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A Rupture Directivity Model and Application in Seismic Hazard

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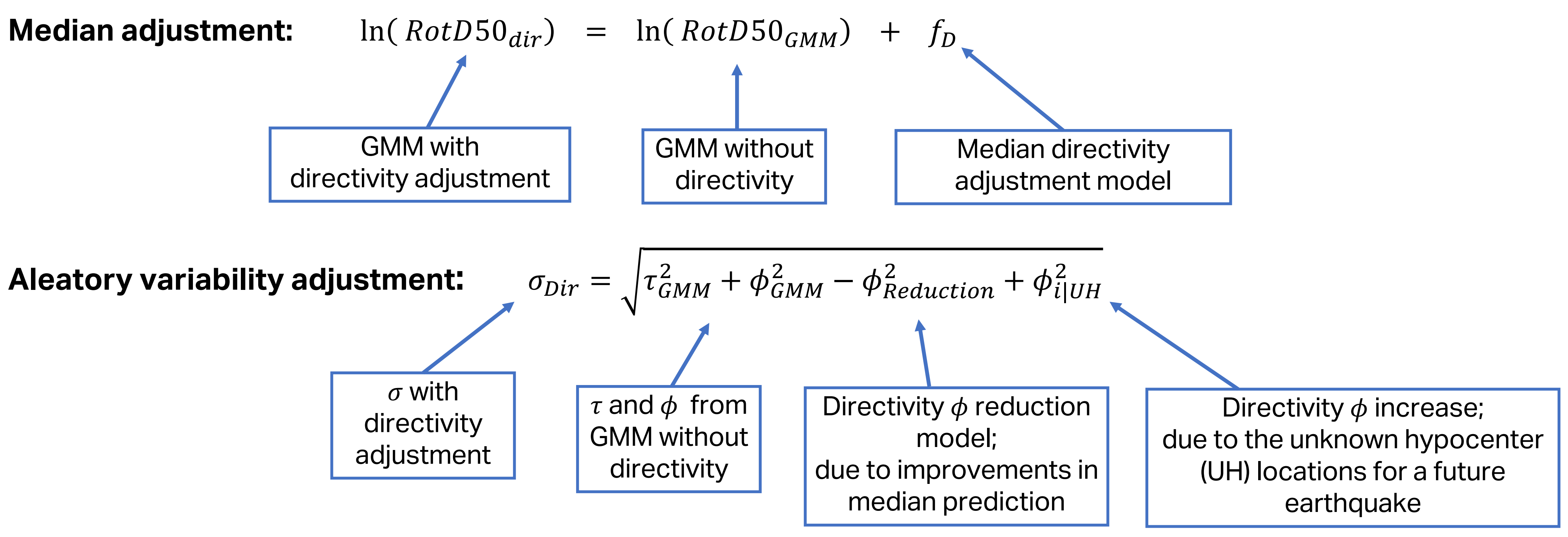
(1) Abstract

We developed a rupture directivity adjustment model which can be applied to a traditional ground-motion model (GMM; one without explicit treatment of rupture directivity) to incorporate rupture directivity effects in either deterministic or probabilistic seismic hazard analyses. Application of the directivity model requires adjustments to both the GMM median and aleatory variability.

The companion paper (ES, in review) provides a description of model development, how to calculate the required directivity parameters, and recommends methods for modeling hypocenter locations and multi-segment ruptures. This poster focuses on the implementation in deterministic and probabilistic seismic hazard analyses using example applications.

The model addresses the RotD50 (Boore et al., 2010) horizontal component of 5% damped spectral acceleration, which is modeled in the NGA-West2 GMMs. The directivity model applies to strike-slip earthquakes only and a future update will address directivity effects for other styles of faulting. The model described here supersedes the previous models developed by the authors of this article: Bayless et al., (2020), BS13 (Chapter 2 of Spudich et al., 2013), Somerville (2003), Abrahamson (2000), and Somerville et al., (1997).

(2) Median and Aleatory Variability Adjustments



Median adjustment: $\ln(RotD50_{dir}) = \ln(RotD50_{GMM}) + f_D$

GMM with directivity adjustment

GMM without directivity

Median directivity adjustment model

Aleatory variability adjustment: $\sigma_{Dir} = \sqrt{\tau^2_{GMM} + \phi^2_{GMM} - \phi^2_{Reduction} + \phi^2_{i|UH}}$

σ with directivity adjustment

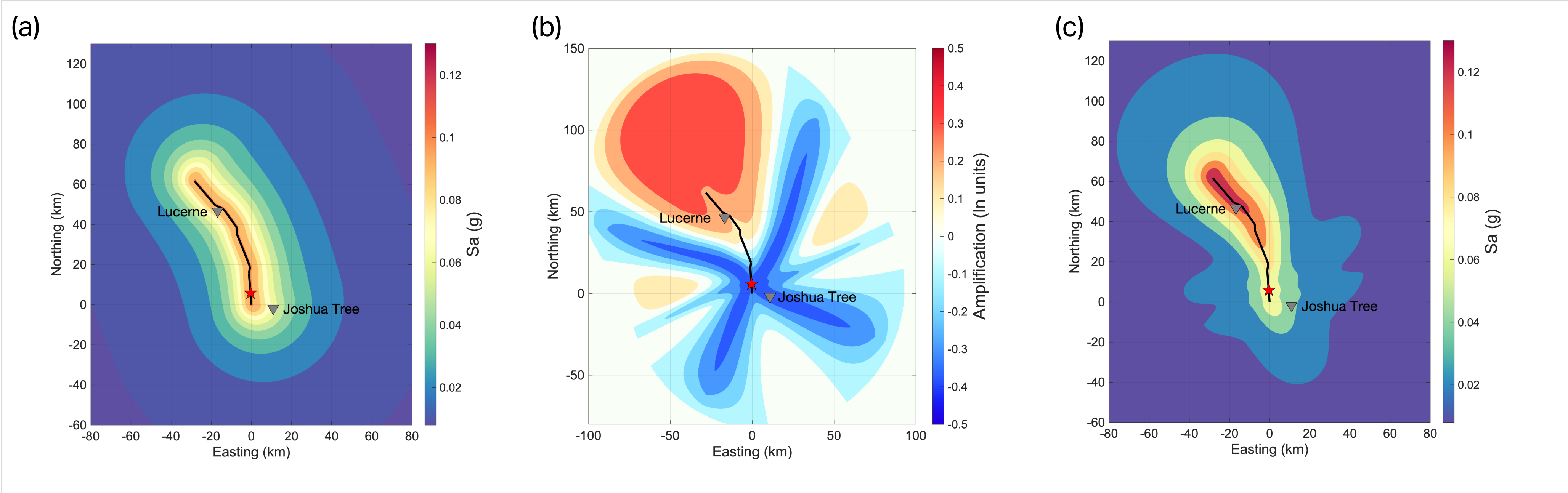
τ and ϕ from GMM without directivity

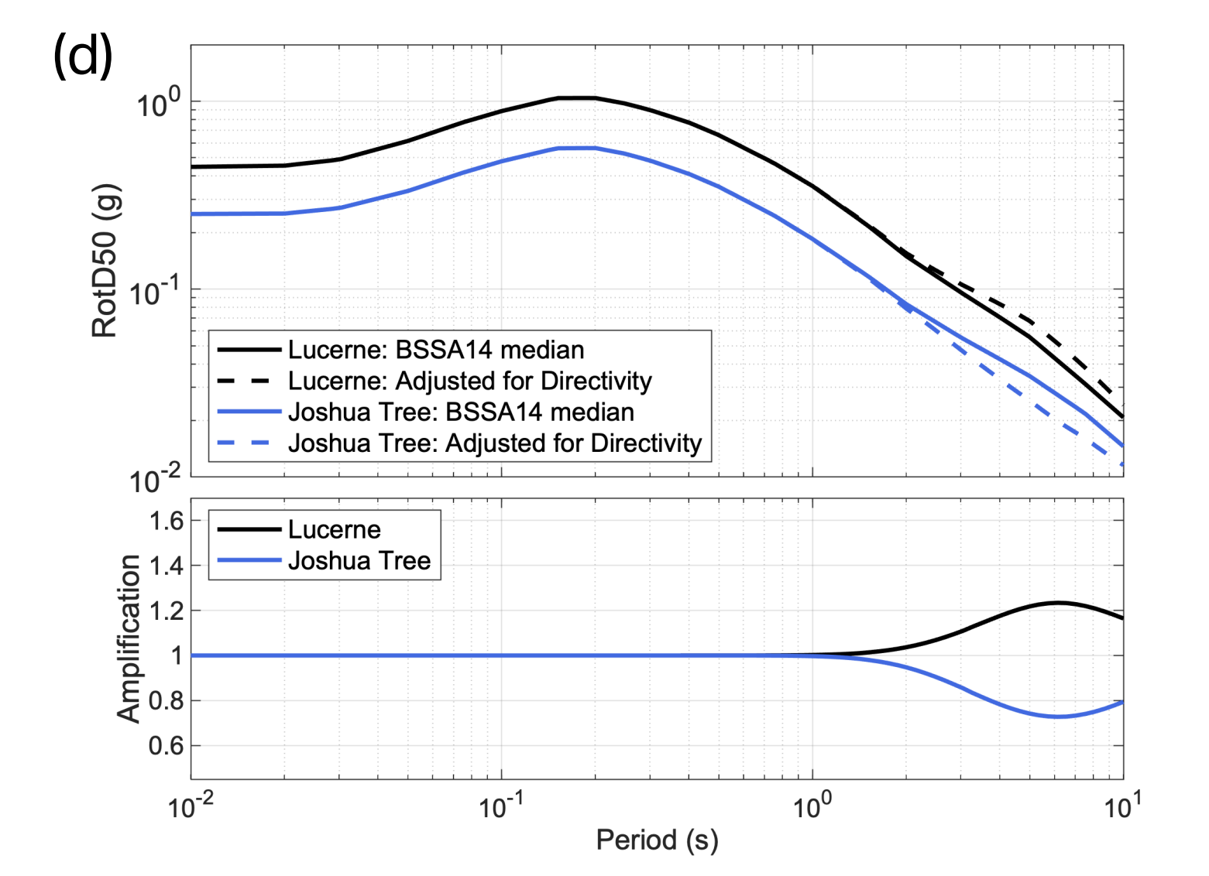
Directivity ϕ reduction model; due to improvements in median prediction

Directivity ϕ increase; due to the unknown hypocenter (UH) locations for a future earthquake

(3) Model Implementation: Deterministic

Case with a Specified Hypocenter – Landers Earthquake





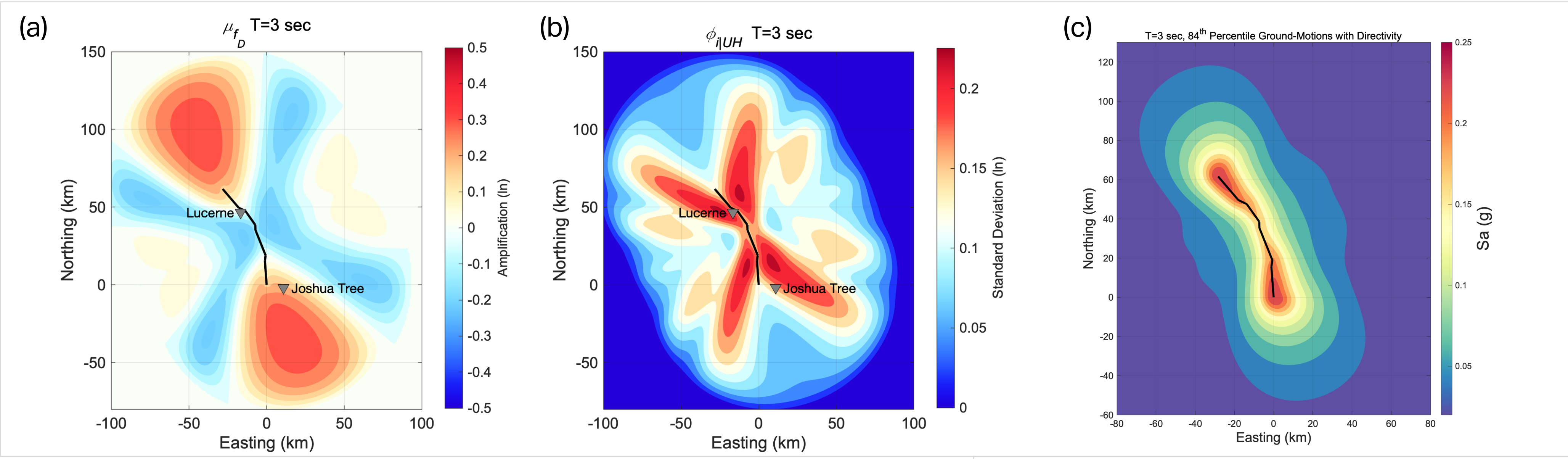
(a) Contours of the BSSA14 GMM median ground motions at T=3 sec. Reference site and basin conditions are used. The black line is the fault trace, and the red star is the hypocenter.
(b) Contours of f_D for this scenario and spectral period (ln units)
(c) Contours of the median spectral acceleration due to adjustment by the f_D values in (b)
(d) Median response spectra at Lucerne and Joshua tree. The 84th (or other percentile) response spectra can be calculated using the adjusted median and σ_{Dir}. In the case with specified hypocenter, $\phi_{i|UH}$=0.

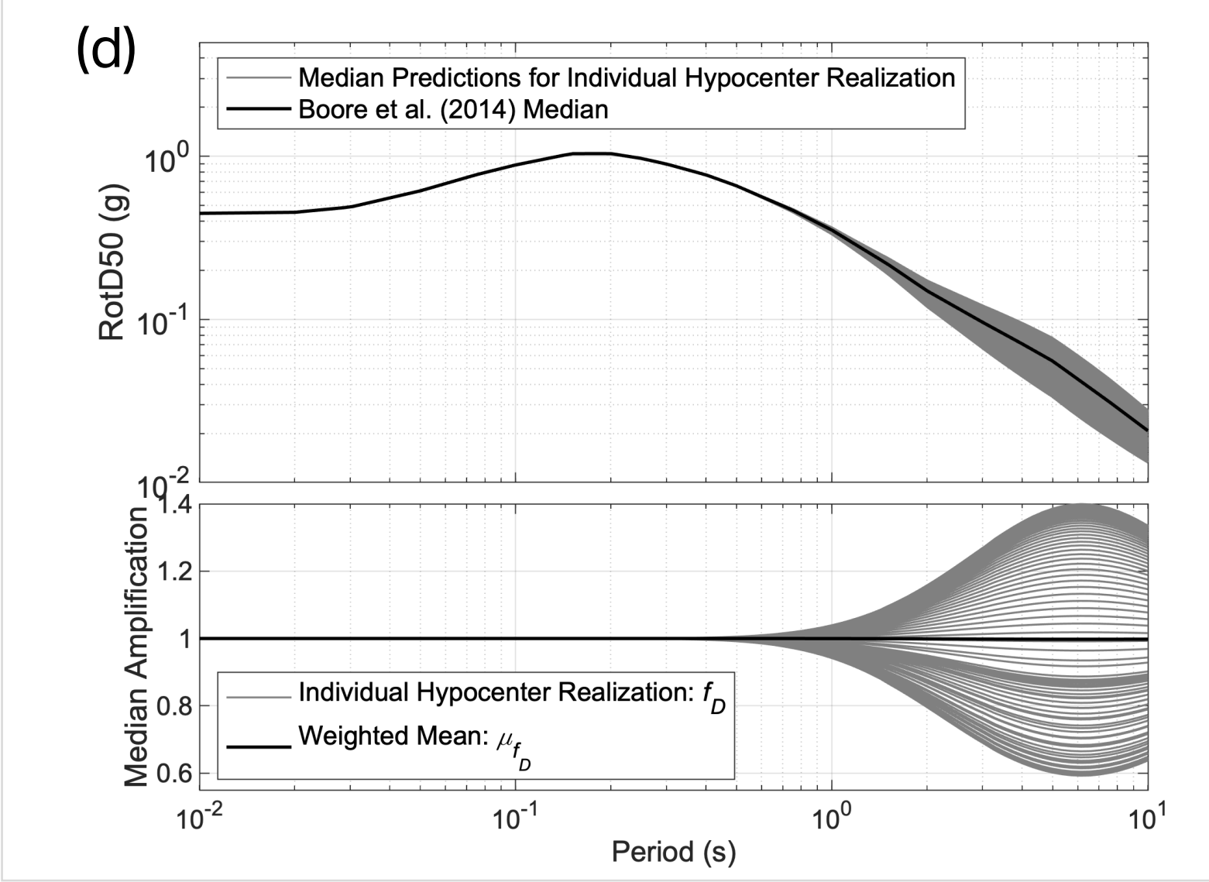
Case with an Unknown Hypocenter – Landers Earthquake

Because the hypocenter locations are not known for future earthquakes, the more appropriate method to use for DSHA is to model the hypocenter locations using a distribution. This is the approach taken in the probabilistic seismic hazard example in Section 4 of this poster.

For a given earthquake scenario and a given site, μ_{f_D} is the weighted mean of the median directivity adjustment accounting for the uncertainty in hypocenter location. There is a similar formula for the parametric variability term, $\phi_{i|UH}$.

$$\mu_{f_D}(\boldsymbol{M},\mathrm{T},x) = \sum_{h=1,N_h} P_h\, f_D(\boldsymbol{M},\mathrm{T},x)_h$$





(a) Contours of μ_{f_D} at T=3 sec.
(b) Contours of $\phi_{i|UH}$ at T=3 sec.
(c) Contours of the 84th percentile spectral acceleration using BSSA14 and the modifiers from (a) and (b) , at T=3 sec.
(d) Median response spectra at Lucerne for individual hypocenter location realizations.

(4) Model Implementation: Probabilistic

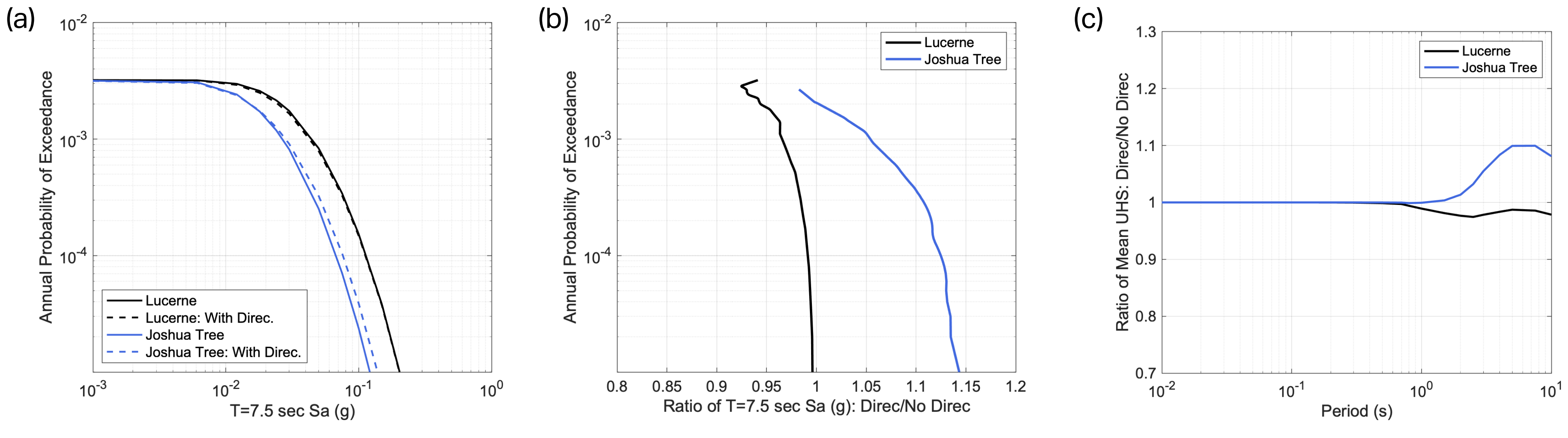
Hypocenter locations are not considered in conventional PSHA because the traditional GMMs do not utilize the hypocenter location. When rupture directivity effects are modeled, the hypocenter locations need to be introduced (added terms in blue):

$$\lambda(IM>z) = \sum_{i=1}^{n_{src}} N_i(\boldsymbol{M}_{min}) \int_M \int_R \int_H P(IM>z|m,r,\theta_D)\, f_M(m) f_R(r) f_H(\theta_D)\, dr\, dm\, d\theta_D$$

Where $P(IM>z|m,r,\theta_D)$ contains both the median and standard deviation directivity adjustments, and implicit integration over the GMM variability. This is called the *full hypocenter randomization* approach (Donahue et al., 2019; Weatherill and Lilienkamp, 2023). In this approach, f_D and $\phi_{Reduction}$ are calculated for each hypocenter location of a given rupture, and $\phi_{i|UH}$ is implicit in the integration over $f_H(\theta_D)$.

Probabilistic Example

A simple PSHA is performed in HAZ45 with the Landers earthquake scenario as the only source. This source is modeled as a vertical strike-slip fault with 12 mm/yr slip rate and with the maximum-magnitude recurrence model (**M**7.28). The Abrahamson et al. (2014) GMM is used with the reference site and basin conditions. 100 hypocenters spaced evenly along strike are used with a uniform distribution.



(a) T=7.5 sec mean hazard curves at Lucerne and Joshua Tree.
(b) Ratios of the mean hazard curves with and without directivity.
(c) Ratios of the mean Uniform Hazard Spectra (5,000-year average return period) with and without directivity.

(5) Conclusions

- Application of the directivity model requires adjustments to both the GMM median and aleatory variability.
  - The variability adjustment has a reduction component, $\phi_{Reduction}$, due to improvements in the median prediction, and an added component, $\phi_{i|UH}$, due to the unknown hypocenter location for a future earthquake.
- There may be an expectation by some that the directivity model should introduce larger changes to the long-period probabilistic hazard than we have shown. The justification behind this perspective is that very large rupture directivity effects have been observed in recorded ground motions; and these observations are correct. The reason that changes to the PSHA are smaller than these observations is because the hypocenter locations are not known for future earthquakes, and so we model them using a distribution which is symmetric along-strike. For a given site and rupture, there are some hypocenter locations which correspond to ground-motion amplification and there are other hypocenter locations which correspond to de-amplification. The net effect is a smaller change due to directivity than seen for a given hypocenter location.
- For a specific scenario (fixed hypocenter), the inclusion of directivity using this model can lead to significant (e.g., ±40-50%) changes in the long-period ground motion for specific sites, but if the hypocenter locations are randomized for future earthquakes using a symmetric distribution, the net effect of modeling directivity in the PSHA calculation leads to a relatively small change (e.g., ±5-10%) in the ground motion at return periods of 1,000-10,000 years.

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