A Ground-Motion Prediction Model for Shallow Crustal Earthquakes in Greece

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ABSTRACT

Using a recently completed database of uniformly processed strong-motion data recorded in Greece, we derive a ground-motion prediction model (GMM) for horizontal-component peak ground velocity, peak ground acceleration, and 5%-damped pseudo-acceleration response spectra at 105 periods ranging from 0.01 s to 10 s. The equations were developed by modifying a global GMM to account for more rapid attenuation and weaker magnitude scaling in the Greek ground motions than in the global GMM. Our GMM is calibrated using the Greek data for distances up to 300 km, magnitudes from 4.0 to 7.0, and time-averaged 30 m shear-wave velocities from 150 to 1200 m/s. The GMM has important attributes for hazard applications including magnitude scaling that extends the range of applicability to M 8.0 and nonlinear site response. These features are possible because they are well constrained by data in the global GMM from which our model is derived. An interesting feature of the Greek data, also observed previously in studies of mid-magnitude events (6.1-6.5), is that they are substantially overpredicted by the global GMM, which may be a repeatable regional feature, but may also be influenced by soil-structure interaction. This bias is an important source of epistemic uncertainty that should be considered in hazard analysis.

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INTRODUCTION

As described in Margaris et al. (202x)—a companion paper to this article—the network of digital strong-motion instruments in Greece has increased substantially since 2000, and these instruments have provided a large number of well-recorded data. Moreover, the source, path, and site metadata for new and older recordings has been substantially improved as part of a long-term effort to raise the level of data quality and modeling in Greece to levels typically applied in Next-Generation Attenuation projects, such as NGA-West2 for active tectonic regions (Bozorgnia et al. 2014).

In this article, we use these data to derive a ground-motion prediction model (GMM) for shallow (focal depth ≤ 30km) crustal earthquakes in Greece. Our objective is for the model to be suitable for the conditions that control hazard at the long return periods used in engineering design; disaggregation indicates these conditions to typically involve events with magnitudes in the range of 6.5 to 7 and distances less than 20 km. Such conditions are challenging for model development for two main reasons: (1) the upper portion of the magnitude range is near the limit of empirical data sets for Greece (Margaris et al. 202x), and indeed Europe (Akkar et al. 2014a; Bindi et al. 2019); and (2) the strong shaking that occurs under these conditions produces nonlinear site response for soil sites, which may be difficult to evaluate directly from data due to limited observations. As a result of these and other factors, the models must be used for ranges of conditions that may be poorly represented in empirical datasets.

To overcome these difficulties, our model development process modifies the Boore et al. (2014) global GMM for intensity measures from earthquakes in active crustal regions; this model is reasonably well constrained for the aforementioned hazard-controlling conditions, for application in Greece. The modifications are targeted towards model attributes that are known to be regionally variable, including the constant term, anelastic attenuation, and site response. Similar approaches have been used previously for Italy, New Zealand, and Turkey (Scasserra et al. 2009; Bradley 2013; Gülerce et al. 2016). This approach differs from those used to develop currently available models, including models intended specifically for Greece (Danciu and Tselentis 2007; Chousianitis et al, 2018) and others intended for Europe (Akkar et al. 2014b; Bindi et al. 2014; Kotha et al. 2016; Kuehn and Scherbaum 2016; Kotha et al. 2020). Those Greece/Europe models are derived from datasets restricted to those conditions...
regions. Recalling the above-referenced challenges, the maximum magnitude in the datasets is 7.1 and all of the models utilize linear site terms.

Because the model developed here is Greece-specific, we briefly review prior Greece-specific models. The most recent previous equations for pseudo-spectral acceleration (PSA) (Danciu and Tselentis, 2007) only used analog data recorded before 2000; the equations were restricted to distances less than 136 km, the site conditions were parameterized by a few site classes, and the equations were given for periods up to 4.0 s. A more recent study (Chousianitis et al, 2018) used some data after 1999, but equations were not provided for PSA. They provide equations for PGA and PGV, for distances up to 200 km and a site parameterization similar to Danciu and Tselentis (2007). Both Danciu and Tselentis (2007) and Chousianitis et al. (2018) use a linear magnitude dependence in their equations, whereas most recent GMPEs find a nonlinear dependence, including those in this article, with the scaling of ground motion being stronger for small magnitudes than large magnitudes for a fixed distance.

The GMM proposed here for Greece is developed for the following horizontal-component ground-motion intensity measures (GMIMs): pseudo-acceleration 5%-damped response spectra (PSA) at 105 periods ranging from 0.01 s to 10 s, peak acceleration (PGA), and peak velocity (PGV). The range of applicable moment magnitudes directly constrained by data is 4.0 to 7.0, but given the “borrowing” of magnitude scaling from a global model, the GMM can be applied (with additional uncertainty) up to $M_{8.0}$ events. The distance range is 0 to 300 km, and the range of applicable site conditions (based on time-averaged 30 m shear wave velocity, $V_{s30}$) is 150 to 1200 m/s.

Following this introduction, we first discuss the data used in the analysis. We then provide the set of equations that define our GMM, and the derivation of the coefficients in those equations is given next (the coefficients are provided in an electronic supplement). This is followed by some comparisons of GMIMs from our GMM with those from Boore et al. (2014) (hereafter BSSA14), and previously published GMMs that are specifically for Greece. The article concludes with a Summary and Discussion section.
DATA

The development of the database used in this article is described in Margaris et al. (202x). The data are from horizontal-component recordings, converted to RotD50 (Boore, 2010), for shallow crustal earthquakes. We used a subset of the dataset for which focal depths are less than or equal to 30 km, and the maximum source-to-site distance is less than or equal to 300 km. In addition, to avoid using singly recorded events and to include data at distances of most engineering interest, we impose the requirement that recordings are used only for events with at least 2 recordings within 80 km (in BSSA14, the greater amount of data allowed this requirement to be events with at least 4 recordings within 80 km). Trials with several other criteria gave results similar to those in this article.

PSAs for a particular recording were not used for periods greater than the maximum usable period ($T_{\text{highest}}$) for that record, as given in the flatfile provided in Margaris et al. (202x). We assume that PGV corresponds to a period of 0.5 s for the purpose of this data selection step, following Bommer and Alarcon (2006, see also Booth, 2007) and based on plots of PGV and PSA for various periods vs. distance and magnitude. After looking at between-earthquake and within-earthquake residuals, we identified 44 records that we considered to be outliers (37 from a single earthquake). Removing these from the dataset used in the analysis does not change the results in any significant way. Finally, we imposed a magnitude-distance-instrument-type screening, similar to that used in BSSA14, but with a modification for modern digital instruments to deal with residuals of smaller earthquakes increasing with distance beyond about 200 km. We assume that these trends are due to the well-known effect on the distance decay if small amplitudes are below the noise levels for recordings at large distances.

Figure 1 shows the distribution of events and stations from the Margaris et al. (202x) dataset after the above screening is applied; the stations are sorted by the number of recordings per site. The stations apparently in the sea are on small islands that do not appear in the figure.

The magnitude and distance measures used in the analysis are moment magnitude, $M$, and Joyner-Boore distance, $R_{JB}$ (the closest horizontal distance from a site to the vertical projection of the fault plane onto the Earth’s surface). Not all events in the flatfile have had...
finite-fault solutions derived for them; these are typically smaller magnitude events. For such
events, Margaris et al. (202x) applied a simulation procedure originally developed by Chiou
and Youngs (2008) and refined and more thoroughly documented by Contreras et al. (2020)
to derive distance parameters that account for fault dimension (including rupture distance,
\( R_{RUP} \), and \( R_J \)).

The magnitude-distance distribution of the data used in this article are shown in Figure 2,
for periods of 0.1 s and 10 s (in this article, for brevity we often use a phrase such as “a
period of 0.1 s” to mean “a pseudo-response spectrum GMIM for a period of 0.1 s”). As a
result of most recordings being on high-resolution digital recorders, there is a much more
uniform distribution of recordings in magnitude and distance space than in previous studies
of Greek data (e.g., Danciu and Tselentis, 2007). Figure 2 contains data using the BSSA14
magnitude-distance-instrument type screening, but only data to the left of the revised
screening shown in the figure were used for the final GMM produced in this article.
Comparing this figure to a similar one in BSSA14, we see some important differences that
are part of our motivation to base our GMM on residuals of the data with respect to
prediction from the BSSA14 GMM: BSSA14 had more data at close distances, as well as for
magnitudes less than 5.0 and greater than about 6.5. These differences in the magnitude-
distance distribution are particularly acute at long periods, as there are few data for periods of
5 s or greater in our dataset (as shown in Figure 2 for 10 s period). Figure 2 also shows that
there are few recordings in our dataset for small magnitudes at a period of 10 s. This
reduction is particularly noticeable for magnitudes less than 4.8, and the reduction occurs
abruptly between periods of 4.6 s and 4.8 s. This is a result of the \( T_{\text{highest}} \) data selection
criteria used in our analysis.

The number of events and records used in our final analysis are shown in Figure 3, as a
function of period (for all magnitudes). The decrease in the number of records and events at
long periods is the result of the low-cut filtering used in the data analysis and the use of the
consequent \( T_{\text{highest}} \) (a fraction of the inverse of the filter frequency) in the data selection.
Note also that the number of strike-slip faulting events and records from such events is
greater than for normal-slip events, and both are greater than for reverse-slip events. The
relative number of strike-slip and normal-slip events is opposite to that shown in a figure in
Margaris et al. (202x), because singly recorded earthquakes have been eliminated from our dataset.

In order to see the basic distance and magnitude scaling characteristics of the data, response spectra from strike-slip earthquakes, adjusted to $V_{S30} = 760$ m/s using the Seyhan and Stewart (2014) site amplification model, are plotted against distance for four periods in Figure 4. The graphs clearly show curvature of the attenuation of motion with distance, with the rate of distance attenuation at large distance ($R_{JB} > 80$ km) being greater for short periods than for long periods. Curvature in the distance attenuation function is accommodated by including an anelastic term in the path function, as described in the next section. There is also a suggestion of distance saturation of motions at short distance (i.e., the motions for a particular magnitude tend to a constant value for small distances). The graphs show an increase of magnitude scaling with period for a fixed distance. Similar graphs in BSSA14, with more data, agree with what is shown in Figure 4, but those graphs also show the need for nonlinear magnitude scaling for a fixed distance and period, as well as magnitude-dependent differences in attenuation. Because of the smaller number of recordings, however, the need for the nonlinear magnitude scaling and the magnitude dependent distance is not as obvious in Figure 4. This is another reason to rely on the BSSA14 GMM, adjusting those coefficients for which there are adequate data from Greece to determine the adjustment, and keeping the other BSSA14 coefficients.

**THE GROUND-MOTION PREDICTION MODEL**

The GMM is made up of a set of ground-motion prediction equations (GMPEs). The GMPEs are very similar to those in BSSA14, with some exceptions: there is no basin depth term (lacking such data for Greece) or regional adjustments (in view of the limitations of the dataset, we consider all of Greece to be one region), the site response is constant for $V_{S30}$ less than a specified value, and the equation for $\phi$ (the within-event aleatory variability) is not a function of $M$, $R_{JB}$, and $V_{S30}$. The predicted ground-motion intensity measures ($Y$) are given by this equation:

$$\ln Y = F_E(M, mech) + F_P(R_{JB}, M) + F_\sigma(V_{S30}, R_{JB}, M, mech) + \varepsilon_v \sigma(M)$$

(1)
where “ln” is the natural logarithm, and $F_E$, $F_P$, and $F_S$ are functions for the event (“E”), path (“P”), and site (“S”) contributions to the motion, and period is implied. The standard normal variate $\varepsilon_n$ is the fractional number of standard deviations $\sigma$ of a predicted motion from the mean (e.g., $\varepsilon_n = 2.0$ will result in a predicted motion two standard deviations greater than the mean). $Y$ has units of cm/s for PGV and cm/s$^2$ for PGA and PSA.

All terms in the equations below except for the predictor variables ($M$, $R_{JB}$, $V_{S30}$, and fault type [mech]) can be dependent on period; for simplicity of presentation, the variable for period has not been shown explicitly.

The equation for the event components of the GMM is given by

$$F_E (M, mech) = \begin{cases} e_0 U + e_1 SS + e_2 NS + e_3 R + e_4 (M - M_h) + e_5 (M - M_h)^2 & M \leq M_h \\ e_0 U + e_1 SS + e_2 NS + e_3 R + e_6 (M - M_h) & M > M_h \end{cases} \quad (2)$$

where mech is shorthand for the fault-type predictor variables $U$, $SS$, $NS$, and $RS$, which have values of 1.0 for unspecified, strike-slip, normal-slip, and reverse-slip fault types, respectively, and 0.0 otherwise. $M$ is the moment-magnitude predictor variable, and $M_h$ is a hinge magnitude given in the table of coefficients.

The path function is given by

$$F_P (R_{JB}, M) = [c_1 + c_2 (M - M_{ref})] \ln \left( R / R_{ref} \right) + c_3 \left( R - R_{ref} \right) \quad (3)$$

where $M_{ref}$ and $R_{ref}$ are period independent constants (chosen as 4.5 and 1.0 km. respectively), and the variable $R$ is calculated from this equation

$$R = \sqrt{R_{JB}^2 + h^2} \quad (4)$$

where $R_{JB}$ is the predictor variable, in km, defined previously and $h$ is a period-dependent finite-fault factor given in the table of coefficients.

The site function is given by the addition of linear and nonlinear site response functions:

$$F_S (V_{S30}, R_{JB}, M, mech) = F_{lin} + F_{nl} \quad (5)$$
The variable \textit{mech} is included because the PGA in the nonlinear site response can depend on \textit{mech}. Note that equation (5) differs from equation (5) in BSSA14 by using the notation $F_{lin}$ and $F_{nl}$ instead of $\ln(F_{lin})$ and $\ln(F_{nl})$ as used in the BSSA14 equation for $F_S$ (in other words, the meaning of $F_{lin}$ and $F_{nl}$ in the BSSA14 equation for $F_S$ is different than in this article). We made this change in keeping with the meaning of the other “$F$” variables in the equations for the GMM. The right side of equation (5) is also the same as equation (1) in Stewart et al. (2020).

The linear site response is given by

$$F_{lin} = \begin{cases} c_{lin} \ln\left(V_1/V_{ref}\right) & V_{S30} \leq V_1 \\ c_{lin} \ln\left(V_{S30}/V_{ref}\right) & V_1 < V_{S30} \leq V_c \\ c_{lin} \ln\left(V_c/V_{ref}\right) & V_c < V_{S30} \end{cases}$$

(6)

This differs from BSSA14 in that the amplification is constant for $V_{S30} \leq V_1$, as in Stewart et al. (2020). The predictor variable is $V_{S30}$, with units of m/s and $V_{ref}$ is period-independent, chosen as 760 m/s. $V_1$ and $V_c$ were determined from the analysis in this article and in BSSA14. All variables and coefficients other than the predictor variable $V_{S30}$ are provided in the table of coefficients.

The nonlinear site response is given by

$$F_{nl} = f_1 + f_2 \ln(\text{PGA}/f_3 + 1)$$

(7)

where $\text{PGA}$ is the peak ground acceleration for a reference rock site (in cm/s$^2$), obtained by evaluating equation (1) with predictor variables $R_{jb}$, $M$, $mech$, and $V_{S30} = 760$ m/s. $f_2$ is given by the following equation

$$f_2 = f_4 \left[ \exp\left\{ f_3 \left( \min\left(V_{S30}, 760\right) - 360 \right) \right\} - \exp\left\{ f_5 \left( 760 - 360 \right) \right\} \right]$$

(8)

and $f_1$, $f_3$, $f_4$, and $f_5$ are given in the coefficient table.

The aleatory variability $\sigma$ is a combination of the within-event variability $\phi$ and the between-event variability $\tau$, as follows
\[ \sigma(M) = \sqrt{\phi^2 + \tau(M)^2} \]  

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where the period-dependent \( \phi \) is given in the coefficient tables, and the \( M \)-dependent between-event aleatory variability is given by

\[
\tau(M) = \begin{cases} 
\tau_1 & M \leq M_{r1} \\
\tau_1 + (\tau_2 - \tau_1)(M - M_{r1}) & M_{r1} < M < M_{r2} \\
\tau_2 & M \geq M_{r2}
\end{cases}
\]

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where \( \tau_1, \tau_2, M_{r1}, \) and \( M_{r2} \) are given in the coefficient table. The equation for \( \tau \) is the same as in BSSA14, except that \( M_{r1}, \) and \( M_{r2} \) have different values in our GMM. \( \phi \) in our study is not dependent on \( M, R_{jb}, \) and \( V_{330}, \) as it is in BSSA14. The explanation for the form of the aleatory variability functions is given later.

DEVELOPMENT OF THE GMPES IN THE GMM

The amount and quality of data from Greece, as given in the Margaris et al. (202x) database, is sufficient to derive GMPEs that would describe ground motion features across the range of the data. However, as described in the Introduction, we adopt a different approach motivated by our objective of developing models that are effective for hazard-controlling conditions. Accordingly, we looked at the residuals of the Greek data relative to a global GMM derived from a richer dataset and derived adjustments for a few of the coefficients for which adequate Greek data were available for the revisions. We used the adjusted coefficients, as well as coefficients that needed no adjustments, for the GMM that is the product of the work in this article.

Method

The essence of the method is to compute total residuals of the data relative to predictions from the BSSA14 global model, perform mixed-effects analysis of the residuals to separate the total residuals into between-event residuals and within-event residuals, look for trends of the between- and within-event residuals with various predictor variables, revise the relevant GMPE coefficients to remove or reduce the trends (usually by doing a regression of the...
relevant residuals to find an adjustment factor and then adding this adjustment to the original coefficient), and then repeat the above steps one or more times. The final step in the analysis is to smooth the coefficients to be used in the new GMPEs. Examples of this process for other datasets are given in Scasserra et al. (2009), Skarlatoudis (2017), and Boore (2020).

The total residual is defined by

$$R_{ij} = \ln(Y_{ij}) - \mu_{ln}(M_{ij}, R_{ij}^{mech}, V_{S30}, mech)$$

(11)

where $i$ and $j$ designate an event and a site, respectively, $ln(Y_{ij})$ is a measured GMIM, and $\mu_{ln}$ is the natural log mean GMIM from a reference GMM. The $i$ and $j$ indices are shown as superscripts in the right-most term in equation (11) to avoid notational complexity with the two predictor variables that have subscripts.

The total residuals are fit, period by period, to the following equation using mixed-effects analysis (R Core Team 2019)

$$R_{ij} = B + \eta_i + \epsilon_{ij}$$

(12)

where $B$ is the overall bias and $\eta_i$ and $\epsilon_{ij}$ are between-event (also known as “event terms”) and within-event residuals. Those residuals have zero mean and standard deviations denoted by $\tau$ and $\phi$.

The mixed-effects analysis described above was repeated for PGV, PGA, and 105 response spectral periods between 0.01 and 10 s. For each analysis, graphs were prepared of the between-event residuals against $M$, $mech$, and hypocentral depth ($Z_{hyp}$), and the within-event residuals against $R_{jb}$ and $V_{S30}$. An example is shown in Figure 5, for a period of 0.2 s (chosen because it had some of the most pronounced trends of the residuals with the predictor variables). The BSSA14 GMM, with no modifications to the original coefficients, was used to compute the total residual for the analysis. From this figure and others like it, we found that modifications of some of the BSSA14 coefficients were needed. These are discussed in separate subsections below.

Before giving the details about the modified coefficients, we discuss here the smoothing done to obtain the final coefficients for the GMPEs. The smoothing was a combination of averaging the coefficients for 11 periods centered on a given period and subjective smoothing.
guided by the variation of the BSSA14 coefficients with period, which are more robustly
determined than the adjusted coefficients in our analysis, at least for longer periods. The
subjective smoothing was done when the adjustments to the BSSA14 coefficients had
noticeable variations over small ranges of periods, probably because of relatively small
numbers of data used to obtain the adjustments. In this article we show the smoothed
coefficients. We repeated the residual analysis to make sure that no unusual trends were
introduced by using the smoothed coefficients.

Revisions to path model

The first and most important modification to the BSSA14 GMM was in the path function.
The need for this modification is shown by the strong trend in the graph of within-event
residuals vs. $R_{jb}$ in Figure 5, where the negative trend of the residuals indicates that the data
attenuate more rapidly with distance than the predicted values. We made similar graphs using
log and linear scales for the distance axis, and determined that a simple and sufficient
modification to the BSSA14 path equation was to find an adjustment for the anelastic
coefficient $c_3$ (which can remove a linear trend in residuals plotted against a linear distance
axis). The geometric spreading model was not modified.

We developed the adjustment by fitting the within-event residuals with a linear function
of $R_{jb}$ period-by-period, adding the slope of that function to the BSSA14 $c_3$. The result is
shown in Figure 6. Also shown in that figure are the BSSA14 global and Region 3 anelastic
coefficients (Region 3 is for Italy/Japan; these regions had the most rapid attenuation
amongst the various regions considered in BSSA14). The adjusted $c_3$ coefficient is generally
more negative than the BSSA14 global or Region 3 coefficients, indicating more rapid
attenuation of the ground-motions in Greece than for either the global database used in
BSSA14 or the Italy/Japan region. On the other hand, the $c_3$ values regressed from the data
for Greece become positive for longer periods (as does the coefficient for Region 3 in
BSSA14). The BSSA14 global $c_3$ coefficient was constrained to be less than or equal to 0.0,
even though the analysis that led to that coefficient showed positive values for most of the
magnitude bins used in determining the coefficient (Figure 4.3 in Boore et al., 2013). We
have not applied this constraint in the present model. While negative anelastic attenuation is
unphysical, it may reflect phenomena such as dominance of longer-period surface waves at large distances that are not included in the geometric spreading model. The impact of this model feature becomes significant only for distances beyond about 300 to 600 km, which is not of practical importance for most hazard and risk applications.

Updated mixed-effects analyses using the BSSA14 model with the adjusted $c_3$ coefficient were performed. No trends of within-event residuals vs. $R_{jb}$ were found for residuals grouped into several magnitude bins (a complete set of residual plots is available in the supplemental material). This was done to determine if changes were needed to the BSSA14 geometrical spreading coefficients $c_1$ and $c_2$ (the latter of which expresses magnitude dependence). We saw no need to make changes.

Revisions to source model

Following adjustment of the path model, we next evaluated the need for potential revision of the BSSA14 source model, with an emphasis on the magnitude-scaling coefficient $e_4$ and the hinge magnitude $M_h$ (we left $e_5$ and $e_6$ unchanged).

Revision of the magnitude-scaling model was primarily motivated by trends in the between-event residuals for small magnitudes, such as those seen in Figure 5 for $M$ less than about 4.6. The results shown in Figure 5 for PSA at 0.2 s, and in similar figures for other periods, have a downward trend at small magnitudes (e.g., $M < 4.6$ for 0.2 s), which suggests that the magnitude-scaling function should be flattened (by reducing parameter $e_4$). At larger magnitudes, trends are either flat or slightly upward (suggesting no change or steeper $M$-scaling, respectively).

We experimented with a number of functions fit to the residuals and decided initially to use a bilinear function hinged at the BSSA 14 $M_h$, this function gave an adequate fit to the residuals and required the least change to the form of the $F_e$ function. The slope of the bilinear function for $M < M_h$ was added to the BSSA14 coefficient, $e_4$. Figure 7 plots smoothed values of $e_4$, as well as the final values of $e_6$ and $M_h$. For $M > M_h$, we considered two options. The first option is to add the slope from the bilinear function to $e_6$, which produces some steepening of the magnitude scaling for $T < 1.5$ sec and no change.
thereafter. The second option is to not change \( e_6 \) from the BSSA14 coefficients and to increase \( M_h \) modestly for short periods, which improves the fit for \( M > M_h \). We selected the second option because while both produce similar model performance in terms of between-event residuals, the retention of the BSSA14 version of \( e_6 \) allows the large-magnitude scaling to be constrained from global data.

After redoing the mixed-effects analysis with a total residual computed using the BSSA14 GMM with modified \( c_3 \), \( e_4 \), and \( M_h \) coefficients, we noticed a small nonzero mean of the between-event residuals for the various fault types, mainly for periods longer than about 3 s. As a result, we next modified the BSSA14 coefficients for fault type \( (e_0, e_1, e_2, \) and \( e_3) \) by using the means as an adjustment factor to the BSSA14 coefficients and then smoothing the coefficients. The results are plotted in the top graph of Figure 8. For periods less than about 2 s the coefficients for SS and RS faults are similar and the NS coefficients are smaller. This agrees with BSSA14 and the findings of Skarlatoudis et al (2003) and Danciu and Tselentis (2007), using much more limited datasets. For longer periods the RS coefficient becomes less than the SS and NS coefficients, but there are a decreasing number of data in the various fault-type classes as period increases. On the other hand, an approximation of the standard error of the mean (SEOM) of the smoothed coefficients (which are shown in Figure 8) shows that the SS and NS coefficients are larger than the RS coefficients by more than one SEOM for periods greater than 3.6 s.

To complete the section on the source model, we show the magnitude scaling for various periods and fault types in Figure 9. This figure is based on a similar one in BSSA14, but in that figure the symbols represent data for each event adjusted to a reference distance using the path model, which was then used to fit the magnitude-scaling function shown in the figure. This is not the case in Figure 9, and thus care must be taken in interpreting the figure. The lines are from the revised function \( F_E \). The symbols shown in Figure 9 are the result of adding the between-event residuals \( \eta_i \) from a mixed-effects analysis using the revised coefficients to \( F_E \) evaluated at the appropriate magnitude to each between-event residual. The figure shows the variable magnitude scaling across GMIMs, and also shows the relative
differences due to fault type. The figure also shows the relatively limited data at longer periods and larger $M$ (e.g., there are no RS data for $M > M_h$ for $T = 3$ s and 10 s).

Model bias and revisions to constant terms

In the mixed-effects analysis using equation (12), the bias $B$ is a fixed effect. The bias that is obtained after adjusting the path and source models as described in previous subsections is shown, following some smoothing, in the bottom graph of Figure 8. The symbols labeled “Greek GMM: $M \geq 4.0$” is the bias in the coefficient file. It is a smoothed version of the bias obtained from a mixed-effects analysis of the Greek data for magnitudes greater than or equal to 4.0, when the Greek GMM with no bias adjustment to the coefficients $e_0$, $e_1$, $e_2$, and $e_3$ is used to compute $\mu_n$ in equation (11). To investigate the sensitivity to the minimum magnitude, the unsmoothed bias for a minimum magnitude of 5.0 is also shown in Figure 8. The biases from the two minimum magnitudes are reasonably similar. This is not true, however, for the bias of the Greek data relative to the BSSA14 model (with the Region 3 anelastic attenuation) without modifications to the BSSA14 path and source functions. The large differences at short periods are a reflection of the need to adjust the short-period magnitude scaling in the BSSA14 GMM for use in Greece, as discussed earlier. A striking feature of Figure 8 is that the biases for all cases are significantly smaller than 0. This indicates that the GMIMs from the recordings in Greece are smaller, on average, than those used in developing the BSSA14 GMM. This finding of overprediction has been observed previously for individual earthquakes in Greece (Margaris et al. 2010) and Italy (Stewart et al. 2012; Zimmaro et al. 2018) (in the case of the pre-2014 publications, the bias was derived relative to the Boore and Atkinson 2008 GMM).

Figure 8 also shows the bias for the BSSA14 GMM (using two minimum magnitudes in the mixed-effects analysis), based on a recent re-analysis of the NGA-West2 data used to develop the BSSA14 GMM. That bias is slightly positive and essentially flat; it is caused by the BSSA14 constant and magnitude scaling terms being set using a subset of the data with $R_{JB} < 80$ km, whereas the bias is evaluated using all data. The difference between the global bias and Greece bias indicates a consistent difference between short-period ground motions in Greece relative to other regions globally. A similar bias may be present in Italy, but we have not formally investigated that as part of this study.
Although the Greek-data bias plotted in Figure 8 is a smoothed version of the bias from the mixed-effects analysis, little smoothing was required for periods less than about 4.7 s. The standard error of the means from the mixed-effects analysis were used with the smoothed coefficients to give an idea of the uncertainty over most of the period range. Many of the Greek instruments are placed in the basements or ground floors of buildings, and it has been shown that for instruments placed in the basements there can be soil-structure interaction (SSI) (NIST 2012; Conti et al., 2018; Sotiriadis et al., 2019 & 2020). The SSI tends to reduce ground motions at short periods in a manner similar to that observed in Figure 8, but it has little impact at longer period (typically > 1 s). While SSI is a factor that could potentially influence the results, arguments against it being the sole (or dominant) source include;

- The bias decreases at longer periods after a stable region from about 0.3 to 2.0 s, which is not expected from SSI principles (this decrease occurs well before the periods--generally greater than 4.6 s--where some of the coefficients in the iterative mixed-effects analysis show discontinuous changes with period because of changing amounts of available data due to the use of $T_{\text{highest}}$ in selecting the data for our analysis).

- Skarlatoudis (2017) found trends similar to those in Figure 8 in his analysis of Greek intraslab subduction GMIMs as compared to global or Japan models. Many of the instruments used in that study were seismometers not housed in building structures (unlike the accelerometers used in the present study).

- The present findings are similar to previously observed trends from Italy, for which most of the instrument housings are relatively small structures.

Ultimately, we do not have a good explanation for the cause of the bias, but its persistence in recent literature suggests it may be a regional feature that should be included in Greek GMM. We provide the bias in the accompanying coefficient table (available in the supplemental material), but we do not add it to the fault-type coefficients $e_0$, $e_1$, $e_2$, and $e_3$ in that table. In application, if it is thought that the bias is due to SSI and GMIMs are to be predicted for free-field sites, it would be reasonable to use the $e_0$, $e_1$, $e_2$, and $e_3$ coefficients as is in equation (2). On the other hand, if it is believed that SSI effects are not important and that the GMIMs in Greece are smaller as a result of repeatable regional effects, the bias $B$
should be added to the fault-type coefficients before their use in equation (2). Of course, the observed bias could be a combination of regional and SSI effects, but without knowing the presumably period-dependent proportion of each, we make no attempt to separate the two contributions. In a later figure we show GMIMs computed with and without the added bias.

**Revisions to site amplification model**

Based on Figure 5, an apparently needed change in the BSSA14 GMM for applications in Greece is in the $V_{s30}$ scaling at both large and, in particular, small values of $V_{s30}$. For $V_{s30} < 200$ m/s, there is a strong trend toward negative residuals with decreasing velocity. Although not shown here for brevity, this trend exists at all periods. For $V_{s30} > 600$ m/s, there is a tendency for the residuals to be positive, particularly at periods between about 0.2 s to 4 s. But for all periods the within-event residuals in the middle range of $V_{s30}$ (approximately 200 m/s to 600 m/s), corresponding to most of the data, are well behaved, being close to 0.0.

The data at both ends of the $V_{s30}$ range are from very few stations. For high $V_{s30}$, the highest value (1183 m/s) is from a single ITSAK station (VSK1). At the low end of the range (less than 197 m/s) the data are from only 3 NOA stations (PREA, 115 m/s; KSLB, 137 m/s; and PATA, 150 m/s). Although we do not think that $F_s$ should be adjusted to fit trends that might be driven by individual station amplifications, we have made a minor modification to the site amplification at the low end of the velocity range using a functional form applied previously for stable continental regions (Stewart et al., 2020). The modification is to make the amplification constant for $V_{s30} \leq V_i$, where we have chosen $V_i = 200$ m/s based on the within-event residual plots. This modification has very little impact on the within-event residuals and is only noticeable at longer periods. Because the single ITSAK station with $V_i = 1183$ m/s largely controls the trend at higher values of $V_{s30}$, we decided not to make any changes to $F_s$ for $V_i > 200$ m/s. For higher velocities, we assume, based on the residuals, that the $V_{s30}$-scaling parameter, $c_{ftn}$, from BSSA14 is applicable to Greece.

**Aleatory variability model**

The aleatory variability model describes between- and within-event variability of GMIMs. We consider only an ergodic model of the variabilities, as we did not think that
enough data were available to extend the models to partially or fully non-ergodic models (Al
Atik et al., 2010). A comparison of the within-event variability $\phi$ from the mixed-effects
analysis and from BSSA14 is shown in Figure 10. Because the BSSA14 $\phi$ is a function of
$M$, $R_{JB}$, and $V_{S30}$, we show the results for representative values of those variables. The $\phi$
from the mixed-effects analysis, using the Greek GMM coefficients in the table
accompanying this article, is shown for two runs, with differing minimum magnitudes (4.0
and 5.0). As is clear from Figure 10, there is little dependence of $\phi$ for the Greek GMM on
the minimum magnitude. We have chosen to let the $\phi$ for our proposed GMM depend only
on period, as we do not feel there were enough data to support a model conditioned on
additional independent parameters. We modified the $\phi$ from mixed-effects analysis to be
nearly constant for periods longer than about 4.7 s, as we are less certain about our results for
periods greater than this value and also felt that $\phi$ should not decrease with period over this
range of periods. This modification of $\phi$ was guided by the BSSA14 results.

The BSSA14 between-event variability $\tau$ depends only on $M$, as given by equation (10),
with the values of $M_{r1}$ and $M_{r2}$ being 4.5 and 5.5, respectively. The values of $\tau_1$ and $\tau_2$ in
the BSSA14 GMM were determined from means of the between-event residuals for different
magnitude ranges. To develop the $\tau$ model (equation 10) for the Greek GMM, we also
computed the means of the between-event residuals for a number of magnitude bins, as
shown in Figure 11 for a suite of periods. Based on this figure, we decided that $\tau$ would be
period independent, with $M_{r1}$ and $M_{r2}$ equal to 5.5 and 6.0, respectively (as shown by the
lower, thin line in the figure). The values of $\tau_1$ and $\tau_2$ were tentatively chosen to be 0.35 and
0.2, as shown in the figure. To provide a more quantitative estimate of $\tau_1$ and $\tau_2$ we ran a
residual analyses with several ranges of magnitude, with results shown in Figure 12. In
comparing Figures 11 and 12, we noticed that the means of the between-event residuals were
less than the mixed-effects estimate of $\tau$ for similar magnitude ranges. This occurs because
mixed effects analyses intrinsically account for the error of the event terms in the dispersion
computation, which increases the standard deviation. Because the number of recordings per
event is relatively small in the Greek data set (average of 11; in BSSA14 the average is 48),
the mixed effects $\tau$ is appreciably larger than the standard deviation of the event terms.
If epistemic uncertainty in $\tau$ is considered in the logic tree applied in hazard analysis, the standard deviation of event terms is preferred for the $\tau$ model. If this is not the case, which is likely more common in practice, we recommend using the mixed-effects (higher) value of $\tau$. On this basis we chose period-independent $\tau_1$ and $\tau_2$ values of 0.5 and 0.35, respectively, as shown in Figure 12. We retained the hinge magnitudes of 5.5 and 6.0 estimated from Figure 11, such that our final $\tau$ model is given by the upper, thick line in Figure 11.

To complete the specification of the aleatory variability, Figure 13 shows the total variability $\sigma$ for $M \geq 6.0$, as given by equation (9), along with its components $\phi$ and $\tau$.

A mixed-effects analysis was performed using the final Greek GMM to compute partitioned residuals. We show the results for $T=0.2$ s in Figure 14, which should be compared with Figure 5. Recalling that the unmodified BSSA14 GMM was used to produce Figure 5, it is clear that the revised coefficients remove the obvious trends of residuals vs. magnitude and distance seen in Figure 5.

**Comparisons to BSSA14 GMM and other Greek GMMs**

We first compare GMIMs from the GMM proposed in this article for Greece with those from BSSA14. Plots of median GMIMs vs. distance and period are given in Figures 15 and 16, respectively. Our GMIM predictions are shown both when the bias $B$ is added and not added to the fault-type coefficient (in this case $e_1$, as we are only considering strike-slip events). To remind the reader, adding $B$ will reduce the motions and make them more consistent with the recorded motions used to derive the Greek GMM. On the other hand, not adding $B$ to the fault-type coefficient should make the predicted median amplitudes for $M > M_h$ events more similar to those from BSSA14 (notwithstanding the revisions in the distance attenuation and the magnitude scaling).

Examination of Figures 15 and 16 shows patterns generally reflecting these expectations. In general, for periods between about 0.2 s and 2.0 s there is relatively good agreement between the GMIMs predicted from the Greek and the BSSA14 GMM. The most obvious differences between the predicted GMIMs are 1) the greater attenuation with distance for the Greek GMM for periods less than about 1.0 s, 2) the large differences at periods less than about 0.2 s for $M$ 5.5, and 3) the increasing difference with period of the Greek GMIMs with...
and without a bias adjustment, especially for periods greater than 2.0 s. The attenuation difference is the result of the revision to the anelastic attenuation coefficient $c_3$. The difference in the GMIMs for $M_{5.5}$ is due to a combination of the reduced magnitude scaling for the Greek GMM (see $e_4$ in Figure 7) and the increase of $M_h$ (Figure 7), and the dependence of the Greek GMIMs on the bias, which is expected from Figure 8, where the bias trends to more negative values for periods greater than 2.0 s. Recall that studies of individual mid-magnitude Mediterranean events (6.1-6.5) suggest that matching BSSA14 is not desirable because it over-predicts some GMIMs (Margaris et al. 2010; Stewart et al. 2012; Zimmaro et al. 2018). Applying the bias for the Greek GMM causes median GMIMs to fall below BSSA14 for $M_{5.5}$ and $6.5$ events, and to approximately equal BSSA14 for $M_{4.5}$ events. The evidence from the mid-magnitude events is admittedly anecdotal, so there is room for alternative interpretations of whether to apply the bias or not in forward analysis. We recommend that seismic hazard analyses consider alternate logic tree branches regarding bias corrections. The effects of the bias are greatly diminished at 1.0 sec, but they re-appear at long periods. Our confidence in the long-period results is lower than that at short periods due to limited data.

Comparison of GMIMs from earlier Greek-only GMMs are shown in Figures 17 and 18. In comparing the GMIMs, it should be kept in mind that the way in which the data from the two horizontal components have been used might introduce some variation. Of the three earlier studies, only Chousianitis et al. (2018) specify how the two horizontal components have been used in the GMMs; in their case, the GMIMs correspond to geometric means (GM). According to Figure 7 in Boore and Kishida (2017), the ratio GM/RotD50 should be less than unity, but no smaller than 0.9 (for $T=10$ s). Other possible treatments of horizontal components could be vector addition or choosing the largest motion from the two horizontal recordings. According to Figures 2 and 6 in Boore and Kishida (2017), these other treatments will be larger than RotD50, but by no more than a factor of 1.29 (for RotD100/RotD50 at $T=10$ s; we assume that RotD100 is similar to the GMIM obtained by vector addition). These differences in how the horizontal components are used are not enough to account for most of the variations seen in Figures 17 and 18. It is interesting and perplexing to see that the two most recent studies—ours and Chousianitis et al. (2018)—span the range of GMIMs for a given distance, magnitude, or period, with our added-$B$ predictions being low and the
Chousianitis et al. (2018) predictions being high. Our PGV and PGA predictions are generally similar to the predictions of Danciu and Tselentis (2007) at close distances, with an increasing divergence at distances greater than about 10 km. The PGA predictions of Skarlatoudis et al. (2003) also agree with ours at close distances and diverge at greater distances, but the PGV predictions of Skarlatoudis et al. (2007) are close to our predictions for most distances. Further investigation of the differences just described would require access to the specific databases used in the earlier studies, but this is beyond the scope of this study. Besides, given the larger number of data used in our study, it is perhaps not surprising that differences exist.

SUMMARY AND DISCUSSION

Using ground-motion data recorded in Greece, available in a recent database (Margaris et al. 202x), we modified a global ground-motion prediction model derived from recordings of shallow earthquakes in active crustal regions for application in Greece. The parameter ranges across which the GMPEs in the modified GMM are calibrated are magnitudes from 4.0 to 7.0, distances from 0 to 300 km, and $V_{S30}$ from 150 to 1200 m/s. However, because the underlying global model is constrained to $M_{8.0}$ and those features of the model were preserved in the regional model development, we consider the range of applicability for the model to extend to $M_{8.0}$.

The Greek GMM produced in this study predicts PGV, PGA, and PSA from periods of 0.01 to 10s. We based our model on a mixed-effects residual analysis, using the BSSA14 GMM in computing the residuals. We found that most of the BSSA14 coefficients could be used as-is. The most important exception was to the anelastic coefficient $c_3$, modified to account for the more rapid attenuation than predicted in the BSSA14 GMM, even for the region in that GMM with the most rapid attenuation (Region 3 for Italy/Japan). The next most important modification was to the magnitude scaling, with weaker scaling than in BSSA14 for small magnitudes. While the limited large magnitude data suggest stronger magnitude scaling for some GMIMs, we retained the BSSA14 values, which are well constrained from global data. The BSSA14 site amplification model is only modified in a minor way, the linear scaling with $V_{S30}$ being truncated below 200 m/s.
A significant finding was a large negative bias in the residuals, implying smaller recorded ground motions for Greece than in the global dataset used in deriving the BSSA14 GMM. This finding is not surprising, as similar results have been obtained in prior studies of individual mid-magnitude events in the Mediterranean region (Margaris et al. 2010; Stewart et al. 2012; Zimmaro et al. 2018) and intraslab subduction earthquakes (Skarlatoudis 2017). We have no definitive explanation for the bias, but available evidence suggests that it is some combination of a regional effect that should be captured in the GMM and soil-structure interaction effects that should not. We provide the bias and the fault-type coefficients separately, so that GMIM predictions can be made with or without the bias in order to capture this source of epistemic uncertainty in hazard analyses. Adding the bias to the fault-type coefficients results in lower predicted motions.

We recommend the following limits for the predictor variables used in our GMM:

- Magnitude: $M_{4.0-8.0}$
- Depth: less than or equal to 30 km
- $R_{jb}$ distance: 0 km to 300 km
- $V_{s30}$: 150 m/s to 1200 m/s
- Includes both mainshocks and aftershocks

These limits are subjective estimates based on the distributions of the recordings in Greece used to develop the equations, as well as the data used to derive the BSSA14 GMM. Note that 7.0 is the upper magnitude limit for normal-slip earthquakes in BSSA14, but for the GMM derived in this article we assume the same upper magnitude limit for all fault types. This assumption was informed by the subjective observation from Figure 6 in BSSA14 and Figure 9 in this article that the magnitude scaling observed both in BSSA14 and in this article seems relatively independent of fault type.

DATA AND RESOURCES

The ground-motion database used in this article is described by Margaris et al. (202x) and is available as an electronic supplement to that article. Most of the analysis used scripts written in R (R Core Team, 2019), relying heavily on the mixed-effects analysis provided by the function lme in the nlme package (Pinheiro et al., 2018). The figures were prepared using
CoPlot (www.cohort.com, last accessed June, 2020). The search for previous GMMs for Greece was greatly aided John Douglas’s compendium of GMMs (Douglas, 2019). The supplemental material includes a csv file of the coefficients in the equations comprising the proposed GMM for Greece and pdf files of the residual plots (similar to Figure 14) and the residuals vs. distance for three magnitude bins, for all 107 ground-motion intensity measures.

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FIGURE CAPTIONS

To be provided in the accepted paper
Figure 1. Map of Greece showing locations of events and stations in the Margaris et al. (202x) database that have produced recordings that meet the screening criteria applied in this paper. Stations are sorted by the number of recordings per site, ranging from 1 to > 20.
**Figure 2.** Moment magnitude-distance distribution of recordings used in this article, separated by fault mechanism (SS, NS, and RS are strike slip, normal slip, and reverse slip events, respectively). The two graphs are for different response spectral periods (0.1 s and 10.0 s). The lines show the magnitude-distance cutoffs for recordings from modern digital instruments, both as used in BSSA14 and the revised cutoffs for this article. The data shown used the revised BSSA14 cutoff criteria, but only data to the left of the lines were used in the analysis in this article.
Figure 3. The number of events (left graph) and recordings (right graph) used in the analysis, as a function of period, for the different fault mechanisms. Plots for PGV and PGA are not shown, as their numbers are very close to those for periods of 0.01 s and 0.5 s, respectively.
**Figure 4.** Response spectral values used in this article, plotted against distance for four periods and separated into three magnitude ranges. Only data from strike-slip events are shown, and the values have been adjusted to $V_{S30} = 760$ m/s.
Figure 5. Between-event and within-event residuals (open circles) from the mixed-effects analysis, plotted against key metadata, for a period of 0.2 s. The predicted values used to compute the total residuals (equation (11)) came from the BSSA14 GMM without modification, and no region adjustment was made to the anelastic coefficient c3. The solid squares are averages in metadata bins.
Figure 6. The smoothed anelastic distance coefficient for Greece, as determined in this article and for BSSA14. Periods of -1 and 0 correspond to PGV and PGA, respectively.
Figure 7. Smoothed magnitude scaling coefficients for Greece, as determined in this article and for BSSA14 (the BSSA14 coefficient $e_5$ was used without change in the Greek GMM). The $e_6$ coefficient from BSSA14 was not revised.
Figure 8. (a) The fault mechanism coefficients. The published coefficients for BSSA14 assume that PGA and PSA have units of g; they have been converted for this figure to correspond to units of cm/s², which are the units assumed for the Greek GMM. (b) The bias $B$, relative to predictions from either the BSSA14 GMM or the Greek GMM, as a function of period. Bias is shown for the proposed Greek GMM and the BSSA14 model when applied to Greek data (using Region 3 anelastic attenuation) and to the global data (where each recording’s region was used in evaluating the GMM). The bias was computed for several lower limits to the magnitudes used in the mixed-effects analysis.
Figure 9. Magnitude scaling ($F_E$ function) for the final Greek GMM. The units of $\exp(F_E)$ are cm/s$^2$ for PGA and response spectra. The symbols are the between-event residuals after adding the $F_E$ corresponding to the appropriate mechanism and magnitude for each symbol. The bias $B$ was added to the mechanism coefficients, but this will only affect the absolute values of $F_E$ and not the relations between the symbols and $F_E$. 
Figure 10. The within-event aleatory variability as a function of period.
Figure 11. The between-event aleatory variability as a function of magnitude. The individual $\tau$ values are standard deviations of the between-event residuals in magnitude bins. The purpose of this figure is to provide guidance for the choice of a magnitude-dependent $\tau$. The individual symbols suggest a function given by the thin line, whereas the function adopted in this article is given by the thicker line.
Figure 12. The between-event aleatory variability as a function of period. The \( \tau \) values for Greece came from the mixed-effects analysis for three magnitude ranges, as shown. The \( \tau \) values for BSSA14 are based in the standard deviation of between-event residuals in various magnitude bins; those standard deviations can be less than the \( \tau \) values from mixed-effects analysis, as shown by comparing the previous figure with this one.
Figure 13. Aleatory variability for our final GMM.
Figure 14. Between-event and within-event residuals (open circles) from the mixed-effects analysis, plotted against key metadata, for a period of 0.2 s. The predicted values used to compute the total residuals (equation (11)) came from the coefficients for the Greek GMM proposed in this article.
Figure 15. Ground-motion intensity measures as a function of distance, for a selection of periods. The measures from the GMM in this article are shown without and with the bias added to the fault-type coefficient ($e_1$ for this figure, which shows GMIMs for a strike-slip fault type).
Figure 16. 5%-damped PSA as a function of period, for a selection of magnitudes. The measures from the GMM in this article are shown without and with the bias added to the fault-type coefficient (\(e_i\) for this figure, which shows PSAs for a strike-slip fault type). For comparison, the PSAs for the BSSA14 GMM are also shown.
Figure 17. Ground-motion intensity measures as a function of distance, for PGV and PGA. This figure compares the GMIMs from the Greek GMM proposed in this article with those from three earlier publications. For clarity, only results for magnitudes 4.5 and 6.5 are shown. The measures from the GMM in this article are shown without and with the bias added to the fault-type coefficient ($e_i$ for this figure, which shows GMIMs for a strike-slip fault type).
Figure 18. 5%-damped PSA as a function of period, for a selection of magnitudes. This is similar to Figure 16, except the GMIMs for BSSA14 have been replaced with those from the Danciu and Tselentos (2007) GMM.