is the modal period. This leading–order value does not incorporate dissipation and momentum, terms that we ignore in subsequent energy estimates.

The ratio of energy stored in the mode resonance to energy supplied driving the resonance is the Q factor. If Q is large (the resonance signal-to-noise ratio is high, as is the case for the shelf–mode at Monterey), it may be estimated from the power spectrum: $\mathrm{Q = f_M/\Delta f}$, where $\mathrm{f_M}$ is the mode resonant frequency and $\Delta\mathrm{f}$ the -3dB (half power) bandwidth of the mode. This allows one to estimate the power required to drive the mode $\mathrm{P_{in} = E_M/(QT) = P_{out}/Q}$.

Modal length scales (λ) are taken from table ~~2~~3, amplitudes (h) are from bandpass filtering the 17.8 year water level record at the NOAA tide gauge, and Q from 1 Hz water level power spectra (95% CI 2.6 dB) modal means over 120 hour windows over 63 days (Park and Sweet, 2015). The alongshore extent of the modes, $\mathrm{L_A}$, are estimated from a regional ocean modeling system (ROMS) implementation in Monterey Bay (Shchepetkin and McWilliams, 2005) as reported in Breaker et al. (2010).

Results of these estimates are shown in table ~~6~~ 7 where we find seiche amplitudes averaged over the 17.8 year period of 0.9, 1.4 and 1.6 cm for the 55.9, 27.4 and 36.7 minute modes respectively, although amplitudes of 4 cm in the 27.4 minute mode are common during seasonal maximums. The 27.4 min shelf–mode is estimated to produce a total power of 998 kW, which is more than sufficient to supply the required input power of both the primary longitudinal (55.9 min, $\mathrm{P_{in}}$ = 23 kW) and transverse (36.7 min, $\mathrm{P_{in}}$ = 169 kW) bay modes. This suggests from a kinematic perspective that a tidally–forced shelf–resonance is energetic enough to drive observed seiches in Monterey Bay. Regarding the O(mm) low–frequency infragravity waves suggested by MacMahan (2015), we note that a 27.4 minute mode with an amplitude of 3 mm would produce an estimated $\mathrm{P_{out}}$ of 41.6 kW (not shown in table ~~6~~7), which would be insufficient to drive the observed 27.4 min mode as it requires a power of $\mathrm{P_{in}}$ = 77 kW.

7 Discussion

Resonant modes are a fundamental physical characteristic of bounded physical systems expressed in bodies of water as seiches. As such, they can be excited to large amplitudes by transitory phenomena such as weather and tsunamis, and since large amplitude seiche are easily observable seiche are often viewed as transitory given that they dissipate after cessation of the driving force. Moving from transient to persistent behavior, seasonal weather patterns are known to sustain nearly continuous seiche for extended periods (Woodworth et al., 2005; Wijeratne et al., 2010) , as are internal waves (Giese et al., 1990) . On the other hand, ~~observations of small amplitudecontinuous seiche are not well documented, to our knowledge those reported in Monterey Bay by Breaker et al. (2008) , Park and Sweet (2015) and MacMahan (2015) , and in Sri Lanka by Wijeratne et al. (2010) are the only clear expressions of perpetual long period resonances. We have found that in addition to Monterey Bay, each of the five other bays examined exhibit persistent seiches, and to our knowledge, this work represents the first clear recognition of continuous seiche across multiple bays which effectively answers the question posed by Breaker et al. (2008) that indeed there is a continuous global excitation.~~

~~Simple geometric and dynamical estimates of tidally–forced shelf–modes are consistent with modes observed in the power spectra at all stations, and their continual presence in spectrograms and time series of mode amplitudes verifies that tidally–forced shelf–modes are continuously present at each location. This result is hardly surprising, yet apart from the recognition by Wijeratne et al. (2010) that tides are a potential forcing of continuous seiche, we are not aware that shelf–modes have been considered as the primary driver of continuous seiche~~ small amplitude, temporally continuous seiche were recognized by Cartwright and Young (1974) and Golmen et al. (1994) , with Giese et al. (1993) and Breaker et al. (2010) posing questions as to the possibility of global excitations. Motivated by these questions we have examined tide gauge water levels around the Pacific basin looking for continuous seiche and forcings.

In the process of analyzing the resonant structure of these bays and harbors, we have quantified resonant periods and estimated spatial scales corresponding to each mode (table ~~2~~3). In some cases, we have identified the physical attributes of a bay or harbor associated with specific temporospatial resonances. In a more general sense, we have also illustrated broad dynamical similarities between bays with affine topologies, such as the clearly defined modes of the semi–elliptical bays when compared to the less structured, shelf dominated bays such as Hilo and Kahului. This analysis also provides empirical verification of the numerically inferred edge–wave by Bellotti et al. (2012) near a period of 42 min along Hawke and Poverty bays.

~~Although spectrograms of tidal records indicate a continuous presence of~~ Simple geometric and dynamical estimates of tidally–forced shelf–modes ~~, closer examination~~ are consistent with modes observed in the power spectra at all stations, and their continual presence in water level spectrograms and mode amplitude time series indicates that tidally–forced shelf–modes are continuously present at each location. Decomposition of shelf–mode amplitude time series identifies metamodes reflecting dynamic behavior of the shelf–modes, and we find that fortnightly metamodes are the dominant mode at periods longer than diurnal. Assuming that these fortnightly modulations are of tidal origin, cross–correlation of fortnightly IMFs of tidal data with the fortnightly metamodes leads to the conclusion that within the bounds of a linear system model from one–third to one–half of the fortnightly metamode variance is coherent with tidal forcing. ~~From an energy perspective, the suggestion of the~~ We therefore suspect that tidally–forced shelf–modes are a continuous energy source in harbors and bays adjacent to continental or island shelves.

A natural question is: does the proposed source contain sufficient energy to sustain the observed resonant oscillation? Power estimates of the most energetic modes at Monterey suggest that the shelf–mode is fully capable as a primary driver of continuous seiche~~is supported~~, while the low–frequency infragravity waves suggested by MacMahan (2015) may not have sufficient energy.

~~Taken together, evidence of continually present~~

8 Conclusions

Examination of 6 coastal locations around the Pacific with diverse shelf conditions finds that tidally–forced shelf–resonances are continually present. An energy assessment of the shelf–mode and primary seiche in Monterey Bay indicates that the shelf–resonance is fully capable of supplying the power input required to drive the primary bay oscillations even though the grave mode produces more output power than the shelf–mode, a consequence of the resonance structure of the Bay. Hawke Bay is dynamically similar to Monterey and we suspect that a similar relation holds there, while at the other locations the shelf–mode is the dominant energy source. Our conclusion is that tidally–forced shelf–modes ~~, their fortnightly amplitude relation to tidal modes, and assessment of modal energy suggests that long period shelf resonances driven by tides are an important excitation of continuous bay and harbor modes.~~ constitute a global candidate for continuous seiche excitation, a view consistent with that of Lynch (1970) , Golmen et al. (1994) and Wijeratne et al. (2010) who identified tidally–forced shelf–resonances as specific seiche modes. In locations where tidally-forced shelf-resonance is a primary seiche generator, we suspect that internal waves and weather, which clearly can be a primary forcing in their own right, serve to modulate seiche amplitudes.

Specific to Monterey Bay, these results offer a simpler explanation for continuous seiche generation than the mesoscale gyre hypothesis proposed by Park and Sweet (2015) which lacked a physical mechanism to transfer energy into the Bay, and is more energetically reasonable than the infragravity waves suggested by MacMahan (2015) .

In the course of attributing tidal forcing as the driver of the observed shelf–resonances, we introduced the idea of metamodes, dynamical modes of shelf–mode amplitude determined by empirical mode decomposition. The metamodes exhibited fortnightly modulation, and it is likely that examination of other metamode components may be useful towards understanding the dynamic behavior of modal structure in coastal environments.

However, it is also clear that we do not understand the cyclic nature of fortnightly tidal and metamode correlation. One possibility is that there is a time varying phase–lag between the two such that destructive superposition episodically creates nulls. A linear spectral analysis might use a coherency statistic to identify this, but such an option is not available for IMFs with variable instantaneous frequencies. It is evident that internal tides play a role, and it may be that episodic changes in stratification as noted by Giese et al. (1990) lead to modulation of the metamodes and contribute to the observed decorrelation, and it is deemed likely that the free, long–frequency infragravity waves suggested by MacMahan (2015) also contribute.

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Table 1. Tidal ranges at the six tide gauges. GT is the great diurnal range (difference between mean higher high water and mean lower low water) and MN the mean range of tide (difference between mean high water and mean low water).

Location	GT (m)	MN (m)
Monterey	1.63	1.08
Hawke	1.78	1.06
Hilo	0.73	0.53
Kahului	0.69	0.48
Honolulu	0.59	0.39
Poverty	1.58	1.06

Table 2. Approximate shelf widths and dimensions of Bays and Harbors, data period of record and sampling interval $\mathrm{T_s}$. Note that data from Hilo and Monterey include both long–period data recorded at $\mathrm{T_s} = 6\,\mathrm{min}$ and short–period data recorded at $\mathrm{T_s} = 1\,\mathrm{s}$.

Location	Harbor (m)	Bay (km)	Shelf (km)	Period of Record	$\mathrm{T_s}$
Monterey Bay and Harbor	600 x 500	40 x 20	15	August 25 1996 – June 23 2014	6 min
				September 14 2013 – November 29 2013	1 s
Hawke Bay, Napier Harbor	650 x 360	85 x 45	60	July 18 2012 – August 9 2013	1 min
Hilo Bay and Harbor	1950 x 1000	13 x 8	17	August 7 1994 – February 15 2010	6 min
				February 18 2014 – March 4 2014	1 s
Kahului Bay and Harbor	1100 x 950	23 x 11	20	February 14 2013 – June 4 2013	1 s
Mamala Bay, Honolulu Harbor	1000 x 500	19 x 5	15	June 30 2012 – September 27 2012	1 s
Poverty Bay, Gisborne Harbor	500 x 300	10 x 7	45	April 19 2009 – August 11 2010	1 min

Table 3. Temporospatial scales according to the dispersion relation $\omega^2 = g\,k\,\tanh(kd)$ where ω is frequency, k the wavenumber, d the water depth corresponding to horizontal dimensions of the respective mode, λ the wavelength and period is $2\pi/\omega$. Periods are in min and lengths in km unless otherwise noted. Periods are obtained from the peak modal energy represented in the power spectra shown in figure 3. Depths for each bay are taken as representative values from nautical charts, depths for shelf–resonances are assumed to be $150\,\mathrm{m}$, one half a nominal shelf–break depth of $300\,\mathrm{m}$. Spatial scales are listed as $\lambda/2$ for modes assumed to be fixed–fixed boundary standing waves, and $\lambda/4$ for fixed–open boundaries.

Monterey				Hawke				Hilo				Kahului				Honolulu				Poverty			
Period	Depth	$\lambda/2$	$\lambda/4$	Period	Depth	$\lambda/2$	$\lambda/4$	Period	Depth	$\lambda/2$	$\lambda/4$	Period	Depth	$\lambda/2$	$\lambda/4$	Period	Depth	$\lambda/2$	$\lambda/4$	Period	Depth	$\lambda/2$	$\lambda/4$
55.9	60	40.7		170.6	30	87.8		30.9	150		17.9	35.5	150		20.4	45.5	150		26.2	86	150		49.5
36.7	150		21.1	167.1	30	86		19.5	150		11.1	25.8	150		14.8	27.1	150		15.6	79	150		45.5
27.4	150		15.8	160.1	30	82.4		14.6	150		8.4	22.3	150		12.8	20.9	150		12	57.3	15		10.4
21.8	60	15.9		105.8	150		60.9	12.7	150		7.3	18.1	37	10.2		11.2	150		6.4	50	15		9.1
18.4	60	13.4		78.4	30	40.3		5.9	12	1.9		15.8	37	9		4.3	14	1.5		42.1	15		7.6
16.5	60	12		65.2	30	33.6		4	12	1.3		10.2	37	5.8		3.9	14	1.4		28	15	10.2	
10.1	60	7.4		56	30	28.8		3	12	995 m		5.1	13	1.7		2.9	14	1		23.2	15	8.4	
9	60	6.6		49.3	30	25.4		1.7	12	566 m		3.1	13	1.1		2.2	14	768 m		19.6	15	7.1	
4.2	60	3.1		47.1	30	24.2		1.3	12	423 m		1.9	13	645 m		1.7	14	587 m		15.7	15	5.7	
1.87	8	480 m		40.5	30	20.8		39 s	12	209 m		1.5	13	503 m		1.5	14	513 m		14.4	15	5.2	
1	8		128 m	36.7	30	18.9		29 s	12	155 m		1.3	13	437 m		1.4	14	475 m		11.8	10	3.5	
41 s	8	175 m		35.1	30	18.1		23 s	12	125 m		1.04	13	349 m		1.2	14	427 m		10.2	10	3	
31 s	8	132 m		33.1	30	17		17 s	12	90 m		51 s	13	287 m		45 s	14	261 m		5.2	10	1.5	
16 s	8	67 m		29.6	30	15.2		15 s	12	78 m		38 s	13	212 m		32 s	14		91 m				
12 s	8	50 m		27.8	30	14.3		14 s	12	74 m		20 s	13	110 m		29 s	14	165 m					
				25.1	30	12.9		13 s	12	68 m		16 s	13	84 m		26 s	14	150 m					
				22.9	30	11.8		12 s	12	61 m		11 s	13	56 m		16 s	14	90 m					
				21.3	30	11		11 s	12	53 m		9 s	13	48 m		14 s	14	77 m					
				19.7	30	10.1		9 s	12	44 m						12 s	14	63 m					
				18.4	30	9.5		7 s	12	34 m						10 s	14	51 m					
				17.2	30	8.9		6 s	12	26 m						8 s	14	40 m					
				14	30	7.2																	
				10.6	30	5.5																	
				7.4	30	3.8																	
				5.4	30	2.8																	
				3.2	20	1.3																	
				2.2	20	0.9																	

Table 4. Estimates of shelf–resonance periods. $\mathrm{T_R}$ is a solution to $L = g\alpha/(\omega^2 - f^2)$ where L is the shelf width, g the gravitational acceleration, α the shelf slope, ω the frequency of oscillation and f the Coriolis parameter. The shelf slope is estimated as break depth / width where we assume a break depth of $300\,\mathrm{m}$. $\mathrm{T_M}$ is from Merian's formula $\mathrm{T_M} = 4L/\sqrt{gd}$ for an open basin where d is the basin depth which we assume to be one–half the shelf break depth. $\mathrm{T_{PSD}}$ are values from the power spectral density estimates from shelf–mode frequencies marked with triangles in figure 3.

Location	Latitude (deg)	Width (km)	$\mathrm{T_R}$ (min)	$\mathrm{T_M}$ (min)	$\mathrm{T_{PSD}}$ (min)
Monterey	36.6	15	28.9	26.1	27.4
Hawke	39.5	60	115.2	104.3	105.8
Hilo	19.7	17	32.8	29.5	30.9
Kahului	20.9	20	38.6	34.8	35.5
Mamala	21.3	15	29.0	26.1	27.1
Poverty	38.7	45	86.6	78.2	79.0

Table 5. Mean period in days (T) of Hilbert instantaneous frequencies and percent variance of shelf–resonance power spectral density IMFs (metamodes). Modes with mean periods close to fortnightly tidal consituents with periods of 14.76 ($\mathrm{M_{sf}}$) and 13.66 days ($\mathrm{M_f}$) are highlighted.

	Monterey		Hawke		Hilo		Kahului		Honolulu		Poverty	
IMF	T	% Var	T	% Var	T	% Var	T	% Var	T	% Var	T	% Var
1	**14.70**	**33.5**	3.34	2.0	**14.47**	**35.2**	0.30	42.6	0.29	40.2	2.42	6.2
2	28.31	22.2	6.27	5.1	29.99	22.3	0.60	17.7	0.51	19.5	5.52	19.6
3	55.48	15.1	9.02	5.9	60.83	14.6	1.26	14.2	0.98	18.5	8.46	13.7
4	105.06	8.1	**13.48**	**13.9**	137.37	18.2	2.41	5.3	1.77	4.7	**14.21**	**17.9**
5	219.06	10.0	17.01	4.4	273.70	11.4	4.65	2.3	3.48	6.2	22.60	10.9
6	387.16	8.4	24.48	7.4	476.62	0.8	**14.58**	**18.1**	6.07	3.6	34.31	8.4
7	726.21	1.8	35.73	6.8	938.04	0.5	28.41	4.5	**13.86**	**7.0**	53.76	11.4
8	1662.14	1.3	45.45	4.8	1790.81	0.2	56.98	2.2	22.55	0.1	68.84	7.1
9	2244.04	0.2	65.67	9.7	4009.13	1.4			46.91	0.8	111.13	4.3
10			162.08	35.9							164.22	5.6

Table 6. Cross–correlation of fortnightly tide and shelf–resonance metamode IMFs. $\mathrm{T_R}\%$ is the percentage of time that the 95% confidence level is exceeded, $\overline{\mathrm{R}}$ the mean value of 95% significant correlation over the record, and $\overline{\mathrm{Lag}}$ the mean lag value of 95% significant correlation over the record.

Location	Tide IMF	Shelf IMF	$\mathrm{T_R}\%$ >95%	$\overline{\mathrm{R}}$ >95%	$\overline{\mathrm{R}}^2$ >95%	$\overline{\mathrm{Lag}}$ days >95%
Monterey	5	1	87	0.67	0.45	-0.35
Hawke	7	4	84	0.71	0.50	-0.26
Hilo	5	1	82	0.71	0.50	0.53
Kahului	7	6	86	0.59	0.35	0.01
Honolulu	7	7	76	0.65	0.42	0.64
Poverty	6	4	82	0.69	0.48	-0.17

Table 7. Estimates of total energy and power generated by resonances in Monterey Bay. Modal amplitudes (h) are mean values from bandpass filtering the 17.8 year record of water levels at ~~tne~~ the NOAA tide gauge. T is the mode period, $\mathrm{W_{FIR}}$ is the filter bandpass, $\lambda/2$ the mode half wavelength, $\mathrm{L_A}$ the alongshore extent of the mode in the bay, V the volume of water displaced, $\mathrm{E_M}$ the potential energy, Q the mode amplification, $\mathrm{P_{in}} = \mathrm{E_M}/(\mathrm{QT})$ the input driving power of the mode, and $\mathrm{P_{out}} = \mathrm{E_M}/\mathrm{T}$ the modal power.

T (min)	$\mathrm{W_{FIR}}$ (min)	h (cm)	$\lambda/2$ (km)	$\mathrm{L_A}$ (km)	V ($\mathrm{Mm^3}$)	$\mathrm{E_M}$ (GJ)	Q	$\mathrm{P_{in}}$ (kW)	$\mathrm{P_{out}}$ (kW)
27.4	25–30	1.4	31.6	38	33.30	1.64	12.9	77.6	998.1
36.7	35–39	1.6	42.2	40	52.55	2.91	7.8	168.6	1319.7
55.9	53–59	0.9	40.7	18	13.27	0.43	5.6	22.7	127.3

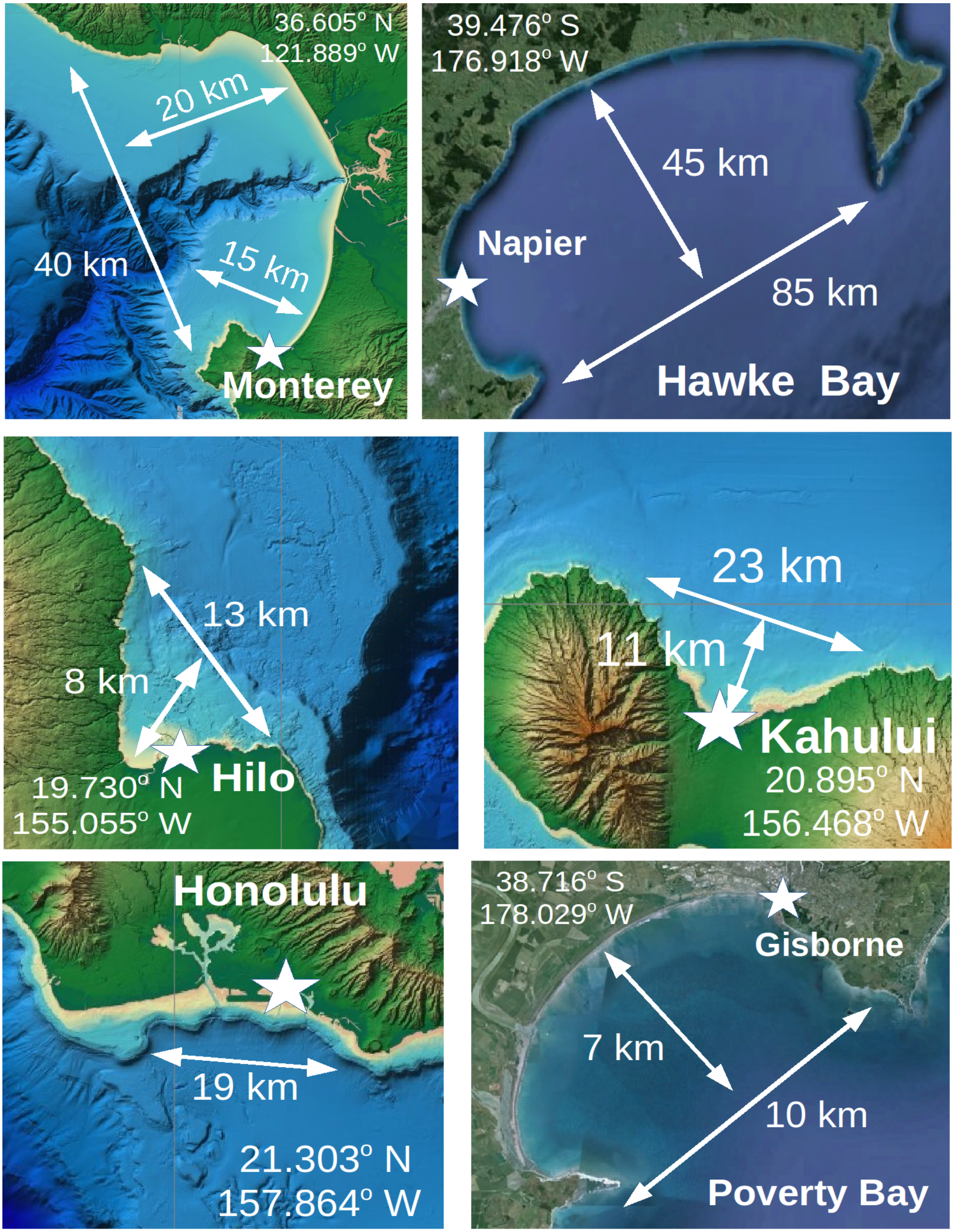

Figure 1. Location and approximate dimensions of bays. Tide gauge locations are marked with a star and denoted by latitude and longitude.

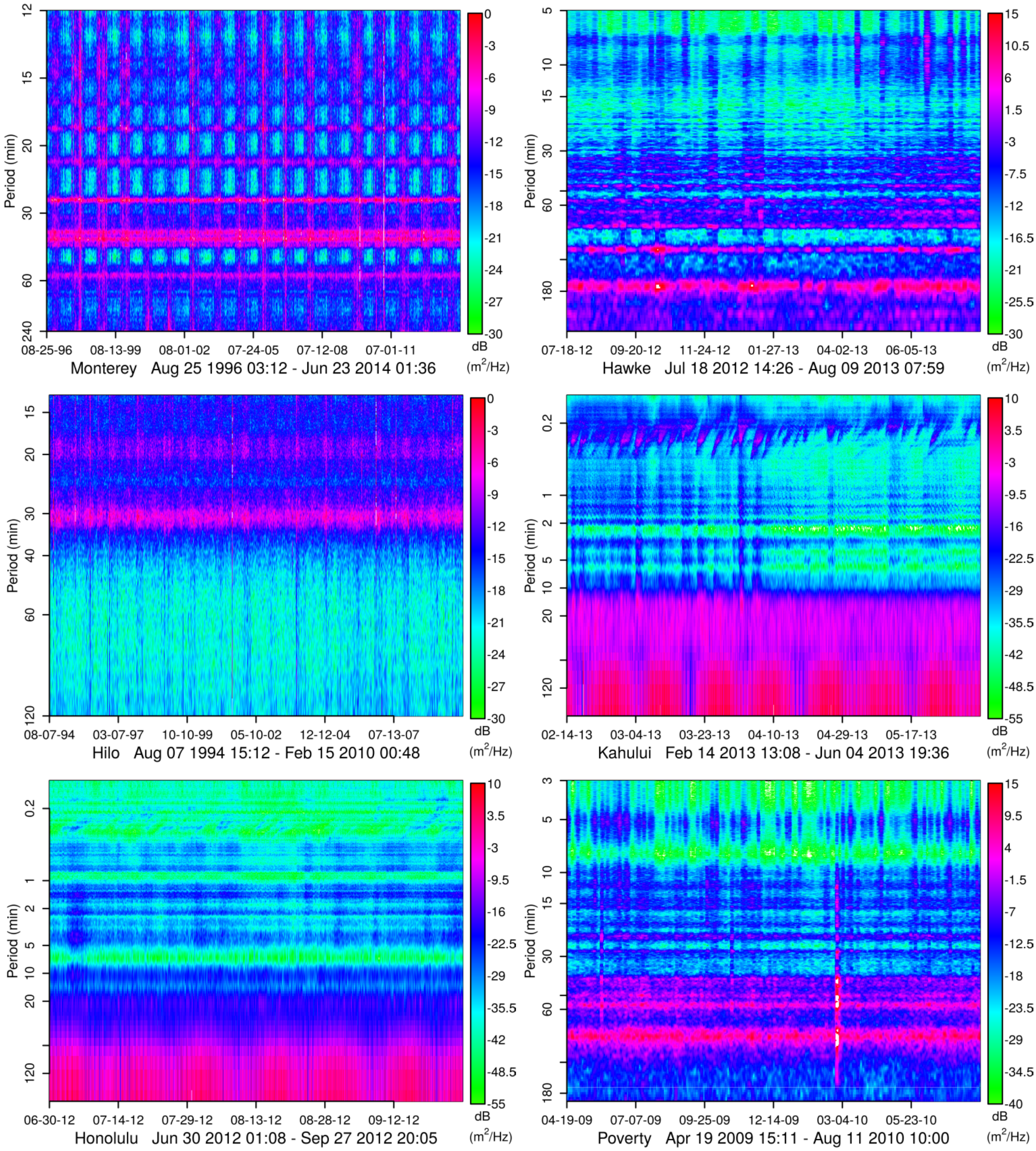

Figure 2. Spectrograms of water level data at each tide gauge. Horizontal bands indicate continuous oscillations, vertical bands are associated with periods of increased wave energy.

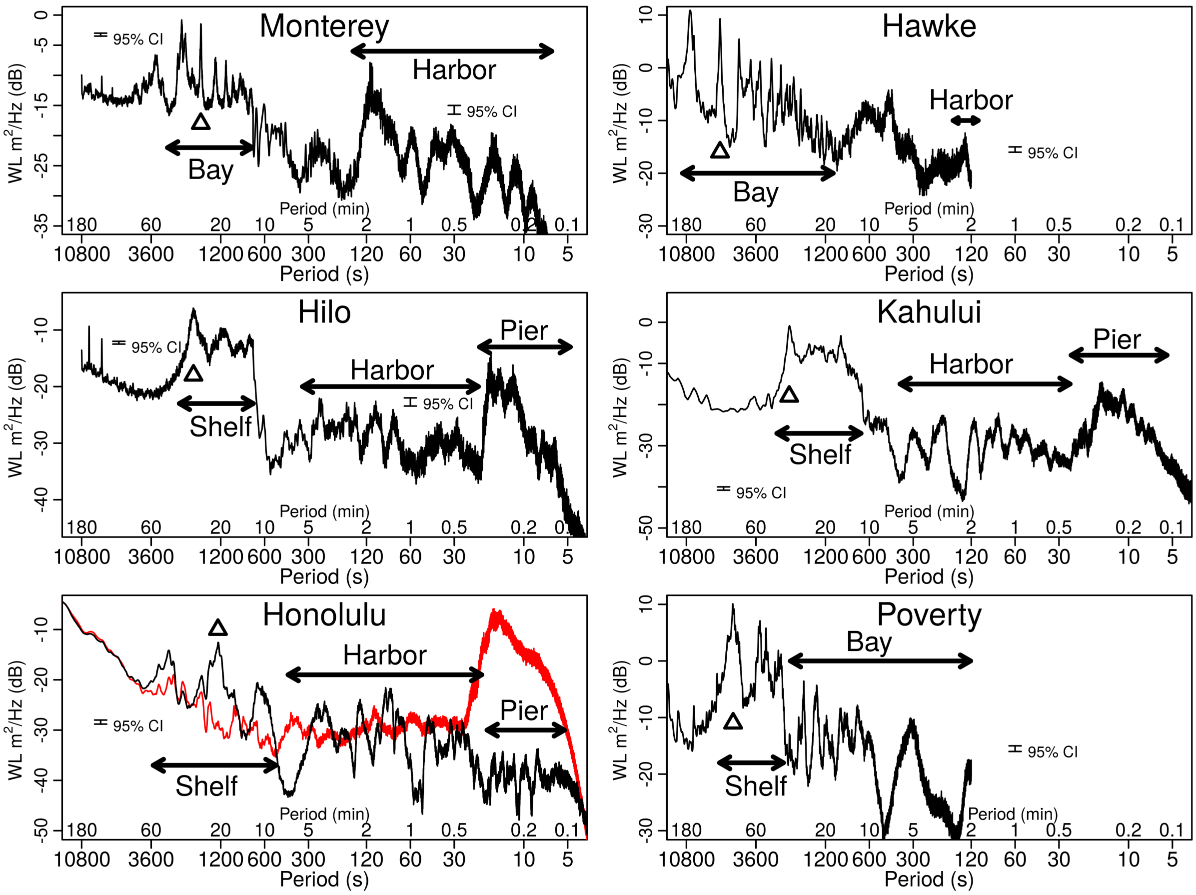

Figure 3. Power spectral density (PSD) estimates of water level (WL) at each tide gauge. Horizontal arrows indicate the frequency span of resonant modes associated with spatial scales. Triangles mark the tidally–forced shelf–resonance. The red curve at Honolulu plots data from outside the harbor.

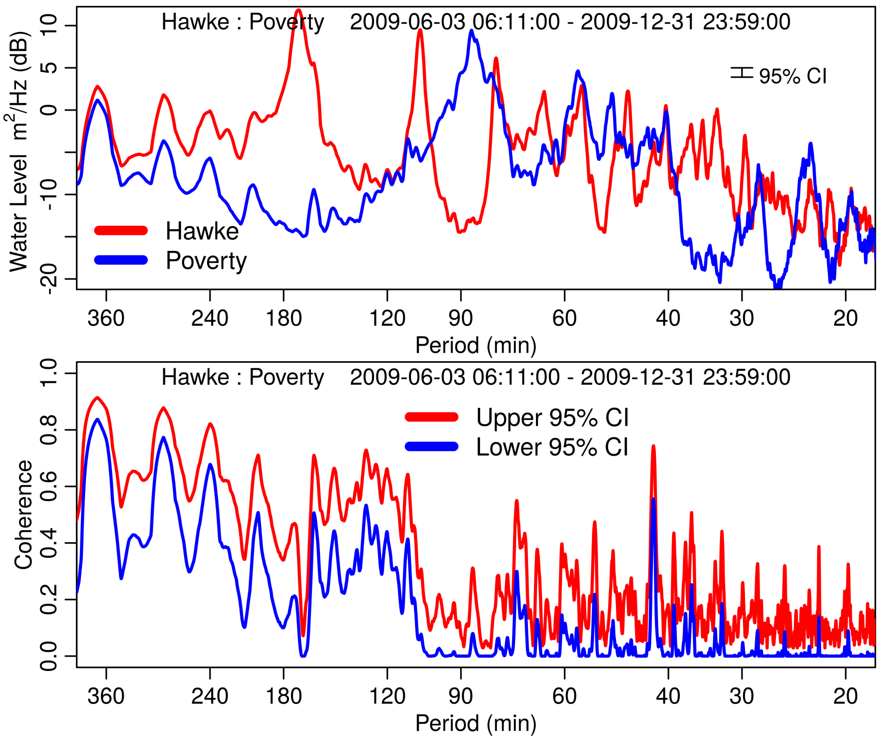

Figure 4. Power spectral density (top) of concurrent water levels at Napier in Hawke Bay, and Gisborne in Poverty Bay. Bottom: coherence of the power spectra shown as the upper and lower 95 percent confidence interval values.

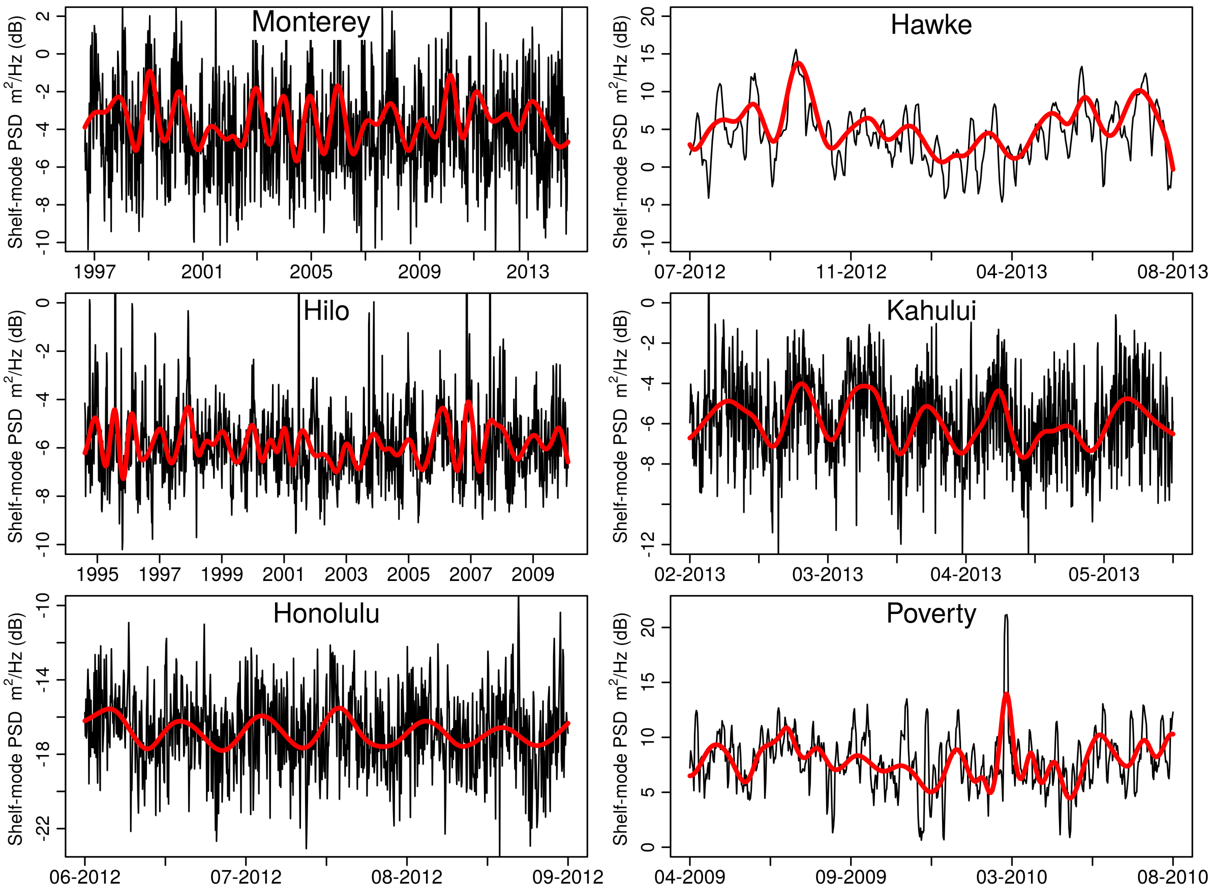

Figure 5. Shelf–resonance power spectral density (PSD) amplitudes (black) with low–frequency IMFs (meta-modes) in red. The large amplitude in Poverty Bay is a result of the February 27, 2010 Chile 8.8 M earthquake and tsunami.

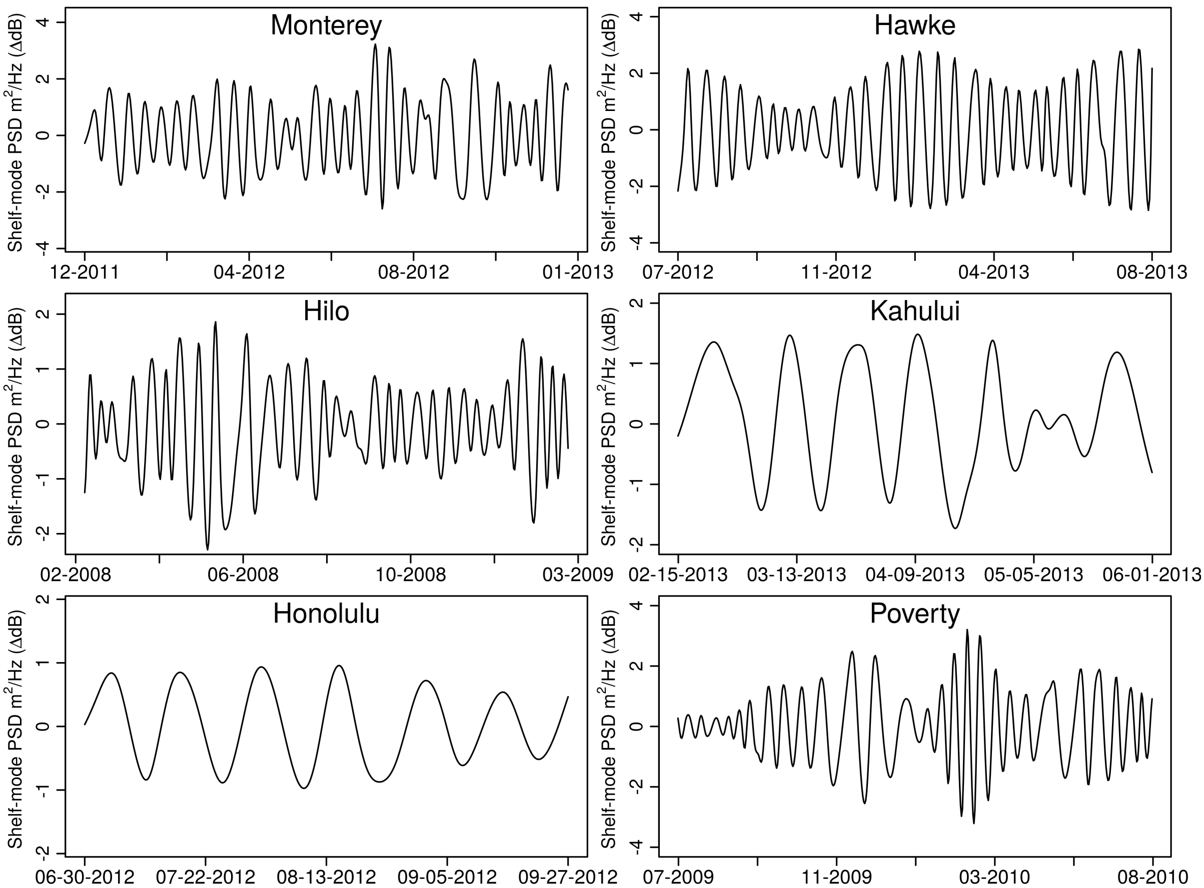

Figure 6. Intrinsic mode functions (IMF) of shelf–mode amplitude variance (metamodes) with mean Hilbert instantaneous frequencies ~~correspoding~~ corresponding to fortnightly periods (highlighted in table ~~4~~5). Amplitudes are with respect to the mean values shown in figure 5. Records at Honolulu and Kahului are limited to 3 months, while the other stations show excerpts of approximately 13 months.

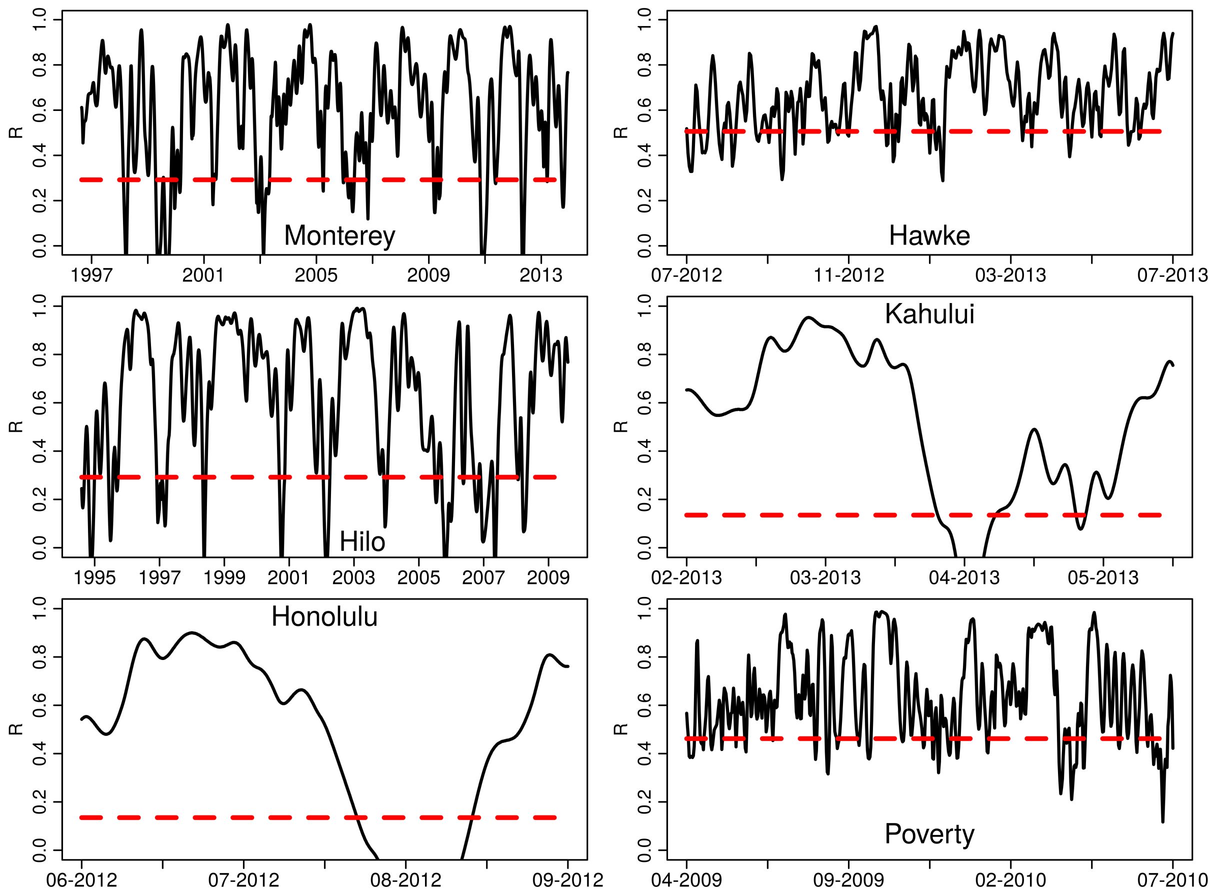

Figure 7. Correlation coefficients between tide and shelf–resonance metamode IMFs with fortnightly periods. The dashed red lines indicate the 95% confidence levels.