mb BIAS AND REGIONAL MAGNITUDE AND YIELD

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ABSTRACT

Traditional seismic yield estimation is performed using body wave magnitude (mb) measured from compressional wave amplitudes recorded across the globe. Stability is obtained by averaging many measurements. These waves traverse the earth’s mantle, and are affected by mantle properties, particularly under the source region, as other variations are averaged out. To monitor individual test sites during the testing era, test site corrections were obtained by various means, most notably the Joint Verification Experiment, and applied to obtain yield. To extend yield estimation to broad areas, we must apply an upper mantle correction on the fly. We have investigated two methods to map upper mantle bias over broad areas. The first estimates the bias at individual stations by inverting for corrections that best fit the collection of amplitudes measured at all stations. These measurements were taken from global monitoring agencies, including the International Data Centre (IDC) and National Earthquake Information Center (NEIC) bulletins, examined separately. We augment bulletin amplitudes by replicating monitoring agency measurement techniques for non-reporting or temporary stations in regions of particular interest, such as the Korean Peninsula, including State University of New York (SUNY) Binghamton's northeast China and Lamont's Sinpo deployments. The second method compares mb to magnitude derived from regional Lg coda, which is not affected by mantle properties, producing a map of the upper mantle effects across broad areas where earthquakes occur. The station-based technique retains near-site effects that the event-based technique does not, thus, resolving any differences between the two techniques is of great importance.

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OBJECTIVES

The North Korea explosion of October 9, 2006, resulted in a variety of yield estimates by numerous individuals and agencies across the globe. This situation created renewed interest in the technical details of yield estimation. A common means of estimating yield is through the use of magnitude-yield relations, and specifically the use of teleseismic P-wave magnitude, mb. However, magnitude bias has long been recognized as an issue in such work, and often a controversial one. Here, we describe a preliminary look into magnitude bias, updating some old techniques of investigating magnitude bias for use with modern data and databases, with measurements such as coda moment magnitudes, and specifically for the region of East Asia. We find significant potential for accurate determination of bias on a regional or even global scale, and present results to support this.

RESEARCH ACCOMPLISHED

Use of Reciprocity to Determine Bias

We extract a subset of events and stations from the United States Geologic Survey (USGS)-produced monthly Earthquake Data Reports (EDR) catalog, and invert these data to determine mb bias at stations. The data used are the individual station body wave magnitudes (mbs) reported in the EDR, during the period 1990–2005. We first examine the complete EDR station magnitude database to determine which stations report mb for a large number of events. We determine that a minimum of 500 events is reasonable to preserve good station statistics and not greatly reduce geographic coverage. This results in a total of 510 stations worldwide.

We then further reduce the data set by restricting the event-station distance to be in the range of 30 to 100 degrees. While mb is often reported at smaller ranges, the station measurements at these small ranges tend to have much greater scatter. We also eliminate any events having reported depths greater than 50 km. We do this out of concern that some stations may see a greater fraction of deep events relative to others, and that this could create a spurious bias, however we do not conduct any specific investigation to see if this is really a problem. We then limit the range of network mbs to between 4.7 and 5.7, which eliminates only about 5% of the data set. We use 5.7 as an estimate of the onset of mb saturation, and 4.7 as an estimate below which scatter and imprecision in magnitude increases. Note that these limits also help deal with data censoring (clipped data at high magnitudes and unreadable data at low magnitudes, problems that are addressed in these ranges using a non-linear maximum likelihood approach to determine network magnitude, but which is not amenable to linear inversion for bias). Finally, we limit the resulting set of events to those that were recorded at a minimum of 25 stations, so that particular events do not bias individual stations. The resulting dataset contains 510 stations, all of which recorded at least 100 events; 11,609 total events, all reported by at least 25 of the selected stations; and a total of 647,522 station magnitudes (about one quarter of the total number of EDR-reported station mbs).

As a final step before inversion, we eliminate all station magnitude outliers that are more than 1 magnitude unit different from the network mb. We then invert the station mbs using an LSQR conjugate gradient algorithm to simultaneously determine station bias and revised network-average mbs, under the constraint that mean station bias is zero across the dataset (and using the reported network mbs as the initial model for event mb, and 0 as the initial model for station bias). Use of an inversion technique is important, since the station biases feedback into the network mbs, and a simple mean station residual could often be a poor predictor of actual station bias (unless, of course, those means were determined using an iterative approach). The results are plotted on a global map in Figure 1, where the size of the symbols is proportional to the number of station mbs used for the station, and the color indicates the station bias. The inversion reduces station magnitude residuals by about 15% on average.

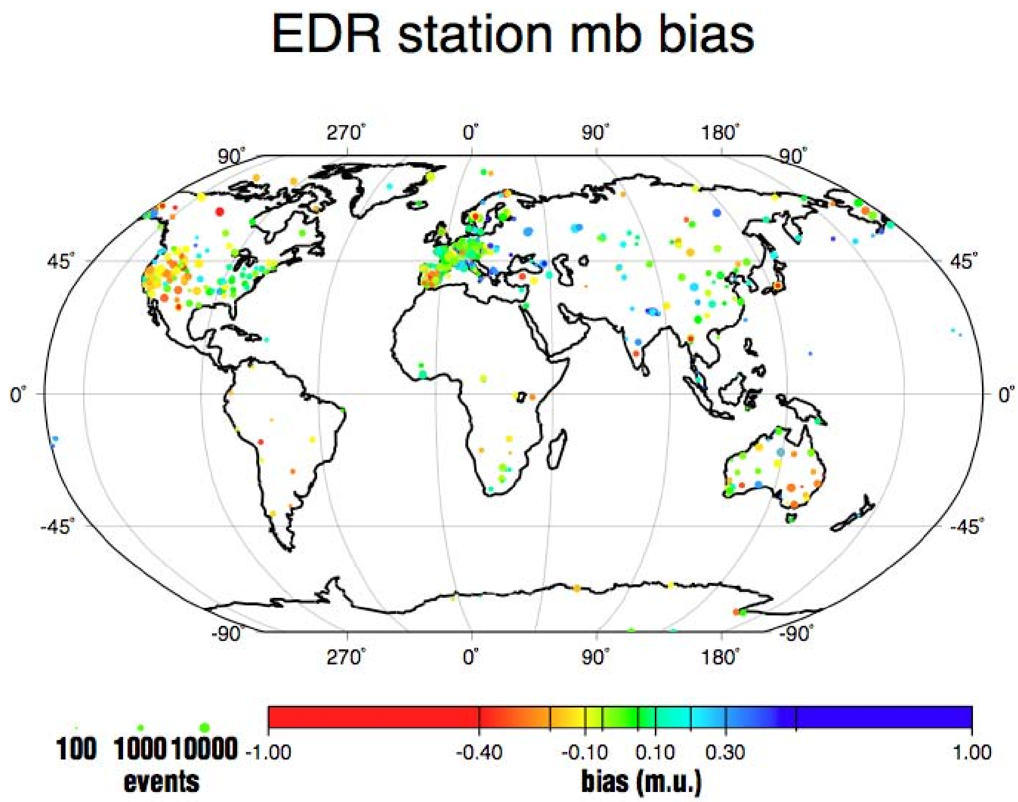

Figure 1. EDR station mb bias.

In general, expected features are present. For example, the prominent difference in bias between the eastern and western US is readily apparent. Several other areas of thin crust or active tectonics also show up with negative relative bias. And ocean island stations show large relative positive bias. However, a significant amount of scatter is also present, as is evident in some cases showing widely differing biases between nearly co-located stations. In particular, some of the large seismic arrays used by the Prototype International Data Center (PIDC) stand out relative to nearby stations. It is known that the USGS, in the past, has used available amplitudes, particularly from the PIDC, as mb amplitude measures, but they were unaware that these were not mb amplitudes. This may have the effect of seriously contaminating the EDR dataset and making it unsuitable for this kind of study without careful evaluation and editing. Indeed, a preliminary look at station residuals as a function of time indicates significant time dependence, but much more work would be needed to make such investigations conclusive. Nevertheless, the established bias at the Nevada Test Site (NTS) relative to Semipalatinsk is well reproduced, which is important for moving forward.

To avoid the question of inappropriate or inconsistently determined station magnitudes, we turn to the Reviewed Event Bulletin (REB) published by the PIDC and IDC. These station magnitudes are determined using a different algorithm from the USGS, but are very consistent. For this dataset, we use the REB from January 1995–May 2007. Given the relative consistency, and the smaller number of stations, we start with an initial limit of 100 events per station and 5 stations per event, and repeat the limit of 30 to 100 degrees in range and 50 km in depth. We revise the mb range to a minimum of 4.4 and a maximum of 5.8, which is more appropriate to this dataset, and eliminates approximately 5% of the of the dataset, as the narrower limit did for the EDR. This results in 158 stations, 15,593 events, and 249,506 station mbs for the inversion. The outlier limit of 1 magnitude unit is again applied, and then the inversion is done the same as for the EDR. The results are shown in Figure 2.

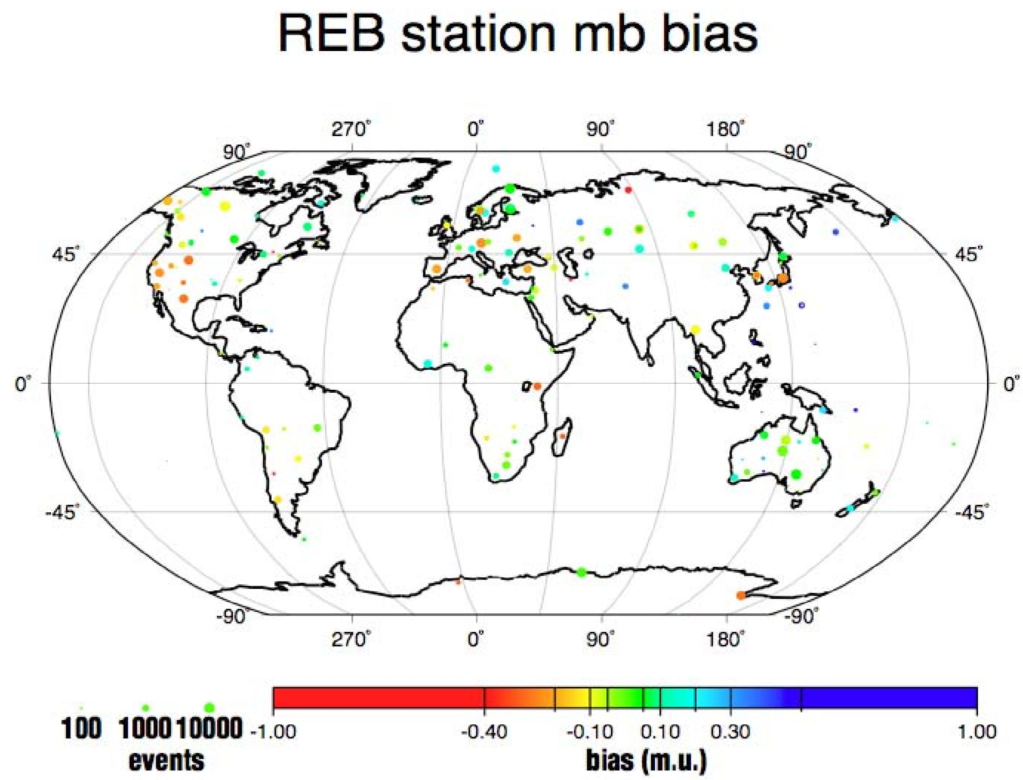

Figure 2. REB station mb bias.

The result for the REB station inversion is grossly similar to that for the EDR inversion, but with many fewer points (the REB uses a very restricted set of stations relative to the EDR). However, there is some evidence of improved consistency, particularly in Australia, which now is quite uniform and similar to other shield areas. This supports the inference above that a carefully vetted dataset extracted from the EDR could be as consistent. Such careful QC of EDR-reported station mbs could also allow the conservative limits on numbers of events and stations to be relaxed, greatly increasing the density of results.

We are interested in what station bias might reveal regarding magnitude bias in the vicinity of Korea. We acquired two PASSCAL datasets in the vicinity of Korea. One is the SUNY Binghamton northeast China project (1998–1999, 19 stations) and the other is Lamont’s Sinpo site survey within North Korea (1995–1996, 3 stations). The Sinpo data should prove quite valuable for further studies of North Korea, see Figures 3 and 4. The northeast China dataset is also quite interesting and includes several regional chemical explosions that were done as part of the experiment. We have the full continuous data from all 22 stations. We select a number of events from global catalogs (EDR and REB, along with others) that would be at teleseismic range from these stations (30–100 degrees) and of sufficient magnitude to be well recorded. For this initial survey of the bias problem, we analyze data from three of the stations: one from the Sinpo dataset, HMP (Figure 3), and two from the northeast China dataset, FROG and CBAI. Teleseismic P for the selected events is then manually picked at each of these stations (Figure 4).

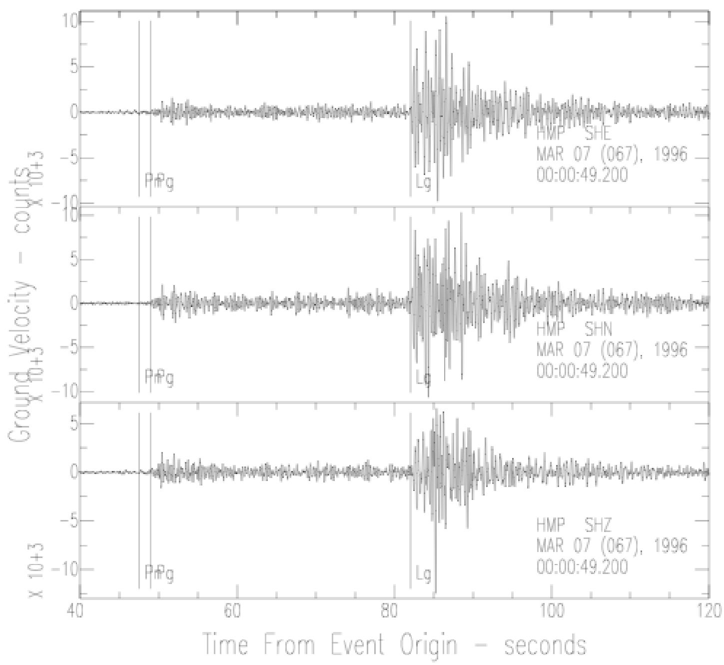

Figure 3. Regional earthquake recorded at Sinpo station HMP in North Korea.

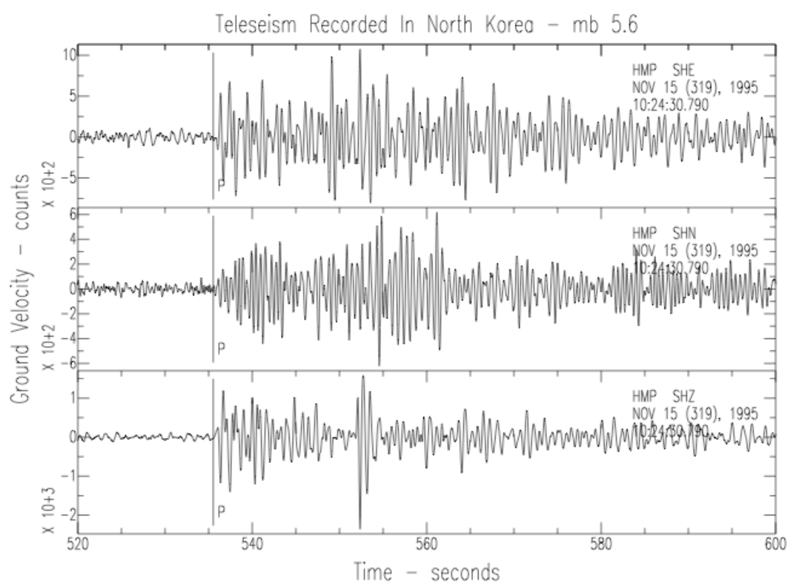

Figure 4. Teleseismic earthquake recorded at Sinpo station HMP in North Korea.

To use data from the PASSCAL studies in a global station magnitude inversion, we need to reproduce, as precisely and accurately as possible, the computation of station mb performed for a global bulletin. We select the USGS EDR primarily due to its greater number of stations. However, reproduction of the determination of station mbs for this bulletin is not a trivial exercise, and the development of this capability is important. Using available documentation (Dewey, et al., 2003, 2004) and a paper that attempted a similar reproduction (Granville, et al., 2005), we are able to reconstruct the EDR mbs reported at station MDJ in eastern China for a large number of teleseisms, and to within

+/- 0.1 magnitude units, which is the precision to which station mb is typically reported (see Figure 5). The steps in the algorithm we use to reproduce the EDR results are the following:

1. Select a segment of the vertical component from about 60 seconds before P to about 200 seconds after;
2. Correct the segment for instrument response to displacement in nm;
3. Filter the segment using a 1.05–2.65 Hz 2-pole Butterworth filter followed by a 0.5-6.5 Hz 2-pole Butterworth filter;
4. Select a window beginning at the P pick and extending 15 seconds into the P waveform;
5. Examine the large window for the maximum peak-to-trough amplitude, using a sliding window of 1.25 seconds;
6. Record half the maximum peak-to-trough amplitude and twice the time in seconds between the positive and negative extrema as the period;
7. Apply a correction to the observed amplitude which accounts for the amplitude attenuation introduced by the bandpass filters; and
8. Compute station mb, restricting the computation to signal-to-noise ratio > 2, using the Gutenburg-Richter formula for mb, along with the station-event distance and the Gutenburg-Richter attenuation correction.

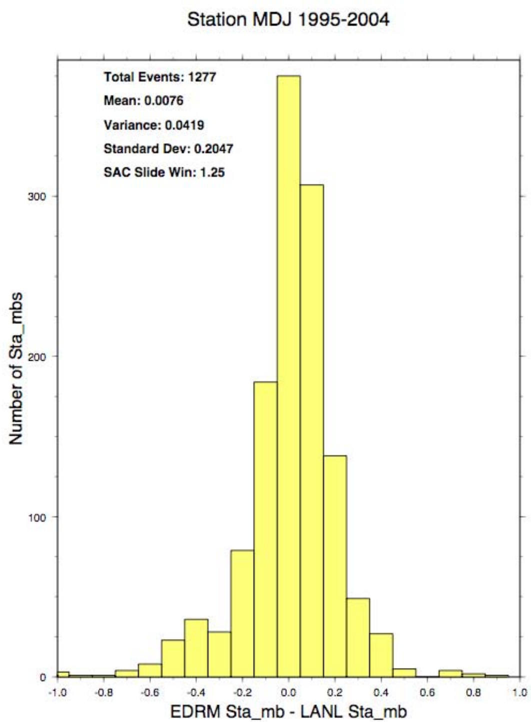

Figure 5. Histogram of station mb measurements differences at MDJ between those reported in the EDR and those computed here.

We apply this algorithm to the selected stations and record the station mbs. A cursory examination of these shows that CBAI has a strong bias for all results of nearly 1 magnitude unit, indicating an error in instrument response. We eliminate the station rather than attempt to determine the source of the error. We add the FROG and HMP data to the EDR dataset used for Figure 1, and re-invert. The results are shown in Figure 6. The dataset must be culled in a similar way to the original EDR selection, resulting in a loss of about half of the results.

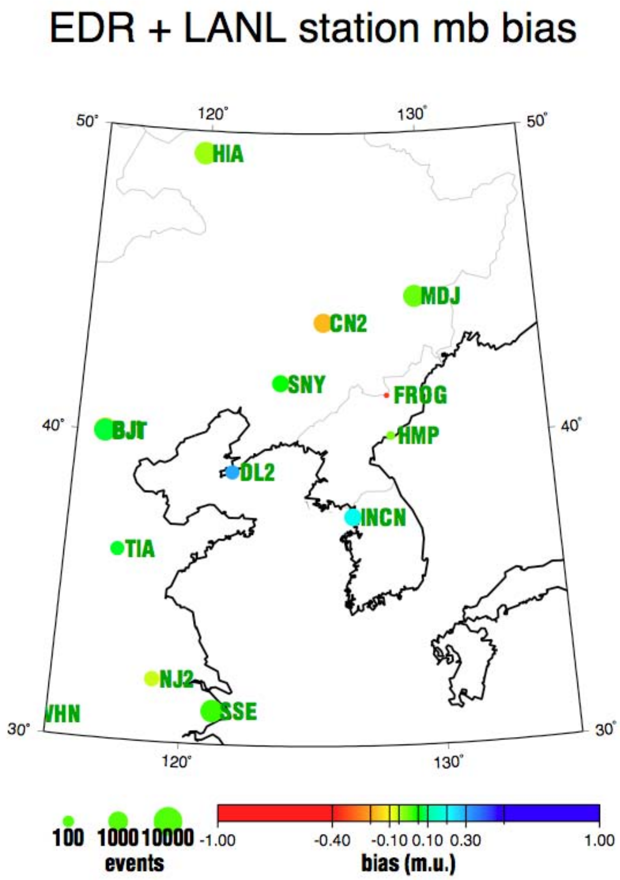

Figure 6. EDR station mb bias, with addition of stations FROG and HMP.

The remaining station mb values at HMP are sufficient, but those at FROG are very limited, and so FROG is probably undetermined. Interestingly, the results at HMP indicate that the station bias is somewhat shield-like, but it must be recognized that this result is highly preliminary and careful work is needed to improve the overall result. Clearly, the variation shown at DL2 and possibly CN2 from the EDR is too extreme, with stations like BJT/BJI showing different bias while nearly co-located are probably contaminated by bad station mbs, etc.

Use of Independent Regional Measures to Determine Bias

We now turn to the use of regional data as an independent estimate of event size, for a means of examining event bias. We select coda moment magnitudes (Mw) for this purpose. We have a large number of network coda Mw measurement available for Asia.

We first investigate the EDR network mbs. We select events that have both a coda Mw and a network mb from a global bulletin, subtract the two, and then use a Kriging algorithm (Schultz, et al., 1998) to produce a map of event bias. In this case we allow a larger range of mb than in the station inversion above, permitting a range of 3.8 to 5.8, and we allow somewhat greater depth, down to 100 km. This is necessary to keep the number of events sufficiently large for good kriging statistics, but knowing that kriging is robust against outliers. The total number of events is 6,417. We remove the mean, then decluster the data to a grid cell size of 1 degree, and then krig on the GRS-80 ellipsoidal earth, using an isotropic exponential blending function with a range of 10 degrees and a background variance of 0.4 and a non-bias constraint. The result is shown in Figure 7. The fine contours are 0.05 magnitude units of bias, the heavy contour is the limit of resolution at 0.2. Small circles are the events used. While the kriging algorithm ignores continental boundaries, we plot only the results within those boundaries, since the ocean basins generally do not produce accurate coda results. We restrict the range of bias plotted to between -0.5 and +0.4 to maintain a good range of color. Those regions outside this range are plotted in magenta.

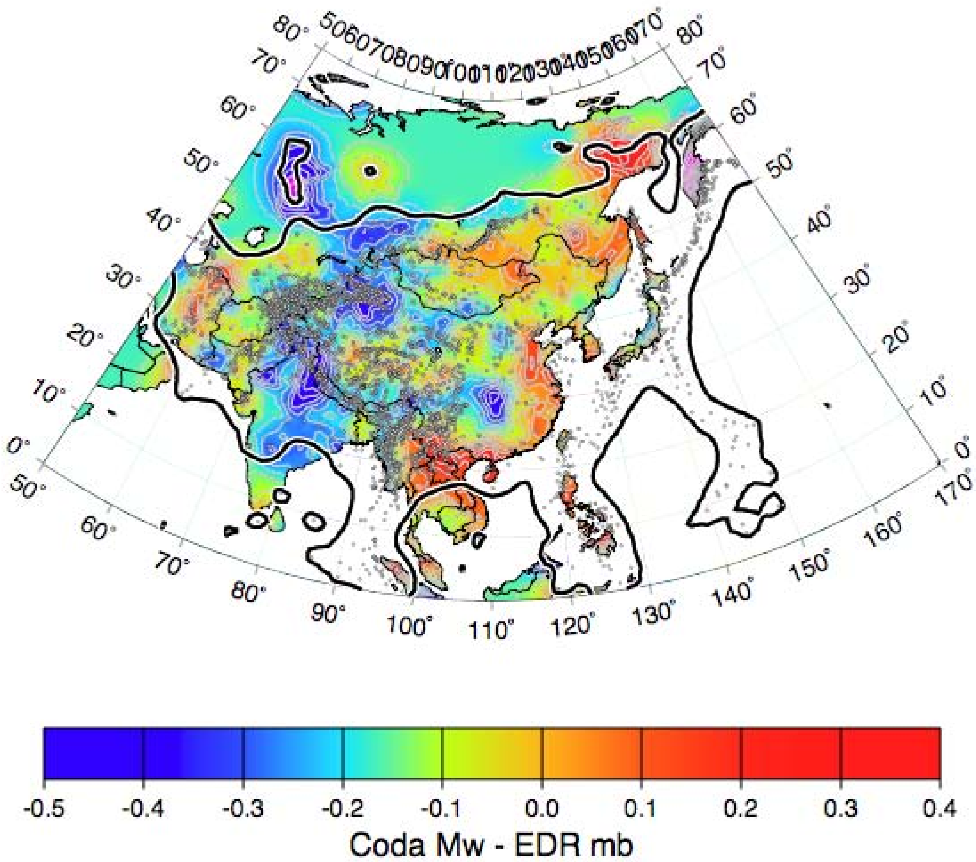

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Figure 7. Kriged EDR mb bias relative to coda Mw.

The figure shows striking correlations with crustal and tectonic features. The thin crust of China's southern and eastern seaboard shows up as having relatively positive bias (Mw > mb), as do some areas of recent tectonic activity such as the central tectonic regions of Iran, and the region around Bhuj in India. These regions would be expected to have relatively high attenuation in the lower crust and upper mantle, consistent with relatively low mbs (more NTS-like). Stable continental regions have a relatively negative bias (mb > Mw), such as the interior of India and north-central Asia. Significant tectonic basins are relatively negative (Sichuan, Ordos, and Tarim basins). The lithosphere tends to be thick under these basins, possibly resulting in lower attenuation in the lower crust and upper mantle, resulting in relatively high mbs (more Semipalatinsk-like). The region around North Korea is interesting, showing a strong gradient from positive in the southwest to negative in the northeast. This is currently controlled by a rather small number of events, but may indicate some complexity in bias in this region, perhaps controlled by crustal thickness or the distribution of recent volcanism. The fact that Punggye would be in the region of relatively low attenuation (high mb) is interesting but certainly not conclusive at this point. The large variation in Iran is also a concern for further investigation. However, the overall strong correlation with tectonics across Asia indicates that this is a promising direction for further study.

Knowing that EDR mbs may have some issues, we proceed with REB mbs. Using the exact same selection criteria as used for the EDR study, and the exact same kriging parameters, we select 6,190 events and present the result in Figure 8.

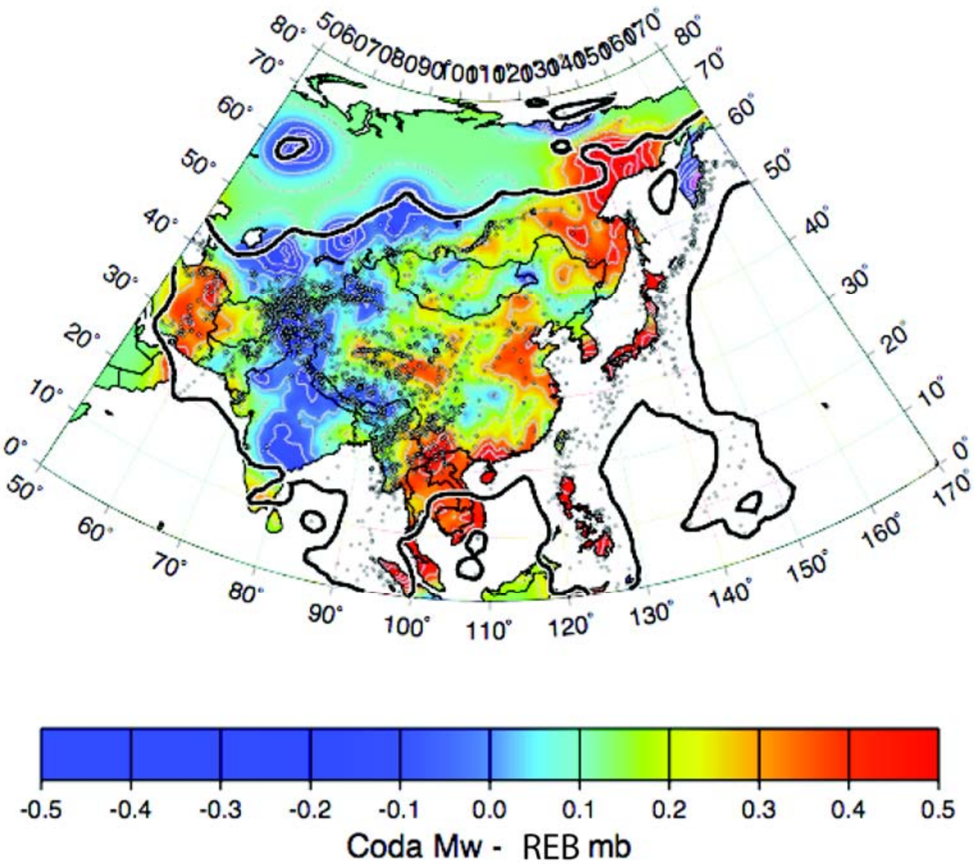

Figure 8. Kriged REB mb bias relative to coda Mw.

The resulting pattern is quite similar to the EDR result, but not identical. The coast of China appears negative again, as does central Iran and Bhuj. Central India, north-central Asia, the Sichuan basin and the Tarim basin are again negative. The Ordos basin is almost absent here relative to the EDR result, and the Sichuan basin is greatly diminished. This is undoubtedly due to the subset of stations used for the REB, which may be having some bias effect on the resulting network mbs. The gradient in the vicinity of North Korea appears to be a robust feature of both the EDR and REB mbs. It appears from the figures that the combination of network averaging of the station mbs by the bulletin authors, and the kriging is robust against any problems in individual station mbs in the EDR bulletin.

CONCLUSIONS AND RECOMMENDATIONS

The results shown from this brief exploration of the mb bias problem indicate a number of promising directions for further work.

1. The station bias method shows excellent promise both to determine broad regional mb bias and mb bias at particular sites where stations exist. There are several aspects of this method to pursue:
   a) The station mbs should be studied, particularly as a function of time, to identify anomalous periods that can then be eliminated from the inversion.
   b) AFTAC station mbs should be used in an inversion similar to the EDR and REB inversions presented.
   c) The algorithms for AFTAC's and the REB's station mbs should be reproduced to the extent possible and applied to stations not represented in those bulletins, particularly the PASSCAL datasets used herein.
   d) Direct RMS amplitude measurements within narrow frequency bands and at a large number of global stations should be pursued, since these should be more stable than comparatively rough mb amplitude measures. In addition, the inversion can be extended in this case to simultaneously operate in multiple bands with the constraint that the amplitude as a function of frequency be linear (that is, that it is directly modeled as t*). A significant advantage to such an inversion is that t* might be directly determined at events as well as at stations.

2. The Mw bias method also shows excellent promise of determining good, regional maps of mb bias. Such maps might be useful for predicting bias in regions without events. There are again several aspects to pursue:
   a) Further constraints on event selection to improve stability and resolution.
   b) Re-computation of network mbs from station mbs, but with strong selection criteria on the station mbs, such as those discussed above.
   c) Use the map to predict station bias, and compare that to the results of the station bias study. Also, use it to correct station mbs before re-computing network mbs for use in the kriging.
   d) Explore the space of kriging parameters to see where the results are truly stable.

3. Investigate other independent constraints on event size, such as Nuttli's mbLg in place of coda Mw.

4. There is no reason to restrict the study to mb, other magnitude measures (Ms, for example), may show evidence of bias and should be explored.

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REFERENCES

Dewey, J. W., P. S. Earle, and B. W. Presgrave (2003). Four decades of PDE mb, *SRL* 74: 2, 249.

Dewey, J. W., P. S. Earle, and B. W. Presgrave (2004). Quantifying year-to-year drifts in PDE mb and explaining their causes, *SRL* 75: 2, 275.

Granville, J. P., P. G. Richards, W.Y. Kim, and L.R. Sykes (2005). Understanding the differences between three teleseismic mb scales, *BSSA*, 95: 5, 1809–1824.

Schultz, C. A., S.C. Myers, J. Hipp, and C.J. Young (1998). Nonstationary Bayesian kriging: a predictive technique to generate spatial corrections for seismic detection, location and identification, *BSSA* 88: 1275–1288.