Comparison between empirical predictive equations calibrated at global and national scale and the Italian strong-motion data

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Abstract

In Italy in the last years many ground motion prediction equations (hereinafter GMPEs) were calibrated both at national and regional scale using weak and strong motion data recorded in the last 30 years by several networks. Moreover many of the Italian strongest earthquakes were included in global datasets in order to calibrate GMPEs suitable to predict ground-motion at very large scale. In the last decade the Sabetta and Pugliese (1996) relationships represented a reference for the ground motion predictions in Italy. At present all Italian strong-motion data, recorded from 1972 by RAN (Italian Accelerometric Network), and more recently by other regional networks (e.g. RAIS, Strong motion network of Northern Italy), are collected in ITACA (ITalian ACcelerometric Archive). Considering Italian strong-motion data with $M_w \geq 4.0$ and distance (Joyner-Boore or epicentral) up to 100 km, new GMPEs were developed by Bindi et al. (2009), aimed at replacing the older Italian relationships. The occurrence of the recent 23rd December 2008, M_w 5.4, Parma (Northern Italy) earthquake and the 6th April 2009, M_w 6.3, L'Aquila earthquake, allowed to upgrade the ITACA data set and gave us the possibility to validate the predictive capability of many GMPEs, developed using Italian, European and global data sets. The results are presented in terms of quality of performance (fit between recorded and predicted values) using the maximum likelihood approach as explained in Spudich et al. (1999). Considering the strong-motion data recorded during the L'Aquila sequence the considered GMPEs, in average, overestimate the observed data, showing a dependence of the residuals with distance in particular at higher frequencies. An improvement of fit is obtained comparing all Italian strong-motion data included in ITACA with the European GMPEs calibrated by Akkar and Bommer (2007 a,b) and the global models calibrated by Cauzzi and Faccioli (2008). In contrast, Italian data seem to attenuate faster than the NGA models calibrated by Boore and Atkinson (2008), in particular at higher frequencies.

Introduction

Empirical Ground Motion Prediction Equations (hereinafter GMPEs) are critical for seismic hazard studies in any region. However the reliability of all GMPEs is strongly influenced by the characteristics of the data set used to calibrate them. The optimal condition to obtain stable regressions would be to have a large amount of data with a wide distribution of magnitudes, distances, and source mechanisms (Douglas, 2003). Unfortunately, this is rarely the case; in fact prediction equations are usually limited to the typical magnitude range observed in the study region that, in general, allows one to derive empirical relationships only for strong motion data (e.g. Sabetta and Pugliese, 1996; Ambraseys et al. 2005a,b; Akkar and Bommer 2007a,b; Boore and Atkinson 2008) or weak motion data (Frisenda et al. 2005; Massa et al., 2007).

The data sets used to calibrate many GMPEs are often characterized by an irregular distribution of data, resulting in inhomogeneous representation of all magnitude-distance ranges. This may lead to erroneous predictions since the final results are governed by the bulk of the distribution (Crouse et al. 1988; Molas and Yamazaki, 1995). Moreover, the spatial distribution of events and stations may introduce an azimuthal effect on the amplitudes of the ground motion (Campbell and Bozorgnia, 1994).

The Sabetta and Pugliese (1996, hereinafter SP96), calibrated using 95 strong-motion waveforms from 17 earthquakes occurred in Italy in the magnitude range 4.6-6.9 (M_L or M_s) and distance (Joyner-Boore, 1981, hereinafter R_{jb} or epicentral, hereinafter R_{epi}) up to 100 km, represent one of the alternative GMPEs considered to calculate the seismic hazard map of Italy in terms of maximum expected horizontal acceleration (10% probability of exceedence in the next 50 years, MPS Working Group, 2004) and acceleration response spectra from 0.1 to 2 s (Montaldo and Meletti, 2007). The extremely limited data set, recorded by analogue instruments, on which these GMPEs were based, needed to be updated and, for this reason, in the past five years, under the agreement between the Italian Civil Protection (DPC) and the Italian National Institute for Geophysics and Vulcanology (INGV) the Italian strong–motion database (ITalian ACcelerometric Archive, ITACA, http://itaca.mi.ingv.it) was developed.

At present ITACA includes records of 1017 earthquakes, 1002 relative to the period range 1972 - 2004 ($1.1 < M \leq 6.9$), the December 2008 Parma earthquakes (M_w 4.9 and M_w 5.4) and 13 events of the April 2009 L'Aquila (Central Italy) sequence ($4 \leq M_w \leq 6.3$). Using a selection of events recorded up to 2004, a set of GMPEs was recently derived for Italy (Bindi et al., 2009, hereinafter ITA08), for the prediction of maximum horizontal and vertical peak ground acceleration, peak ground velocity and acceleration response spectra (5% damping) from 0.04 s to 2 s. The ITA08 data set is composed by 561 three-component records from 107 earthquakes with M_w in the range 4.0–6.9, recorded by 206 stations with R_{jb} up to 100 km.

On April 6th, 2009, 01:32:40 UTC, a M_w 6.3 earthquake occurred in the Abruzzo region (Central Italy), at 9.5 km depth along a NW-SE normal fault with SW dip (e.g. Ameri et al., 2009), very close to L'Aquila, a town of about 70.000 inhabitants. The mainshock was followed by seven aftershocks of moment magnitude larger than or equal to 5, the two strongest ones occurred on April 7th (Mw=5.6) and April 9th (Mw=5.4). The data set relative to L'Aquila sequence was used to verify the prediction capabilities of 5 selected GMPEs, calibrated at national (ITA08, Bindi et al., 2009; SP96, Sabetta and Pugliese 1996), European (AKBO07, Akkar and Bommer, 2007a,b) and global scale (BOAT08, Boore and Atkinson, 2008;CF08, Cauzzi and Faccioli, 2008).

The AKBO07 data set consists of 532 three-component records, from 131 earthquakes, with Mw from 5.0 to 7.6 and R_{jb} up to 100 km, from the European strong motion database (http://www.isesd.cv.ic.ac.uk/ESD/). The CF08 models were calibrated from about 1.000 digital accelerometric records, many of which coming from Japanese strong-motion data set (url: http://www.k-net.bosai.go.jp/k-net/index_en.shtml), recorded at hypocentral distances up to 150 km and M_w in the range 5.0-7.2. The BOAT08 is derived from an extensive strong-motion database compiled by the PEER NGA project (Pacific Earthquake Engineering Research Center's Next Generation Attenuation project, http://peer.berkeley.edu/products/nga_project.html). The data set consists of about 1.500 accelerometric records relative to 58 worldwide events recorded at distances up to 400 km and M_w in the range 5.0-8.0. The characteristics of the GMPEs considered in this study are reported in tables 1 and 2.

Finally, the comparison was extended to the whole recently updated ITACA strong-motion database.

GMPE	**N events**	**N rec (x3)**	**M**	**R [km]**	**Response variables**	**Comp**
ITA08	107	561	4.0 - 6.9	up 100	PGA, PGV, SA up 2s	Hm, V
SP96	17	95	4.6 - 6.8	up 100	PGA, PGV, PSV up 4s	Hm, V
AKBO07 (a,b)	131	532	5.0 - 7.6	up 100	PGA, PGV, RD up 4s	Gm
CF08	60	1155	5.0 - 7.2	up 150	PGA, RD up 20s	Gm
BOAT08	58	1574	5.0 - 8.0	up 400	PGA, PGV, PSA up 10s	GmRot50

Table 1 – Data set used to calibrate the GMPEs considered in this study. *M* is moment magnitude, with the exception of SP96 where for M<5.5 M is local magnitude and for M≥5.5 M is surface-waves magnitude. Both for ITA08 and SP96 the upper bound of magnitude is represented by the 23^{rd} November 1980, Mw 6.9 (Ms 6.8) Irpinia earthquake. *R* is Joyner-Boore distance, with the exception of CF08 where R is the hypocentral distance and of ITA08 for events with M<5.5 (in this case R is the epicentral distance). In the last column *Hm* is the maximum between the two horizontal components, *Gm* is the geometric mean and *GmRot50* is the geometric mean determined from the 50^{th} percentile values of the geometric means computed for all non-redundant rotation angles.

GMPE	M term	Sat. term	Geom. Spread. term	AA term	S term	SF term
ITA08	b_1*(M-M_r)	b_2*(M-Mr)^2	[c_1+c_2*(M-Mr)]*log[(R^2+h^2)$^{0.5}$]	-	e*S_i	-
SP96	b*M	-	c*log[(R^2+h^2) $^{0.5}$]	-	e*S_i	-
AKBO07	b_2*M	b_3*(M)^2	[b_4+(b_5*M)]*log[(R^2+b_6^2)$^{0.5}$]	-	b*S_i	b*F_i
CF08	a_2*M	-	a_3*log[R]	-	a*S_i	-
BOAT08	e_5*(M-M_h)	e_6*(M-Mh)^2	[c_1+c_2*(M-Mr)]*ln[(R^2+h^2)$^{0.5}$/R_r]	c_3*(R-R_r)	b(I)*[ln(Vs_{30}/V_r)]	e*S_i

Table 2 – Single term of each functional form used to calibrate the GMPEs considered in this study. In each column the coefficients are reported as indicated in the relative paper. Column 2 = scaling for magnitude; column 3 = saturation with distance; column 4 = geometrical spreading attenuation term; column 5 = anelastic attenuation term; column 6 = site correction term; column 7 = style of faulting correction term. For *S* and *SF* terms, S_i and F_i are dummy variables that assume either the value 0 or 1 depending on soil type or fault mechanism. For BOAT08 the saturation term (column 3) disappears for $M \geq M_h$ (M_h is the "hinge magnitude" that has to be set during the analysis in order to consider the shape of the magnitude scaling) while for the site correction term (column 6) it is also possible to consider the non-linear site effects (see Boore and Atkinson, 2008 for details).

Fit of the L'Aquila data set to the Italian, European and global GMPEs

The L'Aquila sequence data set is composed of 305 three-components accelerometric waveform from events in the moment magnitude range 4.0 - 6.3 recorded at Joyner-Boore distance in the range 0-250 km (Figure 1, right panel). All data are available at the ITACA web site (http://itaca.mi.ingv.it). The accelerometric waveforms were recorded by several stations belonging to the Italian Accelerometric Network (RAN), generally equipped by Kinemetrics three-component accelerographs (full scale set to 1 or 2 g) coupled to 24-bit digitizers (with sampling frequency of 200 Hz) and by five temporary strong- motion stations installed in the epicentral area by INGV, department of Milano-Pavia (RAIS, url: http://rais.mi.ingv.it) after the mainshock occurrence These stations were equipped by Kinemetrics ES-T Episensors coupled with 24 bits Reftek-130 digitizers. The stations that recorded the events included in the L'Aquila data set are classified following the EC8 soil classes (CEN, 2004). Most of the stations, 6 of which installed inside the surface projection of the mainshock fault plane (R_{jb}=0), belong to class A or B (class A has $V_{s30} \geq 800$ m/s, class B has $360 \leq V_{s30} < 800$ m/s) and only a few sites are classified as class C ($180 \leq V_{s30} < 360$). All data were processed following Massa et al. (2009) procedure that includes the removal of the linear trend fitting the entire record, a cosine taper and band pass filtering with a time-domain acasual 4th order Butterworth filter. Both the high-pass and low-pass frequencies were selected through the visual inspection of the Fourier spectrum. The peak ground accelerations relative to the mainshock in the near-fault area are characterized by values higher than 300 cm/sec^2. However the largest acceleration peak (670 cm/s^2) was recorded for the 7th April (17:47 UTC), Mw 5.6, aftershock, at an epicentral distance of 5 km (MI05 station, class B). The highest value of peak ground velocity (43 cm/s) is related to the 6th April (01:32 UTC), Mw 6.3, mainshock, recorded at an epicentral distance of 4.9 km (AQV station, class B).

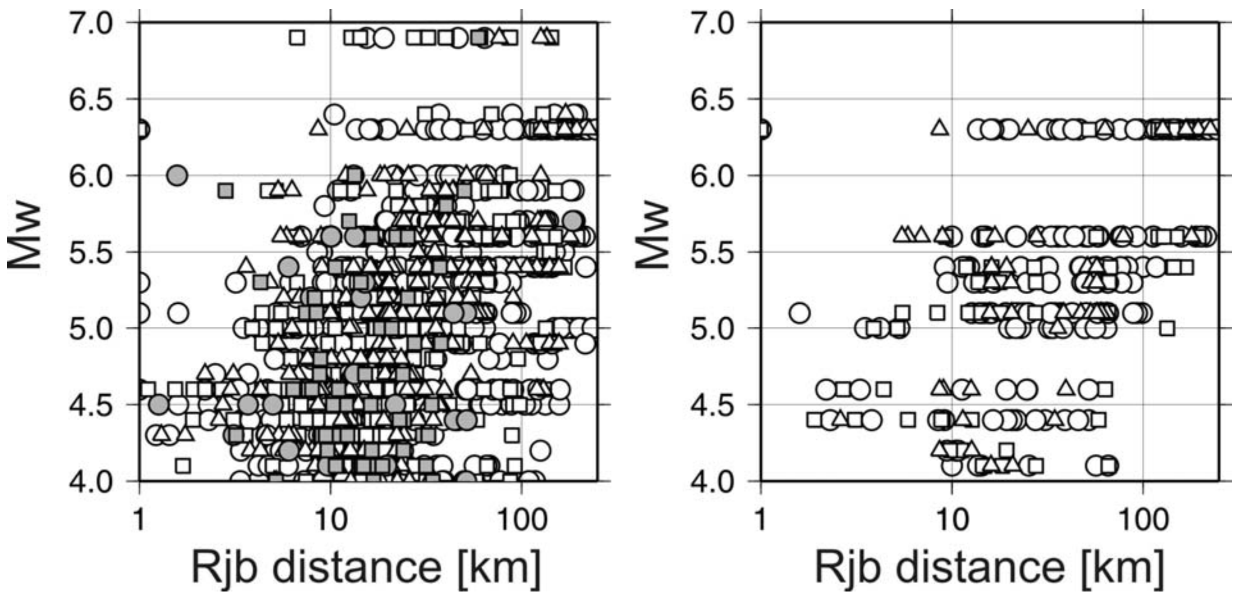

Figure 1 - Left: subset of ITACA data set showing records with M_w from 4.0 to 6.9 and Joyner-Boore distance (Rjb) up to 250 km. Right : L'Aquila sequence data set. EC8 A-class = white circle; EC8 B-class = white square; EC8 C-class = white triangle; EC8 D-class = gray circle; EC8 E class = gray square.

In figure 2 (top panels) the maximum between the horizontal components (PGAs, Hm) for the 6th April, Mw 6.3, L'Aquila mainshock is plotted as a function of R_{JB} along with the attenuation curves predicted by the considered GMPEs, for different EC8 site classes (L'Aquila sequence does not include records in class D or E). For comparisons the original distance measure of the CF08, that is the hypocentral distance, was converted to R_{jb}, through and ad-hoc empirical relation calibrated with the Abruzzo earthquake records, while the geometrical mean between the two horizontal components was converted to the largest value using the relationships proposed by Beyer and Bommer (2006). On average, for PGA, the GMPEs calibrated using European and global data set well fit the data, at least for distances where the empirical models are defined (100 km for AKBO07 and 150 km for CF08). In particular, the median values of AKBO07 and CF08 equations match reasonably well the near-source data recorded at rock sites, even if an increasing overestimation with distance is observable. On the contrary, ITA08 predicts lower median PGA values, due to the adopted Italian data set that poorly samples the near-fault distances (a subset of ITACA data set is shown in the left panel of figure 1). Similar considerations can be done regarding the PGVs (not reported here). The bottom panels of figure 2 show the comparisons between the same GMPEs and the acceleration response spectral ordinates at 2.0 s. The Italian GMPE reasonably fit the recorded data for class A over the entire distance range while the near-source records for class B are, on average, better predicted by the CF08 and AKB07.

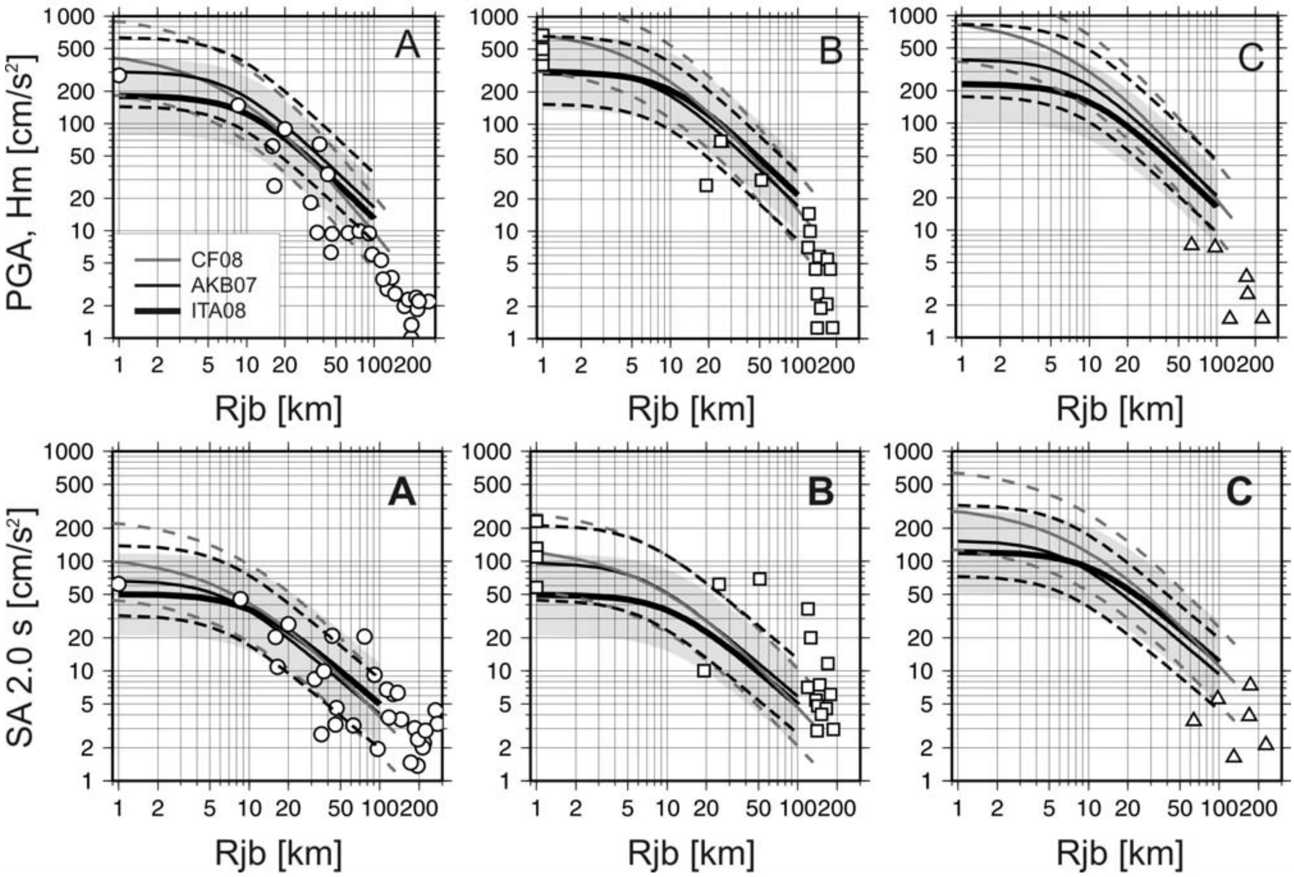

Figure 2 – Top panels: PGAs for maximum horizontal component (Hm) versus R_{JB} recorded for the 06[th] April 2009, M_w 6.3, L'Aquila main-shock. Left panel: EC8 A-class. Central panel: EC8 B-class. Right panel: EC8 C-class. The shaded area represents $\pm 1\sigma$ for ITA08. The black and grey dashed lines represent $\pm 1\sigma$ for AKBO07 and CF08 respectively. Note that points with R_{JB} less than 1 km are plotted at 1 km. Bottom panel: the same as in top panels but for acceleration response spectral ordinates at 2.0s.

In order to provide more quantitative results, the comparisons were performed in terms of bias (Spudich et al, 1999), that is the mean value of the residuals evaluated by the maximum likelihood formalism. The residual is computed as the difference between the logarithm of the observations and the logarithm of the predictions. Moreover, for these analyses, the distribution of residuals was decomposed into the inter-event (η) and intra-event (ε) components, which are assumed to be independent, normally distributed with variances σ^2_{eve} (inter-event component of variance) and σ^2_{rec} (intra-event component of variance), respectively (Abrahamson and Youngs, 1992). The goodness of fit was evaluated considering the maximum horizontal peak ground acceleration (PGA), velocity (PGV) and for response spectra (SA, %5 damping) ordinates at 1.0 s and 2.0 s. An example of the results obtained for ITA08 is reported in figure 3, where the goodness of fit of PGA values recorded during L'Aquila sequence to the new Italian predictive model is shown.

GMPE	Bias PGA (Hm)	Bias SA (1.0s)	Bias SA (2.0s)	Bias PGV
ITA08	-0,318	-0,121	-0,144	-0,192
SP96	-0,504	-0,465	-0,406	-0,486
AKBO07	-0,391	-0,226	-0,244	-0,261
CF08	-0,301	0,104	0,081	/
BOAT08	-0,382	-0,221	0,237	-0,254

Table 3 – Bias values obtained comparing the considered GMPEs to the data relative to the 13 events of L'Aquila sequence with Mw ≥ 4.0. ITA08 and SP96 (Italy); AKBO07 (Europe); CF08 and BOAT08 (Global). The comparisons were made considering for each GMPEs the related independent variables (magnitude, distance, site classification and style of faulting). CF08 not considers PGV.

For ITA08 the overall bias for PGA (Hm) is negative (-0.318, table 3 and figure 3a), denoting a general overestimation of the predictions. Figure 3b shows the results in terms of inter-event errors (i.e. the error obtained considering the variability of all recordings related to a single event, Strasser et al., 2009): all the examined events of L'Aquila data set have negative inter-event error and this is independent on magnitude (Figure 3d). As observed for ITA08, negative inter-event errors are also obtained considering the other predictive models, as shown in figure 4 for PGA. Similar results (not reported here) were obtained for acceleration response spectral ordinates at 1.0 s and 2.0 s, with the exception of CF08 models that show positive, or very close to zero, inter-event errors.

In Figure 3c the ITA08 residuals are plotted as a function of Joyner-Boore distance: in this case a not-negligible slope is observed, indicating a general dependence of the error with distance. In particular, an underestimation is observed in near source area (R_{jb} up to about 10 km) and an overestimation for distance higher than 10 km. The same analysis, performed on PGV (not reported in figure) provides for ITA08 a negative bias (-0.192), confirming the general overestimation of the predictions.

In table 3 the biases obtained for PGA, PGV and response spectra ordinates at 1s and 2 s are shown for the GMPEs considered in this study.

Figure 5 shows the dependence on magnitude and distance of the PGA residuals obtained with the other predictive models. All the considered predictive models show a variable dependence with distance and magnitude. The strongest dependence of residuals with distance is detected for SP96 model (slope -0.546, panel a of figure 5), but this can be explained with the lack of the magnitude dependent geometrical spreading term in the functional form (table 2). However, also the other models show a negative dependence of the residuals with distance, that means a general overestimation of the predictions with increasing distances. In particular, the European model

(AKBO07) has a dependence of the residuals on distance very close to ITA08 (slopes -0.321 for AKBO07, panel c of figure 5, and -0.318 for ITA08, panel c of figure 3). The new Italian (ITA08) and the European GMPEs were calibrated by using the same functional form and a possible cause of the overestimation with distance could be due to the absence of the anelastic attenuation term in both models (table 2). The CF08 models, obtained through a simplified functional form (table 2), suffer of a remarkable dependence of residuals with distance (slope -0.412, panel e of figure 5). The model developed in the framework of the NGA project (BOAT08), although calibrated by using a functional form that includes both the magnitude dependent geometrical spreading and the anelastic attenuation terms (table 2), shows a remarkable dependence of the residuals with distance (slope -0.499, panel g of figure 5) as well. It has to be remarked that the residual analysis has been performed in the range of validity of each model, in terms both of magnitude and distance.

As shown in the right panels of figure 5, all models show a stronger dependence of the residuals on magnitude than ITA08 (see panel d of figure 3). In this case the results probably reflect the distribution of magnitude values of each single data set. Both the European (AKBO07) and the global GMPEs (BOAT08 and CF08) are in fact obtained considering a minimum magnitude (Mw) value of 5.0, that might lead to an overestimation of the prediction for recorded data related to the events having magnitudes close to the lower magnitude bound of those GMPEs (Bommer et al., 2007). The highest magnitude dependence (slope 0.173, panel h of figure 5) is observed for the BOAT08 model that is calibrated considering the highest magnitude range (5.0 - 8.0).

In figure 6 the results obtained for SA ordinates at 1s are shown. Only ITA08 and AKBO07 have a negligible trend of the residuals with distance (panels a and e of figure 6), while a significant dependence is observed for the other models (slope of -0.131 for SP96, panel c, and of -0.126 for CF08, panel g) and, in particular, for BOAT08 (slope of -0.185, panel i). On the other hand, all models, with the exception of ITA08 and AKBO07, show a stronger dependence on magnitude of SA residuals than PGA (from 0.165 to 0.210 for SP96, from 0.096 to 0.195 for CF08, from 0.173 to 0.257 for BOAT08). This indicates a general decrease of the overestimation with increasing magnitude and periods. Similar results were obtained for PGV and for spectral ordinates at 2.0 s (not showed here).

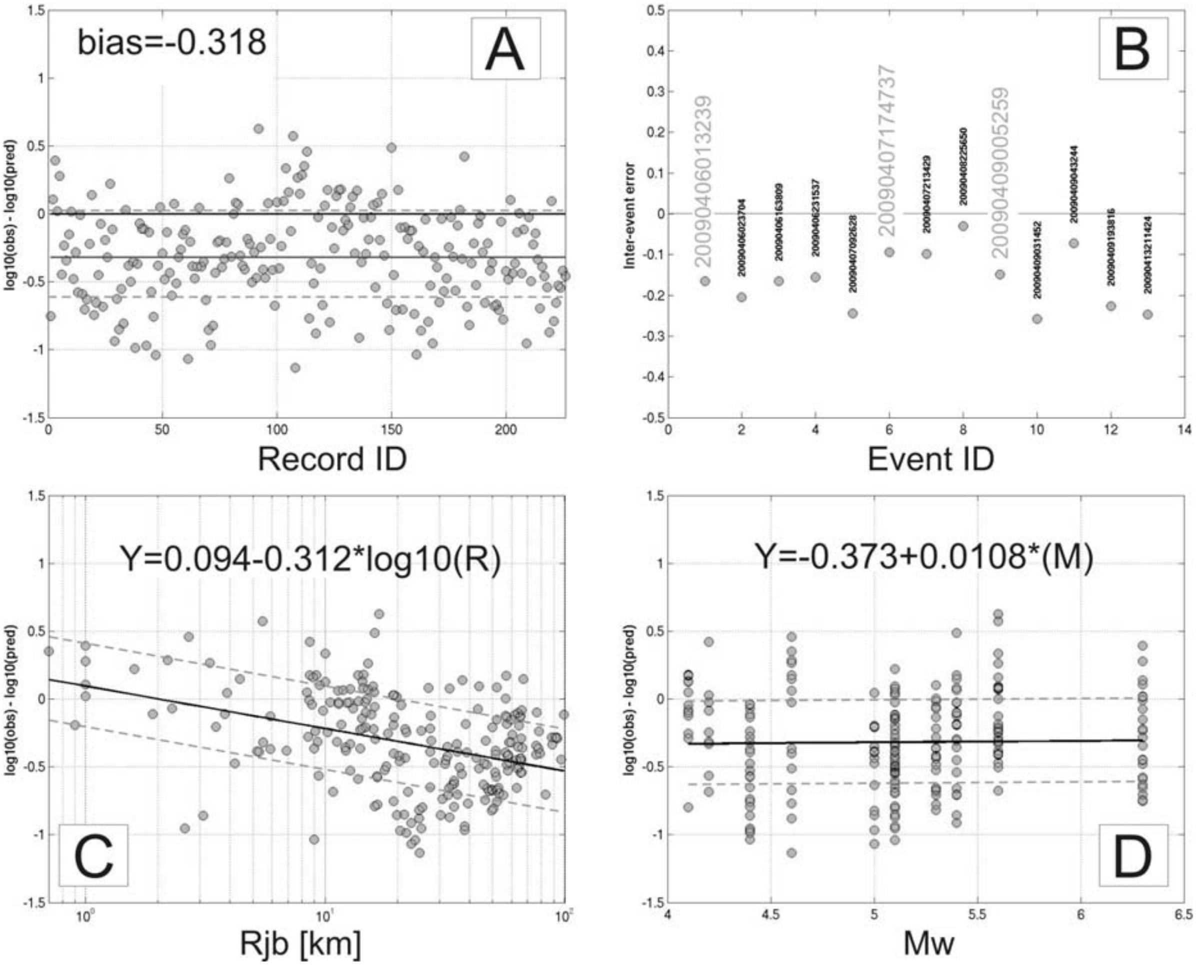

Figure 3 – Results for PGA (maximum horizontal component) comparing ITA08 Vs L'Aquila data (13 seismic events with Mw≥4.0). Top left panel: residuals (i.e. differences between the logarithm of the observations and logarithm of the predictions, grey circles). The bias (black solid line) and its plus/minus one standard deviation (dashed gray lines) are reported. Top right panel: inter-event errors related to the L'Aquila sequence (in grey the Mw 6.3 L'Aquila mainshock and the two strongest aftershocks, Mw 5.6 and 5.4, are indicated). Bottom panels: residuals as a function of R_{jb} distance (left) and M_w (right). In both panels, solid and dashed grey lines represent the fit function and ±1σ respectively.

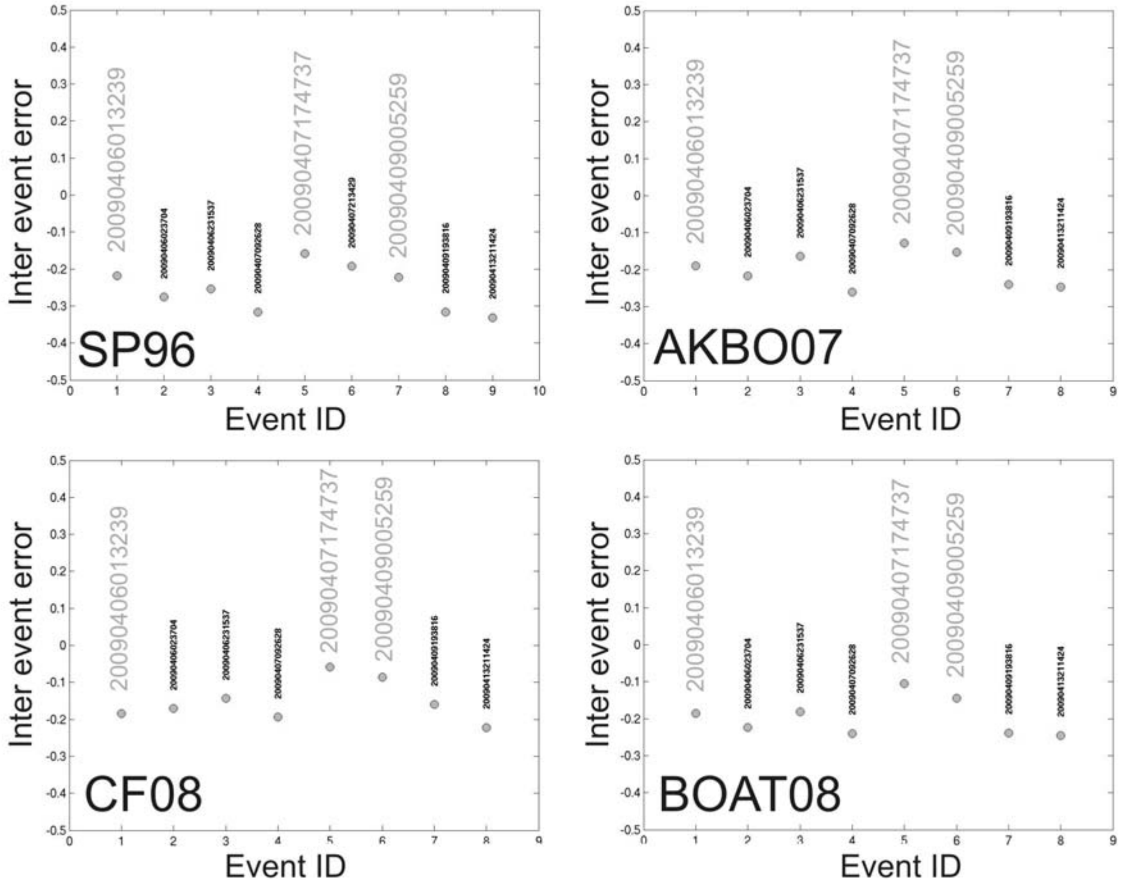

Figure 4 – Inter-event errors for PGA (grey circles) related to the L'Aquila sequence obtained analysing the predictive models considered in this study (the results for ITA08 are reported in the top right panel of figure 3). In grey the Mw 6.3 L'Aquila mainshock and the two strongest aftershocks (Mw 5.6 and 5.4) are indicated.

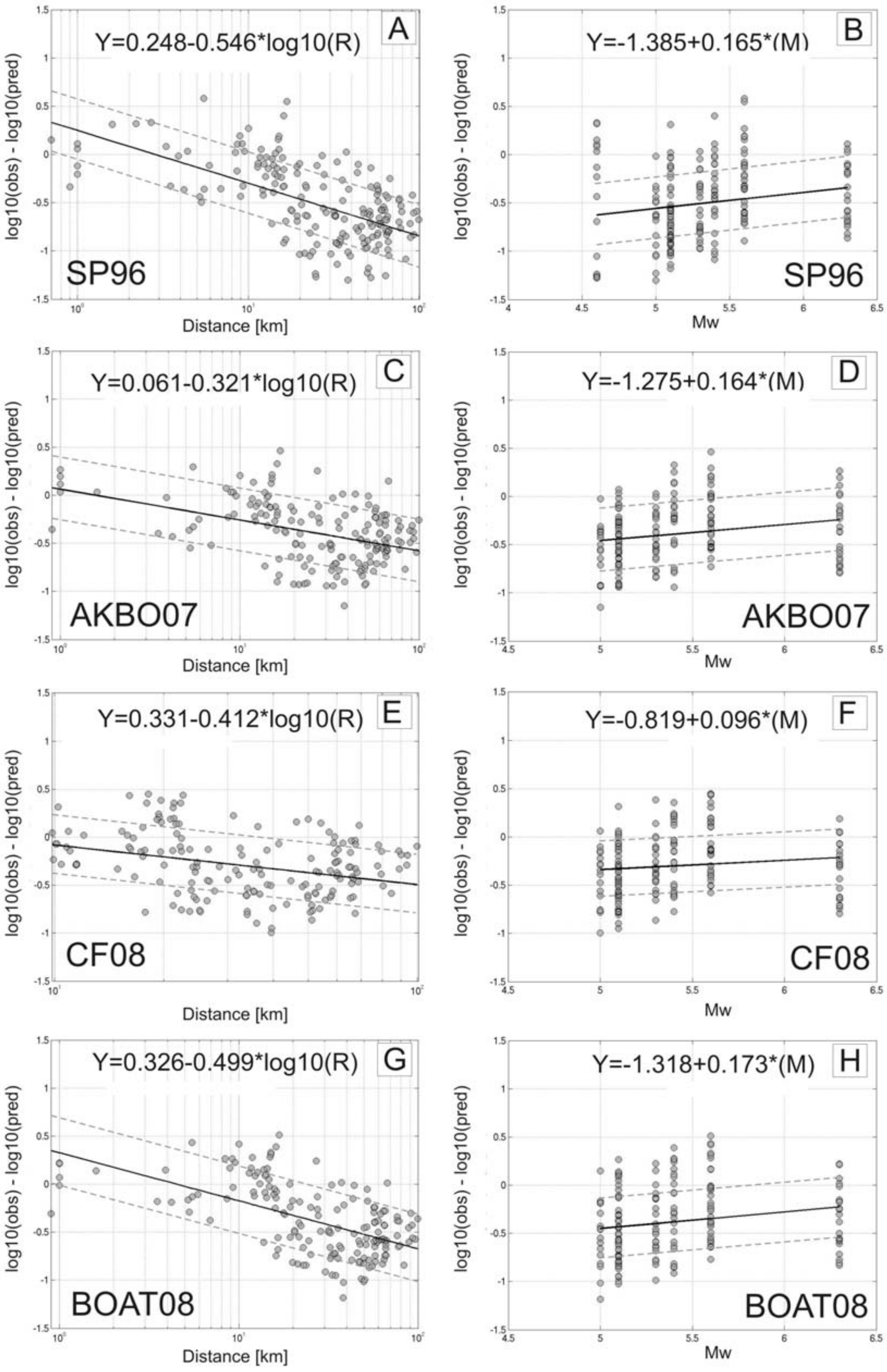

Figure 5 – Comparisons between the predicted values and the PGAs (maximum horizontal component for SP96 and geometric mean between the two horizontal components for the others GMPEs) recorded during the L'Aquila sequence (grey circles). In the left panels the residuals are plotted as a function of distance (hypocentral for CF08 and R_{jb} for the others GMPEs), while in the right panels as a function of Mw. The fit functions and related ± 1σ are represented by solid and dashed lines respectively. The results for ITA08 are reported in the bottom panels of figure 3.

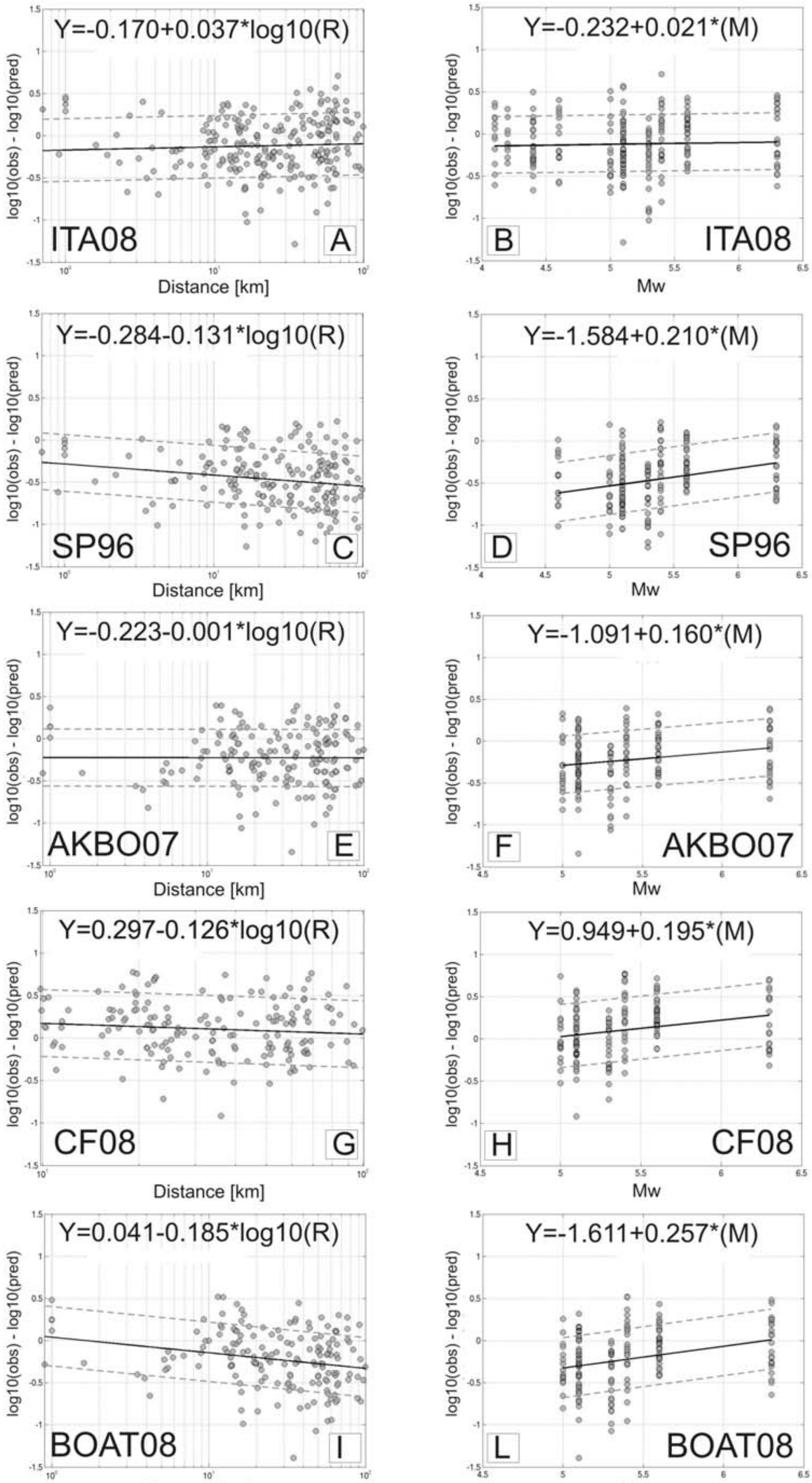

Figure 6 – The same as in figure 5 but for acceleration response spectra ordinates at 1.0 s.

Fit of the ITACA data set to the European and global GMPEs

The Italian strong-motion database, ITACA, was created in the framework of the research agreement between DPC and INGV and it is still in progress.

At present ITACA contains 2550 three-component waveforms, 1821 relative to 1002 earthquakes (maximum M_w=6.9 for the 23rd November 1980, Irpinia earthquake) occurred in the period 1972-2004, 363 of which relative to the 23rd December 2008, Mw 5.4 and Mw 4.9, Parma (Northern Italy) sequence and to the 6th April 2009, Mw 6.3, L'Aquila (Central Italy) sequence (13 events with Mw in the range 4.0-6.3). Acceleration, velocity and displacement time series and the acceleration response spectra (121 periods up to 4s, 5% damping) related to these records are downloadable from the web site http://itaca.mi.ingv.it. The magnitude values (M_w and/or M_L) range from 1.1 to 6.9 with the best sampled distance interval from 5 to 100 km (R_{jb} or R_{epi} for M < 5.5). To calculate R_{jb} distances the fault geometries data available in the DISS database (DISS Working Group, 2009; Basili et al., 2008) were considered. The focal mechanism were assigned to the seismic events following the classification described in Luzi et al. (2008). About 350 accelerometric waveforms have PGA > 50 cm/s^2 while 155 have PGV > 1 cm/s. The station STR (Sturno) recorded the largest PGV (70 cm/s) during the 23rd November 1980, Mw 6.9, Irpinia earthquake, while the largest PGA (670 cm/s^2) value was recorded during the strongest aftershock (7th April 2009, Mw 5.6) of the L'Aquila sequence at station MI05.

The strong-motion data collected in ITACA were recorded by 665 strong-motion stations, the majority belonging to the RAN network (managed by DPC). All stations are classified following the EC8 soil classes (CEN 2004). Where the Vs_{30} values were not available the stations were classified on the base of the geological information (S4 Project, Deliverable D4, 2009, http://esse4.mi.ingv.it).

The same approach used to compare the L'Aquila strong-motion data set to the GMPEs considered in this study, was adopted to verify the performance of the European (AKBO07) and global models (CF08 and BOAT08) in predicting the strong-motion data recorded in Italy from 1972. Magnitude and distance was selected according to the ranges of validity of each model (table 1). The main result is that the bias and the dependence of the residuals on distance and magnitude are lower than those obtained for the L'Aquila data set. At high frequencies (table 4 and figure 7 for PGA) the bias resulting from the European model (AKBO07) decreases from -0.391 to -0.123, but also the global models, in particular CF08, show a relevant decrease of the mean values of the residuals (from -0.382 to -0.132 for BOAT08 and from -0.301 to -0.064 for CF08). Concerning the distribution of the PGA-residuals with distance, the CF08 is the model that shows the best improvement, changing the slope of the fit-function from -0.412 (figure 5, panel e) to -0.081 (figure 7, panel c). BOAT08 confirms to have the highest dependence of the residuals with distance (slope -0.294, figure 7, panel e), although weaker than what obtained for the L'Aquila sequence (slope -0.499, panel g of figure 5). Considering the right panels of figure 7, the result is a general decrease of the residuals dependence with magnitude. Also in this case the CF08 (panel d) is the model that shows the lowest dependence (slope 0.052) whereas the BOAT08 is the model with the highest dependence (slope 0.083, panel f), although an improvement is obtained with respect to panel h of figure 5 (slope 0.173).

At higher periods both AKBO07 and BOAT08 improve their capacity of prediction, whereas the bias resulting from the CF08 shows an increase with increasing periods (see bias values in table 4 at 1.0 s and 2.0 s).

Considering the period of 1.0 s (figure 8) the European model (AKBO07) does not show particular dependence of the residuals with distance (slope -0.026, panel a), even if its negative bias (table 4) indicates a general overestimation of the predictions. A negligible dependence (slope -0.106, panel e) that leads to an increase of the overestimation of the predictions with increasing distance is still present for BOAT08, whereas an opposite trend is detected for CF08 (slope 0.143, panel c): in this case the positive bias (table 4) values obtained both for 1.0 s (0.311) and 2.0 s (0.214) periods indicate an underestimations of the predictions. Considering the dependence of the residuals with magnitude (right panels of figure 8), for all models there is an improvement with respect to the comparisons to L'Aquila sequence (from 0.160 to 0.113 for AKBO07, from 0.195 to 0.162 for CF08, from 0.257 to 0.164 for BOAT08), but also a significant increase of the magnitude dependence of the residuals if we compare the results obtained for 1.0 s to those obtained for PGAs (from 0.07 to 0.113 for AKBO074, from 0.052 to 0.162 for CF08, from 0.083 to 0.164 for BOAT08, see figures 7 and 8).

GMPE	Bias PGA (Hm)	Bias SA (1.0s)	Bias SA (2.0s)	Bias PGV
AKBO07	-0,123	-0,064	-0,098	-0,056
CF08	-0,064	0,311	0,214	/
BOAT08	-0,132	-0,036	-0,075	-0,049

Table 4 – Bias values obtained comparing the European (AKBO07) and global (CF08 and BOAT08) GMPEs to all data including in the ITalian ACcelerometric Archive at the end of 2009. The comparisons were made considering for each GMPEs the independent variables in their range of validity. CF08 not considers PGV.

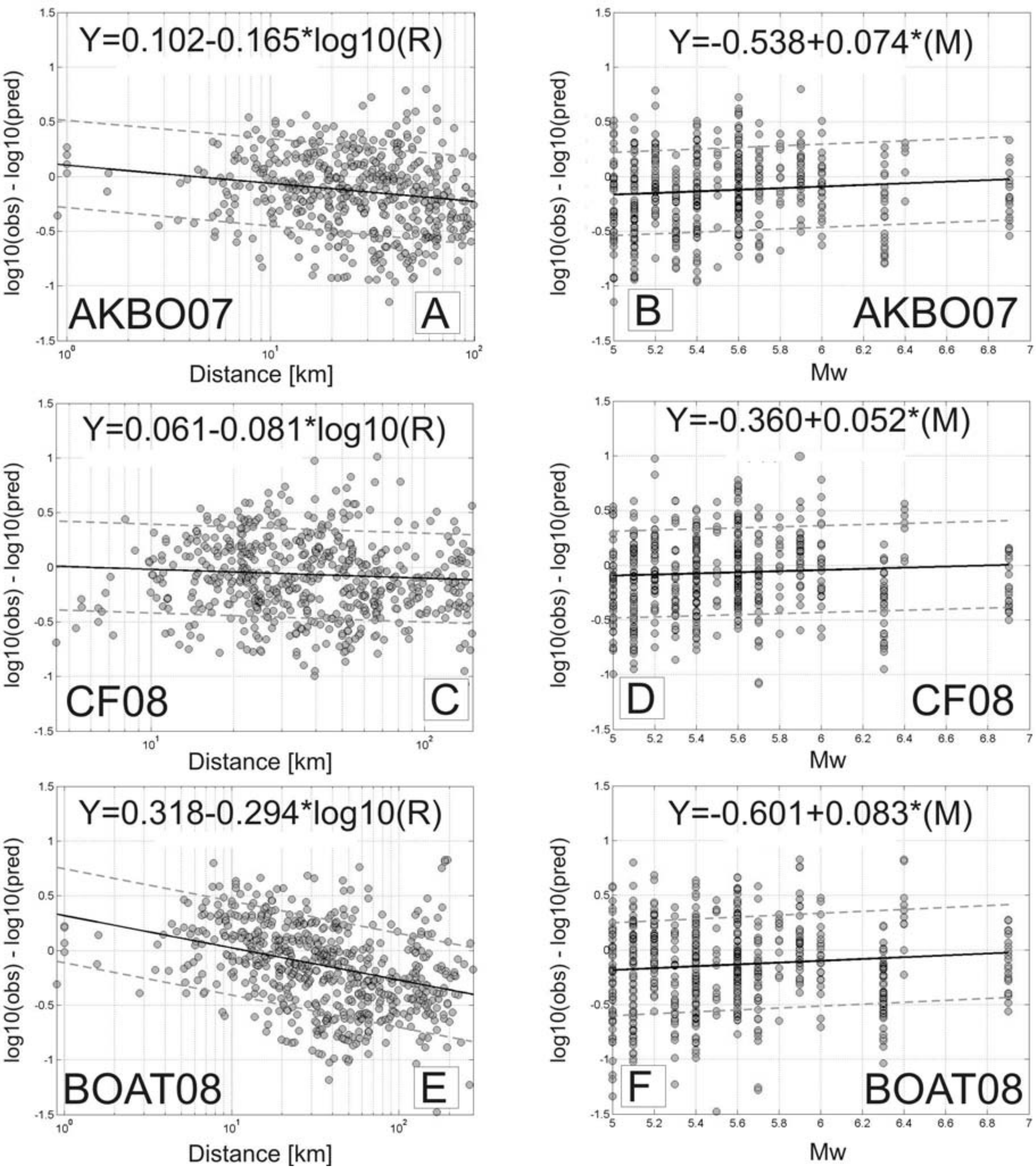

Figure 7 – Comparisons between the European (AKBO07) and global models (CF08 and BOAT08) predicted values and the PGAs (geometric mean between the two horizontal components) at present collected in the ITalian ACcelerometric Archive. In the left panels the residuals are plotted as a function of distance (hypocentral distance for CF08 and R_{jb} for AKBO07 and BOAT08), whereas in the right panels as a function of M_w. The fit functions and related ± 1σ are represented by solid and dashed lines respectively.

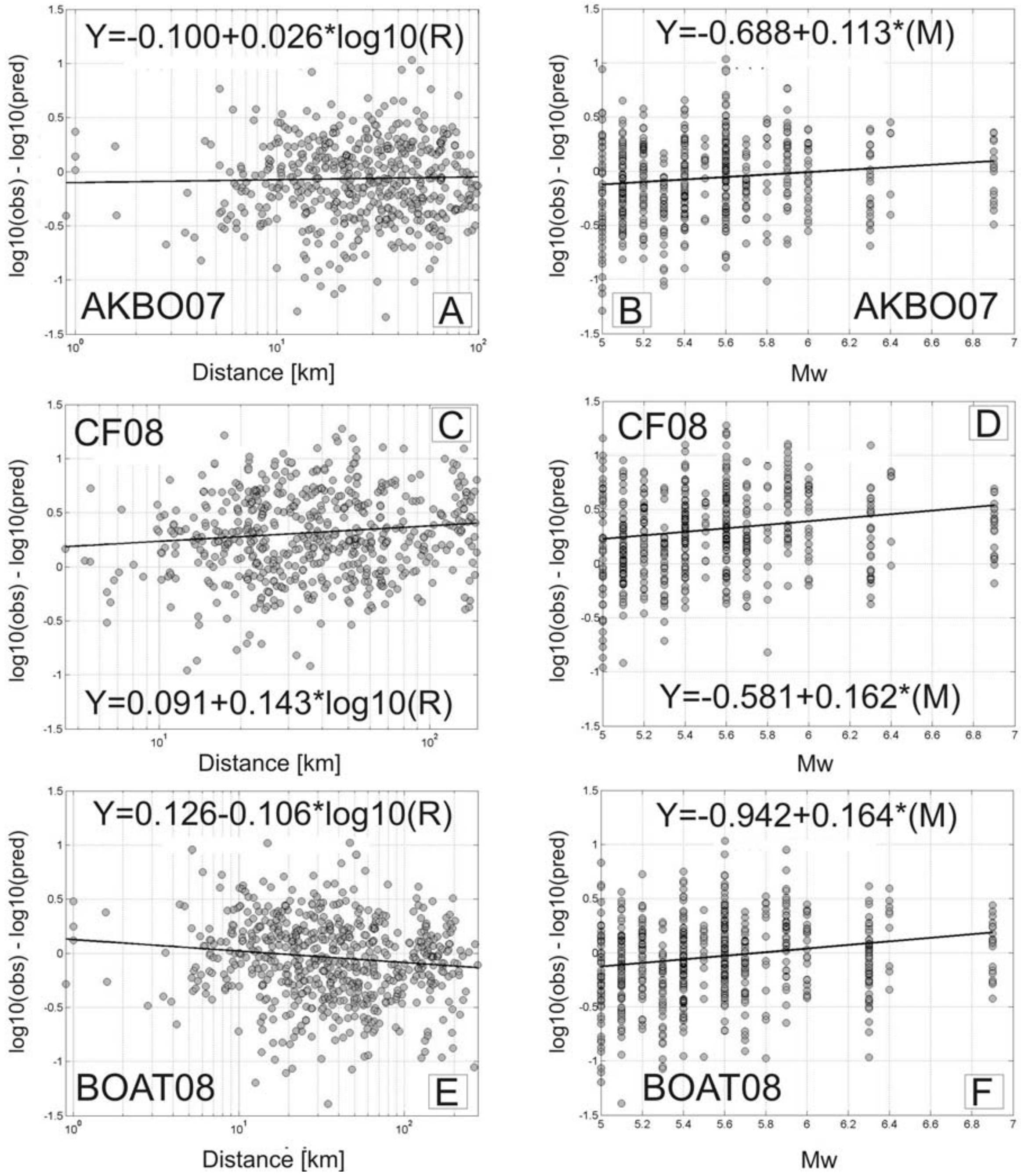

Figure 8 – The same as in figure 7 but for acceleration response spectra ordinates at 1.0 s.

Conclusion

The 6th April 2009 (M_w 6.3) L'Aquila earthquake, occurred in the central Italian Apennines, gave us the opportunity to validate the predictive capability of the newly developed Italian GMPEs (Bindi et al., 2009) and make some comparisons both to the older Italian models (Sabetta and Pugliese, 1996) and the recent predictive equations calibrated from European (Akkar and Bommer, 2007) and global data sets (Cauzzi and Faccioli, 2008; Boore and Atkinson, 2008).

The analyses were performed in two steps: at first the predictive models were compared to the records of the L'Aquila mainshock and 12 aftershocks with $M_w \geq 4.0$ recorded at R_{jb} (or R_{epi}) up to

250 km. In the second phase the comparisons were extended to all strong-motion data at present collected in the ITalian ACcelerometric Archive (ITACA http://itaca.mi.ingv.it, Luzi et al., 2008; Paolucci et al., 2010).

In general all models analysed in this study over predict the ground motions observed during the L'Aquila sequence, especially at high and intermediate (1.0 Hz) frequencies. The overestimation of the predictions for ITA08, AKBO07 and CF08, observed from distances higher than 10 km could be partially justified by the lack of the anelastic attenuation coefficient in the functional form of the considered GMPEs (see table 2). In particular the lack in SP96 of the magnitude dependent decay rate in the geometrical spreading attenuation term could be responsible of the higher overestimation of this model with respect to the other GMPEs calculated using the same type of distance. The one analysed model that include the anelastic attenuation term is BOAT08: the results obtained for the NGA predictions, even if in terms of bias values are comparable with the AKBO07 models (both for low and high frequencies, see table 3), show a significant dependence of the residuals distribution on distance, in particular for higher frequencies.

Considering all Italian strong-motion data, the European GMPEs (AKBO07) and also the global model developed for PGA by CF08 well fit the recorded values without showing particular dependence of the residuals on distance. In this way the best results were obtained for acceleration response spectral ordinate at 1.0 s for AKBO07 and for PGA considering the CF08 global model. On the contrary, also considering all Italian data the model calibrated by Boore and Atkinson (BOAT08) confirms, in particular for higher frequencies, the dependence of the residuals with distance, showing a negative slope of the fit-function that means underestimations in near-source area and overestimations for distances higher than 10 km. This general behaviour of the NGA models with respect to the Italian strong-motion data was already observed in Scasserra et al (2009).

Considering all analysed models, with the exception of CF08 for SA in the case of the whole ITACA database, both bias values and residual dependence with distance are weaker when we move from higher to lower frequencies: figure 6 and 8 and tables 3 and 4 confirm this result. Concerning the residuals dependence on magnitude, with the exception of ITA08 models, the other predictive equations show positive slopes of the residuals fit-functions that means over predictions that decrease with increasing magnitude: this phenomenon is more evident if we consider only the L'Aquila data set but more in general if we move from higher to lower frequencies. In this case an increase of magnitude dependence of the residuals is observed with the exception of ITA08 and AKBO07 models.

In general, the results obtained considering all Italian data with respect to the L'Aquila sequence, show a general decreasing both of the bias values and the dependence of the residuals on distance and magnitude. This evidence could be interpreted as a peculiarity of the waves propagation (or regional attenuation) of the Abruzzo region if compared to the worldwide areas

investigated to calibrate the others models (e.g. Japan for CF08, West Coast of United States for BOAT08, Europe and Middle East for AKBO07), in particular if we consider BOAT08 where no lacks in the functional form are present (table 2).
A preliminary attempt to evaluate the regional differences concerning the ground motion attenuation in Italy was made in a recent paper by Luzi et al. (2010): in that paper the authors demonstrate that, taking into account the different tectonic framework of each zone (homogeneous style of faulting), a distance metric that includes the source depths (hypocentral distance) and supposing an homogeneous site classification, no evident differences in ground motion attenuation were found for different areas of Italy (i.e. Eastern Alps and Northern Apennines, Central Apennines, strike slip areas of Southern Italy).
Thank to the 2007-2009 INGV-DPC agreement (S4 Project, url: http://esse4.mi.ingv.it), from May 2010 a new version of ITACA (Paolucci et al., 2010) is now available at the web site http://itaca.mi.ingv.it.
Using the new database, it will be possible to develop a revised version of ITA08 models, including a complete revision (in terms of processing) of data for the period 1972-2007 (including the 23rd December 2008 Parma earthquake and the April 2009 L'Aquila sequence) and a revised site classification based on EC8 code (CEN 2004).

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