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Further information on the macroseismic field in the Balkan area

Reply on the comment of M.D.Trifunac on the paper 'The macroseismic field of the Balkan area' by C. Papazachos and Ch. Papaioannou

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Abstract

Papazachos and Papaioannou (1997) (called PP97 hereinafter) studied the macroseismic field in the Balkan area (Greece, Albania, former Yugoslavia, Bulgaria and western Turkey) with the purpose of deriving attenuation and scaling relations useful for seismic hazard assessment and study of historical earthquakes. In his comment, Trifunac suggests that our analysis might exhibit certain bias for all countries except Greece due to problems mainly associated with the database (completeness, etc.), conversion of local intensity scales used in the Balkan countries, as well as to the local variations of the attenuation relation due to the variation of the geotectonic environment in this area. Specifically, his most important comments can be summarized as follows:
a) The large participation of Greek data probably biased the scaling relations proposed in the study.
b) The conversion relations used between local macroseismic scales are less accurate than their proposed such relations.
c) The variation of attenuation (geometrical and anelastic) in different regions of the study area is important and local relations (instead of the proposed single relation) should be determined for seismic hazard assessment.

In the following, we study in detail each of these possible bias sources. Additional work on the macroseismic field of the Balkan area shows that none of the previously described factors, suggested by Trifunac, introduces bias in the results presented by PP97. Specifically, it is shown that the database used by PP97 fulfills the basic requirements for a reliable determinations of attenuation and scaling relations proper for seismic hazard assessment in all five countries of this area. Evidence is presented that no strong geographical variation of the attenuation of macroseismic intensities of shallow earthquakes is observed. Relations between local version of intensity scales suggested by Shebalin et al. (1974) are shown to be reliable. Finally, it is demonstrated that national practices for estimation of macroseismic intensities may affect the results of seismic hazard assessment but proper formulation can be applied (PP97) which allows to take into account such differences in national practices. This formulation allows also to introduce and correct for anisotropic radiation at the seismic source as well as the incorporation of site effects.

Attenuation and scaling relations for the Balkan area

Attenuation relations usually applied for geophysical or engineering purposes (attenuation structure, seismic hazard assessment, etc.) are of the Kovesligethy form

$$I - I_0 = n \log\sqrt{1 + \frac{\Delta^2}{h^2}} + c\left(\sqrt{\Delta^2 + h^2} - h\right), \quad (1)$$

where I is the macroseismic intensity at a distance Δ (in km) from the epicenter of the earthquake point source, I_0 the epicentral intensity, n the geometrical spreading factor, c the anelastic attenuation coefficient and h (in km) is the focal depth. Relations of the form

$$I - I_0 = c_1 \log(\Delta + c_2) + c_3, \quad (2)$$

where c_1, c_2, c_3 are parameters, are also frequently applied for engineering purposes (Cornell, 1968).

Papazachos (1992) modified Kovesligethy relation in order to take into consideration the anisotropic radiation at the seismic source, by considering isoseismals of about elliptical shape, and proposed the following relation:

$$I - I_{0_{\min}} = n \log \left(S^{1/2} \sqrt{1 + \frac{\Delta^2}{h^2}} \right) + $$
$$+ c \left(\sqrt{\Delta^2 + h^2} - h \right), \qquad (3)$$

where $I_{0_{\min}}$ defines the apparent epicentral intensity at the direction of minimum radiation energy at the source (at the direction of the small axis of isoseismals) and S is a factor which determines the azimuthal variation of the intensity. Application of relation (3) leads to the determination of much more realistic attenuation parameters, especially for c, than those estimated by (1) which in several cases gives even unrealistic (e.g., positive c) values (see Figure 6 in Papazachos, 1992). He further assumed a linear relation between the 'focal' intensity, I_f, and the magnitude, M:

$$I_f = b_f M + a_f, \qquad (4)$$

where

$$I_f = I_0 - n \log h - ch. \qquad (5)$$

It was also assumed by PP97 (often assumed by many authors) that a linear relation holds between the epicentral intensity, I_0, and the magnitude, M:

$$I_0 = b_0 M + a_0. \qquad (6)$$

PP97 applied the above described methodology to estimate source parameters (I_0, h, I_f, ε = ellipticity of isoseismals, ζ = azimuth of the major axis of the elliptical isoseismals, M_{mac} = macroseismic magnitude) for shallow earthquakes with magnitudes (equivalent to moment magnitude) between 4.1 and 7.7. The total number of these earthquakes is 284 of which 177 (62%) occurred in Greece, 14 (5%) in Albania, 47 (17%) in F. Yugoslavia, 19 (7%) in Bulgaria and 27 (9%) in western Turkey. For the attenuation parameters (n, c, c_1, c_2 and c_3) of relations (1) and (2) they calculated one value for each parameter in the whole study area using this large data sample (33,769 intensity values). Thus, for the geometrical spreading factor, n, and the anelastic attenuation coefficient, c, the following values were calculated:

$$n = -3.227 \pm 0.112, \quad c = -0.0033 \pm 0.0010. \qquad (7)$$

For the intensity-magnitude scaling relations it was shown that the parameters b_f, b_o in relations (4) and (6) take the following values:

$$b_f = 1.61, \qquad b_o = 1.43 \qquad (8)$$

for all Balkan countries but the parameters a_f, a_o differ from country to country. All calculations were made after converting macroseismic intensity, originally estimated in different scales, to the MM scale by graphical relationships proposed by Shebalin et al. (1974).

By combing (1), (4), (5), (7) and (8) we obtain the following relation by which the macroseismic magnitude can be calculated for shallow earthquakes in the Balkan area (Equation 11 in PP97):

$$M = 0.62I + 2.035 \log R + 0.002R + m_{\mathrm{country}} \qquad (9)$$

where $R = \sqrt{\Delta^2 + h^2}$ is the hypocentral distance and m_{country} is a country dependent variable. This relation can be also used to calculate the intensity when the magnitude is known (e.g., from instrumental data). Also by combining relations (2) and (6) and using the values of the corresponding parameters we get the following relation which can also be used to calculate the macroseismic intensity

$$I = 1.43M - 3.59 \log(\Delta + 6) + d_{\mathrm{country}}. \qquad (10)$$

The parameters m_{country} and d_{country} of the relations (9) and (10) can be calculated by macroseismic data for each country (PP97) so that differences in the practices of estimating macroseismic intensities are also taken into consideration. These two parameters can be also calculated for each site (city, town, village), if enough data are available, so that site effects are also taken into consideration (Papaioannou and Papazachos, 1997).

The database of macroseismic intensities

Trifunac suggests that our database is not representative of the Balkan area, as a large percentage of the earthquakes for which macroseismic information is included in this base is located in the area of Greece. He further suggests reexamination of scaling coefficients for the other countries because the determined ones are probably biased by the large participation of the Greek data.

It is natural for a seismological database of a broad area to include data proportionally to the seismicity of each part of the area. The suitability, however, of a macroseismic database for the determination of attenuation and scaling relations proper for seismic hazard assessment depends mainly on the following three factors. The first one is the total number of sites for which macroseismic observations are available and the geographical distribution of these sites, that is, the density of the observation sites must be high in all parts of the area. The second factor is the magnitude range covered by the earthquakes for which macroseismic data are available ($M_{\max} - M_{\min}$) and the frequency distribution of the magnitudes, that is, the magnitude range must be large enough and these magnitudes must be distributed in this range as homogeneously as possible because in this way a reliable estimation of the parameters is ensured for the scaling relations (e.g., b_o, b_f). The third factor, which affects estimation of attenuation parameters used for seismic hazard assessment, is the percentage of strong earthquakes for which data are available, that is, this percentage must be large enough since some attenuation parameters (e.g., c) are frequency dependent and attenuation should be known for wave frequencies corresponding to strong earthquakes which cause damage. On the other hand, the intensity range, $I_0 - I$, is small for small earthquakes and, therefore, unfavorable for a reliable estimation of the attenuation parameters (e.g., n, c).

Application of the methodology applied in our paper (relation 3) requires a large number of macroseismic observations for each earthquake and a good azimuthal and distance distribution of these observations for a reliable estimation of the macroseismic parameters of each event (macroseismic magnitude and focal depth, ellipticity of synthetic isoseismals, etc.). For this reason, from our database, which includes also macroseismic information for other earthquakes (historical, etc.), we used in this study only data for those events of the present century which fulfill these requirements. This leads to a good coverage for the whole Balkan area by observation sites due to the large number of macroseismic observations per event (approximately an average number of 120 observations per event) and the good distance and azimuthal distribution of these sites in respect to the epicenter of each event. Thus, from the total number of observations, 20962 concern sites in Greece, 1080 of Albania, 4715 of F. Yugoslavia, 3346 of Bulgaria and 3666 of western Turkey. The corresponding density of observations (number of sites per 10000 km^2) is $\sim$ 450 for Greece, $\sim$ 300 for Albania, $\sim$ 175 for F. Yugoslavia, $\sim$ 250 for Bulgaria and $\sim$ 202 for western Turkey. Although the number of observations is larger for Greece (due to the lack of data after 1970 for other Balkan countries), the macroseismic observation density is very high (at least one observation for an area smaller than 8 km $\times$ 8 km) throughout the whole Balkan area.

Another important property of the data set used is that, although there is an almost uniform distribution of the earthquake magnitudes (see the magnitude distribution in Figure 11 of PP97) for the whole magnitude range ($M = 4.1 - 7.7$) which favors reliable estimation of the scaling parameters b_f, b_o, the macroseismic observations used in our study are mainly due to large earthquakes. Hence, from the 284 studied earthquakes, 185 (65%) concern strong ($M > 5.5$) earthquakes (see Table 1 in PP97) which correspond to 80% of the macroseismic observations used. Therefore, the macroseismic data were properly collected by PP97 to be representative and appropriate for a reliable estimation of attenuation parameters (e.g., n, c) as well as of scaling parameters (e.g., b_0, b_f) applicable to all Balkan area.

In his comment, Trifunac argues that scaling quantities '$\ldots b_0$ and b_f *are biased by the larger participation of Greek data* ...' and therefore '$\ldots a0_{\text{country}}$ and $a_{f_{\text{country}}}$ *are also biased*'. A similar argument is presented for the attenuation coefficients, n and c. To further test these arguments, we repeated all our calculations, excluding all the data which concerned earthquakes occurring in Greece. The values determined for the attenuation coefficients were found to be equal to

$$n = -3.205, \qquad c = -0.0048 \tag{11}$$

and for the scaling coefficients

$$b_f = 1.61, \qquad b_0 = 1.40. \tag{12}$$

Comparison of these values, which have been calculated by the use of macroseismic data for earthquakes which occurred in Albania, F. Yugoslavia, Bulgaria and W. Turkey, with the corresponding values given by relations (7), (8), which have been calculated by the whole Balkan sample of data used by PP97, shows that both attenuation and scaling relations proposed by PP97 are really applicable for the whole Balkan area and no bias is introduced from Greek data. For the scaling relations this result is clear since the values obtained in (12) are almost identical to the values shown in (8) from PP97. The same is true for the attenuation as also seen in Figure 1 where the attenuation curves proposed by PP97 and those defined using (11) are shown for two different focal depths (7 and 20 km). It is clear that the two curves are almost identical and that any difference is statistically insignificant and definitely much smaller than a change caused by the variation of the generally poorly constrained focal depth. This observation also shows that errors which might have been introduced by conversion of local intensity scales do not have any serious effect on the calculated values of these four parameters.

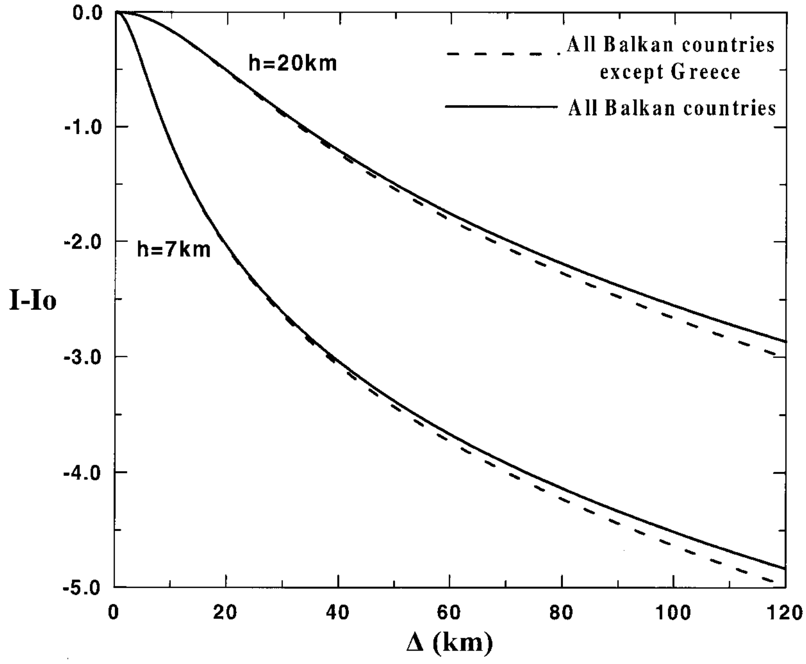

Figure 1. Comparison of the attenuation curve (solid line) determined for all Balkan countries by Papazachos and Papaioannou (1997) with the curve (dashed line) corresponding to all Balkan countries except Greece (present study). The attenuation curves are shown for two macroseismic depths (7 and 20 km).

Trifunac compares the results of PP97 with those of Trifunac et al. (1988) who used also macroseismic data for a similarly large number of earthquakes to investigate attenuation in the Balkan area. It seems, however, that some properties of their database in combination with their hypothesis that values of attenuation parameters vary spatially (e.g., n, c) led to some questionable results. Inhomogeneous distribution of macroseismic observations and estimation of the parameters for each one of the eight 'natural' seismological zones used by Trifunac et al. (1988) in which the Balkan area has been separated led to the calculation of these parameters by a non satisfactory number of observations for some regions. For example, in the south and eastern part of their zone 2 (Hellenic arc), which is one of the most active part of the Balkan area, they used macroseismic data from only two earthquakes. On the other hand, the percentage of relatively small earthquakes in their database is relatively high in some zones (e.g., central Yugoslavia). Since macroseismic effects of small earthquakes are of low intensity and the intensity range ($I_o - I$) for these earthquakes is small, calculated values of attenuation parameters may not represent attenuation of strong earthquakes and their uncertainties are very large. All these explain the unrealistic values of c calculated for some zones and the large scatter of n value which has no physical explanation as it is discussed in detail later in the text.

After demonstrating the absence of bias in the results of PP97 due to the Greek data, both for scaling and attenuation relations, in the next two sections we examine in detail the problem of scale conversion and spatial variation of attenuation, which have been depicted as the two other main sources of bias by Trifunac.

Conversion of local intensity scales

Trifunac suggests that two relations which have been proposed between I_{MSK} and I_{MM} scales (Trifunac, 1977) and I_{MCS} and I_{MM} (Trifunac and Zivcic, 1991) are more accurate than the corresponding graphical relations between local versions of these scales proposed by Shebalin et al. (1974) and applied by PP97. Therefore, he suggests that these relations should have been used by PP97 and that due to the use of less accurate scale conversions '*…most Yugoslavian* (based mainly on the MCS scale …), *Bulgarian and Albanian data may have a systematic bias* (overestimated I_{MM}).'

The first problem with the comments made by Trifunac about scale conversions is that he suggests that Shebalin et al. (1974) proposed that $I_{MCS/MSK} = I_{MM} + 0.5$ for $IV < I_{MM} < X$. This is clearly wrong as an examination of the relation proposed by Shebalin et al. (1974) shows that they suggest that $I_{MCS/MSK} = I_{MM} - 0.5$ for $IV < I_{MM} < X$. However, if we correct for this mistake, the scale conversion problem becomes even worse than originally suggested by Trifunac, as seen in Figure 2. The original MSK/MCS to MM conversion relation proposed by Shebalin et al. (1974) and used by PP97 predicts a much larger difference from the relations proposed by Trifunac than he suggests (more than 2 intensity unit difference for MCS–MM and more than 1 intensity unit difference for MSK–MM). These differences are really very large, e.g., an intensity of $I_{MCS} = 7.0$ is converted to $I_{MM} = 7.5$ in PP97 (Shebalin et al., 1974) and to $I_{MM} = 5.4$ according to Trifunac and Zivcic (1991).

A problem observed in the relations proposed by Trifunac for conversion of MSK and MCS to MM is that they generally do not refer to the local version of these scales. Shebalin and his colleagues, worked for many years in the Balkan area for a UNESCO project and gained significant experience about the way these scales were adapted to the local conditions. For this reason, graphical relationships given by Shebalin et al. (1974) are applicable for the local versions of these scales. For instance, the macroseismic scale applied in Greece concerns specifically the version of MM used in this country as explicitly stated by Shebalin et al. (1974). Similarly, MSK and MCS scales refer to the versions used in Albania, F. Yugoslavia and Bulgaria. On the contrary, the MSK–MM relation proposed by Trifunac (1977) refers to MM observations in USA and MSK observations in USSR, correlated through the use of observed and synthetically created SBM seismometer recordings. Reworking on the original data given by Trifunac (1977) shows that his proposed relation MM (USA)–MSK(USSR) has a standard error of ~ 2.0 intensity units. Therefore, not only is this relation not based on the local scale versions but is also of poor accuracy. Similar conclusions can be reached for the Trifunac and Zivcic (1991) relation which correlate MM (USA) with MCS (Yugoslavia) through velocity records. Again MM does not refer to the local version (used in Greece and Turkey). Moreover, a simple examination of the MCS-Horizontal velocity values, presented in this work, suggests that the uncertainties due to this relation (without examining the additional error introduced by the MM (USA)-Horizontal velocity relation) leads to an intensity error of ~ 2 intensity units.

Further comparison of the relations proposed in Trifunac's comment with those of Shebalin et al. (1974) was performed by testing these relations between the local version of the MM scale applied in Greece and the MCS and MKS scales applied in neighboring countries, on several occasions of strong earthquakes near the borders. In all cases reasonable results were only obtained using the Shebalin et al. (1974) conversion method. This border-comparison was also the method used by Shebalin et al. in calibrating these intensity scales (e.g., see Figure 2 in Shebalin et al., 1974).

Our final test concerns the comparison between different scales for each Balkan country separately. Let us assume that for each Balkan country a single $I_f - M$ or $I_0 - M$ relation applies and macroseismic data are available in different intensity scales (MCS, MM, MSK, etc.). Initially, all intensities are converted to a single scale (e.g., MM) using some conversion relations and I_f or I_0 are estimated. Then, we calculate a macroseismic magnitude, M_{mac}, and its residual from the instrumental magnitude, M, using the constant $I_f - M$ or $I_0 - M$ relation available for this country. Since the same relation (same country) was used for all observations for the estimation of $\Delta M = M_{mac} - M$, these macroseismic residuals from an independent magnitude estimate (instrumental) should be the same for all the original types of intensity observations (MCS, MSK, etc.), provided that the conversion relations are correct. In other words, the residuals of macroseismic to instrumental magnitudes should not differ for the original groups (MCS, MSK, MM) if the scale conversion is correct, since the same $I_f - M$ or $I_0 - M$ relation is used for each country. Therefore, alternative conversion formulas can be applied and checked since the best conversion formula should give similar magnitude residuals for all intensities observations in various intensity scales. As an example, consider two events in western Turkey, the first having I_0^1 (MM) = 7.0 and the second having I_0^2 (MCS) = 6.5. If Shebalin et al. (1974) relations apply then the second event is transformed to I_0^2 (MM) = 7.0, hence these two events should have a similar magnitude or the residuals of their macroseismic magnitude from

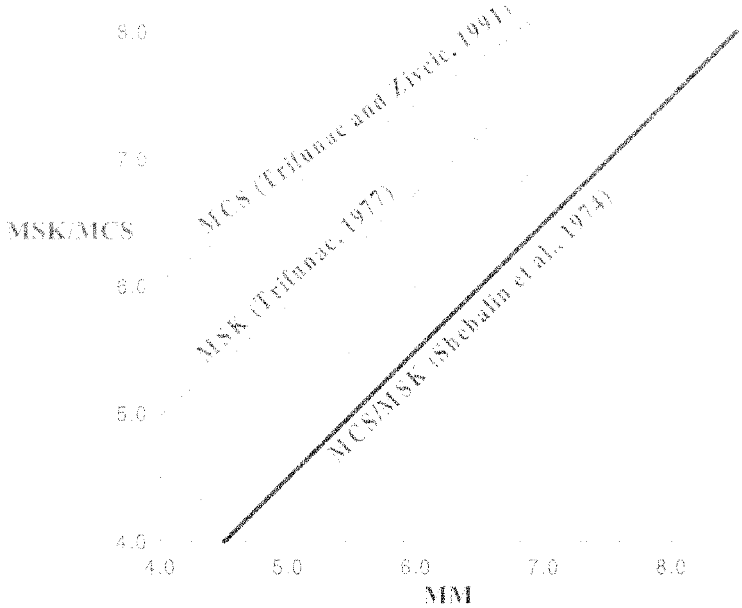

Figure 2. Comparison of the MCS–MM (Trifunac and Zivcic, 1991), MSK–MM (Trifunac, 1977) and MCS/MSK–MM (Shebalin et al., 1974) relations.

the instrumental magnitude (which is an independent observation) should be similar, therefore

$$(M^1_{\mathrm{mac}} - M^1) - (M^2_{\mathrm{mac}} - M^2) = 0. \qquad (13)$$

This equation applies even if the constant a_{country} in the $I_0 = b_0 * M + a_{\mathrm{country}}$ relation is not correct. On the other hand, if the Trifunac and Zivcic (1991) relation is correct then the second event corresponds to I^2_0 (MM) ~ 4.6, and not 7.0. In this case, since we used the Shebalin et al. (1974) scale conversion, the macroseismic magnitude (estimated with the same $I_0 - M$ relation) will exhibit a magnitude residual from the independent and more objective instrumental magnitude, $M^2_{\mathrm{mac}} - M^2$, which will be much smaller than $M^1_{\mathrm{mac}} - M^1$. Specifically, the I_0 difference for the second event (I^2_0 (MM)$_{\mathrm{Shebalin}}$ $- I^2_0$ (MM)$_{\mathrm{Trifunac}}$ $= 7.0 - 4.6 = 2.4$) corresponds to a magnitude difference of 1.7 units (see Equation 10 in PP97). In this case, Equation (13) should be modified to

$$(M^1_{\mathrm{mac}} - M^1) - (M^2_{\mathrm{mac}} - M^2) = 1.7. \qquad (14)$$

Therefore, by estimating the difference of residuals $M^1_{\mathrm{mac}} - M^1$ and $M^2_{\mathrm{mac}} - M^2$, when M_{mac} is determined using Shebalin et al. (1974) scale conversions, we can decide which conversion method is appropriate depending which Equation (13 or 14) is valid.

Following this procedure, we estimated the residual of the macroseismic magnitude, predicted by $M - I_f$ relation from the instrumental magnitude available for all the events of each country. All intensities were converted to MM using the relations of Shebalin et al. (1974). Our first comparison concerns MSK and MCS intensity scales. For Albania, Bulgaria and western Turkey, more events were reported in MSK than MCS and for F. Yugoslavia more events were reported in MCS than MSK. For these events originally reported in these scales, a robust average macroseismic-instrumental magnitude residual was estimated. Then, for each of these countries the macroseismic-instrumental magnitude residual for events reported in the second scale with less observations (MCS in Albania, Bulgaria and western Turkey and MSK in F. Yugoslavia) were also computed and the differences of these residuals from the average magnitude residual of the other intensity scale were estimated. These magnitude differences were converted back to intensity and the distribution of these final intensity MCS–MSK residuals is shown in Figure 3a. If our conversions using Shebalin et al. (1974) relations are correct, the average difference of the MCS and the MSK residuals should be 0, otherwise a value of 0.8 intensity units is expected if we com-

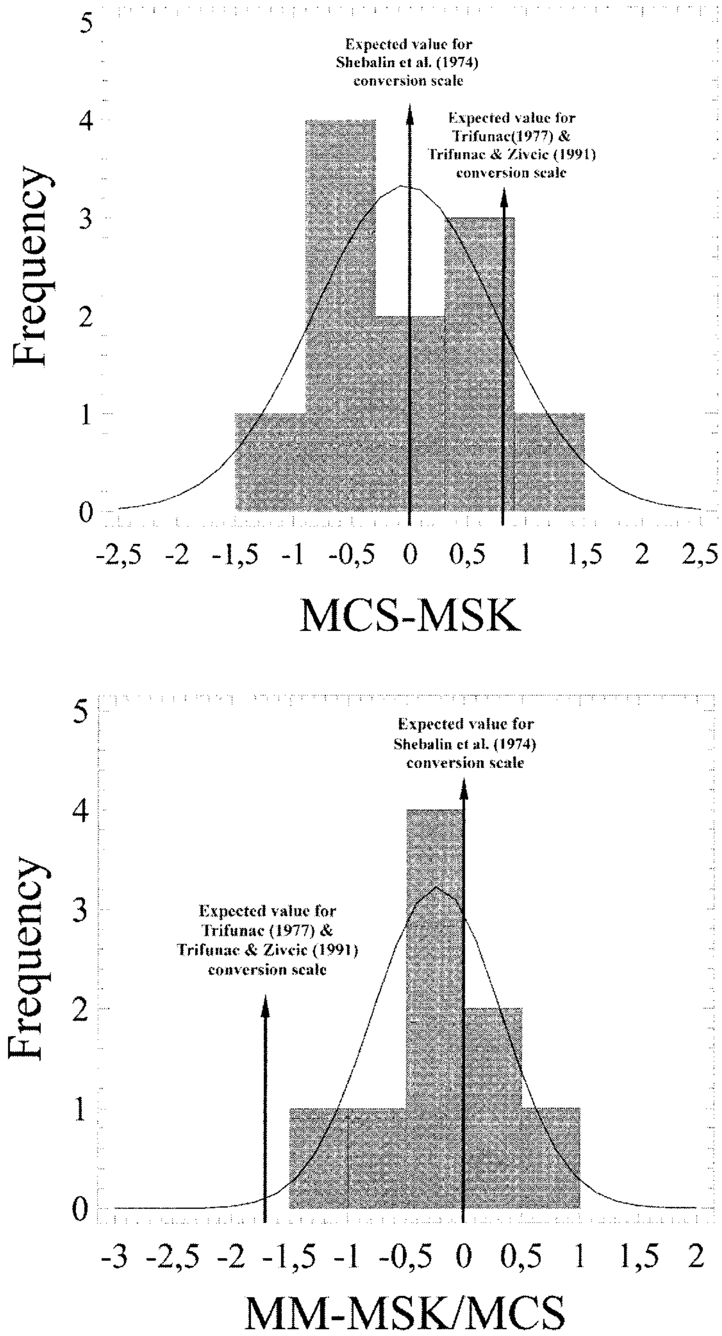

Figure 3. Distribution of the MCS–MSK and MM–MCS/MSK intensity differences computed in the present study after converting all intensity values to MM using Shebalin et al. (1974) relations. The best-fit normal distributions are also shown. The average difference is expected to be close to 0 if Shebalin et al. (1974) relations are valid. The expected difference for the relations of Trifunac and Zivcic (1991) and Trifunac (1977) are also shown.

pare the MSK–MM (Trifunac, 1977) and MCS–MM (Trifunac and Zivcic, 1991) relations (see Figure 2). The best-fit normal distribution for the 10 available earthquakes (shown in Table 1) has a mean value of MCS–MSK $= -0.04 \pm 0.79$. Although the standard deviation is quite large and the number of data is relatively small, there is no indication that MCS values are systematically larger than MSK by 0.8 intensity units as Trifunac suggests.

This comparison is more clear for the MCS/MSK to MM relation. Following a similar procedure for F. Yugoslavia, western Turkey and Greece for 9 earthquakes (shown in Table 2) leads to the MM–MCS/MSK difference distribution seen in Figure 3b. Since MCS/MSK values have been converted to MM by Shebalin et al. (1974) relation, we expect an average difference of 0 intensity units if the Shebalin et al. scale conversion is correct and an average difference of -1.8 intensity units if Trifunac's conversion is valid (see the average difference between MM and MSK/MCS in Figure 2). The average difference obtained in Figure 3 is -0.23 ± 0.56, which is very close to 0 and very different than the value proposed by Trifunac.

From the previous analysis, it is clear that the original relations proposed by Shebalin et al. (1974) are appropriate for use in the Balkan area and that no bias is introduced by the scale conversion scheme used by PP97 for Albania, F. Yugoslavia and Bulgaria. On the contrary, such a bias (very large for the MCS/MSK to MM conversion) might have been introduced if the relations proposed by Trifunac would have been employed.

Our final remark concerns two minor comments made by Trifunac about conversion of intensity scales.

a) Trifunac claims that the systematic bias which is introduced (overestimated MM) in F. Yugoslavia, Bulgarian and Albanian data, due to the use of the relation of Shebalin et al. (1974) for conversion of MCS to MM, may explain in part our observation that recent events show significantly lower epicentral intensity levels. This statement is obviously incorrect, since this observation (lower intensities after 1970) concerns only the Greek data where a single intensity scale (MM) and no conversion is used (see legend in Figure 9 of PP97 which specifically referes to Greece and not to the data of the other Balkan countries).

b) Trifunac states that '…it is not clear why the authors state that 'the majority of …intensity observations were in the Modified Mercalli (MM) intensity scale' … '. Out of 284 events, 197 (69%) of them are in the MM scale. Even if we exclude events after 1970 (as Trifunac suggests), 103 events out of 189 (54%) are still in the MM scale. Therefore, the majority of our observations are really in the MM scale.

Attenuation structure and tectonic environment

Trifunac states that attenuation relations, of a form similar to (1), have to be selected on the basis of specific regional attenuation. Moreover, he gives (Figure 2 in his comment) the calculated values of the geometrical spreading factor, n, and of the anelastic attenuation coefficient, c, as well as of their uncertainties (90% confidence intervals) for each one of the eight seismological zones (Figure 1 in his comment paper) in which the Balkan area was separated on the basis of 'natural' boundaries (Shebalin et al., 1974; Trifunac et al., 1988). Seven of these zones (1, 2, 3, 4, 5, 7, 8) cover about the same area investigated by us (compare with Figure 1 in PP97).

A separation of an area in certain seismological zones of different attenuation structure must be based on the spatial distribution of the relative parameters as well as on tectonic properties for which evidence exists that are related to attenuation structure. Based on the detailed study of a huge sample of macroseismic data (Papazachos, 1992; Papazachos and Papaioannou, 1997), we strongly believe that deviations in the calculated parameters of the attenuation relation (e.g., parameters n and c in Kovesligethy relation) for the Balkan region by the use of macroseismic intensities of shallow earthquakes are mainly due to the quantity and quality of the input data as well as to biases introduced by ignoring the anisotropic radiation at the source, site effects, subjectivity in regionalization, as well as other uncertainties. The deviation of these parameters caused by a real variation of the attenuation structure in these areas is expected to be within the errors introduced by the previously mentioned factors, both from theory and real data. Since this statement is very important for our discussion, we are presenting bellow some further theoretical and observational evidence which strongly support it.

The parameters (n, c, equivalent to b_3 and $b_4/100$ used by Trifunac et al., 1988) which are used for study of the attenuation of the macroseismic intensity (Equation 1) are related to the corresponding para-

Table 1. Information on earthquakes used for the MCS–MSK comparison

Country	Date	Scale	Latitude	Longitude	Magnitude (Instrumental)
Albania	19060928	MCS	40.90	20.70	5.9
Albania	19671130	MCS	41.39	20.46	6.3
F. Yugoslavia	19380527	MSK	42.59	17.00	5.5
F. Yugoslavia	19420827	MSK	41.64	20.46	5.9
F. Yugoslavia	19630726	MSK	42.00	21.40	6.1
Bulgaria	19010331	MCS	43.51	28.69	7.2
Bulgaria	19040404	MCS	41.85	23.00	7.1
Bulgaria	19040404	MCS	41.80	23.00	7.7
Bulgaria	19090214	MCS	42.49	26.51	5.5
W.Turkey	19530502	MCS	38.64	26.53	5.2

Table 2. Information on earthquakes used for the MM–MCS/MSK comparison

Country	Date	Scale	Latitude	Longitude	Magnitude (Instrumental)
Greece	19051108	MCS	40.26	24.33	7.5
Greece	19310104	MCS	37.93	22.86	5.6
Greece	19320929	MSK	40.97	23.23	6.2
Greece	19330511	MCS	40.62	23.53	6.3
F. Yugoslavia	19110218	MM	40.90	20.80	6.7
W. Turkey	19120809	MSK	40.62	26.88	7.6
W. Turkey	19530502	MCS	38.64	26.53	5.2
W. Turkey	19650823	MSK	40.36	26.30	5.6
W. Turkey	19700328	MSK	39.16	29.42	7.1

meters (N, Q) for the attenuation of the peak ground acceleration, a, by the equations

$$N = Bn, \tag{15}$$

$$Q = -\frac{\pi f \log e}{BcV_s}, \tag{16}$$

where N expresses the geometrical spreading coefficient for the seismic waves which are responsible for damage, Q is the quality factor, V_s is the velocity of seismic waves, f is the dominant frequency of the seismic motion and B is parameter of the relation

$$\log a = BI + A \tag{17}$$

(Hashida and Shimazaki, 1984; Papazachos, 1992).

The geometric spreading factor is $N = -1$ for body waves, $N = -5/6$ for the Airy phase of surface waves, $N = -1$ for the surface waves (not Airy phase) if we include the normal dispersion factor and $N = -2$ for head waves (Ewing et al., 1957). Since mainly direct crustal body waves (S_g) as well as surface waves (at larger distances) are responsible for the strong motion, it is natural that we anticipate geometrical spreading factors close to $N = -1$, also confirmed by recent studies using instrumental data up to 120 km. Instead for acceleration, velocities can be used as the seismic parameter to be correlated with seismic intensities. On the other hand, for Greece, the values of $B = 0.29$ (Theodulidis, 1991) and $B = 0.32$ (Koliopoulos et al., 1997) have been determined, using peak horizontal acceleration, and peak horizontal acceleration and velocity data, respectively. For Yugoslavia the corresponding value for the peak horizontal acceleration and peak horizontal velocity to intensity relation are $B = 0.33$ and $B = 0.37$ (Trifunac and Zivcic, 1991), while for the USA the corresponding value is $B = 0.28$ (Trifunac and Brady, 1975). Using the previous values for B, n values from -2.7 to -3.6 are determined (for $N = -1$), which is in agreement with the value determined by PP97 ($n = -3.227$). Using these B values with the value of $n = -3.227$ determined for the Balkan area, we find N values from -0.90 to -1.19, which confirms that macroseismic effects are due to body or surface waves. Independent observations show that S_g waves dominate up to a certain distance and are overtaken by L_g waves at longer distances (Dahle et al., 1990). Therefore, it is natural to anticipate that the values of n are expected to vary in a relatively narrow interval, corresponding to $N = -1$. Observations in United States (Gupta and Nutli, 1976; Anderson, 1978) and in Europe (Ambraseys, 1985; Papazachos, 1992) show values between -2.7 and -3.5. Moreover, even this variation of n should also be attributed to other sources except variations in the acceleration/velocity-intensity relation (scale version used in each country, observational errors) since it is expected that the relation between seismic motion and their effect (expressed by B) should not vary significantly between countries. On the contrary, the n values calculated by Trifunac et al. (1988) for the corresponding zones of the Balkan area (see Figure 2 in his comment) vary drastically (between -2.2 and -4.6) and most of them are outside the previously mentioned interval. This observation indicates that these deviations are mainly due to other reasons (quality of data, etc), which we study in detail in the following.

Equation (1) suggests that the characteristics of the attenuation curve are determined by n, h and c. The macroseismic depth in Equation (1) and the geometrical spreading factor, n, have a similar effect in the attenuation curve. This is demonstrated by Figure 4 where the joint 1-standard deviation (68%) error ellipses are presented for the study of PP97 for n and h. For this figure, all data for the 284 events listed by PP97 were used and n was allowed to vary similarly to h. It is observed that a very strong linear correlation exists between n and h, with an average linear correlation coefficient of $r_{nh} = -0.91$. The result of this very strong correlation is seen in Figure 4: although the errors of n and h (indicated by the thickness of the ellipses along the h and n axes) are not very large, the confidence areas are very elongated due to the strong coupling of n and h. This observation indicates that *it is not possible to determine the geometrical spreading factor, n, and the macroseismic depth, h, from macroseismic data of a single event*. The strong correlation makes these two variables almost linearly dependent and will result in an apparent relation between n and h. In order to confirm this result, we have plotted in Figure 4 the values of n (and their error) for various depth ranges reported for different Balkan countries in the original work of Shebalin et al. (1974). It is clear that n values decrease with increasing h values, as also expected by the large negative linear correlation coefficient. In fact, using Monte Carlo simulation for Equation (1) for a large range of n, h, Δ, and I values, we found an apparent $n - h$ derivative of

$$\frac{\partial n}{\partial h} = -\frac{(\partial I/\partial h)_n}{(\partial I/\partial n)_h} = -0.13. \tag{18}$$

The results of Shebalin et al. (1974) for Balkan countries correspond to approximately equal to -0.09, whereas Ambraseys (1985) suggests a slope of -0.078 for linear relation between n and depth, h, for NW Europe. We therefore suggest that variations in n, observed by Trifunac et al. (1988) for different parts of the Balkan area are mainly statistical artifacts caused by the drift induced in n by the h values used in each part, similar to what is seen for Shebalin et al. (1974) results for the Balkan area. In order to summarize, we believe that our choice of a single n value was not only justified by physical reasons but also by the nature of the data and the physical law describing them (Equation 1) which leads to erroneous $n-h$ variations.

However, it is even more important to study the second attenuation coefficient, c, since it is directly related to anelastic attenuation and the quality factor, Q. Using relation (16), Q is found to be equal to $\sim$ 370 for $f = 1$ Hz, $B = 0.32$, $V_S = 3.5$ km sec^{-1} (Papazachos et al., 1966) and for $c = -0.0033$ calculated by PP97 for the Balkan area. A similar low value for the quality factor ($Q = 200 - 300$) was calculated for the S waves in south Aegean by Kovachev et al. (1991) and attributed to the expansion of the Aegean lithosphere. Recent information on active tectonics (McKenzie, 1978; Jackson, 1994; Papazachos and Papazachou, 1997) shows that this expansion dominates in the Balkan area from the north coast of eastern Mediterranean (Crete island, etc.) up to at least 43° N (Bulgaria, etc.) and from the Dinarides-Hellenides up to 30° E meridian (western Turkey). In the belt along the southern and western coast of the area the tectonic environment is compressional. This belt, however, is relatively narrow and a large part of it is covered by the sea. For this reason, observed macroseismic intensities of earthquakes generated in this belt are due to seismic waves with paths mainly in the expanded area. Therefore, the adoption of one relatively low value of the parameters $c(= -0.0033)$ for the whole area which was calculated by the use of all available macroseismic data for shallow earthquakes is compatible with the dominance of this area by an homogeneous extensional field.

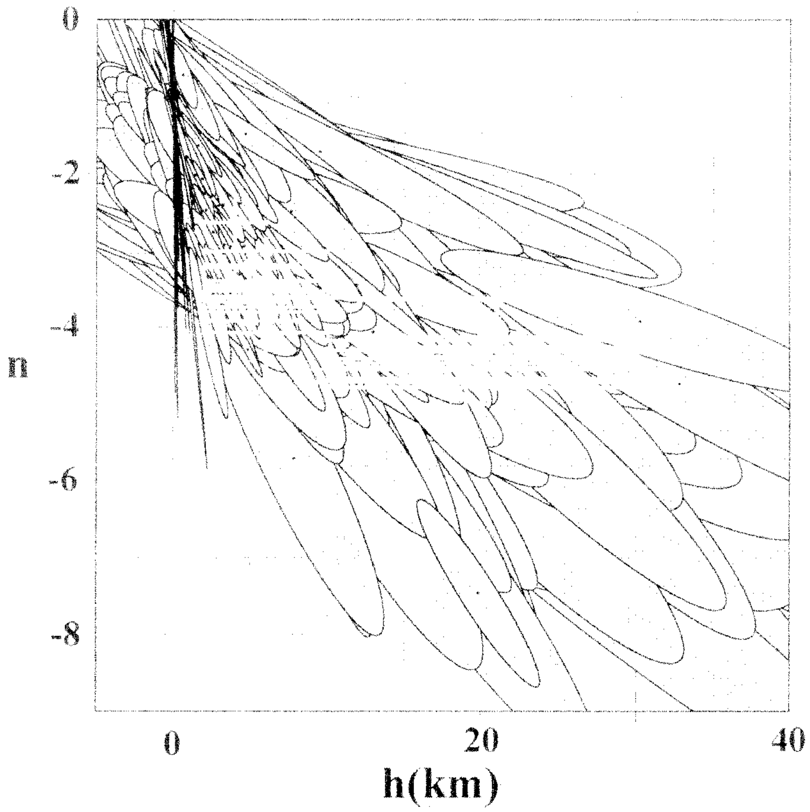

Figure 4. Plot of the 1-standard deviation (68%) confidence error ellipses of the joined $n - h$ distribution for the 284 events used in Papazachos and Papaioannou (1997). The confidence area is determined by allowing both n and h to vary for each earthquake. A very strong linear correlation of n and h is observed for almost all events, leading to an apparent $n - h$ linear relation. This is confirmed by the distribution of n values for various depth ranges reported by Shebalin et al. (1974), shown by the white crosses.

Most of the c values calculated by Trifunac et al. (1988) for the corresponding zones in the Balkan area have rather random deviations from the value proposed by Papazachos and Papaioannou (1997) for the whole area (see Figure 2 in his comment) and for this reason these deviations can be attributed to random errors in the macroseismic data. A portion of the range covered by his c values (for Hellenides-Crete-Rodos, Vrancea, SW Turkey) has unreasonable or even unrealistic c values (e.g., positive c).

Systematic geographical change of the c parameter due to tectonic variations, defined by the 'natural' boundaries (see Figure 1 in Trifunac comment), is questionable since recent information on active tectonics of this area shows that most of these boundaries do not exist as tectonic boundaries. Thus, the 'natural' boundaries, which have been defined to coincide with the borders of Greece with Albania, F. Yugoslavia, Bulgaria and western Turkey do not exist because the same environment of extensional active tectonics dominates throughout the broader Aegean sea area, in almost all continental Greece, eastern Albania, southern central F. Yugoslavia, Bulgaria and western Turkey. The boundary which separates Greece into two zones (2 and 4) must be shifted much to the west and south since it is now known that extension dominates along the crest of Hellenides and Crete while the thrust belt (zone 2) is spatially limited to the narrow convergence belt along the convex side of the Hellenic arc, etc. Therefore, the by Trifunac adopted separation of the Balkan area in seismological zones is not based on what is known today for the geographical variation of the tectonic environment. Besides, the fact that most of these boundaries coincide with national borders indicates that the proposed zonation has little to do with separation of the area in different tectonic environments or in areas of different geophysical properties (attenuation, etc.). On the other hand, the estimation of c can not be based on a limited number of data as the ones used by Trifunac for each 'natural' zone since this is a very sensitive factor. PP97 examined the macroseismic data in great detail (see Figures 3, 4 and 5) in order demonstrate that this factor (resulting in a change of only -0.33 intensity units at Δ=100km) can be separated from geometrical spreading. Moreover, comparison of (7) and (11) suggests that although b_0, b_f and n were not changed after the Greek data (more than 60%) have been removed from the analysis, c varied (almost 50%) which is indicative of the unstable behavior of this constant when not enough data are used.

Summarizing Sections 2 and 4, we conclude that there is no serious evidence for strong systematic geographical variations of the attenuation parameters (n, c), which express rates of variation of the intensity with distance (at least robustly revealed by macroseismic data), or of the scaling parameters, (b_f, b_o), which express rates of variation of the intensity with the magnitude. Also these parameters do not depend much on differences in national practices of estimating macroseismic intensities as we have already shown. The values calculated for these rate parameters (n, c, b_f, b_o) are mainly affected by the quantity and quality of the input data and for this reason Papazachos and Papaioannou (1997) calculated one value for each of these parameters for the whole Balkan area. On the other hand, national factors (practices of estimating intensities, way of building, etc.) do affect the scaling relations but such effects are well taken into consideration by calculating constant terms (a_f, a_o, m, d) of the relations (4, 6, 9, 10) separately for each county after the determinations of the rate parameters by all the available macroseismic data.

Seismic hazard assessment in the Balkan area

There are a few other minor comments made by Trifunac most of which have already been answered in the original paper of PP97. For example, Trifunac determines a magnitude-depth relation, which has been already commented in Figure 12 of PP97. He also questions the lack of physical explanation by PP97 of hypocentral intensities I_f larger than 12, when it is clear that no physical explanation is required for this quantity which refers to a theoretical 'hypocentral' intensity (at distance of 1 km from the point source) which can take very large values, reaching infinity at the source.

The most important final comment of Trifunac refers to the procedure followed in order to assess seismic hazard at any site of the Balkan area. This procedure is based on separation of the area in seismogenic sources and determination of seismicity parameters for each source, as well as on assignment of a specific attenuation function to each source appropriate for the specific path towards the site (Todorovska, 1994; Todorovska et al., 1994). This procedure gives satisfactory results when the parameters of the assigned attenuation function along a such specific path is based on a large sample of intensities due to seismic waves traveling approximately along this path. It also gives good results when the rate parameters (e.g., n, c) are determined by a large sample of data concerning the broader area and constant parameters (e.g., m, d, in relations 9, 10) by the use of data concerning the particular path (Margaris, 1994). Assigned attenuation functions based on zones of constant attenuation structure in the crust of the Balkan area may not be correct since such reliable zonation is very difficult with the present state of knowledge and available data.

On the contrary, we believe that information given in PP97 study created new possibilities for further improvement of the procedure for seismic hazard assessment in the Balkan area by taking also into consideration *anisotropic radiation at the earthquake source*, *differences in the national practices of determining macroseismic intensities and site effects*. This procedure can be separated in two main parts. The first part includes separation of the area in seismogenic sources on the basis of several kind of data (seismological, geophysical, geological, geomorphological) and estimation of seismicity parameters (maximum earthquake magnitude, rate of the number of earthquakes with magnitude larger than a certain value, parameters of the frequency distribution of earthquake magnitudes) as well as of parameters which describe the systematic directivity of the seismic energy at the source based on several information (fault plane solutions, isoseismals, surface fault traces, spatial distribution of aftershocks). The second part includes estimation of the parameters m or d of the relation (9) or (10) using all available macroseismic intensities from past earthquakes which were felt at a site. In this way the attenuation relations are corrected for the site effect and for practices of determining macroseismic intensities in the country where the site (city, town, village) belongs. Such an improved procedure has been already applied for seismic hazard assessment in Greece (Papaioannou and Papazachos, 1998) and calculations were made by a modified version of the EQRISK program (McGuire, 1976). This modified program takes also into consideration the anisotropic radiation of the seismic energy at each one of the 67 seismogenic sources in which southern Balkans were separated and the calculated value of the parameter, d, for each one of 144 sites (cities, towns, villages) in Greece of which 126 are included in the New Greek Seismic Code.

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