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Improving Efficacy of Tsunami Warnings Along the West Coast of the United States

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Abstract—Tsunamis cause significant damage and loss of life, particularly for the nearest communities, where the tsunami may arrive in minutes. These local communities often do not receive an informed or timely alert under traditional warning pathways. In response, numerous tsunami early warning (TEW) algorithms have been developed with the goal of providing informed tsunami source characterization for use in rapid, localized warning. An overlooked aspect of TEW is the means that this crucial information is disseminated. Current operations focus heavily on the time an alert is issued from a warning center, however, that alert passes through multiple groups and agencies before it is conveyed to affected communities. This distribution path can create further delays and contributes to inconsistencies in the message timeliness and content. In this study, we provide the framework and advocate for the use of a rapid dissemination tool, that we call WaveAlert, that would leverage preexisting advances in earthquake early warning systems to provide timely, clear, and consistent alerts to the public by use of the MyShake EEW phone app. This proposed tsunami dissemination tool would be able to provide consistent, public facing tsunami alerts over the duration of the hazard with the added benefit of low message latencies and high spatial resolution in who can be targeted for messages. We illustrate the need for rapid alerting strategies through a retrospective look at the alerting process during the 2022 Tonga tsunami and through a modeled potential near-field Cascadia timeline example affecting the west coast of the US.

Keywords: Tsunami early warning, earthquake early warning, tsunami alerts, tsunami.

1. Introduction

Tsunamis are low-frequency, high-impact events affecting coastal communities globally. Often associated with rapid deformation of the seafloor related to earthquakes and landslides, tsunamis impact not only the coastline immediately adjacent to the source, but potentially coastlines thousands of kilometers away. While large tsunamis can cause hazardous waves, flooding, and currents on a basin scale, the hazard is most extreme at coastlines local to the source. Not only are wave amplitudes often largest near the source, but the arrival time of the tsunami to the shoreline is at its minimum. This leaves little time for residents near the coast to react and evacuate to higher ground. For example, a tsunami originating along the Cascadia Subduction Zone (CSZ) can potentially arrive at the nearest coastlines within five minutes and across the entire near-field region within one hour.

Tsunamis that originate in the far-field, defined here as over one thousand kilometers away, can also generate hazardous waves at distant coastlines through strong currents (Borrero et al., 2015). Often these events do not cause widespread flooding, however, they can still cause significant damage to harbors and marinas (Lynett et al., 2014). For example, both the 2010 Maule, Chile and 2011 Tohoku, Japan tsunamis caused extensive damage at harbors located in Crescent City, California (Wilson et al., 2013). The 2022 Tonga tsunami, visible at tide gauges globally (Carvajal et al., 2022) also generated damaging currents in harbors in Southern California.

Many recent studies have focused on increasing the amount of information available immediately after a seismically generated tsunami is formed to allow for quicker initial alerts from tsunami warning centers. These efforts often fall into the category of tsunami early warning (TEW). While the inclusion of direct observations of tsunamis via tide gauge and pressure gauges are temporally infeasible for most early warning applications (Williamson & Newman, 2019), many studies have found ways to include seismic and geodetic data to produce informed alert

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information. For example, Blewitt et al. (2009) focused on the ability of GNSS to predict deformation occurring offshore, which could be used for forecasting if available in real time. Melgar et al. (2016a) provided the framework for a real-time GNSS-guided earthquake magnitude estimate to aid in rapid tsunami source characterization. An accurate initial magnitude provides information about what level of tsunami alert should be issued, and to what spatial extent. Following this, Williamson et al. (2020) tested the suitability of rapid geodetically derived finite-fault models for their accuracy in tsunami forecasting. This focused on the application of the G-FAST code (Crowell et al., 2016), which has also been used retrospectively to model the tsunami generated from the 2016 M7.8 Kaikoura, New Zealand earthquake (Crowell et al., 2018). Other TEW tools include the estimate of the tsunami potential based on the predominant period of P-wave signals in conjunction with a real-time magnitude estimation (Lomax & Michelini, 2013).

While progress has been made in rapidly detecting and characterizing tsunamis in the near-field, an overlooked but necessary aspect of providing tsunami early warnings is how that alert is transmitted to affected individuals. In order to mitigate the risk of both locally generated and far-field tsunamis, timely, clear alerts targeting affected coastal communities is necessary. Alerts issued immediately following a locally generated tsunami can act as confirmation to residents of the need to stay away from the coast and evacuate to higher ground. Following a tsunami generated in the far-field, alerts indicating the potential hazard due to strong currents can inform vulnerable communities of the need to stay out of the water and away from affected areas. Additionally, consistency in the alert content and timeliness across all affected areas increases the effectiveness of the message (Mileti & Peek, 2000). Despite the need to relay tsunami information quickly, there are limited pre-existing pathways to convey an alert within the United States.

In the United States, alerts originating from the two tsunami warning centers (TWCs) are often available in the minutes following a large tsunamigenic earthquake. While entities of the National Weather Service, which includes both tsunami warning centers do not send direct text or email alerts to the general public, information is available through a handful of alternate formats. Short format alerts are provided to the public through social media platforms, like Twitter in near-real time. Additionally, tsunami warnings often trigger the issuance of a Wireless Emergency Alert (WEA) to all capable phones near the expected hazard. Both can alert users quickly, but because of limitations on the message length and the potentially large geographic distribution of WEA messages, the tsunami alerts do not provide clear and personalized information to the public about the extent of the tsunami hazard and may overalert. For more detailed event information, users are directed from the short format message to the TWC website where standardized messages for all recent tsunami events are available from both centers in a single web table. While more detailed, the content of these messages are not tailored for public users, especially those who are generally unfamiliar with tsunamis (Sutton & Woods, 2016). Additionally, upon review of tsunami messages, the National Research Council of the National Academy of Sciences (NAS) recommended improving the clarity of both official tsunami warning messages, increasing message consistency between both warning centers, and improving the layout and accessibility of the TWC website (National Research Council, 2011). A more recent study conducted by the Science Advisory Board reiterated the same need for consistent message composition and website clarity (Science Advisory Board, 2021).

The limited public-facing dissemination pathways at the TWC level are supplemented by alerts issued through state and local emergency management who decide if, when, and through what platform to relay the tsunami alert at the county level. The dissemination tools used to issue an alert vary across state and local jurisdictional boundaries with many regions alerting on county specific opt-in applications or through reverse 9–11 alerting to pre-registered phones. This leads to spatial and temporal variability in who receives an alert, and when. As noted in Yun and Hamada (2015), the amount of time made available to evacuate directly affects mortality rates following a generated tsunami.

To better serve local communities during a tsunami, we advocate for the creation and dissemination of public facing tsunami alerts that are targeted to coastal regions, consistent in message composition, and use evidence-based design features (Sutton & Woods, 2016). In order to relay this information to a large number of potential communities quickly, we advocate for the modification of existing earthquake early warning (EEW) dissemination systems, which have a tested ability to issue high quality alerts with low latencies to a larger number of people. The scope and goal of EEW is similar to TEW: to alert people prior to a hazard so they can take protective action to mitigate their risk. The current ShakeAlert system (Given et al., 2018), provides EEW information relevant to Washington, Oregon, and California. This information is sent to people through partnered distribution channels. One such partner is the MyShake platform (Allen et al., 2020; Strauss et al., 2020). MyShake issues alerts to users for earthquakes with magnitudes greater than M4.5 to areas with a shaking intensity of at least Modified Mercalli Intensity III (Patel & Allen, 2022). EEW apps, like the MyShake app as well as other systems such as the Android EEW platform (Allen & Stogaitis, 2022), have the tested technology to push an alert to a large number of targeted phones quickly.

Leveraging this technology, we developed the framework for WaveAlert, a TEW dissemination module to integrate TWC alerts within the current EEW alerting scheme of the MyShake smartphone application. The goal of WaveAlert is to provide public focused tsunami alerts to affected coastlines with as little latency as possible. These alerts would provide personalized tsunami hazard and response information to affected users as fast as current rapid dissemination tools such as WEA and Twitter, but without limitations on message length. The alerts would act in supplement to state and local emergency response. This study outlines the current need for a systematic TEW alerting system and how it can be applied for both distantly sourced tsunamigenic events as well as locally generated, high impact tsunamis, where the reaction time of the nearest coastal communities is limited. To achieve this, we first provide a brief overview of tsunami warning center structure and products, focusing on alert dissemination and event response targeting the US West Coast. Second, we provide the methodology and developed workflow to translate current TWC alerts into products that fit within the MyShake EEW platform. Third, we demonstrate the utility of WaveAlert through a retrospective analysis of the 2022 Tonga tsunami alert timeline and a prospective view of a locally generated tsunami on the Cascadia Subduction Zone. Finally, we discuss the merits and limitations of the proposed framework and its future utility alongside currently operational EEW products.

2. *Background: Tsunami Alerts in the United States*

Many countries operate tsunami warning centers with the goal of mitigating the risk tsunamis pose to their coastlines. The United States operates two complementary tsunami warning centers: the Pacific Tsunami Warning Center (PTWC), located in Honolulu, Hawai'i, and the National Tsunami Warning Center (NTWC), located in Palmer, Alaska. Both warning centers identify and alert coastal communities of tsunami threats for their designated service areas. PTWC is in charge of issuing alerts to Hawai'i, U.S. territories, and is a tsunami information provider to partnering Pacific nations. NTWC monitors and alerts for tsunamis affecting Alaska, Canada, and the contiguous United States (Whitmore, 2009). Cooperation is required from both centers when a large tsunami affecting multiple regions occurs. During these events, both centers will issue independent alerts contemporaneously for their respective service areas using agreed on tsunami source parameters.

Alerts issued by the TWCs fall into four categories: warnings, advisories, watches, and information bulletins (Whitmore et al., 2008). Warnings are issued when widespread coastal flooding, often prompting evacuations of low-lying areas, is likely. This level of hazard is defined as when forecasted or observed tsunami heights at coastal observation points exceed one meter. Advisories are associated with forecast wave heights between thirty centimeters and one meter. While smaller in amplitude, tsunamis at an advisory level can generate strong and damaging currents, prompting the need to close beaches and harbors. Watches are used to indicate a pending tsunami threat, often from a far-field source. Informational bulletins are used to address a potential tsunami threat that has been determined to be non-hazardous to the targeted audience as well as to identify small earthquakes that might be felt near the coast but are non-tsunamigenic. In addition to these four alert categories, PTWC issues tsunami threat messages in assistance to international partner nations. The TWCs can upgrade an alert if forecasts or observations at coastal locations indicate a larger than initially anticipated tsunami. For example, a watch can be upgraded to either an advisory or a warning and an advisory can be upgraded to a warning. If a forecasted region overpredicted tsunami waves, the alert level can be downgraded or canceled.

When a potential tsunami threat is identified, the initial alert is linked to a rapid characterization of the (assumed) earthquake source including the location, depth, and earthquake magnitude. The extent of coastline included in this alert is dependent on the earthquake magnitude with larger magnitudes correlating with large tracts of coastline under alert. For example, an earthquake with an initial magnitude of M7.2 would prompt a warning extending 250 km on either side of the source. An M7.6 earthquake would prompt a larger warning area extending 500 km on either side of the coastline. Additionally, the M7.6 would also prompt the issuance of an advisory for coastlines between 500 and 1,000 km away from the source. For even larger magnitudes, a tsunami warning may be issued for all coastlines within a three hour forecasted tsunami travel time from the source. A tsunami watch would then be issued to all remaining coastlines that may be affected. In addition to magnitude dependent alerts, regions that are determined to be in special procedure zones may require different alerting strategies. For example, interior waterways like the Puget Sound in Washington may require the issuance of a warning or advisory for certain cases even though the region does not face the open ocean. Future procedures may be amended to account for non-seismically generated tsunamis. The 2022 Tonga eruptive tsunami, which is not linked to an earthquake and therefore does not have a magnitude, required on-the-fly modifications to alerting procedure and alert content.

There have been numerous tsunamigenic events over contemporary history that have prompted both TWCs to issue an alert at the warning, watch, and advisory levels. These recent events, and the response they prompted for the US West Coast are shown in Fig. 1. Source information for all events shown in Fig. 1 are compiled in Table S1. Most events affecting the US West Coast have had far-field sources. Because of the distance, they often prompted the issuance of a tsunami advisory for local coastlines. Over the past two decades, only two tsunami warning level events have affected the US West Coast. The first event, the 2005 M7.2 Gorda plate earthquake, ruptured close to the coast of northern California. The second warning level event, the 2011 Tohoku-Oki earthquake and tsunami, had forecasted tsunami waves in excess of one meter for parts of the West Coast. Observations along the US West Coast included small but measurable tsunami waves and associated strong currents that caused damage to harbors, particularly at Santa Cruz, California where $28 million in damages was reported (Wilson et al., 2013). Additional recent tsunamigenic earthquakes along the Aleutian Islands have prompted NTWC to issue warnings and advisories along the Alaskan coastline. These events, while tsunamigenic, were not forecasted to be large enough to warrant extending an alert to the contiguous US West Coast. While seismically quiet over contemporary history, the US West Coast is capable of generating a large tsunamigenic earthquake. This was the case in 1700 CE when an estimated M9.0 earthquake generated a large transoceanic tsunami (Melgar, 2021; Satake et al., 2003).

The TWCs subdivide the coastlines of Alaska, Canada, and the contiguous United States are discretized into coastal segments, divided by breakpoints (Fig. 2). Tsunami alerts are then issued at the granularity of these segments. Alerts issued from the TWCs follow multiple channels of communication including e-mail and fax to core partners, weather forecast offices, and public updates to the tsunami.gov website. Wireless Emergency Alerts (WEA) are issued to capable cell phones in the event of a tsunami warning. These alerts are issued on a county scale. Additionally, WEA alerts are issued

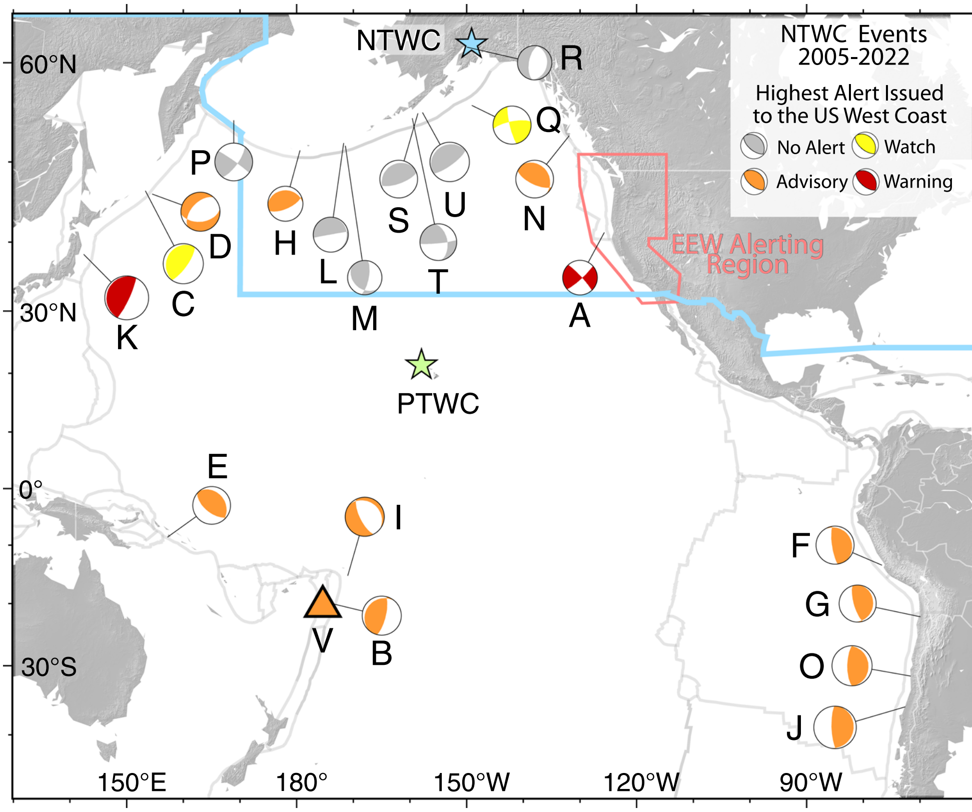

Figure 1
Recent tsunamis that prompted an NTWC response from 2005–2022. Each event is marked by a focal mechanism, for seismic events, or a triangle, for volcanic events. The color of the icon corresponds to the highest alert level raised along the US West Coast: Red marks warnings, orange marks advisories, yellow marks watches, and gray marks no West Coast alert. Events shaded in gray instead only raised alerts for non-West Coast regions, such as the Alaska-Aleutian arc. Locations of NTWC and PTWC are marked with blue and green stars, respectively. The designated service area separating NTWC and PTWC is drawn by a blue line. The current ShakeAlert EEW alerting polygon is drawn in pink. Plate boundaries are drawn in gray. Each event is labeled by a letter that corresponds with an entry in Table S1

only on the first tsunami message; advisories and cancellations will not activate WEA.

Once state level emergency managers receive an alert, they relay the information and provide guidance to county level emergency managers. Often, a local emergency responder is then delegated to issue a public facing alert to their affected communities. The dissemination of a tsunami alert to the public varies across jurisdictions. Many counties along the west coast, particularly within California, send alerts through opt-in emergency messaging apps specific to each county. Social media and software such as reverse 9–11 phone messages to registered phones are also utilized in some local jurisdictions. Figure 2 shows all ocean-facing and intercoastal counties within the west coast region along with the locations of breakpoints used to separate tsunami segments. While multiple counties can be situated inside one tsunami segment, a single county can also be bisected between different segments, potentially requiring different responses.

3. Methodology

This section focuses on how public tsunami products published by a TWC can be translated into a WaveAlert product and how this new product would fit into the existing workflow of the MyShake platform. Currently, MyShake initiates through a trigger

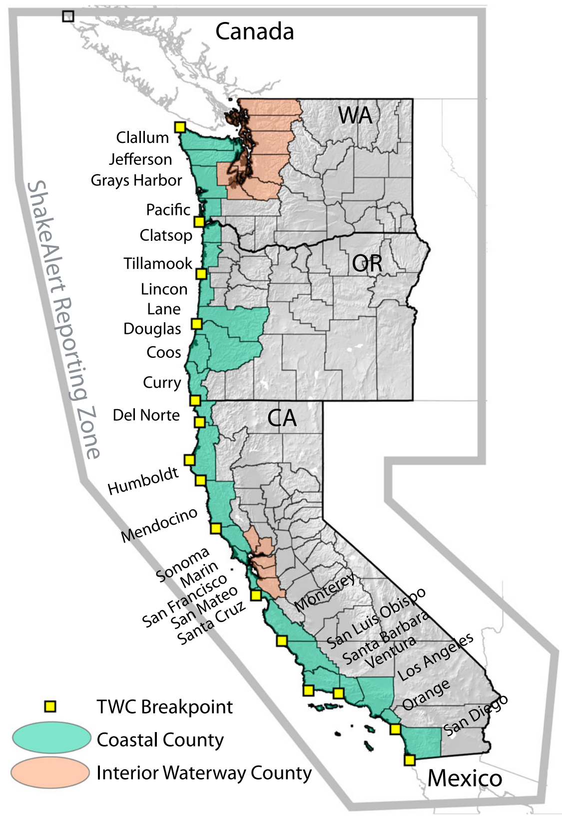

Figure 2
Alerting boundaries along the US West Coast region. Ocean facing coastal counties are shaded in teal and labeled. Interior waterway counties, which may be activated into a tsunami alert are shaded in orange. NTWC breakpoints, which signify the edges of tsunami segments and are marked by yellow squares. The entire region shown here sits inside of the current ShakeAlert reporting region shown as a gray line. CA, OR, and WA indicate California, Oregon, and Washington respectively

from ShakeAlert (Fig. 3). MyShake activates any time an earthquake within the ShakeAlert reporting region has a magnitude exceeding M4.5 and alerts the area forecasted to experience shaking of at least MMI III (weak shaking). MyShake takes the forecasted shaking area and then determines which registered users should receive an alert using either their smartphone location or a user-set homebase location. All user locations are binned into pre-set 10 km by 10 km cells using the geocoded military grid reference system (MGRS). The timeframe between when an earthquake originates and when ShakeAlert produces a solution depends in part on the station density near the epicenter, but is typically on the order of seconds. Once a solution has been created, MyShake can format and disseminate that information to phones with a low latency of a few seconds (Patel & Allen, 2022). The generalized EEW component of MyShake is shown in Fig. 3 for a hypothetical M7.6 earthquake originating just offshore of the California/ Oregon border. For simplicity, we illustrate the EEW workflow using a point source. MGRS cells where predicted shaking intensities of at least MMI III are colored. All cells inside of the MMI III and greater contours would receive a MyShake alert. Additionally, phones within the MMI IV and greater contour would also receive a Wireless Emergency Alert (WEA). As an additional component to the MyShake system, WaveAlert would format tsunami information and disseminate to affected coastal areas using the same MGRS cell structure as is used for EEW. Just as MyShake's EEW component initiates from

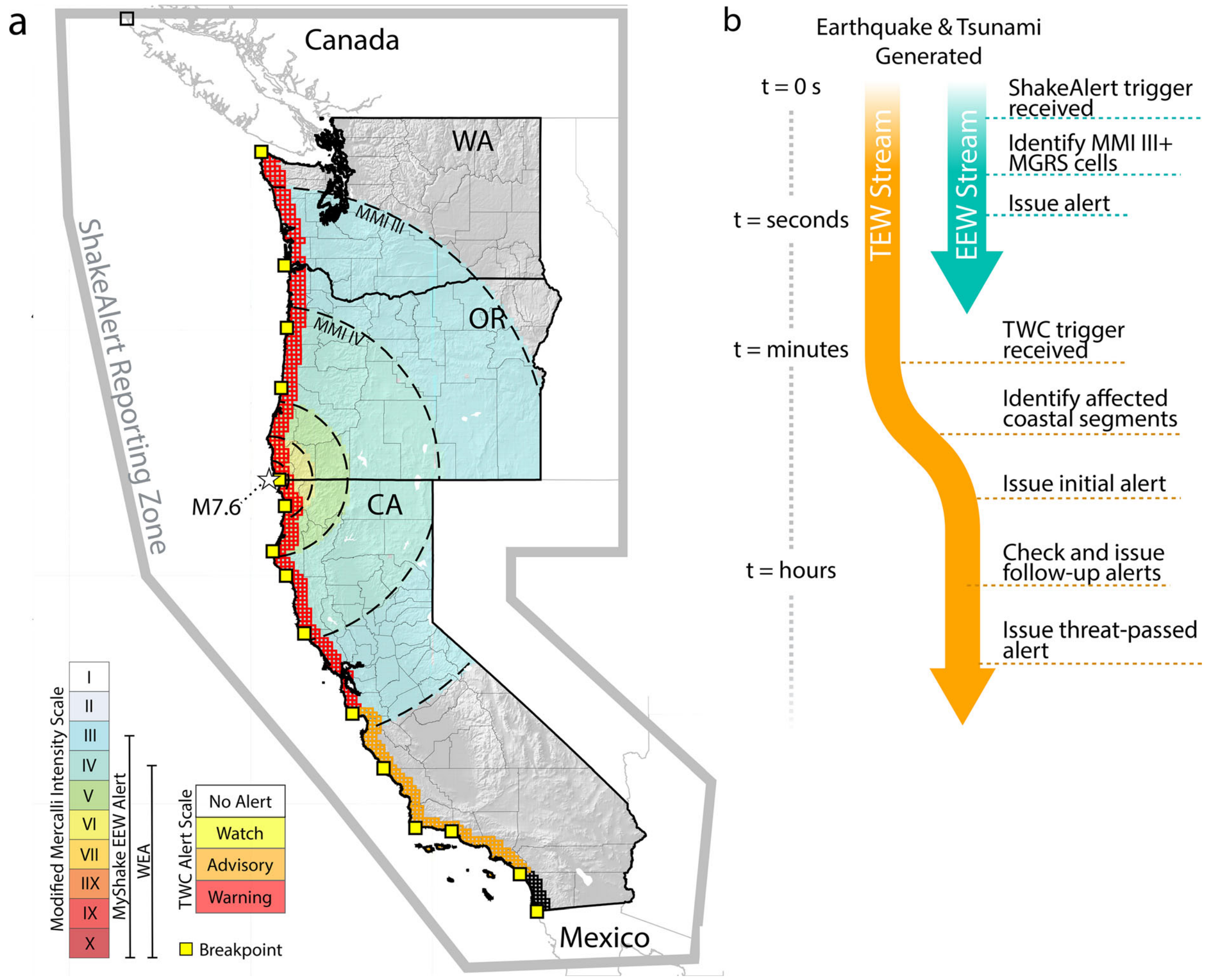

Figure 3

A alerting areas for a hypothetical M7.6 earthquake rupturing just offshore of Northern California. Colored and contoured regions shaded light blue to yellow indicate the area that would receive a MyShake EEW alert based on expected shaking intensity. Regions with expected shaking below MMI II would not receive an alert and therefore are not shaded. Coastal cells that would also receive a TEW alert through the proposed addition to MyShake are outlined red, orange, or black (no alert) based on current magnitude-based warning criteria employed by the TWCs. CA, OR, and WA indicate California, Oregon, and Washington respectively. **B** Generalized timeline of MyShake during a local event where both EEW and TEW modules are activated. The current EEW system (teal track) operates on the scale of seconds to tens of seconds. The proposed TEW system (orange track) operates on the scale of minutes to hours to account for the long duration of tsunami events

information through ShakeAlert, the proposed MyShake TEW component, WaveAlert, would initiate through a new event identifier being provided by a TWC.

For the west coast of the U.S, the primary TWC that issues alerts is NTWC. In addition to publishing a new event identifier, every event published by the TWCs has an associated Common Alerting Protocol (CAP) formatted XML product that is publicly available in real time after a TWC bulletin is issued. CAP formatted files are designed for the exchange of emergency information and are used in operational Emergency Alert Systems and the Integrated Public Alert and Warning System (IPAWS) which is responsible for transmitting WEAs. Within the CAP XML message is information on which tsunami segments, if any, have been elevated into a tsunami warning, watch, or advisory. If this occurs, WaveAlert determines which relevant MGRS cells fall into the alert zones. Here, we designate all cells within

30 km of the ocean-facing coastline as cells that can potentially be alerted (bolded cells in Fig. 3). Additionally, cells within intercoastal waterways that do not reside within 30 km of the coast, such as the area around the Puget Sound, in Washington, are also identified. These cells may be activated during a special tsunami procedure issued from the TWC. The use of a 30 km distance to designate a coastal zone is used to limit the potential of overalerting during an event. An overalert in this case would include communities far inland that would not see the effects of the tsunami, even if they may have felt shaking from a related earthquake. Cells within TWC alerted tsunami segments, colored red for a warning and orange for an advisory in Fig. 3, would receive a WaveAlert tsunami information message. This would be in addition to an earlier EEW alert for regions that also are inside the MMI III or greater contours. Some coastal zones in central and southern California could potentially not receive an EEW message and instead only receive a WaveAlert message. In no scenario would a region that receives an EEW message not receive a WaveAlert follow-up.

The content of a WaveAlert message would depend on the level of alert. Pre-set messages for tsunami warnings and advisories would convey the level of hazard and recommended actions and would be based on the guidance provided from the TWC. For example, California cells that are placed in a tsunami warning would receive an alert identifying the user as being near the coast, relaying that a tsunami warning has been issued, and recommending the user to move to higher ground. If instead, a segment is placed under an advisory, an alternate message conveying the need to stay off the beach, but without the recommendation to evacuate, can be used. In addition to guidance provided and attributed to the TWCs, links to state level tsunami preparedness websites can also be incorporated depending on which cell is alerted. A user located in California, therefore, could also have a link available to access California specific information including evacuation maps. This information would be different from what could be provided to users located in cells within Washington. This can help provide those alerted with local information regarding tsunami preparedness in the event that it takes time for a local county alert to be made available.

Because tsunami events may last for several hours, follow-up alerts provided through the TWC would also be relayed through WaveAlert by means of MyShake. This is a departure from the existing structure of MyShake as EEW alerts occur on a timescale of seconds, negating the need for multiple messages related to the same event. Because of the need for multiple messages, a scheme that provides information to users over the duration of the event while avoiding message fatigue needs to be implemented. Here, we propose using two tiers of message visibility, similar to the two-tiered system of alerts used by some EEW providers like Android (Allen & Stogaitis, 2022). The more visible, higher priority message, akin to the *Take Action* message used by Android EEW systems, would prompt a full screen alert. The goal of this level of alert is to make the user aware of the immediate threat and would be reserved for cases where a tsunami segment is initially placed, or is upgraded into a tsunami warning. In contrast, a lower priority message would be sent for tsunami advisories and cancellations, and follow-up messages provided by the TWC while a coastal segment remains in the same alert level. This would appear on a smartphone as a standard notification card, rather than a high-priority full screen takeover. Because tsunami energy can get trapped between the shelf and coastline, coastal segments may be under a tsunami warning or advisory for many hours. During this time, it is possible for coastal segments to be upgraded from no alert to an advisory or warning, downgraded from a warning to an advisory, or for the alert at a segment to be canceled if the tsunami danger has passed. By using a lower tier of priority for non-warning level messages, information about the ongoing tsunami hazard can be conveyed without sending too many alerts, which may be viewed as excessive, particularly for advisory level events where no action is needed by alerted individuals who are not actively on a beach. All messages related to the current tsunami event personalized to the user's general location, would be available within the MyShake app. This limits the need for a user to navigate through the many messages from both

TWCs issued for all alerted regions through the tsunami.gov website.

It is important to note that the timeline of alert dissemination for a large magnitude, local event, would first focus on the ShakeAlert EEW component, as these messages would be available within the first few seconds following an event. WaveAlert tsunami messages would be issued as information is made available by the TWCs. Often this is within 3–5 min following an event. The latency between receiving a trigger from the TWC and issuing an alert through MyShake is expected to be the same level of latency as with a ShakeAlert product. Because WaveAlert would only alert smartphones at pre-designated coastal cells, which is a small subset of the cells that already can receive an EEW message, we do not expect to encounter an upper limit to the number of phones reached during an event.

4. Application

We use two events as points of reference when discussing the expected performance of WaveAlert. First, we look retrospectively at the 15 January 2022 Hunga Tonga-Hunga Ha'apai, Tonga eruptive tsunami. We choose to focus on this event because it is the most recent event to elevate all coastal segments along the west coast into a tsunami alert at the same time. This allows us to assess publicly available message content and latencies over the duration of the event. Second, we apply our proposed WaveAlert system to a prospective large tsunamigenic earthquake nucleating along a local coastline, i.e.during a near-field tsunami. While there have been few locally generated tsunamis on the west coast in contemporary history, there is potential for a large tsunamigenic earthquake originating along the Cascadia subduction zone. While the arrival time of any tsunami depends on the source location, a large tsunamigenic earthquake rupturing on the Cascadia subduction zone can reasonably arrive at local coastlines within minutes to tens of minutes. To that end, we model a prospective tsunami at this location to gain an understanding of the warning times as well as the exposure of coastal populations to the event.

4.1. Example: 2022 Tonga Tsunami

On 15 January, 2022 at 04:14:45 UTC, a tsunami was generated from a volcanic eruption at the Hunga Tonga-Hunga Ha'apai volcano, located in the southwest Pacific. The tsunami was generated through two mechanisms: displacement due to the volcano eruption, and an atmospheric pressure wave (See Heidarzadeh et al. (2022) for a more detailed analysis of the source mechanisms). The resultant tsunami was observed distantly from the source with selected peak amplitude observations of 40 cm at Adak, Alaska, 54 cm at Hilo, Hawaii, and 80 cm at Crescent City, California (Carvajal et al., 2022). While widespread flooding was not observed along US coastlines, the tsunami caused damage within some harbors, including extensive damage to the Santa Cruz harbor (Lynett et al., 2022).

The tsunami was novel from an alerting standpoint as it was the first non-seismically generated tsunami to require a response from either US TWC. The scale of the event prompted NTWC to issue a tsunami advisory to all Pacific Ocean adjacent tsunami segments at 12:53 UTC (04:53 PST). The advisory extended from the border between the United States and Mexico north and westward to the furthest extent of the Aleutian Islands in Alaska. The simultaneous alerting of all Pacific Ocean facing tsunami segments into an advisory makes it possible to identify trends in how that alert propagates from the warning center through to local response. Here, we focus on the response along the US West Coast from the California-Mexico border to the Washington-Canada border.

As the initial tsunami advisory was created, tsunami arrival times were generated for pre-determined coastal forecast points along the west coast. Arrival times ranged from 15:35:00–16:50:00 UTC (07:35–08:50 PST). This provided a maximum potential time for coastal residents to respond of 3 h and 57 min. This corresponded to the Port Townsend coastal forecast point, located at the northern end of the Puget Sound in Washington, inside an interior waterway. The minimum time to respond, based purely on the NTWC alert, was 2 h and 28 min, for coastal communities near Fort Bragg, in northern California. Even at this shorter response

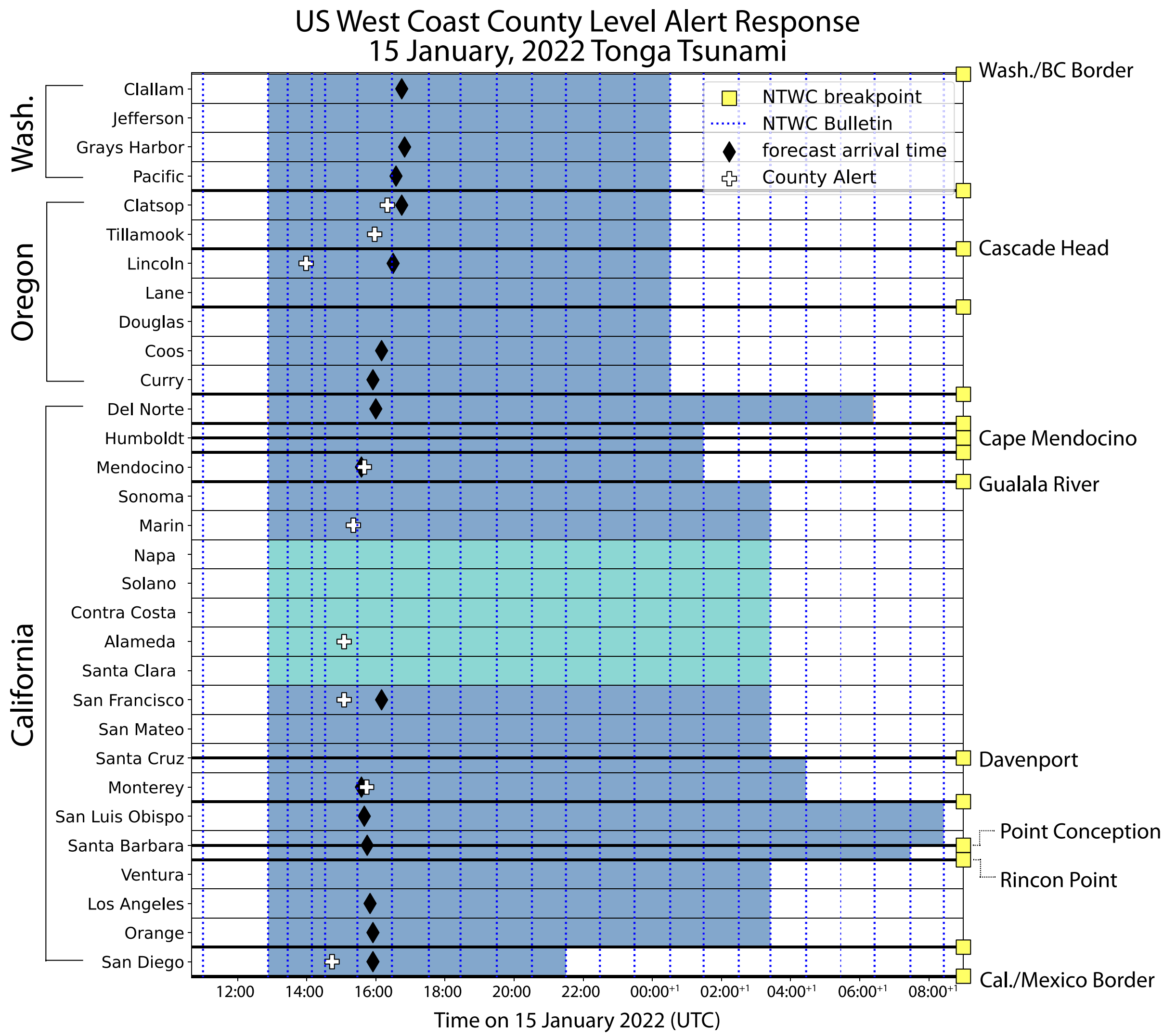

Figure 4
Alerting timeline along US West Coast following the 2022 Tonga tsunami. Shaded horizontal bars mark the duration of the tsunami advisory for each county. Blue shaded bars indicate an ocean facing county. Teal shaded bars indicate an interior waterway county. Vertical blue dotted lines indicate the time that NTWC issued an event related bulletin. Bolded black horizontal lines capped with a yellow square represent breakpoints and group counties based on their corresponding tsunami segment. Forecast arrival times for selected coastal points are marked with black diamonds. The first issuance of a publicly available county alert is marked by a white cross. Note that the absence of a white cross does not necessarily indicate that an alert was not issued, rather it was not archived or publicly available post-event

window, there is sufficient time to take protective measures to mitigate the potential risk of flooding and strong currents, when compared to a locally generated source. In Fig. 4, we plot the extent and duration of the tsunami advisory for each affected West Coast county. The forecasted arrival times from NTWC are plotted as black diamonds.

Because the severity of this tsunami prompted the issuance of a tsunami advisory rather than a warning, alerting cues such as coastal tsunami sirens and WEA were generally not employed. The distance and non-seismic source also meant that coastal residents would not experience ground shaking as an environmental cue. This lower alert level places a larger emphasis on local county level jurisdictions to relay relevant tsunami hazard information to their residents. Here we look at alert response times and alert message content for selected counties. We plot the timing of initial county alerts, where available, as white icons on Fig. 4. The responses from counties analyzed use opt-in publically available alerts and were archived. Additionally, copies of available county level tsunami alert texts, sources, and issue times are available in Table S2 in the Supplement. The messages available both in Fig. 4 and Table S2 are only a subset of messages issued during the event. Alerts that were not publicly archived are not included; this includes alerts from counties that use reverse 9–11 phone calls, which are not logged.

The timing of the first issued alert on a county level varies greatly across the West Coast. For example at 05:59 am PST, one hour after the advisory was issued, Lincoln County, Oregon issued an alert through the Lincoln County Sheriff's office advising residents to stay off beaches due to a tsunami advisory related to a distantly generated tsunami. The quick reaction time meant residents had over two hours before the tsunami was expected to make landfall. Similarly, in San Diego County, California's Alert San Diego system issued a tsunami advisory at 06:44 am, 71 min prior to tsunami arrival. In contrast, Monterey County, California issued an alert through the opt-in Alert Monterey County community alert system at 07:44 am PST, nine minutes after the NTWC forecasted tsunami arrival time. The first tsunami alert issued in Mendocino County, California through the opt-in MendoAlert system arrived at 07:40 am PST, five minutes after the forecasted tsunami arrival time. Both Monterey and Mendocino counties did not issue timely alerts for this event.

The contents of county alerts varied across the advisory area. For example, the tsunami advisory was miscategorized as a tsunami order and a tsunami warning by Monterey and Alameda Counties, respectively. The incorrect terminology can lead to confusion among residents and is contrary to tsunami preparedness information. Some counties choose to write their own messages related to the tsunami advisory, while others relay the NTWC or regional weather forecast office tsunami messages. The number of messages issued also varied by county. Some counties only issued an alert for the initial advisory while others issued follow-up and threat cancellation messages.

The Tonga tsunami highlights several alerting characteristics that could be improved upon through WaveAlert. Because messages through WaveAlert would be sent to all coastal zones regardless of county jurisdiction, better consistency in message content and terminology would be achieved. Messages need to clearly state the alert level (warning or advisory) and then provide guidance on what this level means and what protective measures are recommended. Large tsunami events that include both inter-coastal and ocean-facing counties across a large swath of the west coast lend to situations where numerous counties have distinct interpretations of the base hazard. The absence of a unified and public facing message can reduce the effectiveness and urgency of an alert. Similarly, an effective message needs to be sent to all alerted regions as quickly as possible to ensure as much response time for local communities as possible. With demonstrated low latencies, an alert issued through MyShake would be able to alert all affected coastal zones simultaneously. This would reduce uncertainty for communities on the borders of differing jurisdictions that may otherwise receive alerts minutes or hours apart for the same event with the same hazard.

As shown in Fig. 4, the duration of the advisory along the west coast extended over multiple hours across all tsunami segments. Having a means to maintain awareness of the ongoing threat, through consistent follow-up information and a way to clearly indicate to the public when an alert has been lifted would increase the effectiveness of the alert messages. Variability also exists in alert duration for adjacent segments. This is in part due to the requirement for the tsunami amplitude along the coast to stay below target amplitudes before the TWCs downgrade or cancel an alert. Some tsunami segments may have coastal features or bathymetry that promote site amplifications which will affect the duration of the tsunami hazard. Additionally, some breakpoints, which separate tsunami segments bisect counties. This could place different parts of the same county into different levels of alert, requiring a complex local response.

4.2. Example: Local Generated Tsunami

Locally generated tsunamis pose the greatest potential hazard along the US west coast. As noted in Lindell and Prater (2010), tsunami preparedness along the coastlines of Oregon and Washington has been a longtime topic of interest due to numerous recent far-field events, however the communication of a local hazard is still a challenge. The closeness of the source greatly reduces the response time for coastal communities. A confirmation of the tsunami hazard through a WaveAlert message could act as the driver for residents to take action and evacuate inland and to higher ground. Despite the threat of a locally generated tsunami, the likely source of the event, the Cascadia Subduction Zone has been seismically quiet over recent history. Therefore, to illustrate the need for faster alert dissemination along the west coast, we use a prospective tsunami scenario. We draw our source scenario from the Cascadia focused Fake-Quakes dataset from Melgar et al. (2016b). The rupture scenario recreates a stochastic slip pattern consistent for large magnitude subduction zone events using an application of the Karhunen–Loeve expansion (LeVeque et al., 2016), a regional subduction zone slab geometry (McCrory et al., 2012), and rupture dimensions drawn from Blaser et al. (2010). The event chosen is a M9 earthquake with a peak slip of 36 m. Slip is largely concentrated in a shallow band extending from southern Oregon northwards to Vancouver Island, Canada (Figure S1).

We calculate the seafloor deformation, which acts as the initial perturbation in our tsunami model using the elastic half-space model of Comninou and Dundurs (1975), an adaptation of the classic Okada equations (Okada, 1985) that allows for slip on triangular subfaults. The tsunami simulation is performed using GeoClaw (Clawpack Development Team, 2020; Mandli et al., 2016). GeoClaw solves the two-dimensional depth-averaged non-linear shallow water wave equations and employs adaptive mesh refinement. We propagate the tsunami with a finest resolution of 15” (approximately 350 m resolution) along the coastline for twelve hours of model time. The focus of our model is on the initial tsunami arrival across the US West Coast, however we acknowledge that the tsunami will affect local coastlines for a much longer duration. We query the initial arrival time, here defined as the first time that the water column exceeds 10 cm above mean sea level as well as the maximum tsunami height experienced over the model duration at a series of points immediately offshore of the coastline. As we are focusing on the arrival of the tsunami at ocean facing coastlines, we do not model coastal inundation nor do we model the tsunami into interior waterways, though we acknowledge that interior waterways may be affected during a large subduction zone event. The arrival times of our synthetic event at each tsunami segment, as well as the maximum tsunami amplitude across the near-field region are shown in Fig. 5. The segments of the coast closest to areas of large uplift see a tsunami arrival time within ten minutes. This occurs primarily along central and southern Oregon. Other nearfield coastlines in Washington and northern California see a tsunami arrival time within 20 min. The arrival time increases with increasing distance from the source. The tsunami arrives at ocean-facing coastlines surrounding the Bay Area of California within one hour, and reaches the California/Mexico border just after two hours.

In order to provide an estimate of the exposure of coastal communities to the tsunami, we also determine the population affected in each tsunami segment (Center for International Earth Science Information Network (CIESIN), 2020). Using this estimate, we calculate the total population in each coastal MGRS alerting cell and then the total population estimated in each coastal segment. While not a definitive value as it excludes changes in population since the census, potential inaccuracies in census data, and transient tourist populations, it provides a point of comparison when discussing the need for timely alerts. Using the modeled arrival times and estimated population within each tsunami segment, Fig. 6 shows how many people are potentially exposed to the tsunami and when.

Following the tsunami generation, the six nearest segments, spanning all of Oregon, Washington, and part of Northern California experience a tsunami with a median maximum amplitude exceeding one meter, the minimum threshold for maintaining a tsunami warning alert level. The arrival time of the tsunami at all near-field segments is within 20 min. For all

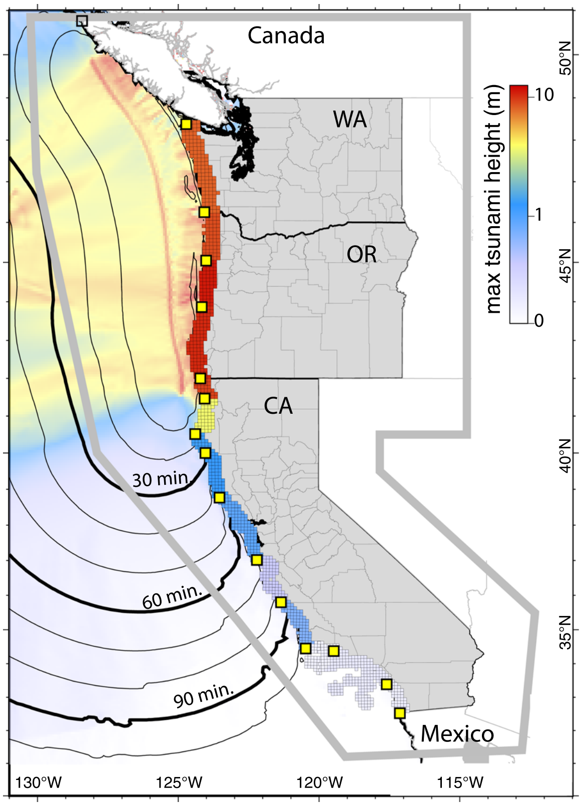

Figure 5
Tsunami arrival and impact along the US West Coast for a large magnitude seismically generated local source tsunami. The maximum tsunami amplitude modeled over the duration of the simulation is shown offshore. Each tsunami segment is colored based on the maximum tsunami amplitude observed. Black contours indicate the tsunami arrival time. Yellow squares indicate TWC breakpoints separating coastal segments. Gray line outlines current ShakeAlert reporting region. CA, OR, and WA indicate California, Oregon, and Washington respectively

events, there is a latency between the earthquake rupture, tsunami generation, and the issuance of the initial tsunami alert. Here we use a latency of five minutes post-earthquake for the initial NTWC alert to be published. This means that if a WaveAlert message was issued immediately following the NTWC alert, the maximum response time for the most affected communities is 15 min. This amounts to 86% of the coastal community receiving an alert prior to tsunami arrival, however, the amount of response time varies by location. Unfortunately, even with an immediate relay of relevant tsunami warning center information, there is a subset of the coastline where the tsunami would arrive prior to alert. This is similar to the subset of who do not receive a timely alert through earthquake early warning due to limitations in detection times. Of the subset of the population in the near-field, 14% would have an untimely alert.

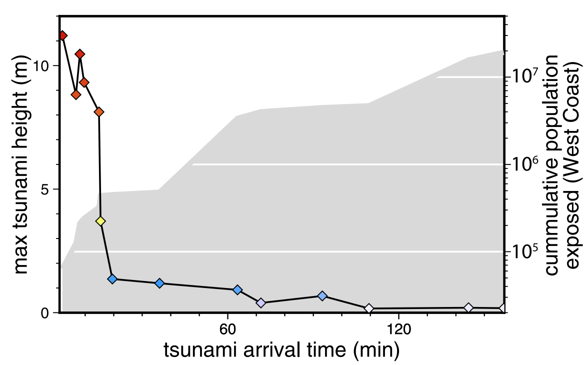

Figure 6
Exposure of coastal communities to the tsunami event. The black line with colored diamond icons shows the maximum coastal amplitude observed per segment against arrival time. Diamonds are colored with the same color scale as in Fig. 5. The shaded polygon shows the cumulative population located inside each coastal segment

South of the rupture area are tsunami segments with modeled amplitudes that range between 30 cm and one meter. While widespread flooding would be less likely with a tsunami of this size, strong currents can pose a threat to people in the water on beaches and to property within harbors. The arrival of the tsunami at these distances ranges between 20 to 90 min. This equates to a longer response time than for near-field communities. Finally, this event also shows that there are a subset of segments far from the source that will likely receive an alert, but may not experience tsunami amplitudes that exceed the 30 cm threshold for an advisory.

It is important to note that even though the true alert level based on the modeled maximum amplitude varies along the coastline, current operational procedure dictates that in the event of a magnitude 7.9 or greater earthquake, all segments within a 3 h tsunami travel time will be raised into a tsunami warning through the first NTWC bulletin. This conservative act of overalerting safeguards against a potential underestimate of the large magnitude and limitations in tsunami forecasting that are available with limited data.

5. Discussion

There are numerous benefits in aligning tsunami alerts with earthquake early warning, these include improving the timeliness of alerts, refining the specificity of the alert boundaries, and improving the consistency of message content. Below we discuss each of these benefits as well as discuss limitations in the proposed WaveAlert system.

Important in early warning is the ability to issue accurate public facing and accessible alerts quickly over the entire affected coastline. By using current EEW distribution platforms, like MyShake, tsunami alerts can be issued over wide areas with low message latencies. Most EEW latency metrics are focused on the seconds it takes to issue an alert. Patel and Allen (2022) analyzed the latency component of alerts issued through MyShake for recent events. The authors demonstrate that alerts issued are timely, meaning they arrive prior to shaking for most phones. The entire process, from processing to receipt on phones can occur as quick as $\sim$ 2 s, as was the case with the M 4.3 Carson, California earthquake. This level of low latency alerting can be leveraged to relay TWC messages to the public in near real-time. While sub-second accuracy in alert timing is not necessary for tsunami alerts, the fast push of information through the MyShake App to users is a tested and demonstrated proof of concept for issuing alerts to a large population.

While important for all tsunamigenic events, the ability to issue an alert quickly is of particular importance during locally generated tsunamis, which may affect the closest coastlines within minutes. In the Cascadia timeline example provided (Fig. 5), all areas close to the earthquake and tsunami source would expect the tsunami's arrival within 20 min. For the nearest region along the coast of Southern Oregon, the arrival time would be within 10 min. After the receipt of an official alert from the tsunami warning center, with the expectation of that alert being issued within 5 min of the presumed earthquake origin, the amount of time for residents to respond is even shorter. The immediate relay of this message through a smartphone app alert like MyShake, would increase the time for users to respond and evacuate. As shown in Fig. 6, the people who experience the highest initial amplitude tsunami are also the people who have the greatest need for an immediate informed alert as the tsunami arrival time is within 20 min. Of the subset of the population that would see a tsunami of greater than one meter, 86% have an arrival time that is forecasted as after the expected first TWC alert. However, if a coastal resident spends time deciding if a short-format WEA alert or message on social media requires action from them or waits for an additional county level evacuation order, the actual time to respond may reduce significantly.

In addition to providing timely alerts, the proposed system is also able to target only affected coastal segments as opposed to issuing an alert on a larger county scale, which may extend far inland. While broadly issuing alerts, even to inland communities may seem like a way to reliably make a warning visible, the overalert comes at a cost. This places the task of deciding whether the alert requires action on the recipient, who may not have an understanding of tsunami hazards. As noted in Sutton and Woods (2016) the usage of county or non-intuitive place names in official tsunami messages makes it difficult for the target audience to determine if they are at risk. This limits the effectiveness of the alert, both for coastal communities as well as for non-local and tourist populations.

Through WaveAlert, a target coastal distance of 30 km is set, wherein any MyShake user with a location inside an MGRS cell within 30 km of an affected coastline will receive an alert. The use of alerting cells also makes it easier to identify and target special procedure zones such as intercoastal waterways like the San Francisco Bay Area and the Puget Sound. These areas can be placed into an alert by NTWC but do not have a corresponding tsunami segment or breakpoint at this time. Because the scale of the WaveAlert cells is much smaller than the current alerting segments used by NTWC, the system can adapt to any future changes. As observational networks and on-the-fly models and forecasts are being developed (Angove et al., 2019), it may be possible to only issue warnings or advisories to smaller segments along the coastline. This is particularly relevant for places like Washington state, where the entire outer coastline falls within the same tsunami segment. If, with time, these areas are discretized into multiple segments, the current MGRS cell alerting scheme can easily be adapted to allow for a finer spatial resolution for alerts.

Unlike rapid short-format messages like WEA, tsunami alerts channeled through MyShake can include more detailed and personalized information for alerted users without sacrificing time. Consistency in message content can also be maintained. Mis-use of and inconsistencies in alerting content reduce the effectiveness of tsunami preparedness campaigns (Mileti & Peek, 2000) and can create confusion about what appropriate actions need to be taken during an event. During the Tonga tsunami advisory, local jurisdictions used terminology such as a tsunami warning, as was the case in Alameda County, California. Monterey County in California initially referred to the event as a tsunami order, a term that does not have defined action. This was later corrected by the county to reflect the actual alert level of a tsunami advisory.

Through WaveAlert, message consistency can also be maintained across the entire coastal zone, including follow-up messages to confirm that the tsunami threat has passed. The duration of the tsunami advisory from the 2022 Tonga tsunami, shown in Fig. 4, highlights the complexity of alerts. Many segments of the coastline were placed under an advisory for many hours. However, the total duration of the advisory varied per each segment; some neighboring segments have multiple hour differences in the duration of their advisory. These differences in duration depend on the interaction of the tsunami with the coastline at observational points within each segment. The observed tsunami needs to be below warning or advisory levels for a length of time before an alert can be either downgraded or canceled. The distribution of alert zones is also spatially complex. Breakpoints between segments sometimes bisect local jurisdictions, as is the case in Humboldt County, located in California, shown in Fig. 4. This leads to potentially multiple messages within the same local jurisdiction with disparate event durations and warning levels. This type of complexity is easily handled through systems like MyShake, which has already shown the ability to alert through set polygons. The inclusion of a final alert indicating when the tsunami threat has passed or a post-event follow-up message can increase the understanding of the hazard, hopefully increasing the effectiveness of future alerts. Because tsunami alerts are significantly less frequent than other hazards such as wildfire, hurricanes, and severe weather, public understanding of the hazard, even within coastal communities can be limited (Sutton & Woods, 2016). Post-alert messaging is also being studied for its use following EEW alerts (McBride et al., 2020).

WaveAlert can act as a standardized way to receive information that is easily visible to the user. By using two tiers of message visibility, WaveAlert aims to draw the user's attention away from their day-to-day activities. This is particularly salient for alerts related to far-field events, where the user will not receive an initial ShakeAlert EEW product and would not feel ground shaking as an environmental cue to take action. While the WEA alert that is associated with a tsunami warning can effectively draw attention from users, no such alert is issued for a tsunami advisory, watch, or cancellation. Other attention seeking methods to alert users include the use of tsunami sirens. While sirens can alert users to an oncoming threat, Lindell and Prater (2010) noted that their effectiveness diminishes in some instances where the sound is drowned out by background noise such as high winds. Gregg et al. (2007) noted that despite repeated tsunami siren tests in Hawai'i, interviewed residents were not always able to recall the meaning of the siren or to link it to a tsunami hazard.

There are challenges associated with the use of WaveAlert to disseminate tsunami information. If WaveAlert messages are issued through the MyShake platform, it would require a user to download the app onto a smartphone. This reduces the visibility of alerts to those without access to a smartphone device. Additionally, by needing to download an app, WaveAlert is effectively an opt-in system, similar to many county level apps currently available. However, unlike each county level app, WaveAlert would not require a user to opt-in to receiving alerts on a per county basis. Anywhere on the west coast that experiences a tsunami alert would be treated equally. This increases the visibility of alerts for coastal residents when they are outside of their home county and makes it easier for tourist populations to receive alerts. Another limitation is that MyShake is currently operationally in only Oregon, Washington, and California. This means that an expansion of MyShake's service area would need to occur before tsunami alerts could be provided to other tsunami prone areas such as Alaska, Hawaii, and territories like American Samoa, Guam, and the Northern Mariana Islands. While MyShake's current alerting area is defined from ShakeAlert's reporting area, any potential expansion need not necessarily be based on ShakeAlert. For example, an expansion to Alaska in the MyShake system could provide tsunami alerts even before any expansion of EEW to the state.

6. Conclusion

The focus of this study is to highlight the current need for rapid tsunami alerts available publicly following large earthquakes and provide a mechanism for message delivery. Alerts, in the form of tsunami warnings, advisories, and watches are issued within minutes of an earthquake by the TWCs. However, these messages, while publicly available, are formatted and primarily disseminated to weather forecast offices and state level and local county level emergency managers. These alerts are then relayed to the public by use of a mix of county level emergency alert apps, reverse 9–11 phone calls, tsunami sirens, and WEA alerts among a long list of varying dissemination paths. We find that this current method of disseminating tsunami alerts to the public is ill suited for the rapid response that would be needed in the case of a locally generated tsunami. Furthermore, we find that even tsunamis generated in the far-field, which often allow for longer lead times before arrival across coastlines, would benefit from an initial public facing message that was consistent in time and content across all alerted zones. Therefore, the use of dissemination tools that are currently focused on EEW, could be leveraged to deliver these alerts with a low latency. One such EEW dissemination tool is the MyShake App, which has successfully delivered ShakeAlert product alerts to affected users for several years.

WaveAlert, our proposed addition to the MyShake App could parse and relay tsunami alerts using a similar workflow to the current ShakeAlert EEW system. These alerts could target pre-set coastal segments on the same scale as current TWC alerts, with the ability to scale down to smaller alerting zones as future tsunami alerts become more refined. These personalized alerts can be relayed to a large number of users in a few seconds, both as a follow-up message after a large local earthquake, or independent of the current EEW system for distant sourced tsunamis. In addition to a fast relay to the initial tsunami alert, WaveAlert can then continue to provide tsunami follow-up messages including alerts for when coastal segments are upgraded or downgraded in alert status, and provide a 'threat has passed' message after the TWCs cancel their alerts. During times without an active tsunami alert, the inclusion of tsunami preparedness information within MyShake also helps increase awareness of potential tsunami hazards. Finally, the merging of earthquake and tsunami early warning into one dissemination system can ultimately increase geohazard literacy for MyShake users on the West Coast, benefitting both the ShakeAlert and US tsunami warning systems.

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Author contributions A.W. and R.A. both contributed to the conceptual design of the project. A.W. wrote the manuscript text and prepared figures. Both authors reviewed and refined the manuscript.

Data availability

No data was generated through this study. Referenced tsunami alerts issued by the US tsunami warning centers are available through tsunami.gov.

Declarations

Conflict of interest The authors declare there are no competing interest related to this paper.

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