REGIONAL CODA MAGNITUDES IN CENTRAL ASIA

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ABSTRACT

Coda waves are known to be influenced less by path and radiation effects than are direct waves, especially for local earthquakes. This is attributed to the averaging effects of the scattered waves that make up the coda. Furthermore, the duration of coda allows multiple independent measurements to be taken. Thus, coda potentially provide high-precision estimates of source size such as magnitude and moment, with less path bias than direct waves. For purposes of nuclear explosion monitoring, we investigated the use of L_g coda to estimate magnitude at regional distances in central Asia. To do this, we processed coda data for over 3000 recordings made at stations MAKZ, WMQ and LZH. The study area is geologically heterogeneous, and includes Tibet, the Tarim basin, the Tian Shan and platform regions to the north. In tests using 1-Hz data, the scatter between coda amplitude levels obtained from stations WMQ and MAK measured 0.12 (standard deviation in the $\log_{10}$ domain). This is over a factor of 2 lower than the scatter observed for direct L_g. However, in this region, bias enters the coda magnitudes through the effects of lapse time and path. The lapse time bias enters through the inability of standard curves to fit coda decay over long time intervals. We reduce this effect by limiting coda lengths to between 30 and 150 s following the L_g arrival. Coda also showed path dependence similar to direct L_g. We corrected for this using an interpolation (kriging) method. Corrections for lapse time and path had little effect on inter-station scatter because these effects were correlated between stations. We conclude that the early coda yields a more precise measure of event size than does direct L_g, but coda results must still be corrected for path effects in this heterogeneous region.

Key Words: magnitude, regional monitoring, coda.

OBJECTIVES

Monitoring requires reliable moment and magnitude estimates for small events that may only have been observed at a few stations. Here, we test the ability of coda methods to reliably estimate magnitude at regional distances in a geologically heterogeneous portion of central Asia. In particular, we examine non source-related effects on coda amplitudes, such as elapsed time and path, and suggest ways to eliminate them.

RESEARCH ACCOMPLISHED

The stability of coda, with respect to path, has been well documented at local distances. The stability, or uniform coda shape, is consistent with the model of coda as the superposition of waves backscattered from random heterogeneities in the earth's crust and upper mantle (Aki, 1969). Thus, coda reflect path-averaged properties of a given region. The coda stability allows the isolation of relative, radiation-pattern averaged source effects apart from site and path effects. The numerous independent measurements that can be made in the coda result in a high precision, allowing a single station to yield results comparable to a network average. These techniques were combined with an empirical Green's function method to estimate absolute source spectra and study source scaling using data from analog, "spectral analyzing" seismographs (Aki and Chouet, 1975; Chouet et al., 1978; Rautian and Khalturin, 1978; Tsujiura, 1978). In addition, coda duration was found to give stable magnitude estimates (Bisztricsany, 1958) and its use has become widespread in local earthquake network operations. Furthermore, Aki (1980) proposed the use of coda amplitudes, rather than duration, to obtain higher precision magnitude estimates.

Coda methods are successful with dense network, local earthquake data sets because the late, or path-averaged, portion of the coda generally exceeds background noise levels and is readily available for study. The late coda is loosely defined to begin at twice the S-arrival time (Rautian and Khalturin, 1978), taken from observations of the point at which coda shapes begin to coalesce. This poses a problem for the use of coda at regional distances because less data are available at twice the S (or L_g) arrival, so sufficient path averaging may or may not have occurred to make coda useful for estimating source spectra. However, Mayeda (1993) showed that magnitudes of NTS explosions based on regional L_g coda were a factor of 5 more consistent between stations than were magnitudes based on direct L_g. Hartse et al. (1995) demonstrated that spectral ratio discriminants were effective using far local to near regional coda data from NTS explosions and nearby earthquakes. Finally, Mayeda and Walter (1996), showed that the empirical Green's function technique could be used to obtain absolute spectra and study source character using regional coda from western U.S. earthquakes and explosions.

In this study, we apply coda techniques to regional distance, central Asia events recorded at stations MAKZ, WMQ and LZH (Figure 1). We hoped to confirm the stability of coda in this region, or, if not, to work out ways to correct the results so that reliable magnitude estimates can be obtained. To do this, we processed over 3000 records from these stations, obtaining coda decay curves in bands from 20 s to 6 Hz (Figure 1). Here, we present results of analyzing vertical component data in the band 0.7 to 1 Hz.

To calibrate the coda, we follow the method of Mayeda et al., (2000). First, coda decay, b, is determined as a function of distance, Δ,

$$A(t)=A_0\ t^{-0.83} \exp -b(\Delta)t,$$

via a linear fit (Figure 2). We then obtain coda source factors (A_0) by re-fitting the coda decay data with the predicted b(Δ). The coda source factors are further corrected based on a linear fit of A_0-m_b (PDE) versus distance (Figure 2). Looking for trends in the coda source factors after subtracting an estimate of source size is the technique we will later use to examine other possible effects on the coda. The distance-corrected coda source factors can be converted to magnitude by another linear fit. We plot the raw, distance-corrected coda source factors for events common to MAKZ and WMQ in Figure 3, along with m_b estimates derived from direct L_g. The inter-station scatter of the coda measurement is a factor of 2 lower than that of L_g. The improvement from coda is not as dramatic as in the western U.S. results of Mayeda (1993); however central Asia is one of the most heterogeneous regions on earth, which may present difficulty to the coda method.

We searched for other effects on the coda in this data set. First, we found that the coda length influences the coda source factors (Figure 4) in a way that is consistent with the well-known lapse time effect (Roecker et al., 1982). Coda decay generally does not fit the single scattering model, on which our fitting equation is based, over long time intervals. The coda decays more quickly early on and more slowly, later, which can be due to penetration to higher Q depths (for S coda) or to multiple scattering. This results in a curve-fitting problem and overestimation of coda source factors for long codas. This effect can be corrected for, but the resulting inter-station consistency does not improve (Figure 4). The lack of improvement occurs because corrections are correlated between stations, as shown by stick and histogram diagrams. We address this problem by limiting coda lengths to 30 to 150 s following the L_g arrival in the remainder of the study.

Because we measure the coda so close to the L_g arrival, we might expect path effects to be present in the results. To examine this, we interpolate distance-corrected coda source factors after subtracting m_b (PDE) using kriging (Schultz et al., 1998), (Figure 5). Results show strong laterally varying effects that correlate well with known L_g path effects in this region (Phillips, 1999). Again, these effects can be corrected, but we obtain little improvement in inter-station consistency due to correlated adjustments (Figure 6). To compare coda and direct L_g on the same basis, kriged corrections were generated and applied to the direct L_g results, which show improved inter-station consistency (Figure 6). The path-corrected coda results are now less than a factor of 2 more consistent than those of direct L_g.

Results for events common to WMQ and LZH show higher levels of scatter (Figure 6). After path correction, these coda results are only slightly more consistent than those of direct L_g.

CONCLUSIONS AND RECOMMENDATIONS

Coda estimates show up to a factor of 2 improvement in inter-station consistency relative to direct L_g. This is more likely the result of a higher precision coda estimate, which employs multiple, independent measurements. Path effects are not eliminated in regional coda as well as for local coda. Such path effects can be corrected for using interpolation methods in the same manner as has been previously demonstrated for direct waves. Coda lengths also introduce bias through deficiencies of the fitting equation in light of the lapse time effect on coda decay. This can be accounted for by a more general fitting equation or by limiting the coda interval. The inter-station consistency is often used to demonstrate the ability of coda methods; however, the biases we find are correlated between stations and, thus, have little effect on consistency. Comparing coda results to independently derived moments (Mayeda et al., 2000) is a more effective way to demonstrate the power of coda methods.

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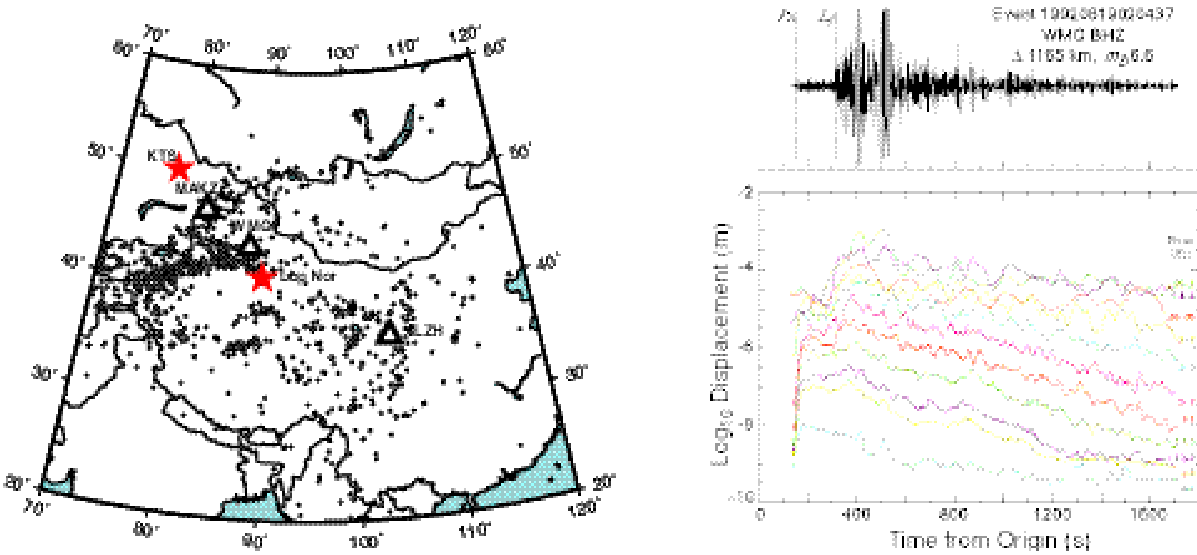

Figure 1. Map showing stations and events used in the study (left) and a sample event with coda decay curves in various bands (right). Energy arriving from a secondary event can be seen at 800 s, illustrating the high level of quality control that must be applied to coda data.

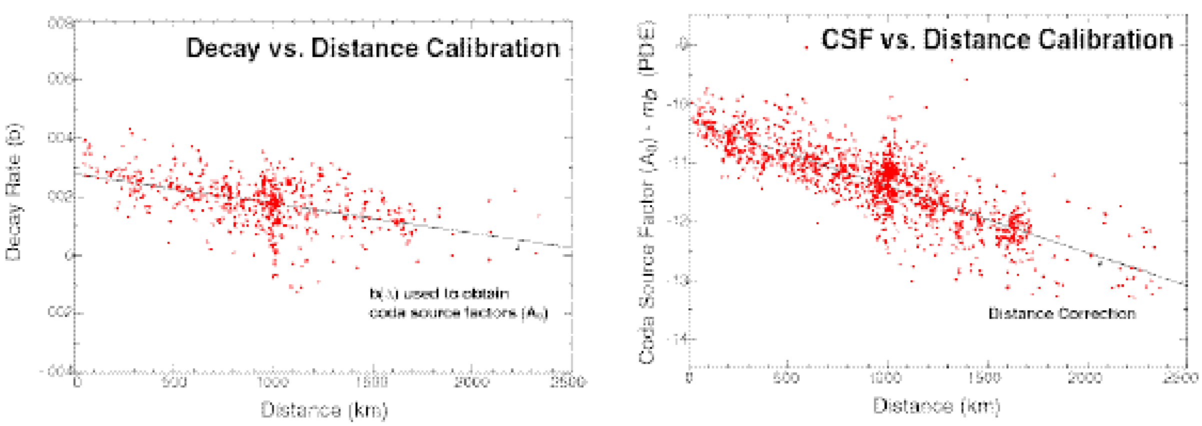

Figure 2. Calibration of 1 Hz band coda data from station WMQ. The temporal decay term is shown versus distance (left) along with a linear fit used to predict decay in the final fit. The fit amplitude or coda source factor is plotted versus distance (right) along with the linear fit used to correct for distance.

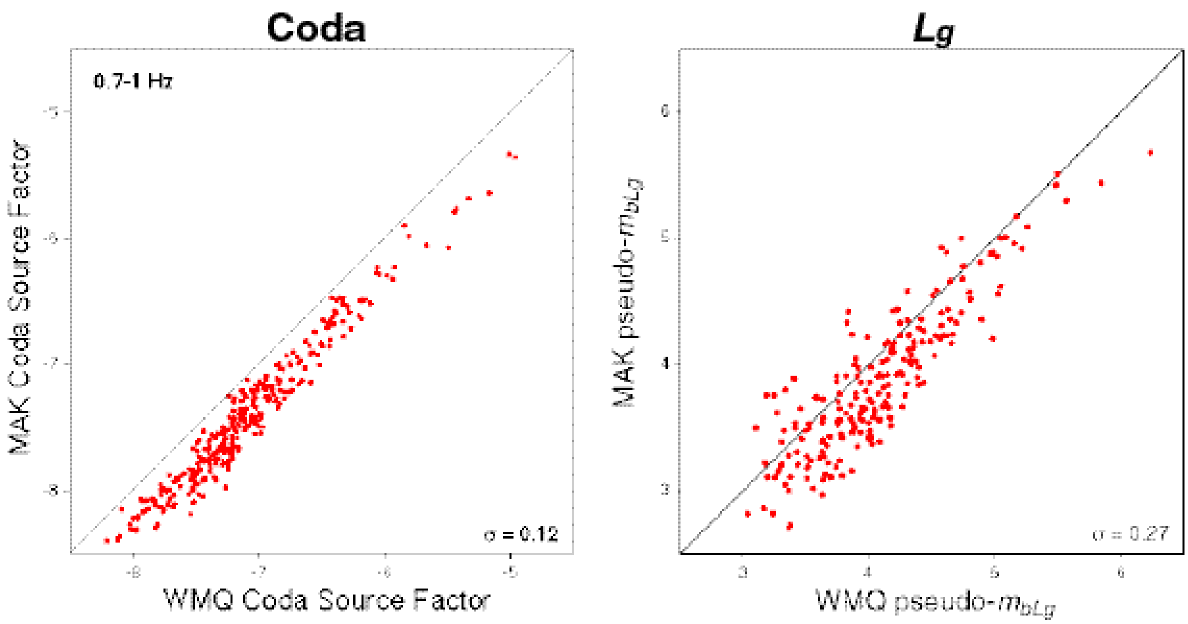

Figure 3. Distance-corrected, 1 Hz coda source factors (left) and m_{bLg} calculated using a Q of 400 (right) for events recorded at MAKZ and WMQ. The σ values give standard deviations of the differences between stations, representing the scatter around the mean offset, which is a site effect. Pseudo refers to slight processing differences from traditional m_{bLg}.

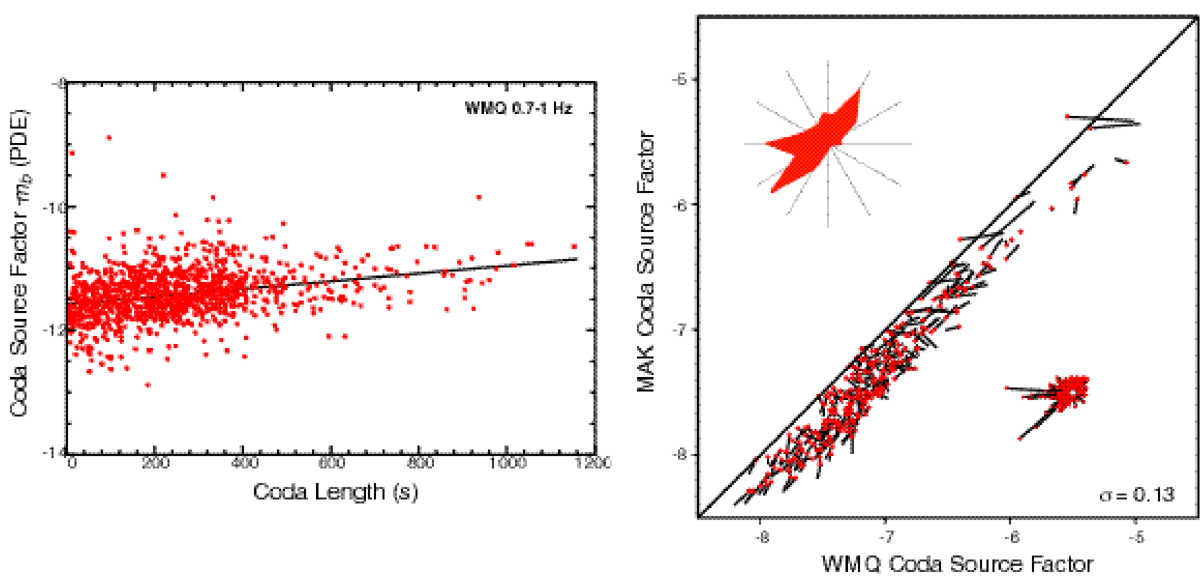

Figure 4. The effect of coda length on distance-corrected coda source factors (left) and corrected values for events recorded at MAKZ and WMQ (right). Open circles represent original values and red dots represent corrected values in the right hand plot. Stick and rose diagrams show that the corrections are somewhat correlated between stations.

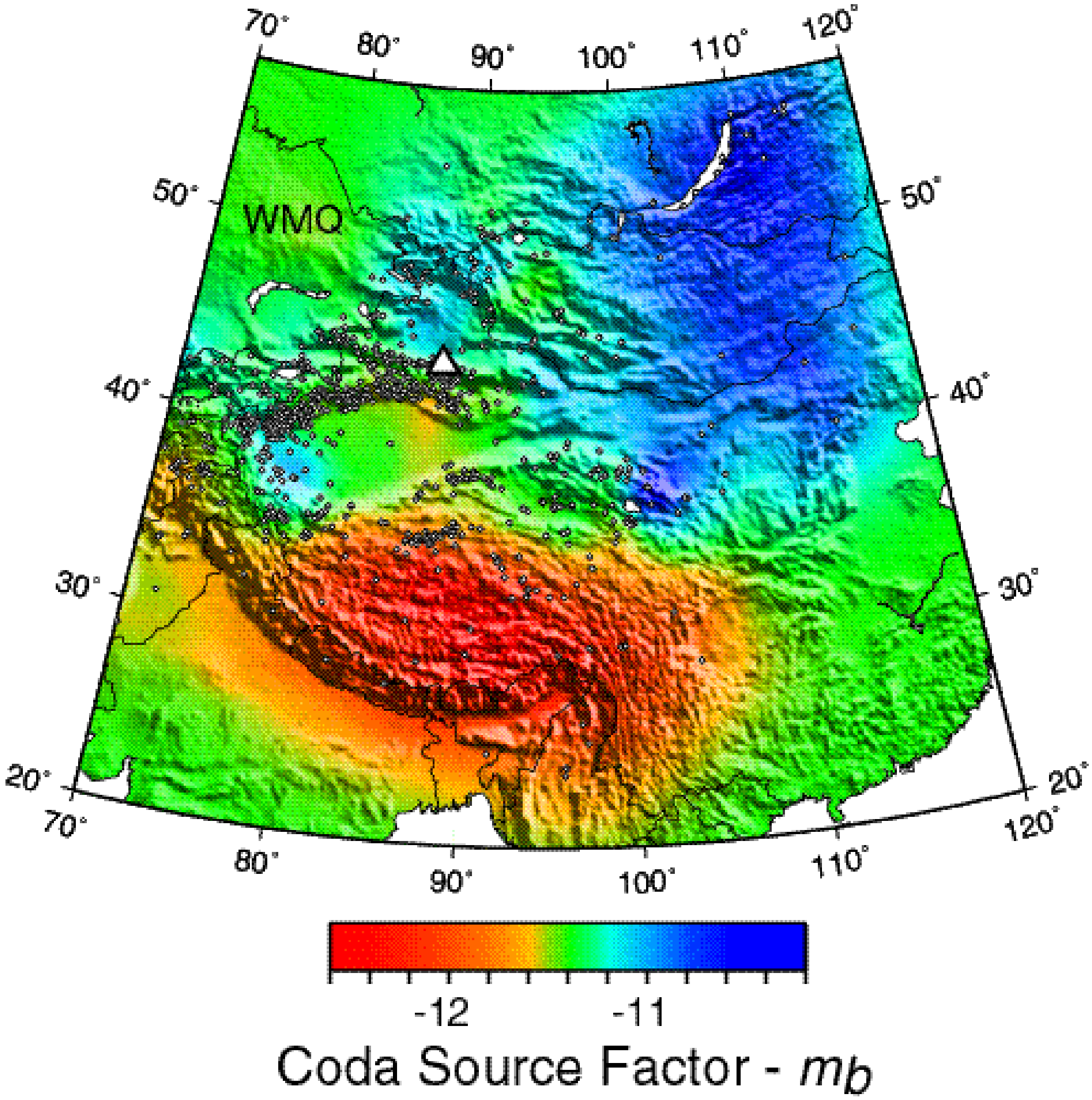

Figure 5. Interpolated (kriged) coda source factors for WMQ, less m_b (PDE), representing path effects on the L_g coda. Events used in the interpolation are shown as open circles. A mean value (green) is indicated in areas where events do not exist. For a particular event, the path correction is calculated by kriging without including that event.

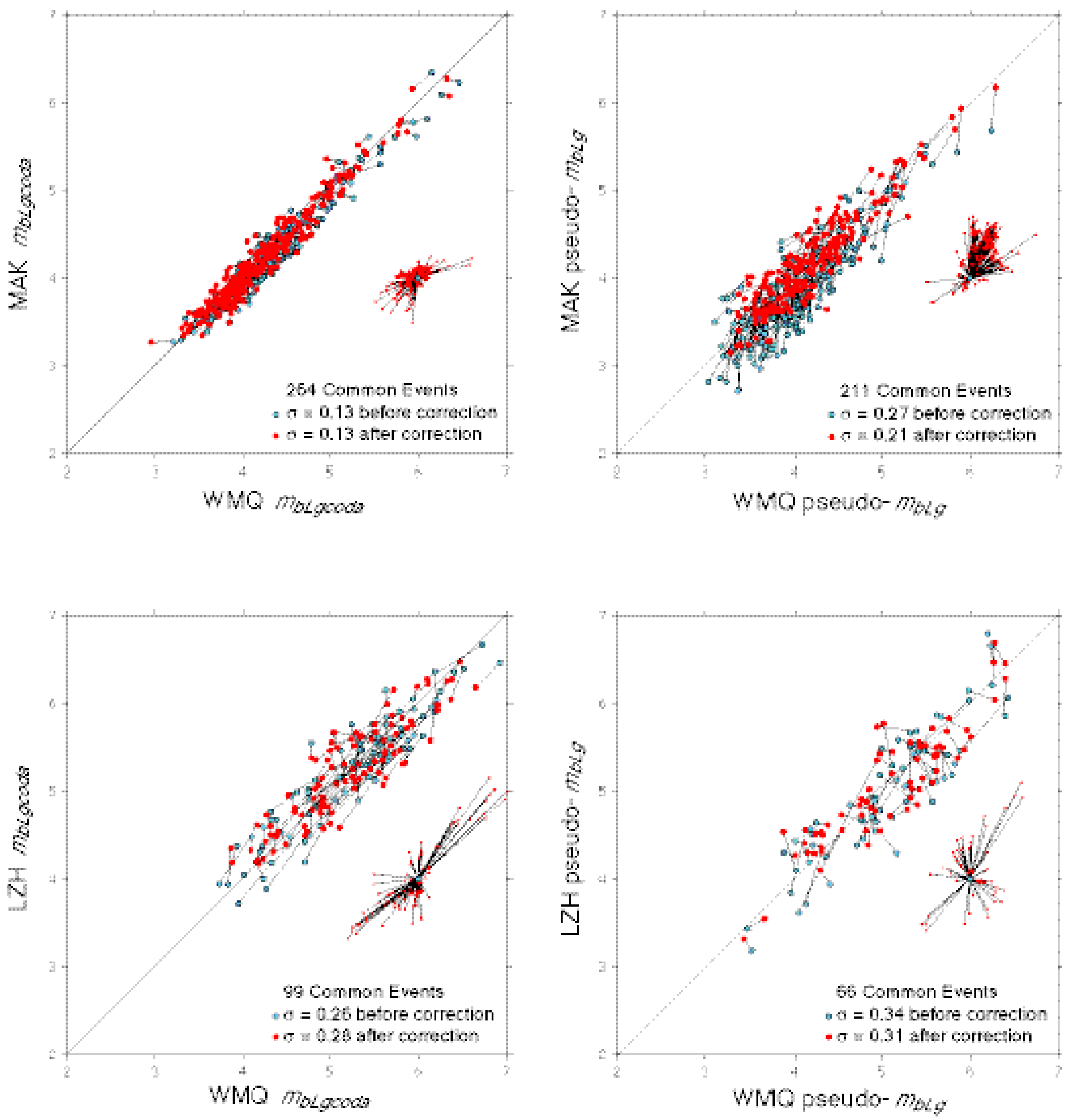

Figure 6. Path correction applied to coda (left) and m_{bLg} (right) for events common to MAKZ and WMQ (top) and LZH and WMQ (bottom). Blue dots represent original values and red dots represent corrected values. Stick diagrams summarize the corrections. Values have been tied to PDE m_b. Site offsets have been removed by the tie to m_b.