

## SITE-SPECIFIC, EXTENDED SHAKEMAPS FOR EARTHQUAKE ENGINEERING APPLICATIONS

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**Abstract:** *The U.S. Geological Survey (USGS) routinely produces ShakeMaps of shaking intensity across the globe. Due to practical constraints, the number of response spectral periods was limited to three standard periods (0.3, 1.0, and 3.0 sec). We have recently developed the tools that are necessary to expand this functionality to include 22 periods (matching the current U.S. National Seismic Hazard Model periods) as well as the orientation-independent components (e.g., “RotD50”). We refer to ShakeMap products that include these extensions as “extended ShakeMaps.” The added level of complexity motivated us to also develop a user-friendly tool called the “ShakeMap Sampling Tool” (SST) that gives all the estimated shaking metrics for a specific location (or list of locations). Additionally, we develop a web application where users can input locations of interest and view/download the SST results. We further familiarize users with the concept of “Composite ShakeMaps.” For earthquake sequences such as a mainshock and larger foreshocks and aftershocks, this provides a map of the maximum value of each shaking metric, which is useful for overall loss estimates, the full extent of ground failure triggering potential, and a better portrayal of the repeated shaking levels at a given point for a series of earthquakes. Such a site-specific shaking history facilitates earthquake forensics at building or infrastructure sites for which damage may be of concern, as described in the Disproportionate Damage Earthquake trigger specified in the IEBC (2018, Section 405.2.2) and in developing ATC-145 guidelines (Guidelines for Post-Earthquake Assessment, Repair, and Retrofit of Buildings). The composite ShakeMap can be combined with the SST for a variety of earthquake-hazard applications, such as systematically inferring triggering shaking estimates at specific sites of geotechnical interest for landsliding, liquefaction, and lateral-spreading hazards.*

### 1 Introduction

The U.S. Geological Survey (USGS) operates and maintains ShakeMap as part of a suite of tools and information products for the purpose of domestic and international earthquake monitoring (Wald, 2023). The term ShakeMap can specifically refer to the software that produces the ground shaking intensity metric (IM) estimates given a wide range of input parameters. The input parameters minimally include the earthquake hypocenter and magnitude, but may also include a finite-fault model, recorded IM data, and macroseismic data. More broadly, the term ShakeMap can refer to the operation of the ShakeMap software, which includes automated retrieval and manual review of instrumental/macroseismic data, interpretation of finite-fault models from various sources, specification of configurable parameters in the software, managing updates as new data become available, and the development/maintenance of the ShakeMap software (Wald et al., 2022). The primary motivations for ShakeMap have been for emergency response and situational awareness, especially when paired with hazard products that are derived from ShakeMap such as ground failure (Allstadt et al., 2022), ShakeCast (Lin et al., 2020), the Prompt Assessment of Global Earthquakes for Response (PAGER; Wald et al., 2010), and the earthquake loss modelling component of the Federal Emergency Management Agency’s HAZUS software (Kircher et al, 2006).

The rapidly available IM maps that are conditioned on the instrumental and macroseismic data (Worden *et al.*, 2018) have led to frequent requests to the USGS ShakeMap team for additional information and products. In particular, engineers would like to be able to get estimates of new IM types, such as the cumulative absolute velocity (CAV; Electrical Power Research Institute (EPRI), 1988), and spectral accelerations at additional periods—ShakeMap currently only provides peak ground acceleration (PGA), peak ground velocity (PGV), and spectra accelerations (SAs) at 0.3, 1.0, and 3.0 sec. The context of these requests is typically for a specific site of interest. So, while ShakeMap has traditionally not been used for site-specific ground motion estimates, these requests have demonstrated a need among the community for an expanded list of IMs and for additional support for getting the best possible estimate of the metrics at a site or a list of sites of interest. For this use case, it is essential that users understand the uncertainty of the IM estimates. In this paper, we refer to this use-case for ShakeMap as post-event engineering forensics. Providing this functionality to support post-event forensics would also support other interests, such as the development of fragility curves and models of ground failure with these new metrics.

An important earlier example of post-event earthquake forensics is the SAC project, which involved the Structural Engineers Association of California, the Applied Technology Council, and the Consortium of Universities for Research in Earthquake Engineering. The project goal was to develop guidelines and standards of practices for repair/upgrade of damaged steel moment frame buildings, the design of new steel buildings, and identification and rehabilitation of at-risk steel buildings (Somerville *et al.*, 1996). The project required detailed information on the performance of steel structures during the 1994 Northridge, California earthquake and characterization of the ground motions for those same structures. Somerville *et al.* (1996) provided estimates of the time histories for the locations of interest, and doing so is a long-term goal of the ShakeMap development team. However, an intermediate solution is to provide a more complete parametric description of the ground motions in the form of additional spectral periods and other ground motion metrics.

## 2 Ground Motion Interpolation Methods

The ShakeMap interpolation method was updated by Worden *et al.* (2018) to apply the conditional multivariate normal (MVN) approach in a manner that considers both spatial correlation and cross-IM correlations. In this approach, the ground motion uncertainties are modelled with the mixed-effects approach that has become the standard practice for ground motion model (GMM) development (Stafford, 2014). The treatment of spatial and cross-IM correlations in the Worden *et al.* (2018) MVN approach is also an extension of the conditional spectrum approach summarized by Baker (2011), in which a target design spectrum is conditioned on a target SA at a period of interest. The Worden *et al.* (2018) approach used a two-step process:

1. Decompose the between- and within-event IM residuals ( $B$  and  $W$ , respectively) and estimate their standard deviations ( $\tau_{IM}$  and  $\phi_{IM}$ , respectively).
2. Apply the conditional MVN to the within-event residuals to estimate the conditional mean ( $\mu_{IM}^*$ ) and standard deviation ( $\sigma_{IM}^*$ ) of the IM at unsampled locations. Note that here we use the asterisk symbol to distinguish the conditional mean and standard deviation from the GMM mean and total standard deviation, denoted  $\mu_{IM}$  and  $\sigma_{IM}$ , respectively.

While developing code for generating spatially correlated realizations of the conditional ground motions, Engler *et al.* (2022) recognized that this two-step process is problematic. To illustrate the problem, it is useful to think through the process of generating realizations of the between-event residual  $B$  (ignoring the heteroskedasticity of  $\tau_{IM}$ ). A simple approach would be to draw a random number from a normal distribution with mean zero and standard deviation  $\tau_{IM}$  and use the resulting value as a realization of the  $B$ . However, in locations where the ground motions have been conditioned on observations, the realization of  $B$  must clearly be zero, and thus there is a clear inconsistency. Engler *et al.* (2022) resolved this inconsistency by accounting for the effect of conditioning the ground motions on both  $B$  and  $W$  simultaneously.

## 3 ShakeMap Predictions and Uncertainties

The rigorous treatment of the conditional IM mean and standard deviation is a critical feature of ShakeMap and is essential for post-event forensics. To help readers who may not already be familiar with these concepts understand  $\mu_{IM}^*$  and  $\sigma_{IM}^*$ , we discuss some important characteristics and trends in the behavior of these variables here. In the absence of any observations of the IM of interest, the conditional mean and standard

deviations will be the mean and standard deviations given by the GMM. As the number of observations increases,  $\mu_{IM}^*$  and  $\sigma_{IM}^*$  become more spatially variable due to the conditioning on the data.

### 3.1 Locations Distant from Observations

Let us consider a location that is distant from any of the observations. The word “distant” in this context refers to locations that are beyond the range of influence of an IM observation. The range of influence is controlled by the spatial correlation model (Jayaram and Baker, 2009; Loth and Baker, 2013) and is a function of spectral period. Thus, this distance threshold is not a single number but ranges from about 10 to 60 km. Nevertheless, in a location for which the IM is not influenced by the IM observations,  $\sigma_{IM}^*$  will be essentially the GMM total standard deviation  $\sigma_{IM}$  if there is only one observation, and as the number of observations increases  $\sigma_{IM}^*$  will approach the within-event standard deviation ( $\phi_{IM}$ ). This is because the estimate of  $B$  becomes precise and so the conditional  $\tau_{IM}$  approaches zero. It is important to note that even in the situation where no observation is available near the location of interest, ShakeMap provides a substantially more accurate estimate of the IM than what can be achieved with a GMM.

This is conceptually illustrated in the Figure 1, in which the GMM mean ( $\mu_{IM}$ ) and total standard deviation ( $\sigma_{IM}$ ) is given as a function of distance. For this illustration, there are three observations of the IM, and all of them are greater than  $\mu_{IM}$ . Thus, the bias  $B$  is positive and the mean of the bias-adjusted GMM ( $\mu_{IM} + B$ ) gives more accurate predictions than the GMM, even in locations that are distant from the observations (e.g., at about 20 and 100 km). The improved accuracy of these predictions is reflected in the standard deviation associated with the bias-adjusted GMM ( $\phi_{IM}$ ).

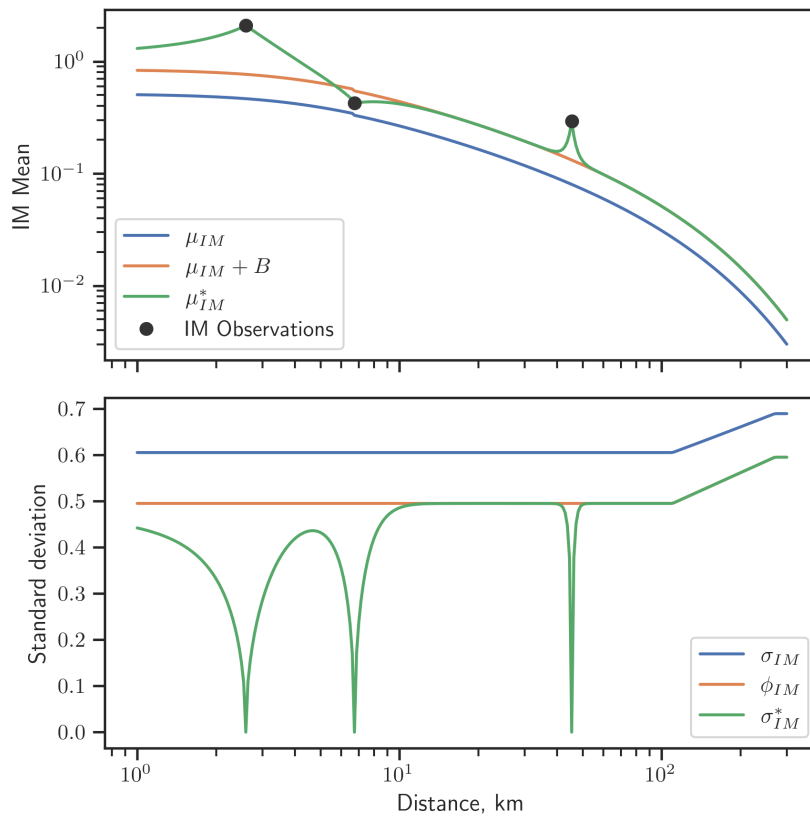


Figure 1. Conceptual illustration of the manner in which the conditional IM predictions (mean  $\mu_{IM}^*$  and standard deviation  $\sigma_{IM}^*$ ) are affected by the observed IM values. The conditional predictions are based on the GMM predictions (mean  $\mu_{IM}$  and standard deviation  $\sigma_{IM}$ ), the between-event residual  $B$ , and the IM observations. The bias-adjusted GMM ( $\mu_{IM} + B$ ) has a standard deviation of  $\phi_{IM}$ .

### 3.2 Locations near Observations

Of course, for the case in which an observation is collocated with the location of interest one would want to use the recorded intensity measure. However, it is rare that the instrument is in the same location as the location of interest, and it is these situations in which the MVN conditioning is especially useful. It is important to note that  $\sigma_{IM}^*$  is the key for understanding the accuracy of the IM prediction from ShakeMap. Note that as the location approaches an observation,  $\sigma_{IM}^*$  approaches zero, reflecting that the prediction is well constrained by the nearby recording. The  $\sigma_{IM}^*$  smoothly transitions to  $\phi_{IM}$  in locations distant from the stations (assuming that there are enough stations so that  $\tau_{IM}$  is essentially zero), reflecting that the GMM has been adjusted by the event term.

## 4 Ground Motion Data

Wald et al. (2022) provides a comprehensive description of ShakeMap operations. Here we focus on issues relevant to meeting the needs of users for additional IM characterization. The ShakeMap software is capable of including expanded IMs, but some operational/logistical hurdles need to be addressed.

ShakeMap systems are operated independently by some regional seismic networks (RSNs) in the US and by various institutions internationally. Within the United States, the RSNs also manage the waveform processing, and these systems are highly optimized for rapid response times. Thus, it is complicated to expand these systems to include many spectral periods, channel combinations (e.g., orientation independent horizontal components; Boore, 2010), and new IM types. Further, these additional products are not necessary for the vast majority of earthquakes for which ShakeMaps are produced, and the timeliness of their availability is not as critical. These factors led us to conclude that the development of a separate systems that are designed for the computation and delivery of extended products with support for site-specific applications are warranted.

The development of the ground motion processing software *gmprocess* (Hearne et al., 2019) provides an alternative mechanism for retrieving and processing the waveforms. The software retrieves records from a wide range of sources, including Federation of Digital Seismograph Networks (FDSN) webservices and the Center for Engineering Strong Motion Data (CESMD). It also supports a wide range of quality checks and can be configured to compute any number of spectral periods and orientation independent combinations of horizontal components, and the resulting IMs can be easily used as inputs for ShakeMap.

ShakeMap users frequently request the waveforms that were used to compute the IMs in ShakeMap. In many cases, the waveforms are useful for engineering forensics analysis. Although the data are publicly available, many users do not wish, and perhaps in some cases do not have the knowledge/expertise, to track down and process the waveform data. Indeed, there are substantial hurdles to doing so; to name a few: the same data can come from multiple sources, and it may not be obvious which to use; the data can be distributed in many different formats, and handling these different formats is a substantial barrier for many users; and standard processing protocols can be difficult for many users to implement. For these reasons, as well as for reproducibility and transparency, it is important to make the ground motion records that were used in ShakeMap available.

## 5 The ShakeMap Sampling Tool

We use the term ShakeMap Sampling Tool (SST) to refer to methods for obtaining ShakeMap estimates of expanded periods and metrics at higher spatial resolution for the purpose of site-specific investigations (Wald et al., 2022). For this paper, we will refer to ShakeMaps with expanded metrics as “extended ShakeMaps.” We have developed two strategies for producing more detailed IM predictions with expanded metrics to support site-specific use cases:

1. Grid SST: Run *gmprocess* to get full waveforms and additional metrics and use these as inputs to ShakeMap that has been configured to use a high-resolution grid.
2. Site-specific SST: Use the *gmprocess* results as an input to ShakeMap and allow the user to specify the location of interest and run ShakeMap for that specific location.

Each of these strategies has advantages and disadvantages. The “grid SST” approach requires more storage space but less computational resources. In this approach, the user simply specifies the location of interest; the extended ShakeMap result is queried for the nearest grid point; and the result at that grid point is returned to

the user. Thus, a disadvantage of this approach is that the pre-computed grid of ShakeMap results will not exactly correspond to the user's location of interest, and this introduces some unnecessary additional uncertainty into the process that may or may not be acceptable depending on the task at hand.

The "site-specific SST" requires that the ShakeMap software be deployed on a server that can be triggered by user requests, and this represents a new challenge for the ShakeMap development team. The key advantage to this approach is that ShakeMap can be run for the exact location of interest and there would be no need to compute nor store and access large grid files on the fly.

Both approaches require an interactive interface for users to specify the site/location of interest. ShakeMap results are currently provided to the public and archived via the USGS Earthquake Hazard Program website, which is supported by the Comprehensive Catalog (ComCat; Guy *et al.*, 2015). The Earthquake Hazards Program (EHP) website and ComCat were not developed for this type of user interaction and so providing access to either of the above approaches would require the development of a new interface. Additionally, the extra bandwidth and storage space required for the grids necessary to support the grid SST would create a new burden on ComCat for which it was not designed. We envision this new system would not need to host nearly as many earthquakes as ComCat, which generally includes earthquakes above magnitude 5.4 globally and above M3.5 in the United States. We have not yet determined a specific policy for generating extended ShakeMaps, but we expect that they would be warranted for any damaging earthquake. Thus, a simple policy would be to generate extended ShakeMaps only for events with PAGER alert levels of yellow or greater; however, we expect that some level of flexibility to add relevant events manually is warranted.

### **5.1 Composite ShakeMap**

Earthquakes frequently occur in sequences, and a striking recent example of this is the 2023 Kahramanmaraş, Turkey (Türkiye), earthquakes (Goldberg *et al.*, 2023). In this specific sequence, multiple damaging earthquakes occurred, and it can be difficult to visualize the extent of the sequence when viewing the ShakeMaps for individual events. Therefore, we have developed the Composite ShakeMap, which gives the maximum IM across all events in the sequence. For this sequence, we have included all events M5.4 and greater. Figure 2 compares the ShakeMap for the M7.8 mainshock (panel a) with the Composite ShakeMap (panel b). Note that panel b also includes the epicenters of the earthquakes included in the composite. The east-west trending zone of high shaking that corresponds to the M7.5 aftershock is clearly visible in the composite, as well as other areas where the intensity was greater in other aftershocks relative to the mainshock.

The Composite ShakeMap can be easily combined with the SST for earthquake forensics purposes. In many situations, it may not be critical to know which event in the sequence caused the greatest levels of shaking, and it could be confusing and time consuming to inspect all possible damaging events during the response to a major disaster. Further, it is possible that for some locations the earthquake that caused the largest value could be different for different spectral periods or IMs.

### **5.2 Prototype ShakeMap Sampling Tool Web Application**

We have developed a prototype web application in collaboration with DesignSafe (Rathje *et al.*, 2017), the cyberinfrastructure component of the Natural Hazards Engineering Research Infrastructure (NHERI). NHERI is a shared-use network funded by the National Science Foundation and provides valuable computation resources and technology for researchers and engineers in natural hazards field as well as a permanent Federal data archive.

Once the extended ShakeMap results have been generated for an event and transferred to DesignSafe, the grid SST results will be available as a web service. The web service allows users to specify locations of interest and get back the raw results. However, we anticipate that many users would prefer a web application that supports additional visualization and interaction. To meet this need, we have developed a prototype user interface for the SST, which is illustrated in Figure 3. Note that the selected site of interest, for which the spectrum is plotted on the right, is labelled on the map with a call-out that has the coordinates of the selected site.

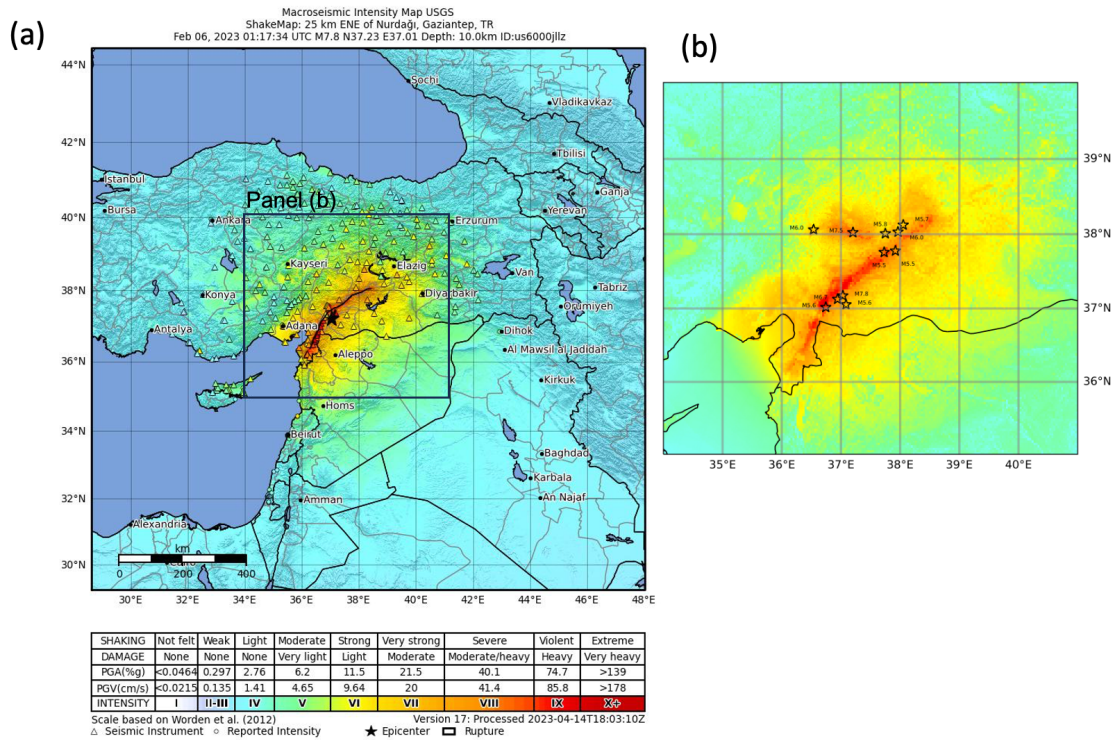


Figure 2. (a) ShakeMap for the 2023 M7.8 2023 Kahramanmaraş, Türkiye, mainshock; (b) Composite ShakeMap for the sequence. For the composite ShakeMap the maximum intensity metric (IM; in this case, the IM is Modified Mercalli Intensity—MMI) is given for each cell across all M5.4 and greater earthquakes in the sequence. The stars in (b) show the epicenters of the earthquakes included in the Composite ShakeMap.

Figure 3. Illustration of the prototype ShakeMap Sampling Tool (SST) web application for the 1989 Loma Prieta, California, earthquake. The transparent red circles on the map are the ShakeMap grid points. This uses the Grid-SST approach, and thus the user can click on one of the grid points, and the response spectra plot is updated to match that point. The data for that point can then be downloaded with the “Download CSV” button in the lower left.

The user interface has a few key features. First, the user needs to be able to select the earthquake of interest. Currently, we simply have a drop-down box that allows the user to select events by year. An improvement to this would be to allow the user to select time/magnitude criteria and draw a rectangle on a map and then select the event of interest from an interactive map. Second, the user can select the location of interest by selecting a location on the map. We can also provide a text box for entering a specific latitude/longitude or the option to upload a spreadsheet with the locations of multiple sites of interest. Third, we display the results for the site of interest. For the United States, we also provide options to compare the ShakeMap estimated ground motions to the design ground motions by linking the USGS Seismic Design Web Services (<https://earthquake.usgs.gov/ws/designmaps/>). And lastly, the data can be downloaded by the user for further analysis.

### 5.3 Case Study: 1989 Loma Prieta, California, Earthquake

To illustrate the use of the SST for a real event with real data, we use the 1989 Loma Prieta, California, earthquake as an example. However, to simplify for this exercise, we use only one station in the ShakeMap: California Strong Motion Instrumentation Program Station 58131, located in Pacific Heights, San Francisco (Fig 3). We select four locations of interest in a transect extending east of the station at separation distances ( $\Delta$ ) of 0, 2, 5 and 10 km. The results are summarized in Figure 4, and the goal here is to imagine that there is a structure of interest at these different distances from the location where the ground motion was recorded. The first thing to notice is that in the case for which the location of interest is collocated with the ground motion station, the conditional mean matches the recording, and the standard deviation is zero. As the distance increases, the conditional standard deviation increases, but it increases more rapidly at shorter periods, reflecting the difference in correlation range in the Loth and Baker (2013) model. At a separation distance of 2 km, the conditional mean still resembles the recorded values at the station, but they are shifted slightly closer to the GMM mean. As the separation distance increases, this trend continues.

## 6 Summary

For post-earthquake engineering analysis, one could estimate the relevant IMs at a site with a GMM or by selecting the nearest ground motion recording, assuming there is a station within a reasonable distance. Or, recognizing that neither of the two IM estimates are exactly what is desired for the site of interest, one could decide to take a weighted mean of the two different estimates. Then the question becomes what should the weights be? And it would be logical that the weights should be a function of the distance to the nearest station. The problem becomes more challenging when many stations are available. Thus, simple and/or heuristic rules for estimating IMs are problematic. What we have shown in this paper is that ShakeMap provides a result that matches the intuitive expectations for simple cases (e.g., collocated sites, and events without records) and does so within a rigorous statistical framework so that an analyst or engineer need not solve these problems during post-earthquake investigations. Further, the uncertainties in the estimated IMs are rigorously reported so that users can easily understand the level of confidence for which the IM is known. We also demonstrate the usefulness of the Composite ShakeMap and present a prototype ShakeMap Sampling Tool to facilitate the use of ShakeMap products for earthquake engineering applications.

## 7 Acknowledgements

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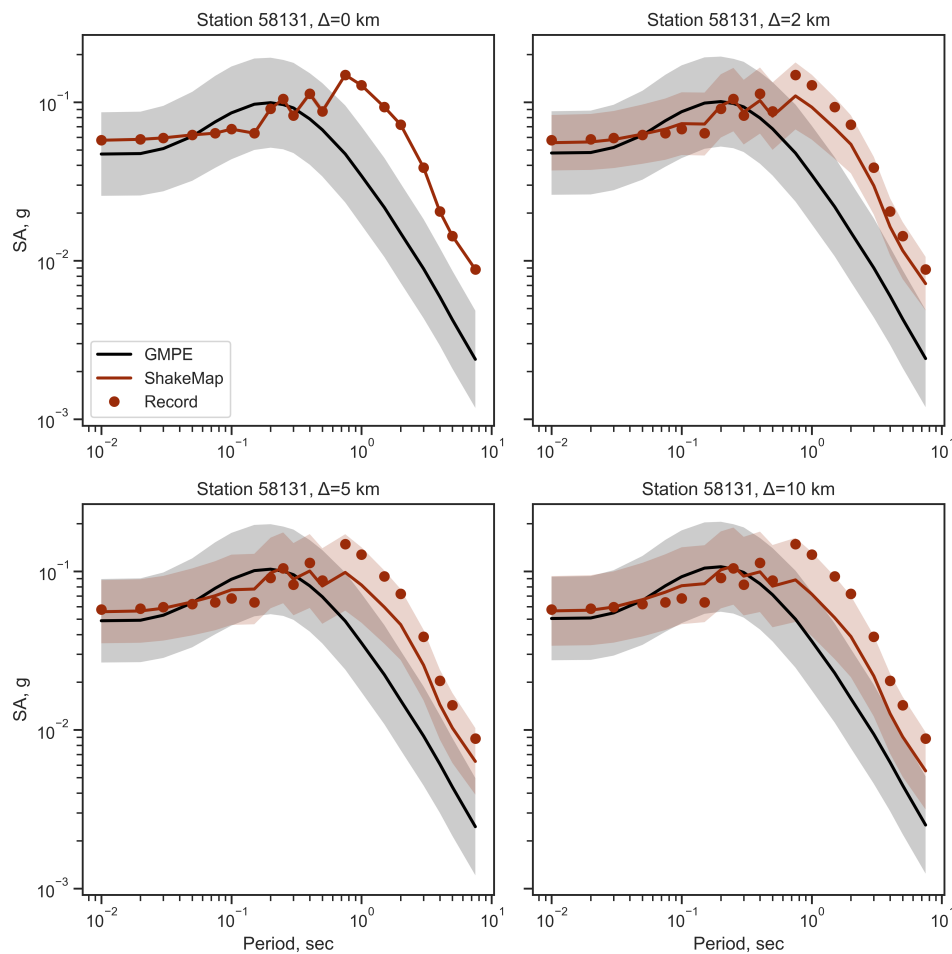


Figure 4. Spectral acceleration (SA) plots for four locations of interest at varying separation distances ( $\Delta$ ) from California Strong Motion Instrumentation Program Station 58131. Each plot shows the ground motion model (i.e., ground motion prediction equation, GMPE) mean ( $\mu_{IM}$ ; solid black line) with  $\pm 1$  standard deviation ( $\sigma_{IM}$ ) shown as the gray shaded area, the conditional mean ( $\mu_{IM}^*$ ) as computed by ShakeMap (solid red line) with  $\pm 1$  standard deviation ( $\sigma_{IM}^*$ ) shown as the red shaded area, and the recorded spectral acceleration (SA) values at station 58131.

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