Selection and ranking of ground motion models for seismic hazard analysis in the Pyrenees

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Abstract The issue addressed in this paper is the objective selection of appropriate ground motion models for seismic hazard assessment in the Pyrenees. The method of Scherbaum et al. (2004a) is applied in order to rank eight published ground motion models relevant to intraplate or to low deformation rate contexts. This method is based on a transparent and data-driven process which quantifies the model fit and also measures how well the underlying model assumptions are met. The method is applied to 15 accelerometric records obtained in the Pyrenees for events of local magnitude between 4.8 and 5.1, corresponding to moment magnitudes ranging from 3.7 to 3.9. Only stations at rock sites are considered. A total of 720 spectral amplitudes are used to rank the selected ground motion models. Some control parameters of these models, such as magnitude and distance definitions, may vary from one model to the other. It is thus important to correct the selected models for their difference with respect to the magnitude and distance definitions used for the Pyrenean data. Our analysis shows that, with these corrections, some of the ground motion models successfully fit the data. These are the Lussou et al. (2001) and the Berge-Thierry et al. (2003) models. According to the selected ground motion models, a possible scenario of a magnitude 6 event is proposed; it predicts response spectra accelerations of 0.08–0.1 *g* at 1 Hz at a hypocentral distance of 10 km.

Key words seismic hazard · ground motion models · acceleration response spectra · Pyrenees

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Introduction

The Pyrenean range is one of the most seismically active regions in France (Souriau and Pauchet 1998; Souriau et al. 2001). To perform seismic hazard assessments in the Pyrenees, there is a need for strong ground motion models which predict the expected distribution of ground motions at a site due to possible earthquake scenarios (e.g. Reiter 1990; Abrahamson and Shedlock 1997). In the best-case scenario, we would be able to derive an indigenous model. However, an accelerometric network was deployed only recently (between 2001 and 2004 in the Pyrenees), and the existing ground motion record dataset does not allow users to derive such a model, due to the lack of strong earthquakes.

We therefore propose to test if the models recently developed in other regions could be appropriate for this particular target region. Unless the prerequisites for "appropriateness" are defined very carefully and the reasoning for the selection process is fully documented step by step, the selection of candidate models becomes a very subjective process. Possible selection criteria such as the tectonic environment, the stress regime, and/or the propagation properties in the target region are often hard to quantify, and there is no common understanding about the relative importance of individual criteria (e.g., Cotton et al. 2006).

There is an additional related problem which is easily overlooked. The definition of control parameters in ground motion models such as magnitude and distance definitions usually vary between different models, which implies that users will have to correct the proposed models with their own distance metrics or magnitude definitions. There is therefore a need to not only judge the original models, but also the "corrected" ones in a consistent way. A more detailed discussion of these issues is given in Bommer et al. (2005).

The visual comparison between the observed spectra and the model predictions provides only a qualitative evaluation of the fit between data and model predictions. Scherbaum et al. (2004a) provide an example for how even a rather small data set of observed ground motion records in a region of interest (target region) can help to guide the selection of appropriate ground motion models in a systematic and comprehensible way. A key element in this method is a likelihood-based goodness-of-fit measure which has the property to quantify the model fit and also to measure to some degree how well the underlying statistical model assumptions are met. By design, it naturally scales between 0 and 1 with a value of 0.5 for a situation in which the model perfectly matches the sample distribution both in terms of mean and standard deviation. This data-driven evaluation allows users to measure the performance of the ground-motion model selection and particular conversions.

The goal of this paper is to provide new constraints on the selection of ground motion models for seismic hazard analysis in the Pyrenees by using a set of records of recent earthquakes. Since seismic hazard assessment is commonly conducted for rock site conditions, our analysis is focused on rock ground motion models. At the same time, we will show the importance of the conversion relationships between the different magnitude scales for a correct ground motion modelling.

After a brief description of the existing rock accelerometric dataset, we perform a pre-selection of eight candidate ground motion models. For simple practical reasons, e.g., considering the large number of potential candidate models, the selection process naturally starts with the identification of candidate models adapted for the Pyrenean context. The moment magnitudes of Drouet et al. (2006) are used to describe the Pyrenean earthquakes. Then, the candidate models are "corrected" for differences in their predictor variables in a consistent way following Bommer et al. (2005). Using the Scherbaum et al. (2004a) method categorization scheme, the "corrected" candidate ground motion models are finally ranked into a total of three different quality classes.

Data selection in the Pyrenees

The Pyrenean range results from the collision between the Eurasian and the Iberian plates, the North Pyrenean fault (Fig. 1) being the suture between the two plates. According to the NUVEL-1 model (De Mets et al. 1990), the convergence rate between Africa and Eurasia is 6 mm year^{-1}. However, since the deformation is distributed over a large area including the whole Spain (which is not assumed as a plate in the NUVEL-1 model), the convergence across the Pyrenees is assumed to be only of the order of 1 mm year^{-1}. A recent study using GPS array (Nocquet and Calais, 2003) gives an actual convergence rate of even lower values.

There is a seismic activity along the whole Pyrenean range but limited to small to moderate events (Souriau and Pauchet 1998; Souriau et al. 2001). Two local magnitudes are commonly used. The local magnitude computed by the Observatoire Midi-Pyrénées (M_{OMP}) is based on the maximum amplitude of the vertical record, with a decay curve adapted from the one valid for California. At a national level, the Laboratoire de Détection Géo-

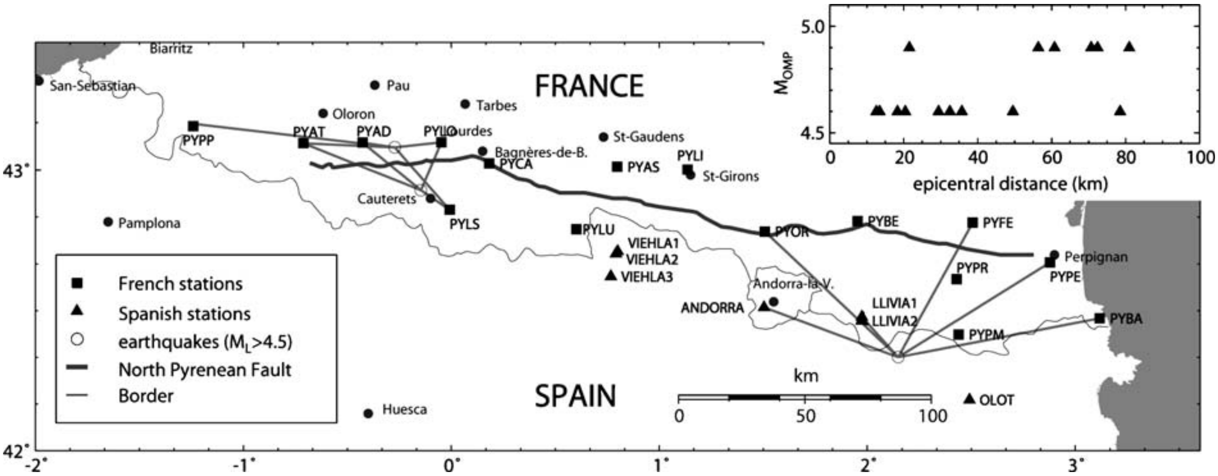

Fig. 1 Events and stations considered in this study, and paths effectively used (distance<100 km). The upper right box shows the epicentral distance vs. magnitude for the records used

physique of the Atomic Energy Commission uses a magnitude (M_{LDG}) based on L_g waves at distances ranging from 100 to 500 km, with a distance correction valid for the whole French territory. On a historical time scale, large earthquakes have been reported. From 1373 to 1967, eight earthquakes with epicentral intensity greater than VIII are reported in Lambert and Levret-Albaret (1996). These earthquakes are supposed to be equivalent to magnitude 6 events (Marin et al. 2004). Therefore, the earthquake hazard assessment is of great importance in this region.

Since 1996, the French Accelerometric Network has been operating in France, but the 18 Pyrenean stations have been set up only since 2001. The site classification for these stations is based on superficial geological considerations. On the Spanish side of the range, especially in Catalonia, a few more accelerometers are running. In the present study, we use the largest earthquakes recorded in the Pyrenees since 2001. To stay within the magnitude range of the different candidate ground motion models, we have selected earthquakes with magnitude (M_{OMP}) larger than 4.5. For these earthquakes, we only kept the records corresponding to stations located on rock sites or stiff soil sites and to hypocentral distances less than 100 km. A list of the stations together with their site characteristics is provided in Table 1. We obtained 15 records for three earthquakes (Table 2), with paths equally well distributed in Eastern and Western Pyrenees (Fig. 1). Response spectra with 5% damping have been computed between 0.5 and 24 Hz, with steps of 0.5 Hz. In order to use a single horizontal component, the geometrical mean between the east and north components has been computed. We obtained 720 data points (number of records * number of frequencies) for analysis of the residuals between the data and predictions from the ground motion models.

Pre-selection of the ground motion models

Due to the improvement and expansion of strong motion networks, the number of empirical ground motion models has increased considerably in the past decade. Douglas (2003) summarized more than 120 studies that have derived equations for the estimation of peak ground acceleration and 80 studies that derived equations for the estimation of response spectra. Starting from a comprehensive list of available equations, we then applied criteria for rejecting those considered as inappropriate in terms of quality, derivation or applicability (Cotton et al. 2006). Models from a clearly irrelevant tectonic regime, or not published in an international peer-reviewed journal, or with a frequency range not appropriate for engineering application have been rejected.

After this pre-selection phase, the next stage is to consider geophysical criteria regarding the degree of similarity between the host regions from where the candidate models have been derived, and the Pyr-

Table 1 Stations used in the present study

Station	Latitude (°)	Longitude	Altitude (m)	Site condition
French stations				
PYAD	43.097	−0.426	450	Rock
PYAT	43.095	−0.711	340	Rock
PYBA	42.474	3.117	70	Rock
PYFE	42.814	2.507	280	Stiff soil
PYLO	43.098	−0.048	410	Rock
PYLS	42.860	−0.009	770	Rock
PYPE	42.673	2.878	100	Stiff soil
PYOR	42.783	1.507	230	Rock
PYPP	43.163	−1.232	230	Rock
Spanish stations				
Andorra	42.513	1.504	1078	Rock
Llivia 1	42.479	1.974	1413	Rock

enees. This involves identifying the key geophysical parameters that characterize the host and Pyrenees regions. Slip and deformation rates in the Pyrenees area are less than 1 mm year^{-1}, implying very long recurrence times. According to the Scholz et al. (1986) classification, this area constitutes a plate boundary related area. Since regional average stress drop may increase with average recurrence time, large stress drops – and large variations in stress drops – cannot be excluded. Various source mechanisms are obtained for the Pyrenean events (Souriau et al. 2001). In order to cover the corresponding epistemic uncertainty, spectral attenuation relations for various types of source properties need to be used. According to Mooney et al. (1998), our target region belongs to the 'orogen' type. L_g wave studies in the Pyrenees (e.g., Campillo et al. 1985; Campillo and Plantet 1991) show that the attenuation in this region lies between the values typical of active and stable regions, as inferred by tomographic images of broad-scale variations L_g coda Q (e.g., Singh and Herrmann 1983; Mitchell et al. 1997).

Following the criteria based on the tectonic environment, stress regime, and/or the propagation properties, eight models have been selected. A first set of models is provided by European 'plate boundary related' empirical models (Sabetta and Pugliese 1996; Ambraseys et al. 1996; Berge-Thierry et al. 2003). Worldwide models or western US models are based on better data quality, near source, larger magnitude coverage or better site categorization (Abrahamson and Silva 1997; Campbell and Bozorgnia 2003). The Lussou et al. (2001) model for shallow Japanese events is also based on a large data set. Relations developed for eastern North America, notably those reported by Atkinson and Boore (1997), cannot be excluded because of low deformation rates. There is also a need to evaluate if the ground motion from strong earthquakes can be correctly predicted by models derived from weak motion data. To this purpose, the Bay et al. (2003) model developed for Switzerland has been included in the ground motion selection. These eight candidate models are described in Table 3. All these models

Table 2 Earthquakes selected for this study (M_L> 4.5) and number of records used (distance less than 100 km)

Earthquake	Latitude (°)	Longitude (positive east) (°)	Depth (km)	M_L		No. of records (distance < 100 km)
				M_{OMP}	M_{LDG}	
1: 05/16/2002 14 h 56 m	42.929	−0.146	9.5	4.6	4.8	4
2: 12/12/2002 17 h 59 m	43.080	−0.272	8.8	4.6	4.9	5
3: 09/21/2004 15 h 48 m	42.335	2.148	3.7	4.9	5.1	6

M_{OMP} and M_{LDG} are two different local magnitudes

Table 3 Data coverage and parameters definitions of the selected empirical models

	Magnitude definition	Horizontal component definition	Distance definition	Dataset magnitude range	Dataset distance range	Frequency range	Area and time coverage of dataset
Abrahamson and Silva (1997)	M_w	Geometric mean	R_{rup}	4.4–7.4	3–150	0.2 –100	Worldwide (90% WNA) 1940–1994
Ambraseys et al. (1996)	M_s	Larger envelope	R_{jb} *Repi* (M_s<6)	4.0–7.0	0–260	0.5–10	Europe Middle East 1969–1994
Atkinson and Boore (1997)	M_w	Random	R_{hypo}	4.0–7.25	10–500	0.5–20	ENA (point source simulations)
Bay et al. (2003)	M_w	Transverse component	R_{hypo}	2.0–5.2	10–300	0.5–20	Europe (Germany, Switzerland) 1984–2000
Berge-Thierry et al. (2003)	M_s	East and North	R_{hypo}	4.0–7.3	4–330	0.1–33	Europe (17%) California 1952–1997
Campbell and Bozorgnia (2003)	M_w	Geometric mean	R_{seis}	4.7–7.7	3–60	0.25–20	Worldwide 1957–1997
Lussou et al. (2001)	M_{jma}	East and North	R_{hypo}	3.7–6.3	10–200	0.1–50	Japan 1996–1998
Sabetta and Pugliese (1996)	M_s and M_l	Larger PGA	R_{jb}	4.6–6.8	0–100	0.25–25	Italy 1976–1984

M_{jma}: Japanese Meteorological Agency magnitude; R_{rup}: rupture distance; R_{jb}: Joyner–Boore distance; R_{epi}: epicentral distance; R_{hypo}: hypocentral distance; R_{seis}: distance to seismogenic part of the rupture; ENA: eastern North America; WNA: western North America.

have been previously used and tested in recent ground motion evaluations. At this stage, we ignored the fact that some of these models do not fully cover the frequency range between 0.5 and 25 Hz, the magnitude range down to 4.5 and a distance range up to 100 km.

This article focuses on "rock" ground motion, which is often used as reference motion in seismic hazard projects. However, the geotechnical or geophysical characterization of the so-called rock site stations is usually rather poor, and geologically defined rock can be affected by weathering (Steidl et al. 1996; Boore et al. 1997). All the models are used with equations corresponding to rock sites; however, the definition of "rock" used in each of the equations is different (see Table 2 of Cotton et al. 2006).

Magnitude and distance conversions

As magnitude and distance definitions vary between different models, we first have to correct the proposed models with our own distance metrics or magnitude definitions. We will rank both the original models and the "corrected" ones in a consistent way in order to show the impact of the corrections.

Most of the seismic hazard analyses are based on moment magnitude earthquakes catalogues. Moment magnitudes are taken from Drouet et al. (2006), who used a simultaneous inversion of source, path and site parameters to determine these magnitudes. The earthquakes we used have M_w in a narrow range, from 3.7 to 3.9. Since all the ground motion models which require a conversion from moment magnitude to surface wave magnitude are "European", we then used the Ambraseys and Free relation (without depth dependence) (Ambraseys and Free, 1997). For the conversion to JMA magnitude which is used by Lussou et al. (2001), we assumed a one-to-one relationship to M_w as suggested by Heaton et al. (1986). The same was done for the local magnitudes of Sabetta and Pugliese (1996), which according to Sabetta (personal communication, 2002) do not require any conversion. The component conversions into a single horizontal component were based on the empirical relationships determined by Bommer et al. (2005).

The use of different measures of the distance from the source of seismic energy release to the location of the accelerometric station in the candidate prediction equations is probably an important incompatibility among the various models, particularly at short distances. The distance metrics used in the selected models includes: the hypocentral distance (R_{hyp}), the epicentral distance (R_{epi}), the closest horizontal distance to the vertical projection of the rupture (R_{jb}), the closest distance to the seismogenic part of the rupture (R_{seis}) and the closest distance to the rupture surface (R_{rup}). The issue of obtaining compatibility amongst ground motion prediction equations using different distance metrics has been addressed in detail by Scherbaum et al. (2004b), to which the reader is referred. However, in our case, as earthquakes are of moderate size and superficials, the distance conversion has only a small effect as will be shown below.

Ground motion model ranking

Following the approach of Scherbaum et al. (2004a), we use a statistical analysis of the normalized differences between data and model predictions (residuals) in order to rank the different ground motion models. The input quantity of the study is the difference between the logarithms of the data values and logarithmic-model predictions, divided by the corresponding standard deviations of the logarithmic model. Ideally, this should result in residuals that are normally distributed with zero mean and unit variance.

This method assumes that each ground motion model can be described by a lognormal distribution. Scherbaum et al. (2004a) developed a new goodness-of-fit measure that they called LH, which quantifies the model fit, as well as the underlying statistical assumptions (i.e., the lognormal distribution). An LH distribution is drawn from the residual distribution. Scherbaum et al. (2004a) used the median to quantify the properties of the distribution of LH values in a single number, mainly because of its stability regarding outliers. In the case in which the residual distribution is gaussian with unit variance, the median LH equals 0.5; if the residual distribution does not match the mean or the spread of the gaussian, the median LH value departs from 0.5.

Ranking of the different models is then based on the LH median value together with the mean, median, and standard deviation of the residuals. This allows users to characterize the central tendency, as well as the spread of the distribution (which takes into account the informativeness of a model). The data are resampled by removing either a particular frequency in each spectrum, or a whole spectrum among the 15 which are available. The ranking parameters are then recomputed in order to estimate their variances. The square root of the sum of the variances after these two resamplings is assumed to be an estimate of the overall standard deviation.

Scherbaum et al. (2004a) applied this analysis to the residual distributions generated with the eight ground motion models and their original data, and finally defined the following ranking scheme:

- Class (C) (the lowest acceptable one) – a median LH value of at least 0.2 is required, with the absolute value of mean and median of the normalized residuals, and their standard deviation smaller than 0.75. In addition, the normalized sample standard deviation is required to be smaller than 1.5.
- Class (B) – a median LH value of at least 0.3 is required, with the absolute value of mean and median of the normalized residuals, and their standard deviation smaller than 0.5. In addition, the normalized sample standard deviation is required to be smaller than 1.25.
- Class (A) – a median LH value of at least 0.4 is required, with the absolute value of mean and median of the normalized residuals, and their standard deviation smaller than 0.25. In addition, the normalized sample standard deviation is required to be smaller than 1.125.

A model that does not meet the criteria for any of these categories is ranked unacceptable or class (D).

Ranking using $M_L=M_w$

In a first test, we compute the ground motion models by using the two local magnitudes M_{OMP} and M_{LDG} as input. Figure 2 shows the observed spectra together with the eight ground motion models computed with the magnitude M_{OMP}. The ground motion predicted by the classical models is clearly overestimated regardless of the magnitude type used (M_{OMP} or M_{LDG}), as shown in Fig. 2 and by the residual distributions in Fig. 3. The values of the LH measure (MEDLH), the median (MEDNR), the mean (MEANNR), and the standard deviation (STDNR) of the normalized residual distribution as well as the standard deviations for all these quantities are given in Table 4. The central tendency is over-estimated,

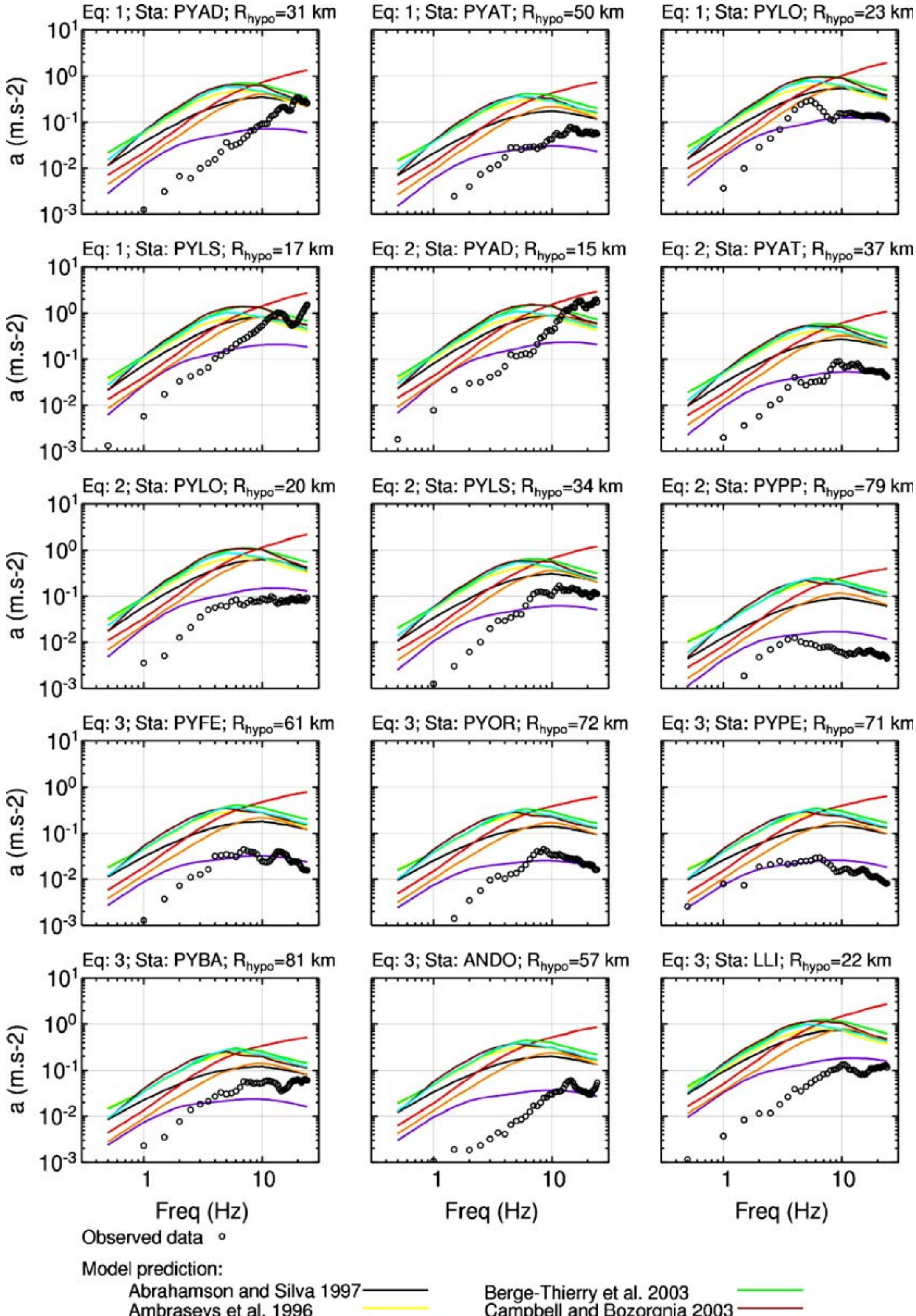

Fig. 2 Comparison of the observed spectra with the model predictions using the magnitude M_{OMP}

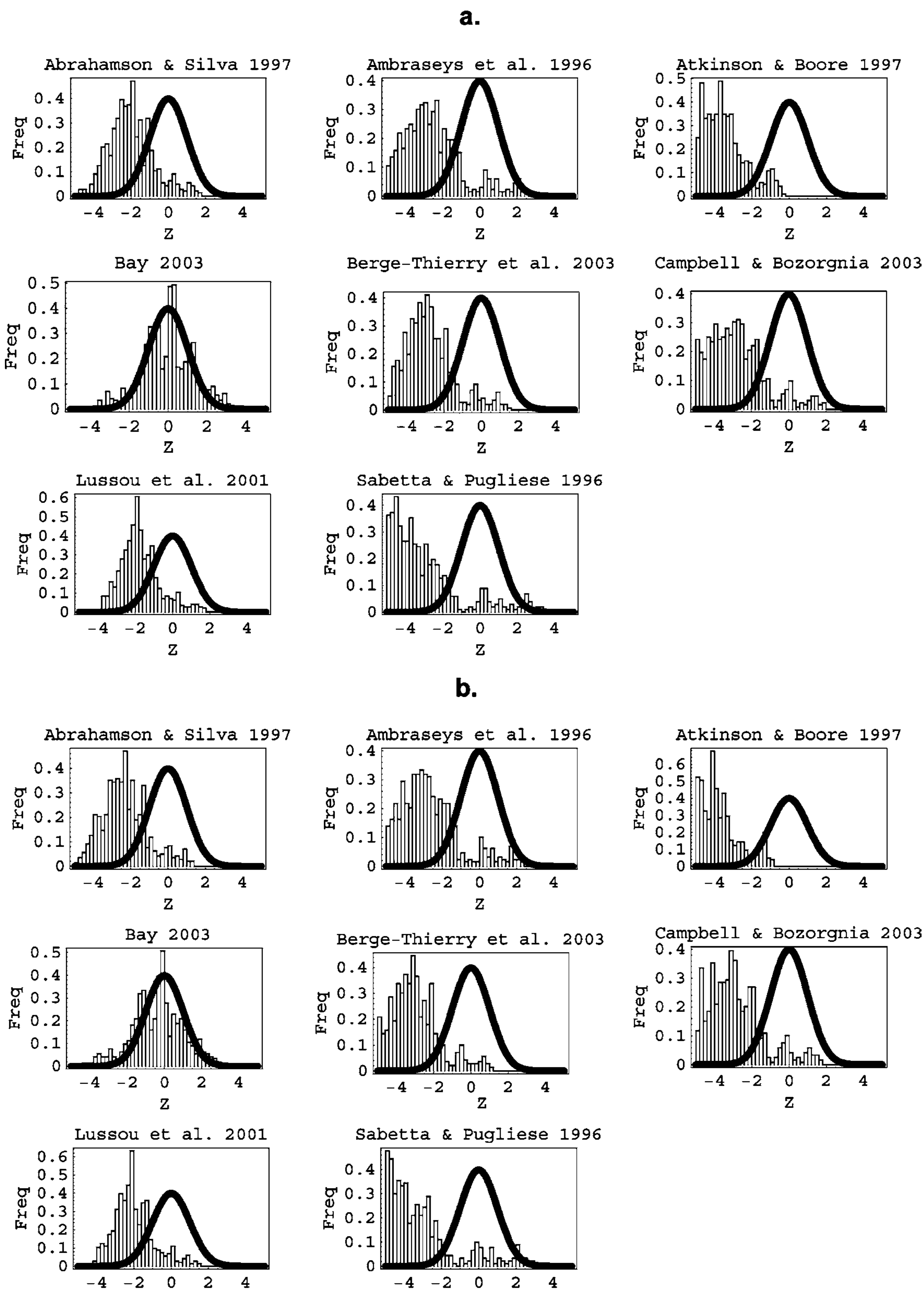

Fig. 3 Residuals (*z*) using two different local magnitudes: (a) M_{OMP}, (b) M_{LDG}, compared with a gaussian distribution with unit variance (black curve)

Table 4 Models ranking and statistical parameters

Modelname	Input M	Rank	MEDLH	σ	MEDNR	σ	MEANNR	σ	STDNR	σ
Abrahamson and Silva (1997)	M_{OMP}	D	0.040	0.010	−2.06	0.100	−1.97	0.162	1.19	0.15
	M_{LDG}	D	0.016	0.005	−2.41	0.107	−2.33	0.167	1.25	0.15
	M_w	D	0.352	0.056	−0.804	0.049	−0.677	0.123	1.03	0.130
Ambraseys et al. (1996)	M_{OMP}	D	0.004	0.003	−2.91	0.251	−2.73	0.26	1.7	0.241
	M_{LDG}	D	0.002	0.002	−3.11	0.233	−2.96	0.256	1.72	0.237
	M_w	D	0.261	0.034	−0.755	0.311	−0.556	0.236	1.56	0.222
Atkinson and Boore (1997)	M_{OMP}	D	0.0001	0.0001	−3.83	0.219	−3.81	0.228	1.33	0.151
	M_{LDG}	D	0.00002	0.00003	−4.25	0.322	−4.25	0.217	1.33	0.151
	M_w	D	0.052	0.026	−1.94	0.243	−1.91	0.219	1.38	0.128
Bay et al. (2003)	M_{OMP}	C	0.385	0.056	0.061	0.088	−0.022	0.130	1.32	0.121
	M_{LDG}	C	0.335	0.05	−0.311	0.06	−0.42	0.124	1.36	0.121
	M_w	D	0.105	0.010	1.62	0.048	1.67	0.110	1.10	0.113
Berge-Thierry et al. (2003)	M_{OMP}	D	0.003	0.002	−2.94	0.148	−2.8	0.194	1.32	0.191
	M_{LDG}	D	0.002	0.001	−3.17	0.162	−3.03	0.19	1.33	0.188
	M_w	C	0.333	0.046	−0.667	0.199	−0.505	0.199	1.30	0.193
Campbell and Bozorgnia (2003)	M_{OMP}	D	0.002	0.002	−3.11	0.242	−3.01	0.215	1.63	0.203
	M_{LDG}	D	0.001	0.001	−3.36	0.246	−3.32	0.218	1.71	0.206
	M_w	D	0.032	0.012	−2.11	0.163	−2.01	0.177	1.38	0.188
Lussou et al. (2001)	M_{OMP}	D	0.059	0.016	−1.89	0.115	−1.74	0.161	1.05	0.15
	M_{LDG}	D	0.034	0.007	−2.13	0.087	−2.0	0.156	1.07	0.147
	M_w	B	0.475	0.045	−0.5	0.129	−0.375	0.159	1.04	0.142
Sabetta and Pugliese (1996)	M_{OMP}	D	0.00002	0.00005	−4.21	0.407	−3.86	0.353	2.2	0.347
	M_{LDG}	D	0.000006	0.00001	−4.51	0.367	−4.19	0.347	2.2	0.342
	M_w	D	0.002	0.002	−3.02	0.302	−2.75	0.301	2.09	0.314
Ranking values		A	>0.4		<0.25	<0.25	<0.25	<0.25	<1.125	
		B	>0.3		<0.5	<0.5	<0.5	<0.5	<1.25	
		C	>0.2		<0.75	<0.75	<0.75	<0.75	<1.5	
		D	UNACCEPTABLE							

For each model, the three lines indicate the results using different magnitudes as input parameter for the models computations

MEDLH: median LH value; MEDNR: median of the residual distribution; MEANNR: mean of the residual distribution; STDNR: standard deviation of the residual distribution

indicating that the magnitude used to compute the models is also over-estimated. The only model that does not over-estimate the data is the Bay et al. (2003) model, which is ranked C. For this model based on data from moderate magnitude earthquakes in Switzerland, the central tendency of the residuals is close to 0. However, considering Fig. 2 and the rather low LH value, we observe that the shape of the spectra is not well predicted.

Ranking using M_w

Instead of using the local magnitudes as the input, moment magnitudes are taken using the results of Drouet et al. (2006). The moment magnitudes for the three earthquakes are 3.7, 3.7 and 3.9. As can be seen in Figs. 4 and 5, the central tendency of the residual distribution tends to 0; however, these distributions are still not clearly gaussian. In our case, the distance conversion has only a small effect on the results and the ranking does not change before or after the conversions, as only three records are at distance less than 20 km. Figure 6 shows the effect of the magnitude and distance conversions one after the other on the residuals computed with the Abrahamson and Silva (1997) model, and emphasizes the fact that the magnitude conversion has considerably more effect than the distance conversion in our case.

The goodness of fit is increased and some models are compatible with the observations (i.e., ranked B or C, see Table 4). The Lussou et al. (2001) model is ranked B, and the Berge-Thierry et al. (2003) model

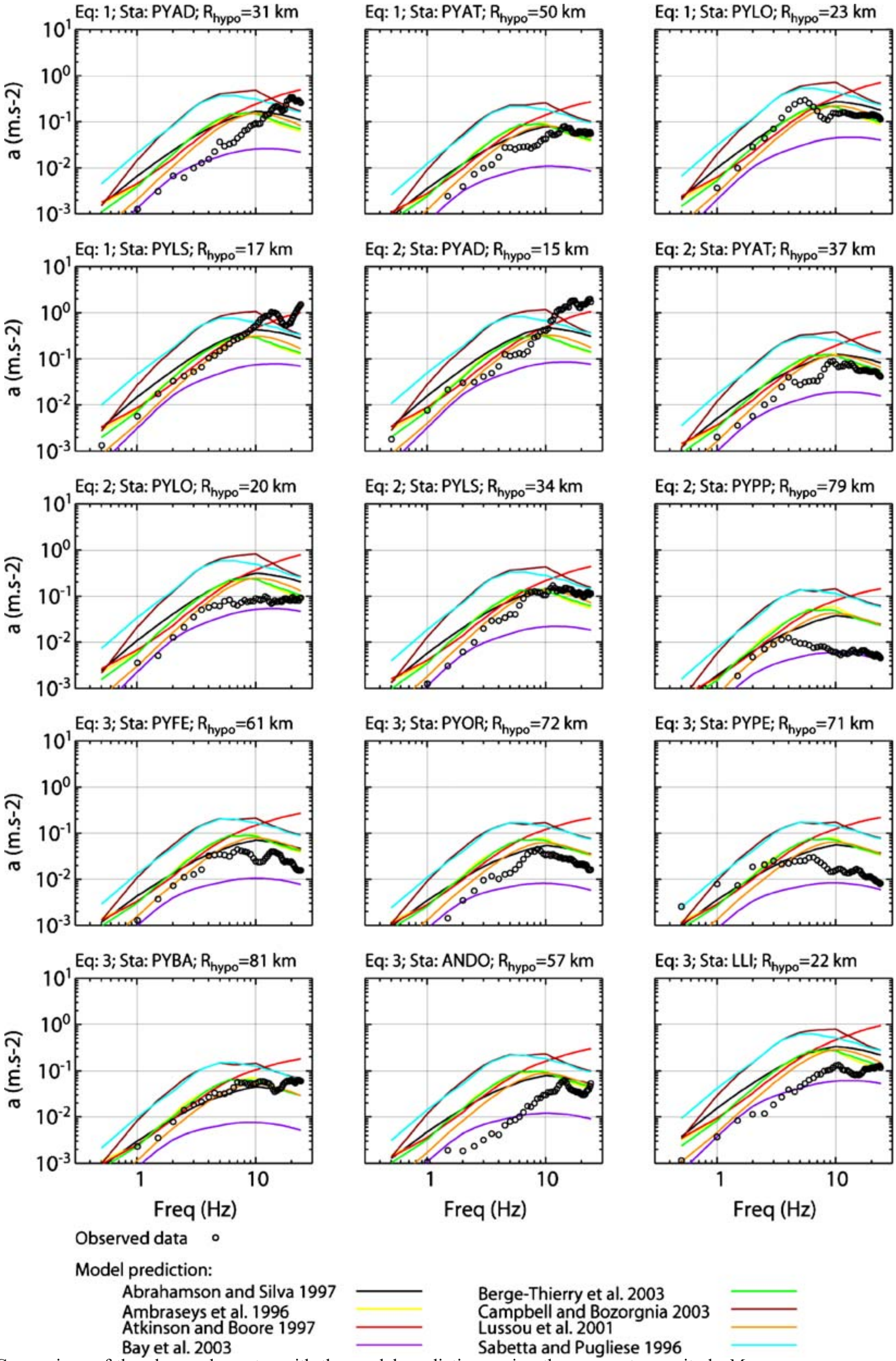

Fig. 4 Comparison of the observed spectra with the model predictions using the moment magnitude M_w

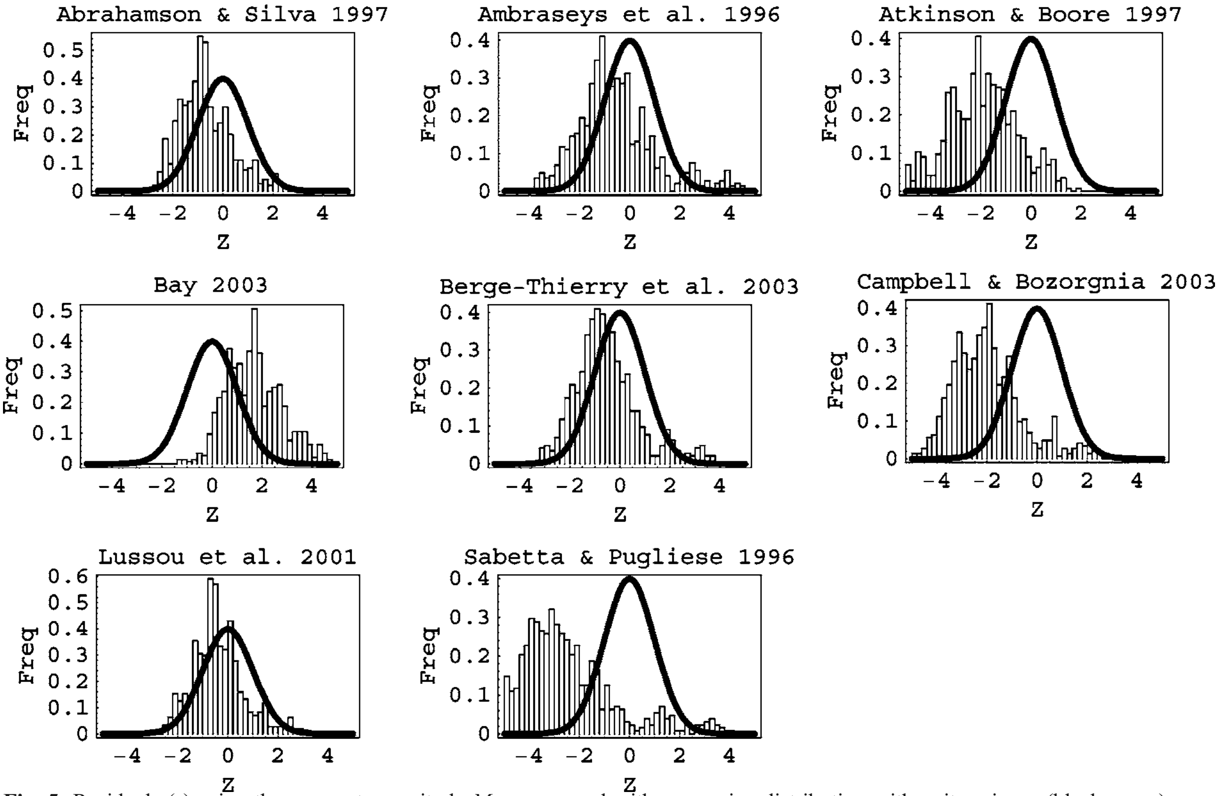

Fig. 5 Residuals (z) using the moment magnitude M_w, compared with a gaussian distribution with unit variance (black curve)

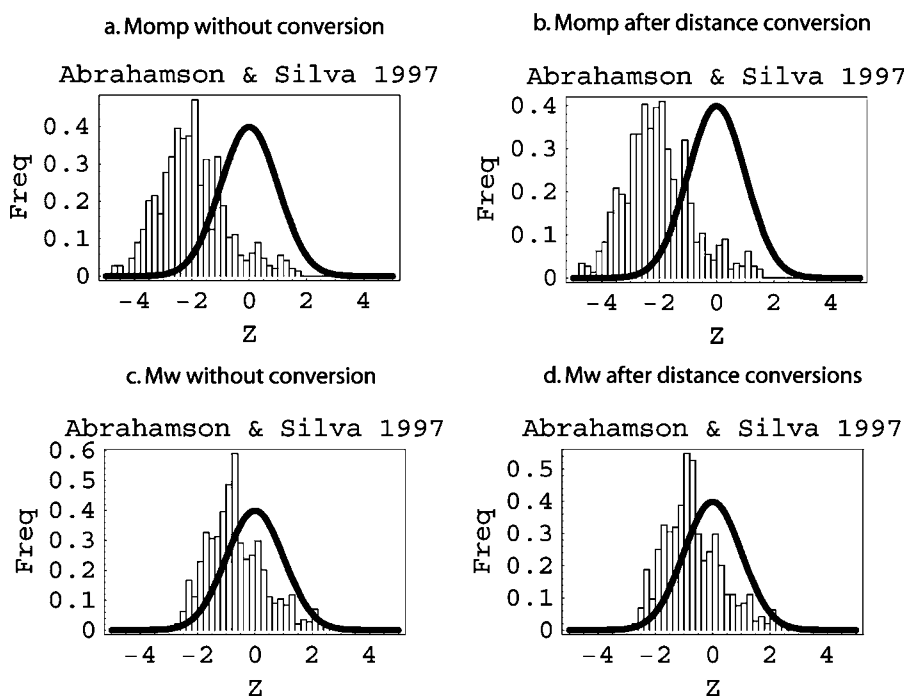

Fig. 6 Influence of the distance conversion on the residuals computed with the Abrahamson and Silva (1997) model. Residuals using M_{OMP} (a) without and (b) with distance conversion. Residuals using M_w (c) without and (d) with distance conversion. Panels (b) and (d) are identical to the residual distributions in Figs. 3 and 5

is ranked C. The latter overestimates the central tendency of the ground motion, has a rather low LH value, and a high standard deviation – indicating that the shape of the spectra is not well predicted. On the other hand, the Lussou et al. (2001) model also over-predicts the ground motion, but has a high LH value and a low standard deviation. One surprising feature is the poor rank obtained by models specifically derived for Europe (Sabetta and Pugliese 1996; Ambraseys et al. 1996).

Large earthquake scenario

Once the ground motion models applicable in the Pyrenees are determined, we can use them to predict the ground motion in case of a large earthquake. To this end, we first have to determine a realistic earthquake scenario. We focus on the city of Lourdes, which is an important place of pilgrimage with more than 5 million visitors each year. It has been damaged by earthquakes several times, in particular in 1660 and 1750 (Lambert and Levret-Albaret 1996). These two events occurred within 5–20 km from the city with MSK intensities IX and VIII, respectively, corresponding to a maximum magnitude of 6 (Marin et al. 2004). Thus we adopt as a probable scenario an earthquake with moment magnitude 6 at a hypocentral distance of 10 km. We must keep in mind that our selection of “best models” was made from events with much lower M_w values. However, this simulation may give an estimate of the expected ground motion, which will have to be refined when larger events will have been recorded.

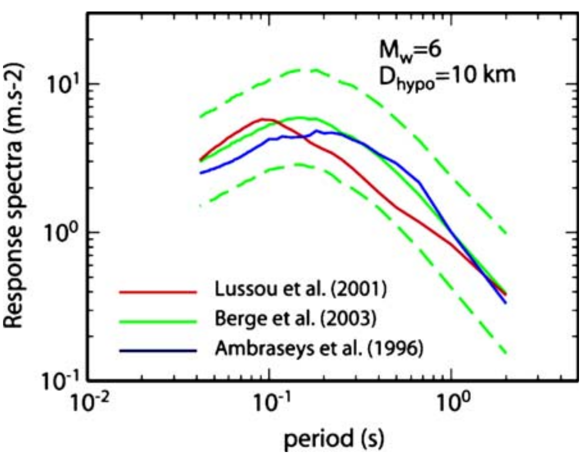

Fig. 7 Response spectra predicted for a realistic large earthquake scenario (M_w=6, D_{hypo}=10 km) using the ground motion models (median values) relevant for the Pyrenees. Distance conversions have been applied to compute the response spectra. The dashed lines indicate the standard deviation associated with the Berge-Thierry et al. (2003) model

We compute the response spectra predicted by the models which were ranked as acceptable in the previous section (i.e., Lussou et al. 2001; Berge-Thierry et al. 2003), taking into account the magnitude and distance conversions. We also add the Ambraseys et al. (1996) model because it is used as well as the Berge-Thierry et al. (2003) model in the seismic hazard studies in France. The results displayed in Fig. 7 show that the best-ranked models in the above selection give different results in term of median value. However, all the models lay within the domain defined by the standard deviation associated with the Berge-Thierry et al. (2003) model. This suggests that even with a small data set, one can reduce the epistemic uncertainty (associated with the models). At a period of 0.1 s (10 Hz), the ground motion on rock sites may reach 0.4–0.6 g (where g is the earth’s gravitational acceleration), and at a period of 1 s (1 Hz) we obtain accelerations between 0.08 and 0.1 g. This result is consistent with the study of Dubos et al. (2004), who obtained a horizontal acceleration of 0.1 g in the frequency range 1–5 Hz for a similar scenario.

Discussion and conclusions

This study is aimed at the determination of ground motion models applicable for the Pyrenean region. For a model to be applicable, it has to predict the central tendency of the ground motion, as well as the internal variability of ground motion. One of the limitations of this study is the number of data: only 15 records for three earthquakes were available. Moreover, the magnitude range is very limited (M_w=3.7–3.9). However, as we consider the residuals between data and models at each frequency, the number of data points (residuals) is equal to 720. Even in the absence of strong ground motion records, the method of Scherbaum et al. (2004a) allows the use of a small number of data to test the applicability of some ground motion models.

This study confirms that local magnitudes are too high to be used with the ground motion models; in other words, the relationship M_L=M_w should not be used, as it is sometimes done in France due to the lack of moment magnitudes determinations. Braunmiller et al. (2005) also observed from Swiss data that the LDG magnitude is higher than moment magnitude by about 0.6 units.

We obtain two models that meet the criteria to explain the currently existing moderately strong ground motion in the Pyrenees: Lussou et al. (2001) and Berge-Thierry et al. (2003). The other ground motion models always over-predict the observed records. A similar effect has been observed for the Atkinson and Boore (1997), Bay et al. (2003) and Sabetta and Pugliese (1996) models after the Saint-Dié earthquake (Scherbaum et al. 2004a). The Atkinson and Boore (1997) intraplate model derived for eastern North America does not seem appropriate, which is not surprising since the Pyrenees constitute a plate boundary. The high magnitude range used in the Campbell and Bozorgnia (2003) and the Sabetta and Pugliese (1996) models compared to the magnitude of our data can explain the low rank for these models. One surprising result is the poor fit obtained with the Ambraseys et al. (1996) and the Bay et al. (2003) models specifically derived for Europe, and the good fit obtained by the "Japanese" Lussou et al. (2001) model. However, these conclusions are seen as preliminary, since in this study we could only consider earthquakes with rather low magnitudes ($M_w \leq 4$), partially outside the validity range of the candidate models. Only the Lussou et al. (2001) and Bay et al. (2003) models cover the magnitude range of the observations.

The record variability seems to be higher than the one predicted by the ground motion models, but our data set is too small to make a very reliable analysis of variability. However, considering Fig. 4, stations PYPP and PYPE seem to attenuate the high frequency content of ground motion, while PYAD and PYLS may amplify the same frequencies. There is also an amplification of low frequencies at PYPE, while an attenuation is observed at ANDO. This suggests a site effect for these stations and/or that rock site classification needs to be refined in the Pyrenees. Some studies are in progress concerning site characterization in France, based on the global inversion of weak motion data (see Drouet et al. 2005 for the Pyrenees) or using spectral ratio methods.

Finally, we compare the prediction of the best-ranked models in this study and the models used for seimic hazard assessment in France, for a large earthquake scenario. On the basis of the seismicity in the Pyrenees, an event with M_w=6 at a hypocentral distance of 10 km is considered. This leads to median response spectra accelerations of the order of 0.4–0.6 g at a period of 0.1 s and 0.08–0.1 g at a period of 1 s, information which may prove useful for future urban development in the Pyrenees.

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