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Reply to Comment by R. A. W. Haddon on "Evaluation of Models for Earthquake Source Spectra in Eastern North America" by Gail M. Atkinson and David M. Boore

by Gail M. Atkinson and David M. Boore

In his comment, Haddon attempts to refute the conclusions of our 1998 article, in which we evaluated proposed source models for eastern North America (ENA). We used a clearly defined procedure based on the well-known stochastic model to make ground-motion predictions based on each proposed source model, and then we compared the predicted motions with all recorded ENA data of **M** > 4. Haddon's objections to the stochastic approach, and more specifically to one of the evaluated source models (ours), are based on his theoretical interpretations. We disagree with almost all of Haddon's opinions and the manner in which he has expressed them. However we think that little will be gained by replying in detail. The technical details of our disagreement have already been discussed at some length (Atkinson *et al.,* 1997; Haddon, 1997). So rather than providing a blow-by-blow rebuttal, we limit our reply to the following salient remarks.

Seismology is an observational science, wherein the validity of proposed ground-motion models is judged empirically, based on their ability to predict observed ground-motion data. The stochastic ground-motion model is a simple tool that combines a good deal of empiricism with a little seismology, and yet has been as successful as more sophisticated methods in predicting ground-motion amplitudes over a broad range of magnitudes, distances, frequencies and tectonic environments (e.g., Atkinson and Somerville, 1994; Hartzell *et al.,* 1999). Many find this surprising; some find it infuriating.

Widespread interest in the stochastic model was aroused when McGuire and Hanks (1980), Hanks and McGuire (1981), Boore (1983), and McGuire *et al.* (1984) demonstrated that a very simple stochastic model predicted high-frequency ground-motion amplitudes in California surprisingly well. Subsequently, Atkinson (1984), Boore and Atkinson (1987), Toro and McGuire (1987), and Ou and Herrmann (1990) showed that the model could be readily extended to the data-poor eastern North America (ENA) region. The stochastic model has since been widely examined and used, not just in ENA but also in California (e.g., Joyner, 1984; Joyner and Boore, 1988; Silva and Green, 1989; Silva *et al.,* 1990; Chin and Aki, 1991; Boore *et al.,* 1992; Silva and Darragh, 1995).

Subsequent refinements to the stochastic prediction methodology included the modeling of finite-fault effects, which cause an intermediate spectral 'sag' relative to the spectrum of an ω^2 (i.e., single-corner) point-source (Beresnev and Atkinson, 1999; Atkinson and Silva, 1997, 2000). These effects are well understood and can be modeled in a simple way by using a two-corner source spectrum. The spectral shape has nothing to do with Haddon's "Rg spectral humps" or any other distant phases, but is a direct consequence of propagation of a point source along a finite fault, as demonstrated by Beresnev and Atkinson (1999) and Atkinson and Silva (1997, 2000); it is important at both near and far distances. Haddon's theoretical interpretations, to the effect that the model should result in "errors of up to about an order of magnitude in ground-motion estimates", is in stark contrast with actual computed errors, not only from distant vertical-component ENA data (Atkinson and Boore, 1995, 1998; Beresnev and Atkinson, 1999), but also from near-source horizontal-component California data. Atkinson and Silva (2000) applied the stochastic method to California, using a theoretical two-corner source model derived from a propagating point-source and attenuation and duration parameters obtained from analysis of small-magnitude seismographic recordings (Raoof *et al.,* 1999); all input parameters were obtained independent of the strong-motion database. Atkinson and Silva show, based on hundreds of strong-motion recordings, that two-corner stochastic estimates of horizontal-component ground motions are accurate to within 20% on average, for earthquakes of **M** 6.5 to 7.4, at distances from 1 to 50 km of the fault, and for frequencies from 0.2 to 10 Hz. This covers the magnitude, distance, and frequency range of most engineering interest and addresses Haddon's stated concerns for public safety more directly than does any number of theoretical arguments.

The stochastic method has also been useful in a variety of other tectonic environments, including Mexico (Beresnev and Atkinson, 1998b; Singh et al., 1989), the Cascadia region (Silva *et al.,* 1991; Atkinson and Boore, 1997), Greece (Margaris and Boore, 1998), Russia (Sokolov, 1997) and Italy (Rovelli *et al.,* 1991, 1994; Berardi *et al.,* 1999). It is widely used in ENA, not only by us but by others (Toro and McGuire, 1987; Toro *et al.,* 1997; Frankel *et al.,* 1996; Wen and Wu, 2000). Haddon's concern that our high-frequency amplitudes are underestimated for large events is apparently restricted to our article, yet we actually predict larger high-frequency amplitudes and peak ground accelerations than those of the alternative stochastic models in common use, namely those of Toro *et al.,* 1997 and Frankel *et al.,* 1996 (Atkinson and Boore, 1997b, 1998).

As Haddon notes, many of the implications of differing source models are apparent without actually using the stochastic model to make ground-motion predictions. Where the ground-motion predictions are useful is in facilitating comparisons with actual data, both from ENA and other regions. It is interesting and significant that the Haddon source model, as implemented in our stochastic formulation, reproduces the Saguenay ground-motion data better than any of the other source models, but overpredicts most of the other data. Our two-corner source model, by contrast, underpredicts the Saguenay motions, while reproducing motions from other ENA events and from events in more data-rich regions such as California. To a large extent, then, the essence of the debate is the question of whether (a) Saguenay was a typical ENA earthquake, and all other data are irrelevant; or (b) the Saguenay ground motions were one to two standard deviations above the median, in relation to other relevant ENA data. This question has been discussed at some length in previous papers (Boore and Atkinson, 1992; Atkinson, 1993; Atkinson and Boore, 1995, 1998; Atkinson *et al.,* 1997); the arguments will not be repeated here.

Haddon has misunderstood the source model used by AB95 (Atkinson and Boore, 1995) in a number of ways. The behavior of the AB95 ENA source model at frequencies less than 1 Hz was determined by the source-duration estimates of Somerville *et al.* (1987), which were used to define the lower corner frequency (see Atkinson, 1993), not by Rg spectral amplitudes, as Haddon mistakenly believes. Subsequently, the role of finite-fault effects in controlling the spectral shape became apparent (Atkinson and Silva, 1997, 2000; Beresnev and Atkinson, 1999). Furthermore, the moment magnitude estimates used in our ground-motion predictions were not derived by us from our data, as Haddon contends, but are the independent determinations of others, based on conventional teleseismic techniques (see Boore and Atkinson, 1987, for references). It is true, though, that the moment estimates inferred by Atkinson and Chen (1997) from the regional spectral data agree with conventional moment estimates, which may be the reason for Haddon's misunderstanding on this point.

The underlying attenuation models that describe the overall decay of spectral amplitudes with distance, which Haddon suggests are "notions" that cannot be supported, have been independently derived by numerous investigators based on both empirical and theoretical wave-propagation techniques (Burger *et al.,* 1987; Ou and Herrmann, 1990; Campbell, 1991; Atkinson and Mereu, 1992; Boatwright, 1994; Raoof *et al.,* 1999). Detailed comparisons have shown that the stochastic approach, despite simplicity in the attenuation and duration model, provides ground-motion predictions that are as accurate as those based on more sophisticated approaches such as the ray-theory approach or the 3-D finite-difference method incorporating full theoretical elastic wave-propagation synthetics (Atkinson and Somerville, 1994; Beresnev and Atkinson, 1997, 1998a; Hartzell *et al.,* 1999).

We find the weight of evidence in support of the stochastic-model approach compelling, notwithstanding Haddon's assertion that, according to his interpretation of seismological principles, it ought not to work.

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