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A RISK-TARGETED ALTERNATIVE TO DETERMINISTIC CAPPING OF MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION MAPS

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Abstract

Since their inception nearly 20 years ago, the so-called Maximum Considered Earthquake ground motion maps in building codes of the United States of America (USA) have represented the lesser of probabilistic and deterministic values. Before the *2009 NEHRP (National Earthquake Hazards Reduction Program) Recommended Seismic Provisions for Seismic Regulations for New Buildings and Other Structures* and the *2012 International Building Code*, the probabilistic ground motions were uniform-hazard values corresponding to 2% probability of exceedance in 50 years. Since then, the probabilistic ground motions have been so-called risk-targeted values that are expected to result in building designs with uniform risk of collapse, namely a theoretical 1% probability of collapse in 50 years that is based on nonlinear response history analysis simulations. In either case, in arriving at the mapped ground motions, the probabilistic values have been capped at some locations by smaller deterministic ground motions from characteristic earthquakes on known active faults. Generally speaking, the locations where the deterministic ground motions cap their probabilistic counterparts are high-hazard areas near very active faults (e.g. the San Andreas Fault in California). A consequence of deterministic capping of risk-targeted ground motions is unspecified increases in collapse risk in those high-hazard areas. In the *2015 NEHRP Recommended Seismic Provisions* (which are in the process of being adopted into the *2018 International Building Code*), deterministic capping can increase the collapse risk by factors of up to 9.5. In lieu of the unspecified increases in collapse risk that result from deterministic capping, this paper explores an alternative that specifies a higher target risk of collapse in high-hazard areas, up to only three times the theoretical 1% in 50 years. Since many high-hazard areas are also highly populated, changing deterministic capping can have significant societal impacts. Fortunately, the alternative Maximum Considered Earthquake ground motions are within ±20% of those mapped in the *2015 NEHRP Provisions*, except near the New Madrid seismic zone (NMSZ) in central USA (where the current mapped values are the largest in the USA), in coastal northern California and southern Oregon (where the current ground motions are almost as large as those near the NMSZ), and near limited portions of the San Andreas Fault (where the current ground motions have return periods of less than 500 years).

Keywords: building code ground motion maps; risk-targeted ground motions; performance-based design

1. Introduction

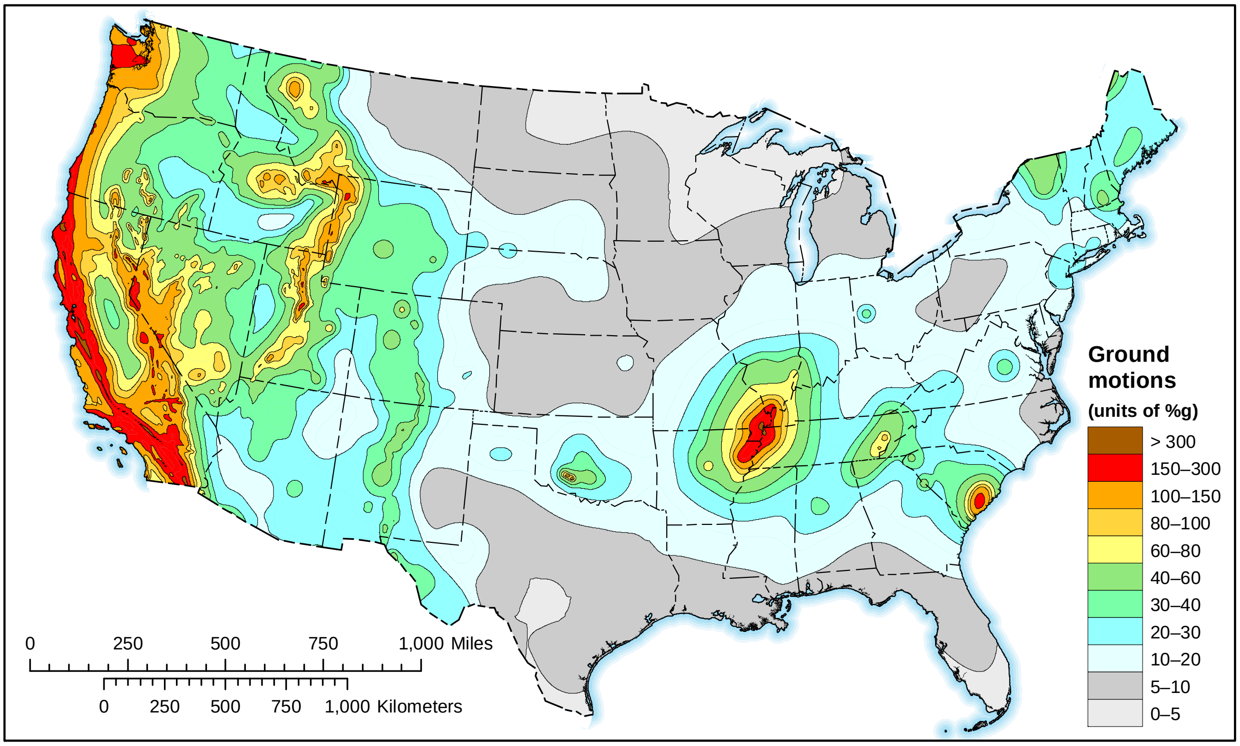
Since their inception in the *1997 NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* [1], and subsequent adoption in the *2000 International Building Code* [2], the so-called Maximum Considered Earthquake ground motion maps in building codes of the United States of America (USA) have represented the lesser of probabilistic and deterministic values [3]. Before the *2009 NEHRP Recommended Seismic Provisions* [4] and the *2012 International Building Code* [5], the probabilistic ground motions were uniform-hazard values corresponding to a 2% probability of exceedance in 50 years. The deterministic ground motions were values corresponding to 150% of the largest median ground motions from characteristic earthquakes on known active faults within the region, with lower limits of 1.5g and 0.6g for 0.2- and 1.0-second spectral response accelerations, respectively. Generally speaking, the deterministic ground motions were less than their probabilistic counterparts in high-hazard areas near very active faults in coastal California (e.g. the San Andreas Fault). As explained in the commentary of the *1997 NEHRP Provisions* [6], page 292, "the use of the deterministic earthquakes to establish the maximum considered earthquake ground motions for use in design in coastal California result[ed] in a level of protection close to that implied in the *1994 Provisions* [7] and consistent with maximum magnitude earthquakes expected for those seismic sources. Additionally, this approach results in less drastic changes to ground motion values for coastal California than the alternative approach of using probabilistic based maps."

Starting with the *2009 NEHRP Provisions* and the *2012 International Building Code*, the probabilistic ground motions were changed to so-called risk-targeted ground motions [8] that are expected to result in building designs with geographically uniform risk of collapse, namely a theoretical 1% probability of collapse in 50 years based on nonlinear response history analysis simulations. The deterministic caps on these probabilistic ground motions remained, slightly changed from 150% of median to 84th-percentile values. The probabilistic (risk-targeted) and deterministic ground motions that underlie the Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motion maps in the latest (2015) edition of the *NEHRP Provisions* [9, 10] are mapped in Fig. 1. These MCE_R ground motion maps have been adopted into the next (2016) edition of the *American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI) 7 Standard*, and are in the process of being adopted into the next (2018) edition of the *International Building Code*.

2. Collapse Risks resulting from Current MCE_R Ground Motion Maps

A consequence of the deterministic capping of probabilistic (risk-targeted) ground motions described above is increased collapse risk. At a given location, a lower MCE_R ground motion relative to the risk-targeted value results in a building design with higher risk of collapse in 50 years than the targeted 1% probability. For a 0.05-degree grid of locations covering the conterminous USA, the collapse risks resulting from the MCE_R ground motion maps in the *2015 NEHRP Provisions* are provided in the upper map of Fig. 2. Since at most locations the MCE_R ground motions are probabilistic, most of the collapse risks are equal to the targeted 1% probability of collapse in 50 years. At the locations where the MCE_R ground motions are deterministic, which encompasses a population of 11-12 million, the collapse risks are 2-3% and up to 9.5% in 50 years. All of these collapse risks, and those to follow, are calculated via the so-called risk integral [e.g. 11, 12, 13], using the 2014 ground motion hazard curves of the U.S. Geological Survey [14] and the MCE_R-dependent collapse fragility curves specified in the site-specific ground motion procedures (Chapter 21) of the *2015 NEHRP Provisions*.

In the upper panel of Fig. 3, the collapse risks from the upper map of Fig. 2 are plotted against the level of hazard for each location, quantified here by the uniform-hazard ground motion with 2% probability of being exceeded in 50 years. The level of hazard is normalized by the deterministic ground motion lower limit mentioned in Section 1 (and shown on the lower map of Fig. 1), since MCE_R ground motions below that lower limit are, by definition, probabilistic. With this normalization, the probabilities of collapse in 50 years at locations where the level of hazard is below unity (approximately) are equal to 1%. Above a level of hazard of unity, the collapse risks increase with the level of hazard, but with much scatter. For example, at a level of hazard approximately twice the deterministic lower limit, the probabilities of collapse in 50 years range from 1% to 7%.



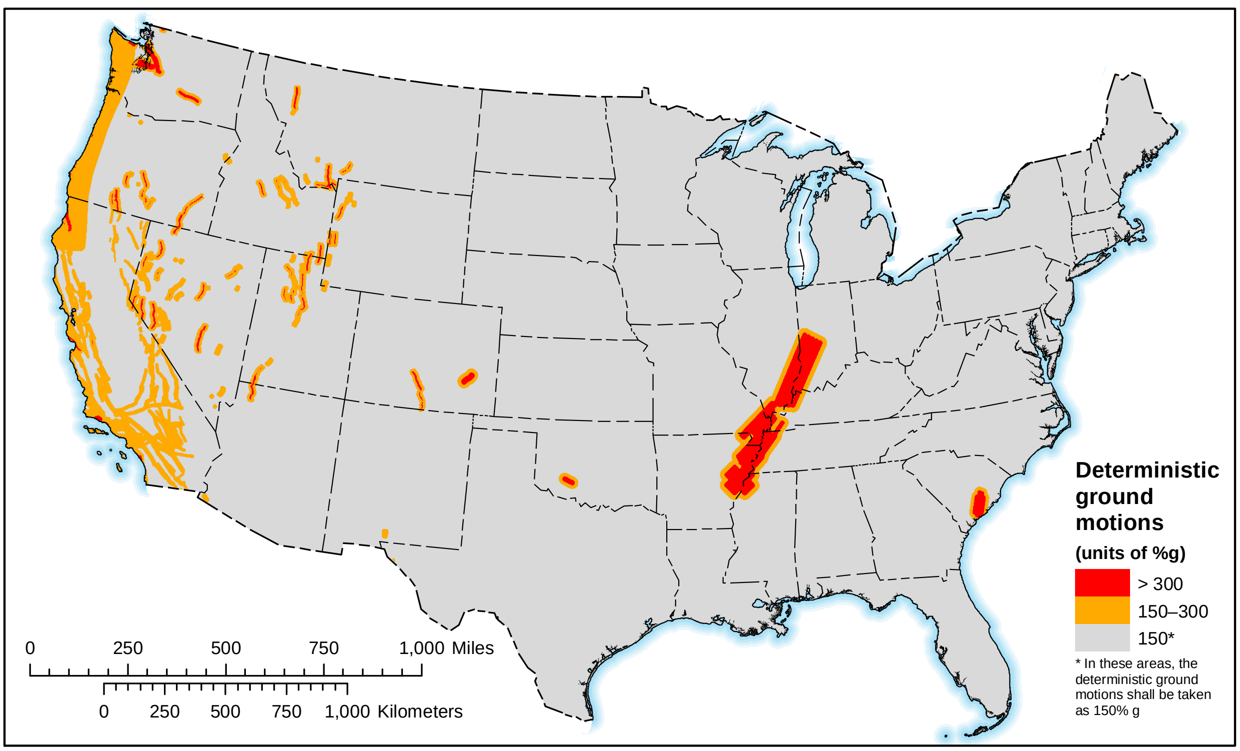
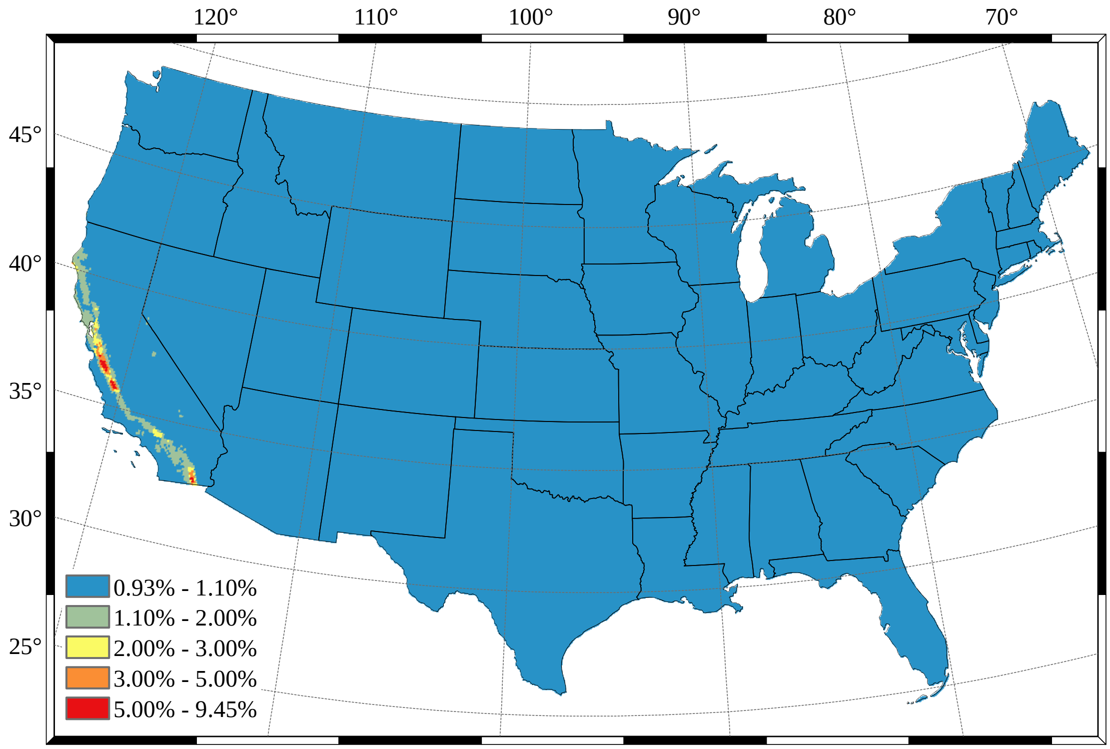


Fig. 1 – Probabilistic (upper map) and deterministic (lower map) spectral response accelerations at 0.2 seconds and 5% of critical damping that underlie the MCE_R ground motion maps in the *2015 NEHRP Provisions* (which take the lesser value at each location). For brevity, the corresponding spectral response accelerations for 1.0 second, and those for the other USA states and territories included in the *2015 NEHRP Provisions* (see https://www.fema.gov/media-library/assets/documents/107646), are not shown.



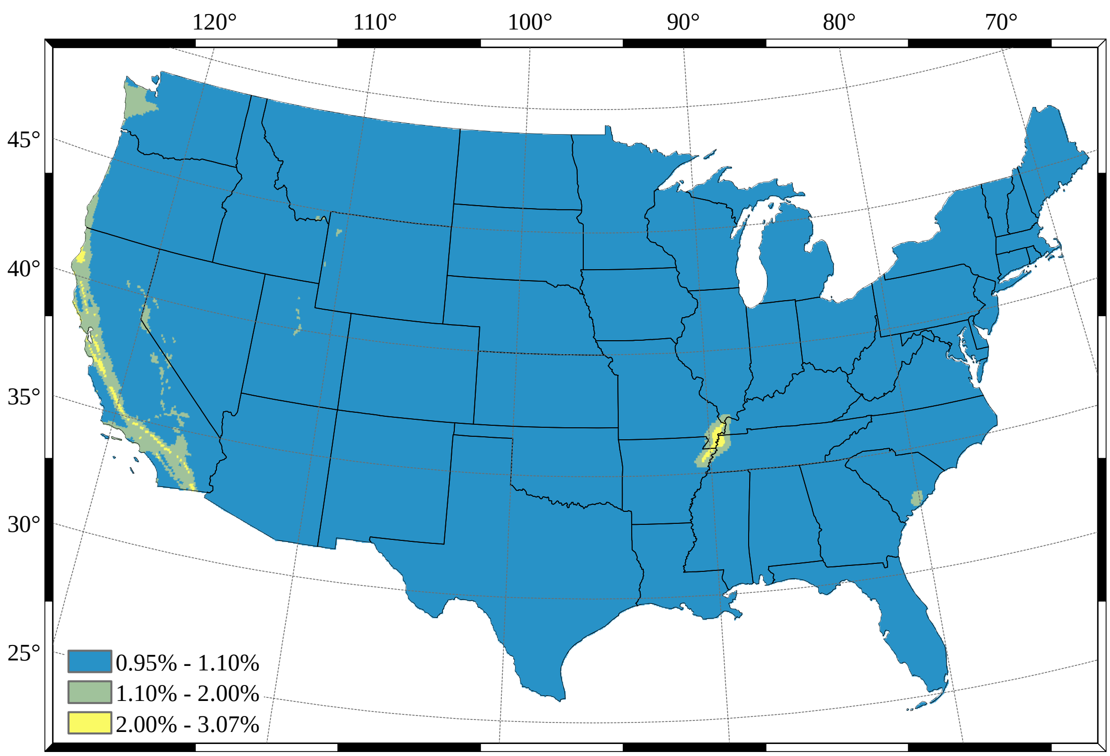


Fig. 2 – Theoretical (based on nonlinear response history analysis simulations) probabilities of collapse in 50 years for buildings designed against the MCE_R ground motions in the *2015 NEHRP Provisions* (upper map) and the alternative, purely probabilistic MCE_R ground motions explored by this paper (lower map). Both maps correspond to a spectral period of 0.2 seconds, like Fig. 1. The maps for a spectral period of 1.0 second, not shown for brevity, are similar. Please see Fig. 8 for zoomed-in maps covering California.

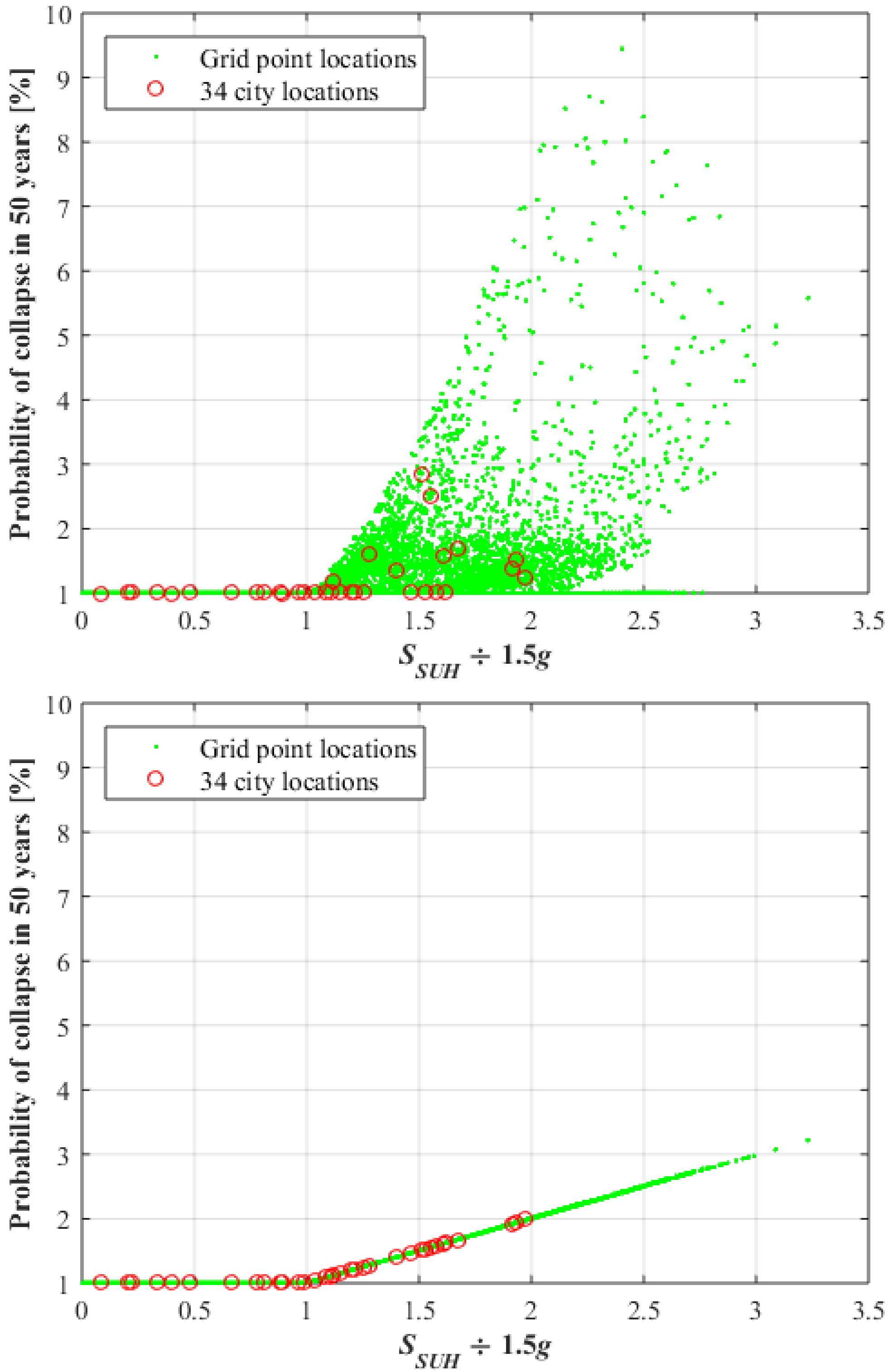


Fig. 3 – Theoretical collapse risks from Fig. 2 plotted against the level of hazard for each location, i.e. the uniform-hazard, 2%-in-50-year ground motion (S_{SUH}) normalized by the deterministic ground motion lower limit–1.5g for the 0.2-second spectral response accelerations considered in this and the other figures of this paper. The upper panel is for buildings designed against the MCE_R ground motions in the *2015 NEHRP Provisions*, the lower is for the alternative, purely probabilistic MCE_R ground motions explored by this paper.

3. Alternative, Purely Probabilistic MCE_R Ground Motion Maps

The observed increase in collapse risk with increasing level of hazard shown in the upper panel of Fig. 3 (for the current MCE_R ground motion maps in the *2015 NEHRP Provisions*) brings to mind a purely probabilistic alternative to deterministic capping. At higher levels of hazard, the target probability of building collapse could be set higher than the current 1% in 50 years. As shown in Fig. 4, increasing the target probability of collapse results in lower ground motion, like capping probabilistic ground motions by deterministic values does.

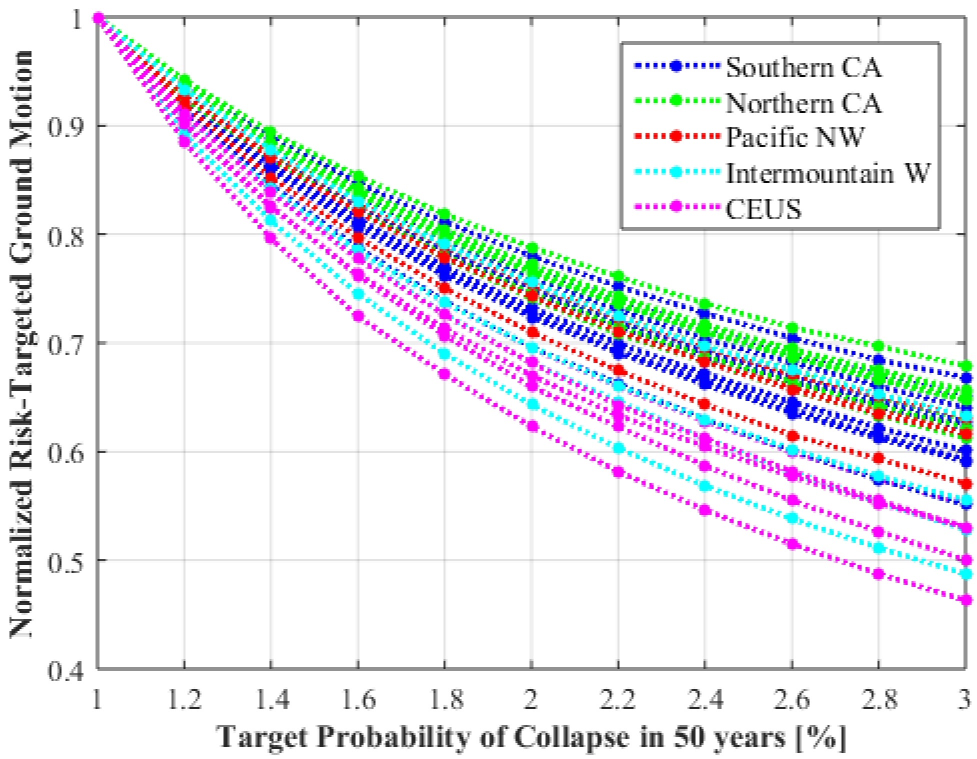


Fig. 4 – Examples of the decrease in probabilistic risk-targeted ground motions with increasing target probability of collapse in 50 years, for the 34 locations listed in Table 1 and 0.2-second spectral response accelerations. The risk-targeted ground motions are normalized by their values for a 1% target probability of collapse in 50 years. CEUS stands for Central and Eastern USA.

The lower panel of Fig. 3 illustrates a target probability of collapse that increases with the level of hazard. At levels of hazard less than the deterministic ground motion lower limit in the *2015 NEHRP Provisions* (i.e., at normalized levels of hazard less than unity), the target probability of collapse is set to 1% in 50 years. At higher levels of hazard, the target probability of collapse is set equal to the normalized level of hazard, e.g. 2% in 50 years at twice the deterministic lower limit, 3% in 50 years at three times. Other target collapse risks could be defined, but this one provides a simple example.

The alternative, purely probabilistic MCE_R ground motion maps that result from the target collapse risks defined in the preceding paragraph are illustrated in Fig. 5, and example values are listed in Table 1. To show the differences with respect to the current MCE_R ground motions in the *2015 NEHRP Provisions*, Fig. 6 maps the ratios of the alternative divided by current ground motions. For the vast majority of locations—encompassing more than nine-tenths of the population in areas that are currently deterministically capped, and nearly all of the remaining population—the alternative MCE_R ground motions are within ±20% of the current values (i.e. the ratios are 0.8 to 1.2). Near the New Madrid seismic zone in central USA and in a few other areas, the alternative ground motions are 20 to 40% lower (than the current values). Along limited portions of the San Andreas Fault in California, mostly near El Centro and between San Jose and Parkfield, the alternative ground motions are 20-70% higher. Consequently, whereas the largest 0.2-second MCE_R spectral response acceleration from the maps in the *2015 NEHRP Provisions* (3.3g) is in the New Madrid seismic zone (at a latitude and longitude of 36.60 and -89.60 degrees, respectively), the largest value from the alternative, purely probabilistic maps (3.0g) is near the San Andreas Fault (at a latitude and longitude of 32.85 and -115.50 degrees, respectively). On the maps in the *2015 NEHRP Provisions*, there are several other locations where the 0.2-second MCE_R spectral response accelerations are larger than 3g, encompassing a population of approximately 14,000 in the states of Missouri, Kentucky, and Tennessee. Likewise, the largest 1.0-second MCE_R spectral response accelerations in the *2015 NEHRP Provisions* are also in these states, whereas the largest such values from the alternative maps are in California.

4. Collapse risks resulting from Alternative MCE_R Ground Motion Maps

For comparison with the collapse risks resulting from the current MCE_R ground motion maps in the *2015 NEHRP Provisions*, those resulting from the alternative, purely probabilistic MCE_R ground motion maps discussed in Section 3 are provided in the lower map of Fig. 2. Whereas the current probabilities of collapse are as high as 9.5% in 50 years, the alternative probabilities are, by design, limited to approximately 3% in 50 years. Furthermore, whereas the current probabilities of collapse only significantly exceed 1% in 50 years near the San Andreas Fault in California, the alternative probabilities of collapse also significantly exceed 1% in 50 years in high-hazard areas near: the New Madrid seismic zone in central USA; Charleston, South Carolina; coastal Washington State; and the Wasatch fault in Utah.

5. Return Periods of Current vs. Alternative MCE_R Ground Motions

The return periods of the current MCE_R ground motions in the *2015 NEHRP Provisions* and those of the alternative, purely probabilistic MCE_R ground motions explored by this paper are mapped in Fig. 7. For the current, deterministically capped MCE_R ground motions, the return periods are as short as 181 years, along limited portions of the San Andreas Fault. The shortest return period of the alternative ground motions is 581 years, still along the San Andreas Fault. Elsewhere along the San Andreas Fault, the return periods of both the current and alternative MCE_R ground motions are roughly 1000 years (500 to 1500 years). The return periods of the alternative MCE_R ground motions are also roughly 1000 years near the New Madrid seismic zone; Charleston, South Carolina; and Reno, Nevada. Otherwise the return periods of the current and alternative MCE_R ground motions are similar: roughly 2500 years (2000 to 3000 years) across most of the conterminous USA, but 1500 to 2000 years in a significant amount of area that encompasses approximately 15% of the total population.

6. Conclusions

The alternative MCE_R ground motion maps explored in this paper, like the current maps in the *2015 NEHRP Provisions*, cap the values in high-hazard areas, e.g. along the San Andreas Fault in California. The current maps do so with deterministic ground motions, which result in unspecified risks of building collapse. In contrast, the alternative maps cap the ground motions in high-hazard areas by targeting probabilities of collapse higher than the current theoretical (based on nonlinear response history analysis simulations) target of 1% in 50 years. The alternative ground motions are within ±20% of the current values, except near the New Madrid seismic zone in central USA (where they are lower), in coastal northern California and southern Oregon (where they are lower), and near limited portions of the San Andreas Fault (where they are higher). Whereas the current maps result in theoretical collapse risks that are as high as 9.5% in 50 years, the highest collapse risk on the alternative maps is approximately 3% in 50 years. Correspondingly, the return period of the current ground motions is as short as 181 years, whereas it is at least 570 years for the alternative ground motions. Whereas the current maps for 0.2-second spectral response acceleration are largest near the New Madrid seismic zone, and larger than 3g at other locations, the alternative maps are largest in California and at most 3g. As the alternative MCE_R ground motion maps are purely probabilistic, they do not require computation of deterministic ground motions. The alternative maps could be considered by the Building Seismic Safety Council "Project '17" [15] as it reassesses the targeted risk of collapse and deterministic caps for the MCE_R ground motion maps to be in the next edition of the *NEHRP Provisions*.

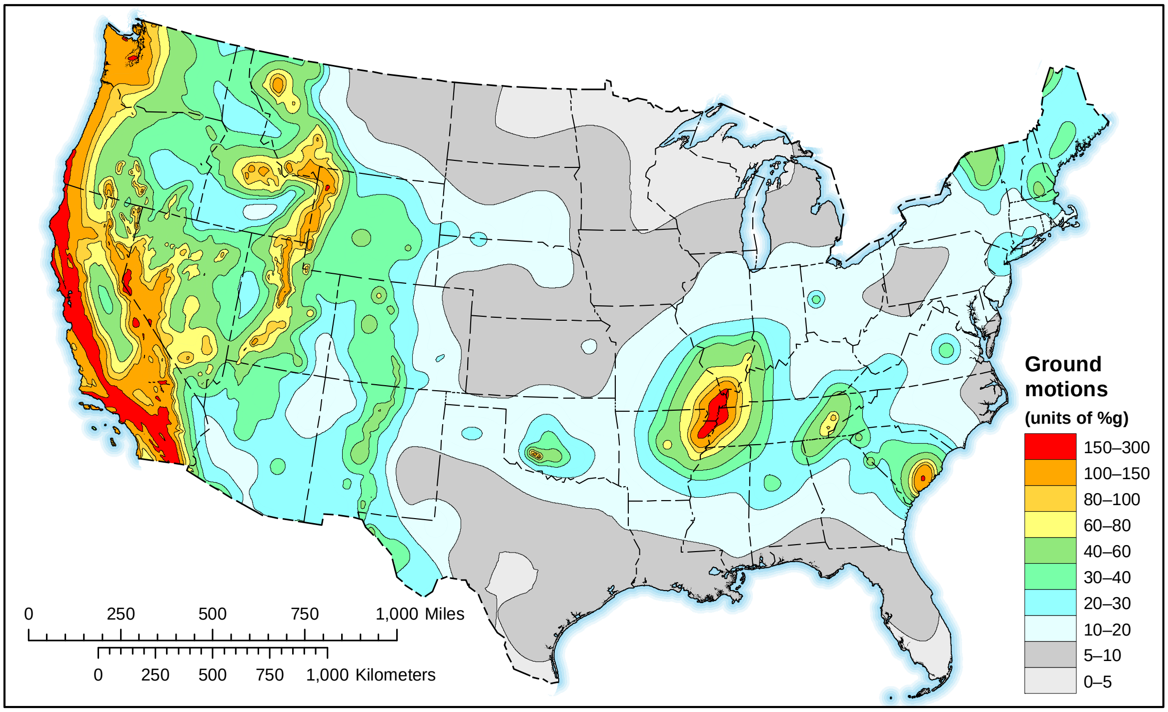


Fig. 5 – Alternative, purely probabilistic MCE$_R$ ground motion map at a spectral period of 0.2 seconds.

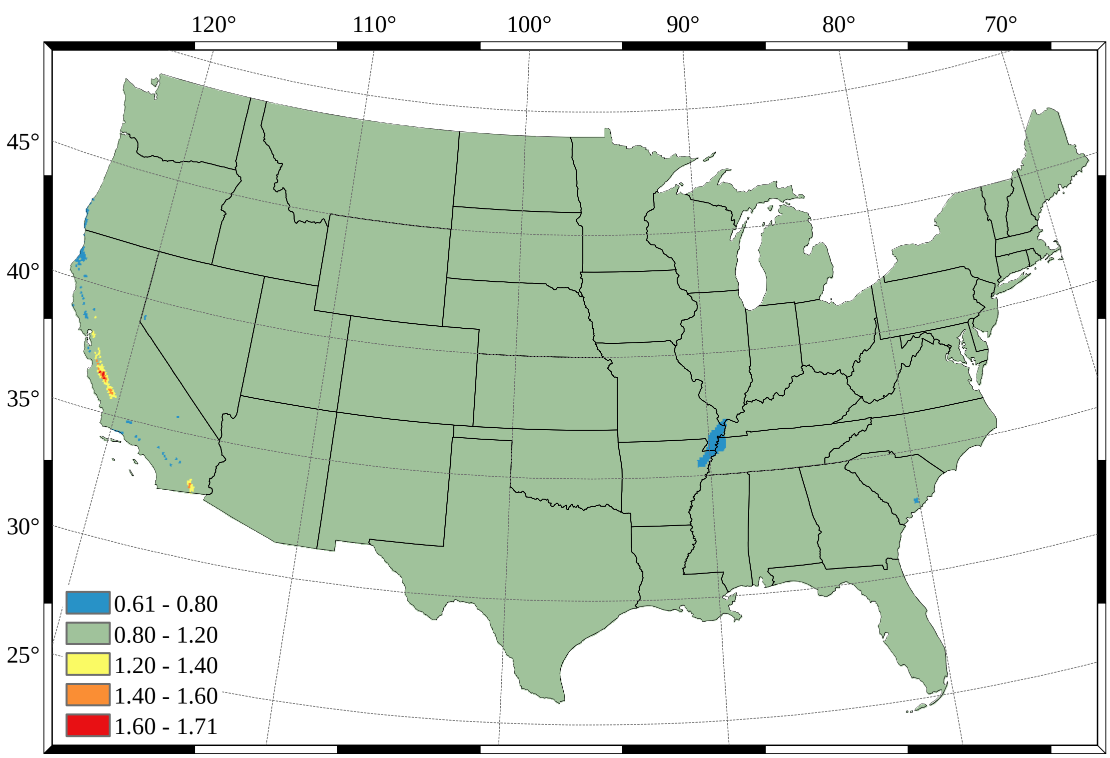


Fig. 6 – Ratios of the alternative, purely probabilistic MCE$_R$ ground motions (from Fig. 5) divided by the MCE$_R$ ground motions mapped in the *2015 NEHRP Provisions*, for the 0.2-second spectral response accelerations shown in other figures of this paper. The ratios for the 1.0-second spectral response accelerations are similar. Please see Fig. 9 for a zoomed-in map covering California.

Table 1 – For 34 example locations in the high-risk (high-hazard and/or high-population) cities identified in the 2009 (and 2015) editions of the *NEHRP Provisions*, the current MCE_R ground motions from the *2015 NEHRP Provisions* and the alternative, purely probabilistic MCE_R ground motions explored by this paper. CEUS stands for Central and Eastern USA.

Latitude	Longitude	City, State	Region	Current S_S (g)	Alternative S_S (g)	Current S_1 (g)	Alternative S_1 (g)
34.05	-118.25	Los Angeles, CA	Southern CA	2.0	1.7	0.70	0.63
34.05	-118.40	Century City, CA	Southern CA	2.1	1.8	0.75	0.65
34.20	-118.55	Northridge, CA	Southern CA	1.7	1.7	0.60	0.63
33.80	-118.20	Long Beach, CA	Southern CA	1.7	1.5	0.61	0.57
33.65	-117.80	Irvine, CA	Southern CA	1.2	1.2	0.45	0.45
33.95	-117.40	Riverside, CA	Southern CA	1.5	1.5	0.58	0.57
34.10	-117.30	San Bernardino, CA	Southern CA	2.3	2.0	0.93	0.78
35.30	-120.65	San Luis Obispo, CA	Southern CA	1.1	1.1	0.40	0.40
32.70	-117.15	San Diego, CA	Southern CA	1.6	1.4	0.53	0.52
34.45	-119.70	Santa Barbara, CA	Southern CA	2.1	1.7	0.77	0.65
34.30	-119.30	Ventura, CA	Southern CA	2.0	1.7	0.76	0.64
37.80	-122.25	Oakland, CA	Northern CA	1.9	1.9	0.72	0.72
37.95	-122.00	Concord, CA	Northern CA	2.2	2.0	0.67	0.73
36.60	-121.90	Monterey, CA	Northern CA	1.3	1.3	0.50	0.50
38.60	-121.50	Sacramento, CA	Northern CA	0.57	0.57	0.25	0.25
37.75	-122.40	San Francisco, CA	Northern CA	1.5	1.6	0.60	0.64
37.55	-122.30	San Mateo, CA	Northern CA	1.8	1.8	0.74	0.71
37.35	-121.90	San Jose, CA	Northern CA	1.5	1.9	0.60	0.70
36.95	-122.05	Santa Cruz, CA	Northern CA	1.6	1.5	0.60	0.58
38.10	-122.25	Vallejo, CA	Northern CA	1.5	1.8	0.60	0.68
38.45	-122.70	Santa Rosa, CA	Northern CA	2.4	2.0	0.94	0.76
47.60	-122.30	Seattle, WA	Pacific NW	1.4	1.4	0.49	0.49
47.25	-122.45	Tacoma, WA	Pacific NW	1.4	1.4	0.47	0.47
48.00	-122.20	Everett, WA	Pacific NW	1.2	1.2	0.43	0.43
45.50	-122.65	Portland, OR	Pacific NW	0.89	0.89	0.39	0.39
40.75	-111.90	Salt Lake City, UT	Intermountain W	1.5	1.4	0.55	0.54
43.60	-116.20	Boise, ID	Intermountain W	0.31	0.31	0.11	0.11
39.55	-119.80	Reno, NV	Intermountain W	1.5	1.4	0.52	0.52
36.20	-115.15	Las Vegas, NV	Intermountain W	0.65	0.65	0.21	0.21
38.60	-90.20	St. Louis, MO	CEUS	0.46	0.46	0.16	0.16
35.15	-90.05	Memphis, TN	CEUS	1.0	1.0	0.35	0.35
32.80	-79.95	Charleston, SC	CEUS	1.4	1.3	0.41	0.41
41.85	-87.65	Chicago, IL	CEUS	0.12	0.12	0.063	0.063
40.75	-74.00	New York, NY	CEUS	0.29	0.29	0.060	0.060

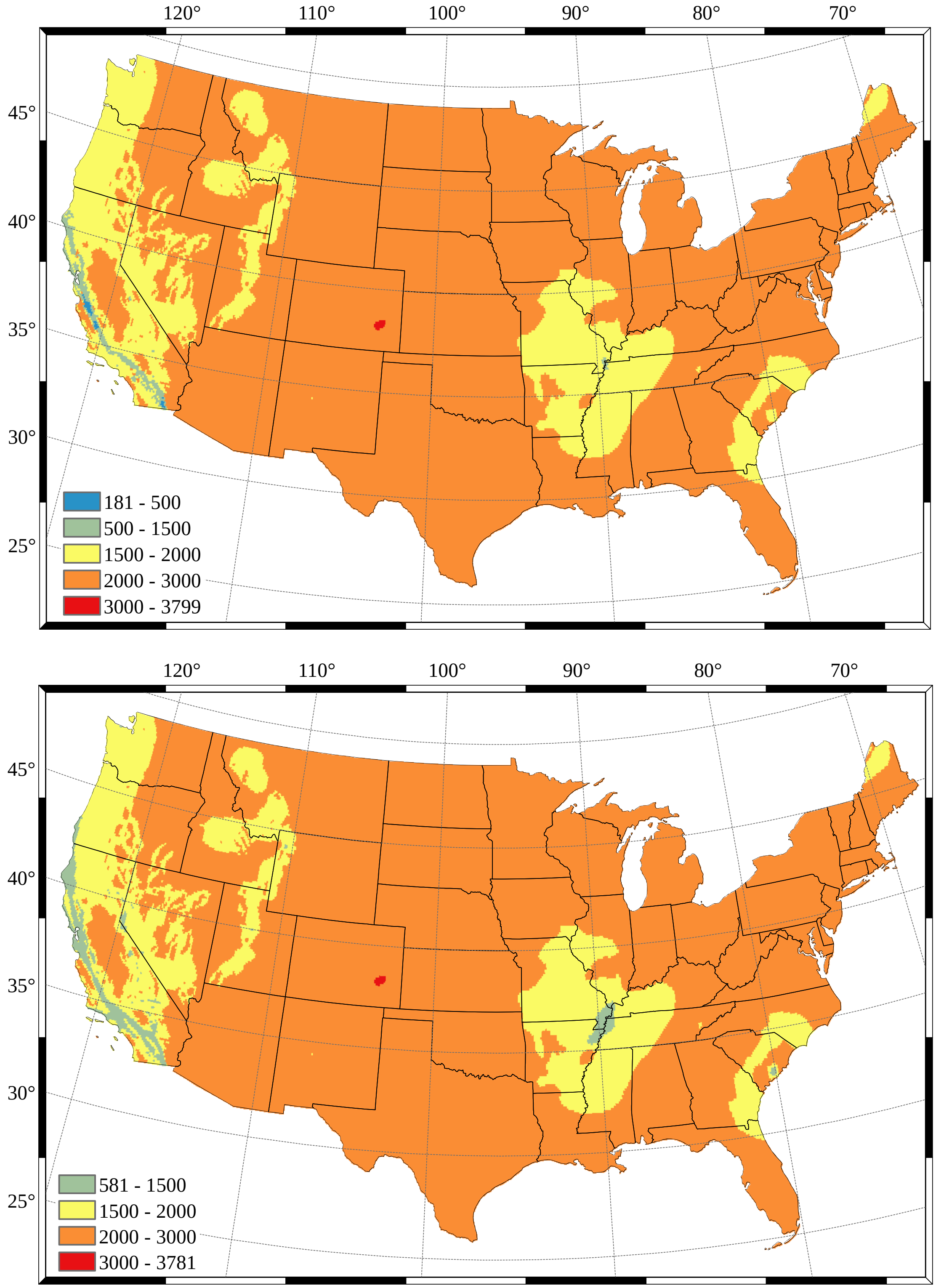


Fig. 7 – Return periods of the MCE_R ground motions mapped in the *2015 NEHRP Provisions* (upper map) and the alternative, purely probabilistic MCE_R ground motions (lower map), again for 0.2-second spectral response accelerations. The return periods for the corresponding 1.0-second spectral response accelerations are similar, except that the areas in which they are 1500 to 2000 years are larger, encompassing almost 60% of the total population of the conterminous USA.

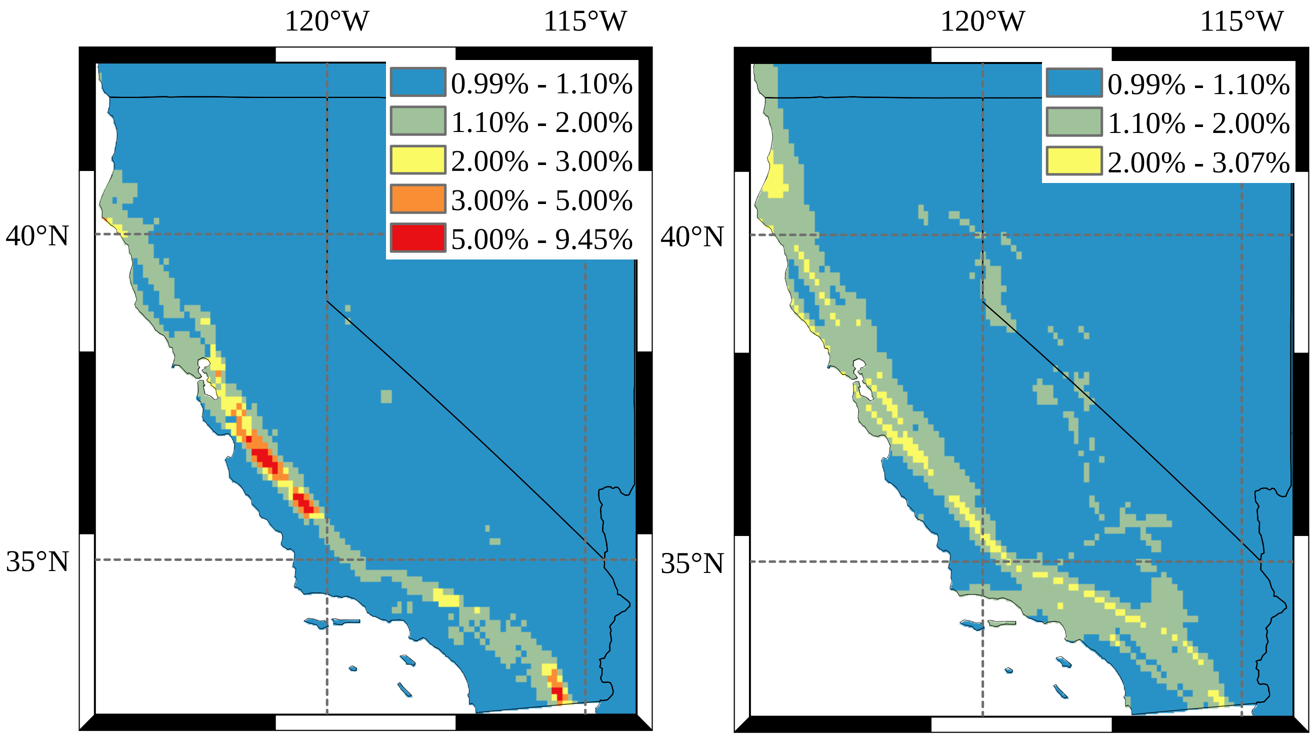


Fig. 8 – Zoomed-in versions of Fig. 2, covering California. Please see the Fig. 2 caption for more information. The color scales indicate the largest and smallest values within the mapped area.

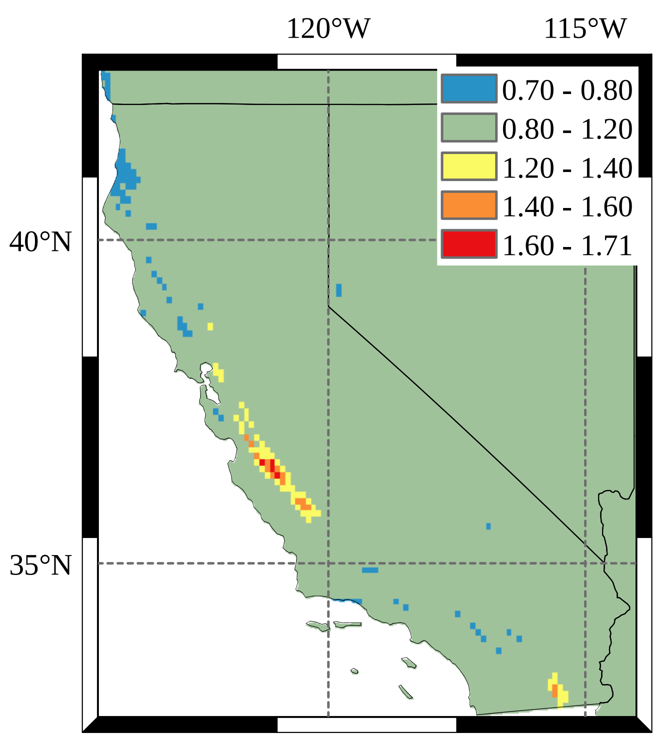


Fig. 9 – Zoomed-in version of Fig. 6, covering California. Please see the Fig. 6 caption for more information. The color scale indicates the largest and smallest values within the mapped area.

7. Acknowledgements

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