New ways to measure waves and their effects at NOAA tide gauges: A Hawaiian-network perspective

William V. Sweet1, Joseph Park2, Stephen Gill1, and John Marra3

1NOAA Center for Operational Oceanographic Products and Services, Silver Spring, Maryland, USA, 2National Park Service, Homestead, Florida, USA, 3NOAA National Center for Environmental Information, Honolulu, Hawaii, USA

Abstract

We use the standard deviation (sigma) of continuous 1 s water level sampling at 46 U.S. NOAA tide gauges available since 1996 as a high-frequency variance measure. Sigma estimates local infragravity and incident wave band variability, is significantly correlated (r = 0.5–0.9) to significant wave height (Hs), and scales linearly to local observations and output from the global ocean wave reanalysis at most ocean-exposed and harbor-sheltered locations. Empirical orthogonal functions of daily mean sigma from six Hawaii tide gauges distinguish northerly and southerly modes that closely match local Hs observations. Depending on tide gauge location, the 99% of daily maxima sigma can be as large as or larger than the nontidal residual component of the water level sample. Our findings provide new uses of land-based tide gauge data to estimate significant wave heights and dynamic water levels to better monitor for local conditions leading to impacts.

1. Introduction

Coastal communities are increasingly at risk from high-water events [Salas and Obeysekera, 2013; Sweet and Park, 2014], whose flooding and erosion threaten homes, public works and infrastructure, freshwater resources, harbor operations, etc. Since tide gauges (TG) are located at the land-sea interface, they are an optimal platform to monitor for damaging water levels. TGs offer decadal and longer-scale observations of water levels that support hazard-to-climate investigations of storm surge [Zhang et al., 2000; Bromirski et al., 2003], ocean circulation [Ezer, 2015] and sea level rise [Merrifield et al., 2012; Church et al., 2013].

TGs are designed to record slow changes in water level. Due to the mechanical low-pass filtering associated with their protective wells, multi minute averaging scheme and general placement in protected waters, their data are considered a still water level (SWL) estimate:

\[ \text{SWL}(t) = \text{MSL}_{\text{Datum}} + \text{tide}(\text{astronomic, MSL cycle}) + \text{NTR} \text{ (storm surge, anomaly, wave setup)} \]  

defined as a water level height averaged over sampling period, t, relative to mean sea level (MSL) or an appropriate tidal datum [CO-OPS, 2001], a tidal contribution usually consisting of the astronomical tide and a MSL seasonal/annual constituent and a nontidal residual (NTR) representing localized storm surge, any prior-existing sea level anomaly and wave setup if present during sampling from breaking waves in the surf zone and within coral-reef lagoons [Vetter et al., 2010] and atolls [Aucan et al., 2012].

Hydraulic impacts, on the other hand, during extreme water level events [Tebaldi et al., 2012; Zervas, 2013] result from more of an instantaneous total water level (TWL; H. Mortiz, et al. (2015), U.S. Army Corp of Engineers Adaptation Approach for Future Coastal Climate Conditions, J. of ICE Maritime Engineering, in press.), which include higher-frequency (seconds - min) wave processes typically associated with runup effects on a sloping beach. TG platforms are located at the land-ocean interface (i.e., docks, seawalls, piers) and typically do not experience such swash-related motions. A TG without consideration of its averaging scheme and physical dampening from its protective structure experiences more of a dynamic water level (DWL):

\[ \text{DWL}(t) = \text{SWL} + \alpha \ast \text{sigma} \]  

where SWL is obtained from equation (1), \( \alpha \) is an exceedance duration coefficient associated with the sampling period (e.g., 1.96 approximates the 95% of the Gaussian distribution) and sigma represents the standard deviation of the high-frequency oscillations that directly impinge upon TG platforms from incident (\( \text{wave}_{inc} \)) wind waves/swell (periods of 5–25 s) generally attenuated in harbors by design and by longer-period (25 s to tens of minutes) infragravity waves (\( \text{wave}_{ig} \)) often pronounced in harbors...
The magnitude of sigma is presumably dependent upon the TG location. Estimates of DWLs and TWLs typically require additional data (e.g., wave buoy or model output) and more complex methods to determine. Wave-related impacts are the primary concern within the Pacific [Marra et al., 2012], such as island overwash that occurs when large swells hit during seasonally high tides [Hoeke et al., 2013]. Along the U.S. West Coast, such events cause extensive erosion [Barnard et al., 2011] and increasing significant wave heights ($H_s$) over the last couple decades have been more of a factor than sea level rise [Ruggiero, 2013].

Here we utilize the standard deviation (“sigma”) computed during water level sampling as a physical measurement instead of its intended use as a SWL performance metric for U.S. National Oceanic and Atmospheric Administration (NOAA) TGs. Sigma estimates water level variability occurring over the waveles + waveig bands, and together with the reported TG “mean” value, quantifies instantaneous exposure levels and durations above a reference elevation. We show that daily mean TG sigma is (1) highly sensitive to and can provide a local approximation for $H_s$ and (2) is a major DWL component at exposed (e.g., ocean piers) and harbor TG locations. Our findings offer novel approaches for monitoring local wave and water level conditions and extend earlier TG satellite [Parke and Gill, 1995] and next-generation sensor performance [Park et al., 2014a] comparison studies.

2. Study Area and Data

We use hourly TG measurements from NOAA (www.tidesandcurrents.noaa.gov) and specifically those collected since ~1996, which include the water level (mean) and its sample standard deviation (sigma). Both estimates are derived from 181 continuous 1 s samples collected every 6 min (i.e., “3 min on and 3 min off” sampling scheme) from an acoustic-based sensor inside a protective well, which is designed to mechanically dampen water level oscillations with periods $\leq$ 5 s [Park et al., 2014a]. We recognize that this sampling strategy leaves oscillations with 3–6 min unresolved. NTR values are obtained by subtracting the local NOAA tide predictions from the water level observations at each TG. We analyze wave-related responses (1) regionally across the Hawaiian Islands Region, (2) locally at three Hawaiian TGs (sites 2, 4, and 6; Figure 1a) where Seabird 26Plus wave and water level recorders with Paroscientific Digi-quartz pressure instruments sampling at a 1 s rate were codeployed near NOAA TGs by the University of Hawaii Sea Level Center and
TG water level sigma are compared to nondirectional $H_s$ recorded by buoys (wave sites 1, 4, and 6; https://cdip.ucsd.edu) and at wave site 2, whose hourly $H_s$ is approximated as 4*standard deviations of hourly 1 s samples obtained by a SBE26 Plus. We also utilize hourly nondirectional $H_s$ from the global ocean wave (GOW) reanalysis over 1996–2013 [Perez et al., 2015], which is based upon the WaveWatch III wave model [Tolman, 2014]. The model has a 1°×1.5° spatial resolution, and $H_s$ are considered an offshore estimate. Nearest model output directly offshore each NOAA TG is used. Although the Hawaiian Island topography is not resolved by the model, obstruction grids are included in the numerical simulation using the approach described in Chawla and Tolman [2008].

3. Findings

3.1. TG Water Level Mean and Sigma Parameters

The HI Islands are located in the central North Pacific (Figure 1a) and subjected to several directional surface gravity wave climatologies [Bromirski et al., 2005; Aucan, 2006] that cause substantial variability during NOAA TG sampling. Figure 1b shows a record of 181 1 s water level samples made by our Seabird instrument co-located at the NOAA TG 4 (Kahului) on 2 April 2013 at 04:12:00 with the resultant 3 min sample mean, NTR (difference between water level and tide), and sigma values. This sample occurred during a large northerly swell (shown in Figure 3b), and the 1 s water level data reveal distinct 15 s oscillations with amplitudes of 0.6 m. Figure 1c shows daily mean NTR and sigma values recorded by NOAA TGs in Kahului and Midway Atoll. At Kahului, high sigma values do not translate into higher NTR (no correlation) even when very large water level oscillations are present in the harbor. On the other hand, NTR and sigma are well correlated ($r = 0.69$; $p$ value < 0.01) at Midway Island, a phenomenon quite rare for NOAA TGs, which is attributed to wave setup from breaking waves that drive water over the reef, raising levels within the atoll lagoon [Aucan et al., 2012] as well as increased variability during sampling.

3.2. Spatial Signature of Sigma and Regional Wave Climatology

When analyzed regionally via empirical orthogonal functions (EOFs), sigma measured by a network of TGs distinguishes distinct wave climatologies impacting Hawaii. The first EOF explains 42% of the signal variance and is a mode representing the northerly wavefield impacting TGs that are north facing (TGs 4 and 6) or north sensitive (TG 5) (Figure 2a). The principle component (PC) for EOF mode 1 has a very similar pattern to the seasonal storm and predominant wave climatology in the north Pacific [Aucan, 2006], which is highest in the boreal winter and smallest during summer (Figure 2b). Daily mean time series of PC 1 and $H_s$ recorded at wave site 2 off of the north shore of Oahu (which is shielded to all but northerly waves) are significantly correlated ($r = 0.79$; $p$ value < 0.01) as shown in Figure 2c. The second EOF explains 22% of the signal variance and is a mode primarily experienced at southern facing TGs 1 and 2. Opposite to PC 1, PC 2 has a seasonal distribution that peaks in boreal summer (i.e., austral winter) and is lowest in winter (Figure 2b). Its high correlation ($r = 0.83$) to $H_s$ measured for several months off Oahu’s south shore at wave site 2 (Figure 2d) indicates that EOF 2 is capturing swell generated in the Southern Hemisphere, which is largest during the austral winter-storm season.

3.3. Local $H_s$ and TG Water Level Response

Our high-resolution sampling focuses on the harbors of Honolulu (TG 1), Kahului (TG 4), and Hilo (TG 6), where we make comparisons to $H_s$ measured by in situ platforms (Table S2). Multimonth records of 1 s water levels recorded by the Seabird instrumentation co-located at the NOAA TGs capture the harbor response to increasing $H_s$ (Figure 3). As daily $H_s$ increases in each harbor, there is no discernable concurrent daily water level setup (no NTR correlation; Figure 3, top). However, daily sigma is correlated ($r = 0.78$, $p$ value < 0.01) to the changing
We use daily mean values to illustrate the relationship, but note that similar patterns exist but with progressively weakened correlation strength when using shorter averaging spans (e.g., 1–24 hours).

Each harbor oscillates at several \( w_{qnc} + w_{qg} \) bands as shown in the respective spectrogram (Figure 3, bottom), which are composed of daily spectral densities estimated by the Welch [1967] method with a 12 h sliding window. The spectra show that the harbors experience relatively continuous swell energy at event-specific periods (<25 s). The spectra also reveal several horizontal bands at periods much longer than wind waves associated with wave-forced standing waves (\( w_{qg} \)) likely specific to pier structures and harbor dimensions (periods < 600 s). Wave\( g \) associated with shelf dimensions (periods > 600 s) are more persistent and presumably a resonance driven by tidal energy [Woodworth et al., 2005; Wijeratne et al., 2010]. The wave-forced \( w_{qg} \) (harbor oscillations) are similar to those discussed by Thotagamuwage and Pattiaratchi [2014] in Two Rocks, Australia, and Park et al. [2015] in Monterey, CA. Although Honolulu (Figure 3a) was sampled under smaller \( H_s \) conditions (daily averages less than 1 m), its harbor appears a better spatial filter of wave\( nc \) energy as compared to Kahului (Figures 1b and 3b) and Hilo (Figure 3c), where large spectral peaks exist in wave\( nc \) bands during high \( H_s \) events. All three harbors possess similar linear regression coefficients of ~0.01 between daily mean \( H_s \) and sigma (both expressed in meters), implying that for every 1 m increase in \( H_s \), sigma increases by ~1 cm on average.

### 3.4. National Relationships

#### 3.4.1. GOW \( H_s \) and TG Water Level Sigma

Water level sigma measured at NOAA TGs around the U.S. reveal a high degree of sensitivity to wave forcing at both ocean-exposed (pier) and harbor-sheltered locations (Figure 4a and Table S1). Linear regression between daily mean GOW \( H_s \) and TG sigma over 1996–2014 or maximum period of TG record (Table S1) are correlated \( (r = 0.5–0.9) \) above the 99% significance level; \( p \) values < 0.01) at the majority of the study’s TGs. The amount of landward attenuation between offshore \( H_s \) to shore-measured TG sigma is related to its linear regression coefficient, with differences presumably from regional topo-bathymetric characteristics and TG placement/exposure. For example, along the U.S. West Coast where \( H_s \) and sigma have highest correlations \( (r = 0.7–0.9) \), the regression coefficients have broad similarities (blue and green dots, Figure 4a) with sigma increasing by 1–5 cm locally for every 1 m rise in \( H_s \). Higher coefficient values (>0.05) along the U.S. East Coast.
are found at exposed ocean-pier mounted TGs. The two locations with highest regression coefficients (red dots, 0.075–0.1) are on piers in Wrightsville Beach, NC, and La Jolla, CA. The GOW-derived coefficients based upon daily mean $H_s$ for the Hawaiian TGs are 2–3 times larger at TGs 4 (Kahului) and 6 (Hilo) and about a third of the magnitude at TG 2 (Honolulu) than as estimated using daily mean $H_s$ measured locally (Figure 3) likely related to the longer period for comparison and difficulties in resolving the complex HI topography.

### 3.4.2. Relative Magnitude of Water Level NTR and Sigma

Wave-related variability can be quite large during NOAA TG sampling (e.g., Figure 1b) with daily maximum sigma values $>$0.3 m not uncommon throughout the year (Table S1). We provide a ratio comparing the 99% of daily maxima over the period of record derived from hourly NTR and sigma values in Figure 4b. This ratio assesses the magnitude of wave$_{pe}$ and wave$_{sg}$ during large annual events as compared to the NTR ($\approx$storm surge) component. A similar ratio comparing TG astronomical tidal and NTR components (i.e., in equation (1)) quantifies the overall importance of storm surge and tide range during annual extremes [Merrifield et al., 2013; Sweet et al., 2014]. Along the East Coast, where large storm surges occur, NTR is 1 to 5...
times larger than sigma’s magnitude during such events. Along the West Coast and in some HI and Caribbean harbors where continental shelves are narrower, however, sigma is on par and/or greater (ratio < 1) than the NTR component itself.

4. Summary Remarks

Due to their maritime history, TGs have been purposely engineered to measure slow-changes in water levels. Here we use the standard deviation (sigma) computed during sampling at NOAA TGs as a dynamical measurement of wave-related variability present during sampling. TG sigma is correlated ($r = 0.5–0.9$) with changing offshore (nondirectional) $H_s$ at ocean-pier and harbor TG locations around the U.S. One-second water level samples at three HI Island TGs show that $\text{wave}_{\text{inc}}$ and $\text{wave}_{\text{tg}}$ modulate in response to changing $H_s$ and their correlations are higher ($r > 0.7–0.8$) when comparing to in situ measured $H_s$, than using modeled $H_s$ likely from the course GOW model resolution. Relationships are further enhanced ($r > 0.9$) when comparing water level sigma obtained from the bottom-mounted Seacat sensors without a protective well (Honolulu) or when applying a 10–22 s band-pass filter to the wind/swell $H_s$ (Kahului and Hilo). Directional $H_s$ information is obtained through EOF spatial analysis of sigma from a network of Hawaiian TGs that distinguish a northerly and southerly $H_s$ mode that closely match ($r \approx 0.8$) local $H_s$ time series and their season climatologies. With sufficient local calibration, TG sigma shows promise as an estimator for local offshore $H_s$.

Coefficients between daily average $H_s$ and TG sigma reveal regional attenuation patterns (Figure 4a), such as along the U.S. West Coast (Figure 4a), where wave-related effects and DWLs are of greater concern during extreme events (Figure 4b). Additional factoring by an exceedance coefficient ($\alpha$) in equation (1) provides duration estimates of DWLs over a measurement period. For instance, a DWL expected to occur 95% of a given time period could be estimated by the TG sample mean (SWL) + 1.96*sigma, assuming a Gaussian distribution of 1 s sampling, which is generally found to be the case (not shown). Such observational-based DWL estimates should improve impact climatologies and help validate nearshore water level-wave models.

We recognize that sigma is only a partial estimate of $\text{wave}_{\text{inc}}$ and $\text{wave}_{\text{tg}}$ variability at a TG location due to its sampling scheme, which does not fully resolve oscillations with periods between 3 and 6 min. Sigma as reported (181 1 s samples every 6 min) is >95% of the sigma computed using continuous 360 1 s samples at the three HI Island TGs with continuous 1 s samples (not shown). Local calibration is also needed to determine specific attenuation or amplification imparted by the TG protective well, which dampens oscillations <5 s and can create a resonance at periods near 5 s [Park et al., 2014a]. For instance, regression (not shown) between hourly sigma computed by the NOAA TG acoustic sensor within its protective well and the subsurface Seabird pressure sensor are highly correlated, but reveal linear biases imparted by the protective well.


References


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