The Euro-Mediterranean Bulletin: A Comprehensive Seismological Bulletin at Regional Scale

Stéphanie Godey,[1] Rémy Bossu,[1,2] Jocelyn Guilbert,[2] and Gilles Mazet-Roux[1]

INTRODUCTION

The Euro-Mediterranean Seismological Center (EMSC) is in charge of collecting parametric data to operate a real-time information and alert system for potentially damaging earthquakes and to publish a comprehensive seismological bulletin for the Euro-Mediterranean region.

The region is a seismically active area associated with a complex tectonic structure (Dercourt *et al.* 1986) but monitored by numerous local or national seismological networks. To obtain a coherent image of the seismicity, it is important to gather and merge data from all countries. The Euro-Mediterranean bulletin computed at the EMSC therefore provides a coherent source of information for the scientific community, for seismic hazard studies, or for tomographic and tectonophysic studies.

At the global scale, the three main seismological bulletins are produced by the International Seismological Centre (ISC), the International Data Center (IDC), and the National Earthquake Information Center of the United States (NEIC). The ISC produces a worldwide and exhaustive bulletin with a two-year delay and is considered the most comprehensive database (Willemann *et al.* 2001). The ISC is a nongovernmental and nonprofit organization mostly funded by academic institutions; it works closely with the International Association of Seismology and Physics of the Earth's Interior (IASPEI). Until 2001, the ISC bulletin location had been solely based on P arrivals. After 2001, all phases have been included in the location. The magnitude completeness varies among regions, but the ISC aims to report all events as well as review and relocate those recorded by more than one network. In addition to known earthquake location determination, the ISC searches for events unidentified by the local networks by associating groups of phases from different agencies. The other global bulletin available is provided by the NEIC, which provides three bulletin publications: the Quick Epicenter Determinations (QED), produced daily; and the Preliminary Determination of Epicenters (PDE), produced both weekly and monthly. The QED is a real-time worldwide information and alert system gathering automatic and/or manually revised data. The monthly version of the PDE is published after a delay of about four months (Sipkin *et al.* 2000) and includes location revision when necessary, significant earthquake information, and additional data received after the weekly publication. The NEIC also operates the WDC (World Data Center) for seismology, which maintains a worldwide database of seismograms, waveforms, and station information. At the NEIC, as for the ISC, no magnitude threshold is systematically defined, and the magnitude threshold can vary among regions. Finally, the IDC, which is operated by the the Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), has produced revised global bulletins about 10 days after events since 2001. These global bulletins are available through the ISC one year after production.

BACKGROUND

The EMSC is a nonprofit, nongovernmental organization created in 1975 following a resolution of the European Seismological Commission (ESC) to rapidly locate earthquakes in the Euro-Med region. It is governed and funded by its members, which are seismological institutes and observatories (72 members from 46 countries in 2006). Since 1994, the EMSC has been hosted by the Laboratoire de Détection Géophysique (LDG) at the Commissariat à l'Energie Atomique (CEA) in Bruyères-le-Châtel, France. The first activity developed by the EMSC concerns a real-time earthquake information and alert system operated with the support of LDG and the Instituto Geografico Nacional (IGN) of Madrid, Spain, and relies on parametric data provided by the Euro-Mediterranean networks. Earthquake information (location, magnitude, moment tensors, field reports) is made available on the EMSC Web site, and information for source parameters also is available by e-mail, fax, and cell phone. These activities are now completed by the Euro-Med bulletin presented in this article. Information on the EMSC activities and updated reports are available at http://www.emsc-csem.org.

1. Euro-Mediterranean Seismological Center, France
2. Laboratoire de Détection Géophysique, France

Following a request from its members, the EMSC began in 1998 to collect and merge seismological bulletins of the Euro-Med region. The EMSC aims to maintain a database of collected parametric bulletins in a single format that is quickly accessible to all seismologists. It also aims to regularly produce a comprehensive bulletin for the Euro-Mediterranean region with delay of a few months and a magnitude completeness of 3. The successful Euro-Med bulletin will reproduce the seismicity as imaged by the local agencies when events occur within their networks and improve locations in border and offshore regions. Currently, epicenters are computed if at least one network has reported a location. Therefore no new epicenter is created from groups of phases for which no reported location is available. The risk of creating ghost events is too high, while proof of the newly reported event would require retrieving and analyzing waveform data.

The different tools necessary for the Euro-Med bulletin production have been developed during the two-year Earthquake Parameters and Standardized Information (EPSI) project funded by the European Commission, which concluded at the end of 2002. The project was carried out in collaboration with 10 partners (BGR, Germany; GII, Israel; SED, Switzerland; IGN, Spain; INGV, Italy; IPE, Czech Republic; ISC; UHIS, Finland; LDG, France, and NOA, Greece). The output of the project included the tools and procedures for data collection, archiving, and dissemination; software for merging the bulletins; manual validation tools; and specific velocity models for border regions. A first set of seismic bulletins was processed for the period of January 1998–July 1999. Numerous tests, relying mainly on the azimuthal coverage and the number of phases used, were then performed to validate and improve the automatic processing of the bulletins for reliable operational production, *i.e.*, routine production. The Euro-Med bulletin was then computed until the end of 2003, creating in total six years of data (1998–2003). Before starting the operational production, the reliability of the Euro-Med bulletin was evaluated. Results in the Aegean region were statistically assessed and analyzed, then network operators and seismologists in the region were asked for their feedback. We believe that having passed this test, the Euro-Med bulletin can be considered a good image of the seismicity of the region. This paper presents an overview of the project, its results, its planned improvements, and its benefits for the seismological community.

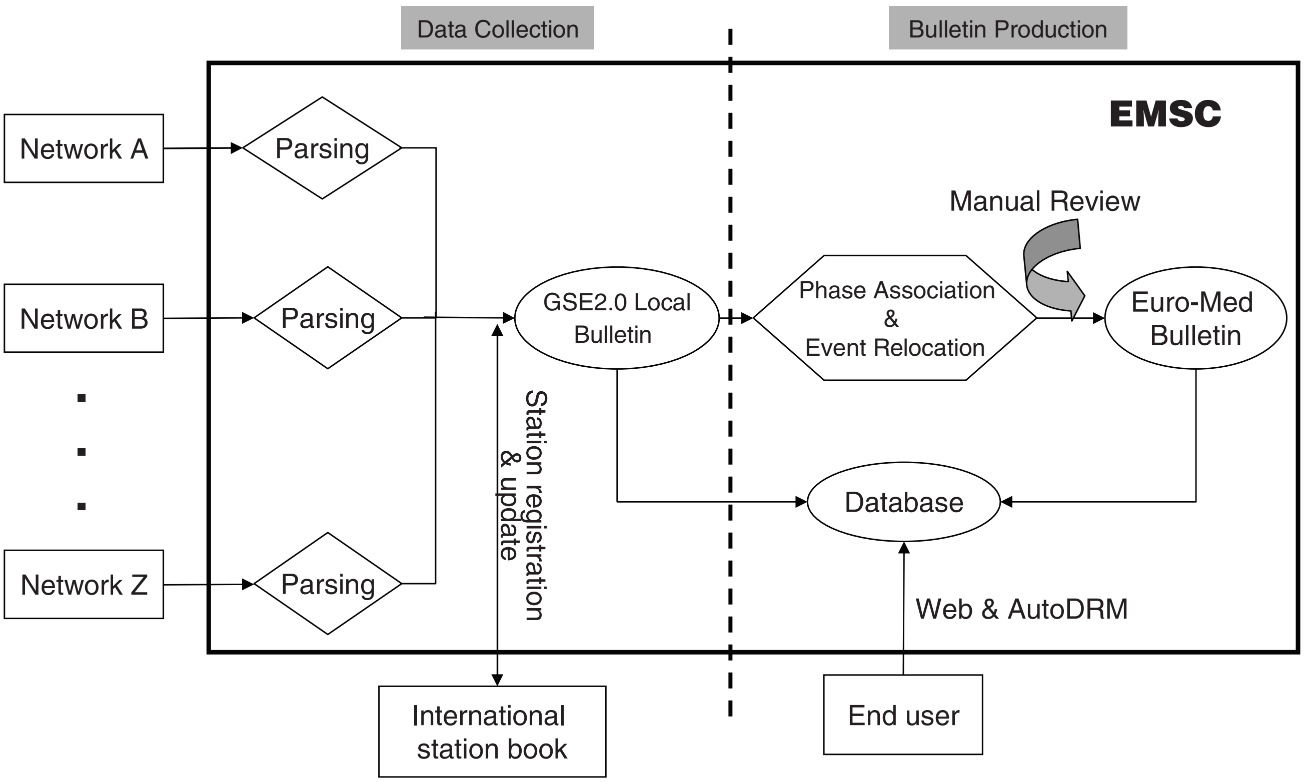
DATA COLLECTION, PARSING, AND ACCESS

Data are collected from national and regional seismological agencies that monitor the Euro-Med region. Gathering the data from several networks requires international collaboration in terms of electronic exchange, data format, and periodicity. The collected parametric data can include: (1) earthquake source parameters (origin time, epicenter, depth, and magnitudes) and their associated arrivals; (2) groups of arrivals for which no location was computed but which are expected to originate from the same event; and (3) isolated phases. Groups and unassociated arrivals data provide important information to constrain event location and increase the azimuthal coverage. For all data types, the arrivals include: station code, phase type, arrival times, and calibrated amplitude/period information when available. Amplitude/period data are crucial to compute reliable magnitudes (m_b or M_L) and to ensure homogeneity in the Euro-Med bulletin. Data nomenclature, seismic phase name prerogatives, earthquake information definition, and magnitude computation are defined following the IASPEI standards (Bormann 2002; Storchak *et al.* 2003; the full description of the IASPEI seismic format is available at http://www.isc.ac.uk/documents/isf.pdf).

For each data contributor, a specific parser is developed to automatically convert the data and archive them in the EMSC database (figure 1). Since 1998, the number of seismological institutes that provide bulletin data to the EMSC has been steadily increasing, growing to 66 contributors from 53 countries in 2005 (table 1). Efforts are continuing to find new contributors, especially in areas where coverage needs to be improved (*e.g.,* North Africa, the Middle East). Several new agencies recently joined the EMSC: SORS (Bosnia-Herzegovina), NSSP (Armenia), CRAAG (Algeria), SPGM (Morocco), CNRS (Lebanon), GGS (Georgia) and INMT (Tunisia).

Among the 66 contributing networks, 47 provide bulletins containing locations, while the remaining networks provide group or isolated arrival times. Throughout 1998–2003, the number of contributing stations has increased, reaching a maximum of about 1,630 (figure 2). The EMSC has registered 350 previously unidentified seismological stations at the International Registry maintained by the ISC and the NEIC, and these stations were allocated a unique international code (black triangles on figure 2). Recordings from those stations appear for the first time in an international bulletin. Delay time in data reception is a key parameter for the rapid and regular production of the Euro-Med bulletin. In collaboration with the local networks, the production procedure and dissemination delays are reviewed to set up a periodic data exchange. If the electronic production and diffusion of bulletins is not systematic in an institute, specific procedures are developed to receive data as soon as possible on a weekly to monthly basis. Currently, only half the networks provide bulletin data within six months. Several networks, mainly in the Middle East and Northern Africa, disseminate data once or twice a year, and therefore cannot be easily integrated in the Euro-Med bulletin. However, these data are stored in our database and can be retrieved. The EMSC is encouraging the regional networks to provide data with less than a three-month delay in order to include as many data as possible in our bulletin and keep its additional value in comparison with the solely local bulletins.

The current database, starting in 1998, contains more than 7.8 million arrival times including redundancies (*i.e.*, identical arrivals reported by several networks). Locations and source parameters are available from more than 340,000 local bulletins. Free and full access to the local bulletins and to the Euro-Med bulletin is given for noncommercial uses to all data contributors and EMSC members via autoDRM. In addition to the collected bulletins, access to the Euro-Med bulletin database also is provided. The Euro-Med catalog (for which phase pickings are discarded) and seismicity maps are available at http://www.emsc-csem.org.



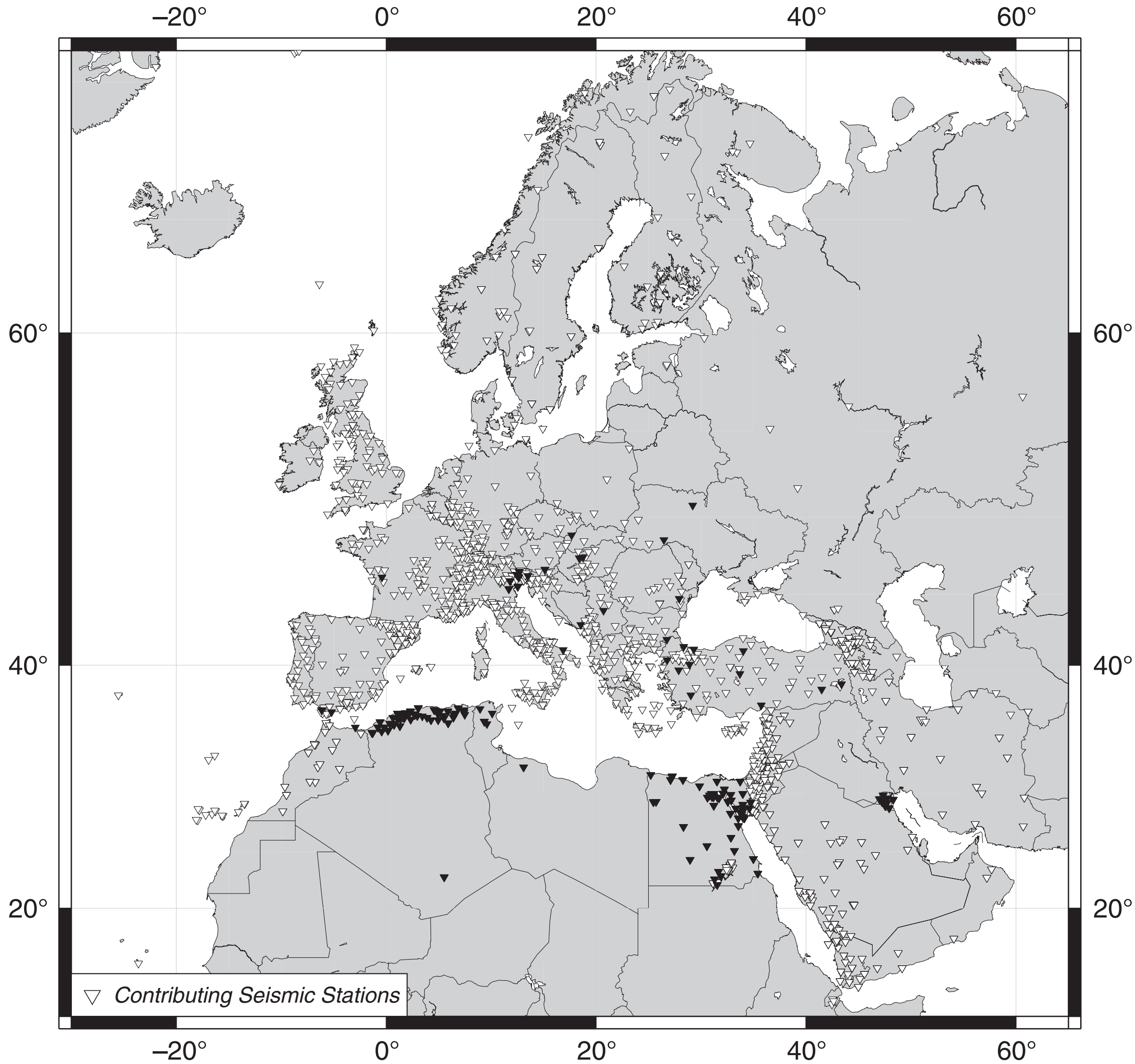
▲ **Figure 1.** Data reception and processing at the EMSC from the network contributions to the database storage.

TABLE 1
List of EMSC bulletin contributors. Those in bold have provided data to the EMSC since 2004 or later.

	Country	Institution
ALG	Algeria	Centre de Recherche en Astronomie, Astrophysique et Géophysique, Algiers
ATH	Greece	National Observatory of Athens, Athens
BARI	Italy	Osservatorio Sismologico Universita di Bari
BEO	Serbia-Montenegro	Seismological Survey of Serbia, Belgrade
BER	Norway	University of Bergen, Bergen
BGR	Germany	Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover
BGS	UK	British Geological Survey, Edinburgh
BRA	Slovakia	Geophysical Institute, Slovak Academy of Science, Bratislava
BUC	Romania	Romanian Seismic Network, Bucharest
BUD	Hungary	Hungarian Seismic Network, Budapest
CNRM	**Morocco**	**Centre National pour la Recherche Scientifique et Technique, Rabbat**
DBN	The Netherlands	Koninklijk Nederlands Meteorologish Instituut, De Bilt
DHMR	Yemen	National Seismological Observatory Center, Dhamar
DIAS	Ireland	Dublin Institute for Advanced Studies, Dublin
DNK	Denmark	The Geological Survey of Denmark and Greenland, Copenhagen
DUSS	Syria	Damascus University Seismological Station, Damascus
GBZT	**Turkey**	**Earth Sciences Research Institute, Tubitak, Gebze-Koacaeli**
GEN	Italy	Rete Sismica Igg, Genoa
GFU	Czech Republic	Geofyzikální ústav Akademie vìd Ceské republiky, Prague
GII	Israel	Geophysical Institute of Israel, Tel Aviv
GRAL	Lebanon	Centre National de Recherche Scientifique, Beirut

TABLE 1 (continued)
List of EMSC bulletin contributors. Those in bold have provided data to the EMSC since 2004 or later.

	Country	Institution
GRF	Germany	Seismological Central Observatory, Erlangen
HEL	Finland	Institute of Seismology, Helsinki
HLW	Egypt	National Research Centre for Applied Geophysics, Cairo
INMG	Portugal	Instituto de Meteorologia, Lisbon
IPEC	Czech Republic	Institute of Physics of the Earth, Brno
ISK	Turkey	Kandilli Observatory, Istanbul
ISN	**Iraq**	**Iraqi Seismological Network, Baghdad**
JSO	Jordan	Jordan Seismological Observatory, Amman
KISR	Kuwait	Kuwait Institute for Scientific Research, Kuwait
LDSN	Libya	Libyan Centre for Remote Sensing and Space Science, Tripoli
LDG	France	Laboratoire de Détection et de Géophysique, Bruyères-la-Châtel
LJU	Slovenia	Agencija Republike Slovenije za okolje, Ljubljana
MDD	Spain	Instituto Geografico Nacional, Madrid
MOLD	**Moldova**	**Institute of Geophysics and Geology, Chisinau**
MRB	Spain	Institut Cartografic de Catalunya, Barcelona
NAO	Norway	Norwegian Seismic Array, Kjeller
NEIC	USA	National Earthquake Information Centre, USGS, Denver
NIC	Cyprus	Geophysical Survey Department, Nicosia
NSSC	Syria	National Syrian Seismological Centre, Damascus
NSSP	Armenia	National Survey for Seismic Protection, Yerevan
OMAN	Oman	Earthquake Monitoring Center of Oman, Muscat
PDA	**Portugal (Azores)**	**Instituto de Meteorologia, Azores University, Ponta Delgada**
PDG	Serbia-Montenegro	Montenegro Seismological Observatory, Podgorica
ROM	Italy	Istituto Nazionale di Geofisica e Vulcanologia, Rome
RYD	**Saudi Arabia**	**King Saud University, Riyadh**
SBS	**Tunisia**	**Seismological Service, Institut National de la Meteorologie, Tunis**
SFS	Spain	Real Instituto y Observatorio de la Armada, San Fernando
SKO	Macedonia	Seismological Observatory, Skopje
SNSN	Saudi Arabia	Saudian National Seismological Network, Riyadh
SOF	Bulgaria	Geophysical Institute of Sofia, Sofia
SORS	**Bosnia-Herzegovina**	**Republic Hydrometeorological Institute, Banja Juka**
SPGM	Morocco	Service de Physique du Globe, Rabat Agdal
STR	France	Réseau National de Surveillance Sismique, Strasbourg
TEH	**Iran**	**Institute of Geophysics, University of Tehran**
THE	Greece	Aristocle University of Thessaloniki, Thessaloniki
THR	Iran	International Institute for Earthquake Engineering and Seismology, Tehran
TIF	Georgia	Georgian National Survey of Seismic Defence, Tbilisi
TIR	Albania	Albanian Seismological Network, Tirana
TRI	Italy	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste
UCC	Belgium	Observatoire Royal de Belgique, Brussels
UPP	**Sweden**	**Uppsala station, Uppsala**
WAR	Poland	Warsaw Seismic Network, Warsaw
ZAG	Croatia	Seismological Survey, Zagreb
ZAMG	Austria	Central Institute for Meteorology and Geodynamics, Vienna
ZUR	Switzerland	Swiss Seismological Service, Zurich

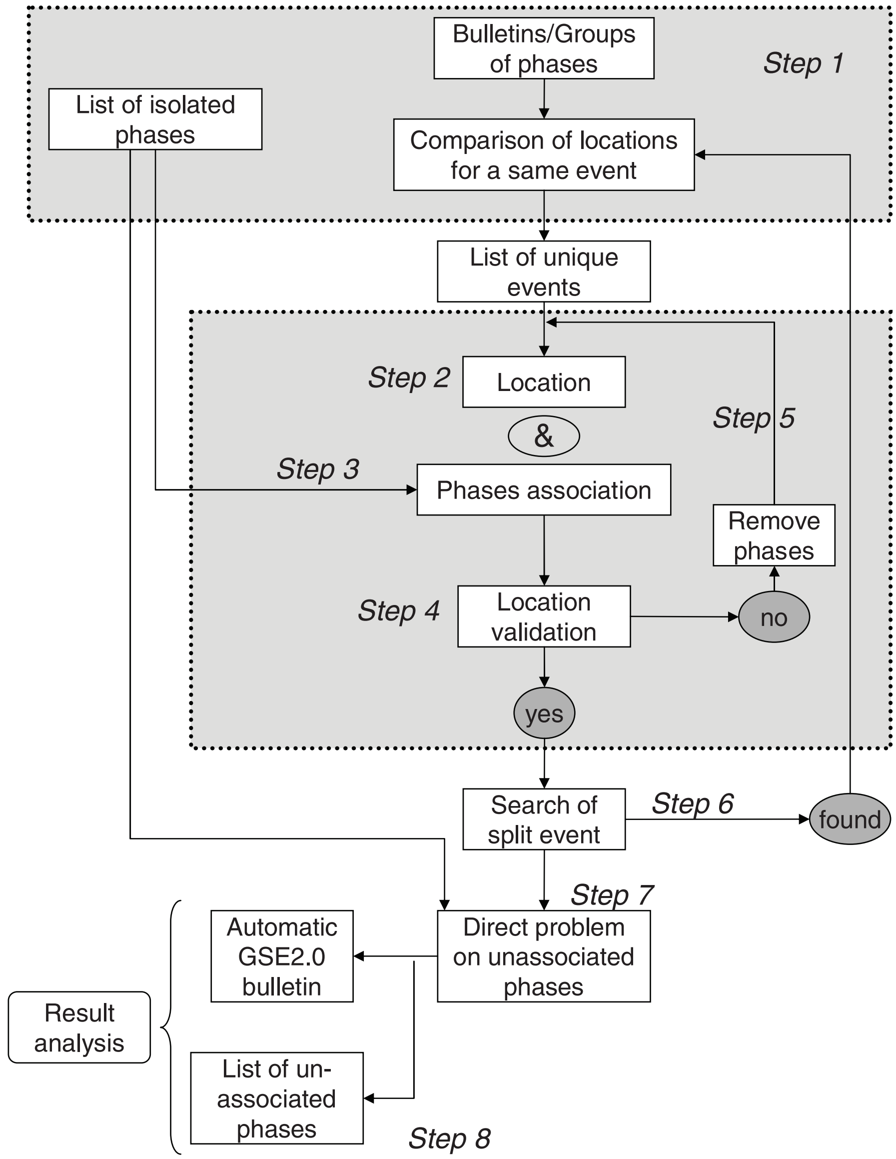


▲ **Figure 2.** Location of the contributing stations to the Euro-Med bulletin. Black triangles correspond to stations registered for the first time at the International Registry upon request of the EMSC.

METHODOLOGY

The Euro-Med bulletin production relies on the association of independent data from several networks and the computation of event hypocenters using the associated readings. The software to perform the data merging and event location was developed by the LDG and was incorporated in the Euro-Med bulletin automatic production in the framework of the EPSI European Project. The procedure follows three steps. An automatic location is first computed for each unique event after phases from different networks have been associated. The location is then evaluated in terms of geophysical coherence before entering a manual review.

Local agencies can report both isolated arrival times and hypocenters. From the collected bulletins, groups of associated phases related to the same event are extracted (step 1 on figure 3). When several hypocenter locations are given for one unique event, they are identified by comparing origin time within 20 s and location within 160 km. The location provided by the network owning the closest station to the epicenter is defined as the reference location solution (mentioned as reference event or reference solution hereafter). The phases related to redundant solutions are split and are considered as unassociated phases. A list of distinct events is then created and the phase association process starts. For each initial event, the software computes a preliminary location and origin time (step 2 on figure 3) by calculating travel times through the input velocity models. The epicenter location method is based on an improved version of the Geiger algorithm (Geiger 1910). The event location solution is computed iteratively by minimizing the least-square travel time residuals. The algorithm was developed to integrate both far- and near-field events in order to include as many data as possible. A triangulation method is applied for local events and a classical Husebye method (Husebye *et al.* 1989) is performed



▲ **Figure 3.** Schematic showing the data-merging procedure and event relocation used to produce the Euro-Med bulletin.

for teleseismic events. According to the epicentral distance to the first recording station, each event is defined as a local or teleseismic event. A limit distance is defined for each network. Arrivals recorded at a distance larger than this limit are characterized as teleseismic phases. The location procedure uses both local and global velocity models. For teleseismic events, global velocity models are accurate enough and the Jeffreys-Bullen velocity model is used for *P* and *S* phases (Jeffreys and Bullen 1940). Other phases are calculated according to the IASPEI phase lists (Storchak *et al.* 2003; Kennett and Engdahl 1991). For local events, more detailed velocity models are needed to enable better travel time calculation and to minimize station static problem. In the Euro-Med bulletin, 53 velocity models are provided by the local networks. In addition, four trans border models were developed by R. Di Giovambattista at INGV (Italy) in the framework of the EPSI project for the alpine areas: France-Italy, Italy-Slovenia, Italy-Switzerland, and Italy-Austria. Other local models in border regions are available for France-Spain, Portugal-Spain, and Israel-Jordan.

Based on the location, the list of isolated phases is scanned to associate relevant recordings in a time window based on theoretical arrival times determined with the computed location (step 3). Constraints are applied in the phase association; for example, the distance between the hypocenter and the recording station is currently limited to 12,000 km (to avoid misidentification of later arriving phases), and the residual time is limited within 25 s or the distance between two stations with contributing phases.

Once a new location is computed using the local velocity models, the result is validated (step 4) by testing the difference in location upon the preliminary hypocenter, the variation in RMS, the travel time residuals variation, and the number of defining phases. When the location is not validated, the phase with the worse residual is rejected (step 5) and the process of phase association/location is iterated. Once an event location has been validated, it is compared to the already processed events to avoid redundancy. If another event shows the same origin time and location, the best solution is kept, and the phases of the second event are associated to the first event before entering again the process of phase association/location (step 6).

The last step involves searching for remaining isolated phases that could potentially belong to the located event but were discarded in the association process. A phase is associated based on its theoretical arrival time computed by direct propagation. This phase is only reported in the bulletin but is not used to compute a new location (step 7).

At the end of the automatic bulletin production, the software outputs a seismic bulletin in GSE2.0 format and a list of unassociated phases (step 8). This automatic part of the Euro-Med bulletin production takes approximately eight hours for a five-day bulletin period (on a Sun V880 using one processor) but can take up to 20 hours depending on the complexity and the number of recordings for a particular event.

The events are analyzed before editing to control the validity of their location. Presently, an event is not included in the final bulletin when the number of recording stations is fewer than five, when the magnitude is lower than 2.8, or when no magnitude is available. An event meeting at least one of the following criteria is described as dubious and manually reviewed: the final hypocenter diverges by more than 10 km in the crust and by more than 30% from the reference location (dz/z); the magnitude difference compared with the magnitude reported in the reference solution is larger than 1.0; the RMS variation is greater than 0.01 or the RMS is greater than 1.0; the location variation is greater than 10 km; the azimuthal gap variation is larger than 15°; the error ellipse surface is greater than 5,000 km^2. In addition, events with magnitude 4.5 or events reported as nonseismic are manually reviewed. Manual processing is performed for approximately 80% of the events. The review of five days of seismicity can take the analyst up to five hours.

Differences in reported magnitudes by several institutes for the same event can be significant and may reach 1.5 magnitude units. In the Euro-Med bulletin, m_b and/or M_L magnitudes are computed only when calibrated amplitude/period information at the stations is available . However, all magnitudes reported by the networks are kept in the bulletin header. A priority is given in the Euro-Med bulletin to reported M_s and M_w magnitudes, which do not saturate for strong events. Then computed m_b (with the respective number of stations used in the calculation) and computed M_L are listed before reported duration magnitude. If no magnitude can be computed, the first magnitude of the reference solution is reported in the bulletin.

Event type information also is included in the Euro-Med bulletin and can be earthquake, rock burst, induced event, mine explosion, experimental explosion, nuclear explosion, or landslide with the nomenclature defined in IASPEI format (Bormann 2002). However, reporting induced seismicity is only possible when the contributing networks provide this information. The lack of information on an explosion, for example, can lead to its report as a seismic event in the Euro-Med bulletin (see section on validation of results, below).

THE 1998–2003 EURO-MED BULLETIN

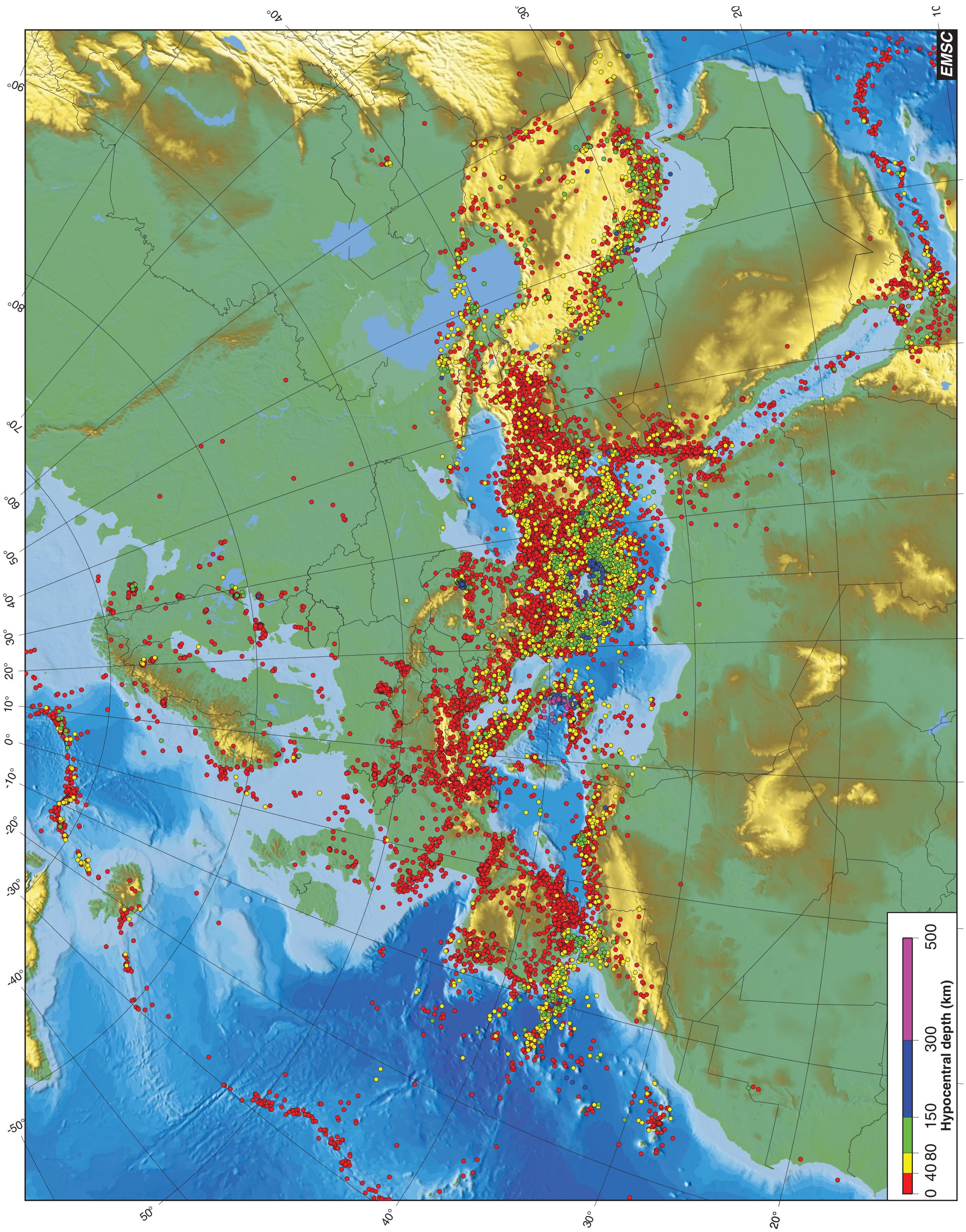
For the period January 1998 to December 2003, the Euro-Med bulletin contains 32,000 events (figure 4) recorded by a total of 1,438 stations. The number of events per year in the Euro-Med bulletin has been increasing steadily, with more than a 50% increase in six years (table 2). An EMSC location was computed for 16,800 events or 52% of the complete bulletin, and these are referred to as "located events." The remaining events are "reported events" (figure 5) for which no phase association was possible, and generally are events that only one network has recorded. In that case, the information provided by the detecting agency is the most complete, through the extensive seismicity knowledge and the use of local specific location method. Therefore, we rely on this information and report without calculation the local bulletin solution. Most of the reported events (figure 5) display small magnitudes and take place in seismically active regions such as Turkey or Greece. In other areas such as Yemen, southern Iran, Romania, Algeria, western France, and southern Spain, events are reported because no contributions from neighboring countries are available. Several agencies that recently joined the EMSC have started to provide data from 2004 onward and will provide additional constraints on the seismicity in specific areas where events larger than M 3.6 are reported (figure 5, black dots); these areas include the Tunisian and Moroccan networks for the Alboran sea, the Georgian network for eastern Turkey, the Moldovan network for Romania, and the Lebanese network in the Dead Sea region.

Magnitudes could be computed for 10,000 events (out of the 16,800 located events) for which amplitude/period information were available. An M_L magnitude could be computed for 50% of the located events; m_b could be computed for 32% of the events. These values are in agreement with the ISC assessment, where a m_b or M_s magnitude can be computed for 25% of the located events worldwide (Willemann 2000). For m_b magnitude, the completeness threshold is 4.0 (figure 6), which is of the same order as the one computed at the ISC (m_b 3.8, Storchak 2004) but using events worldwide. The Euro-Med bulletin is complete

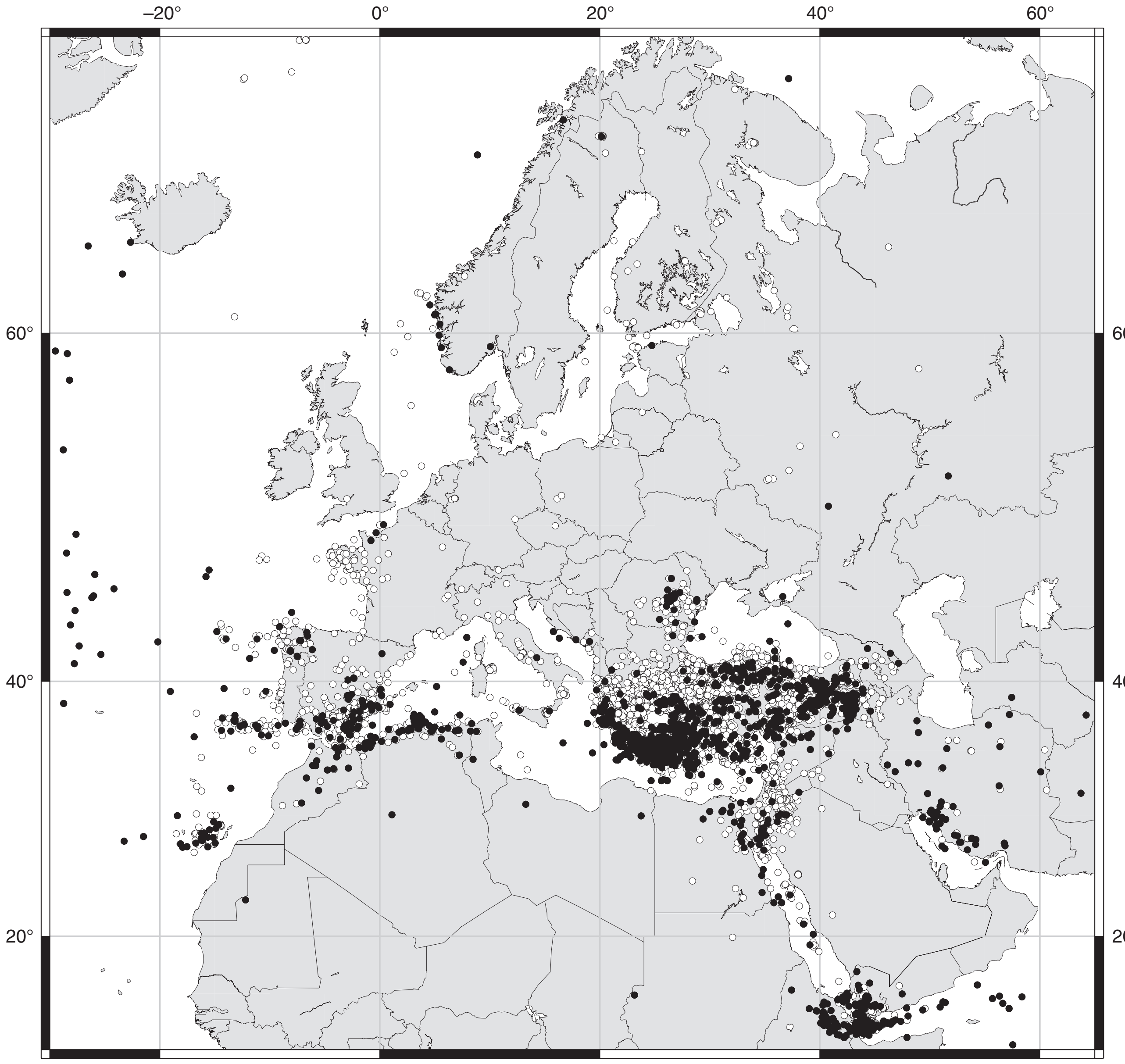
TABLE 2
Evolution of the number of arrivals and events published in the Euro-Med bulletin between 1998 and 2003 (values including reported events).

Year	Number of Arrivals in the EMB	Number of events in the EMB
2003	188,653	6,452
2002	157,854	5,332
2001	134,770	4,796
2000	137,543	4,675
1999	161,910	6,419
1998	117,481	4,156

The higher values in 1999 are related to the widely recorded 01 May 2003 M 6.4 Bingol, Turkey, earthquake.



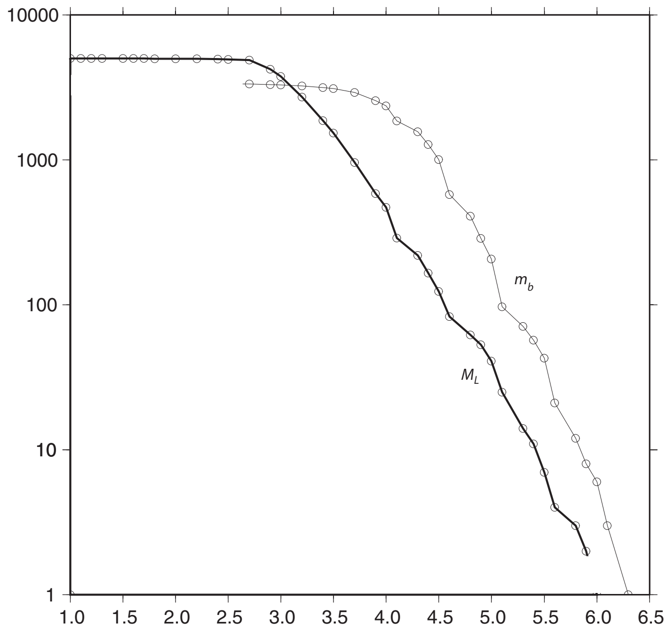
▲ **Figure 4.** Hypocentral location of earthquakes in the Euro-Med bulletin between 1998 and 2003.



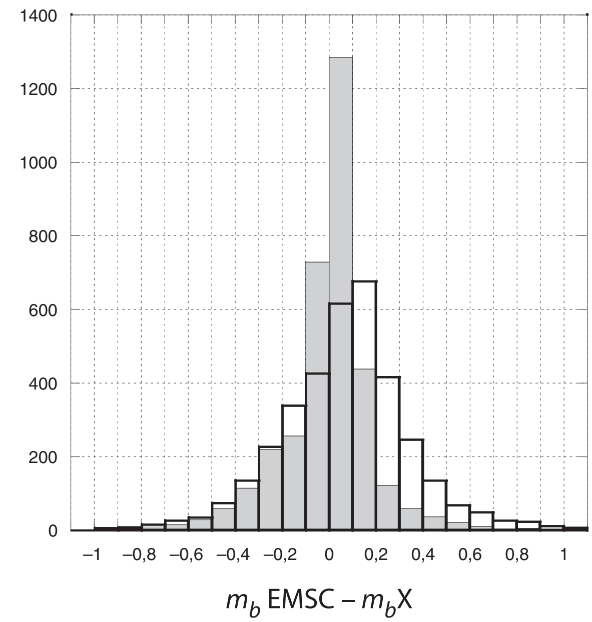
▲ **Figure 5.** Epicenter locations of earthquakes reported in the Euro-Med bulletin between 1998 and 2003 (the plotted location is the one provided by the local network). Black dots correspond to events with magnitude larger than 3.6.

for M_L magnitude above 3.0. M_w magnitudes, which provide the basis of most modern seismic hazard studies, are reported when made available, mainly by the NEIC (United States) and GII (Israel) networks. In the period 1998–2003, only 4% of the events have an associated M_w magnitude. M_s magnitudes are included in the Euro-Med bulletin for the year 2000 (because of later processing) and from 2004 onward, thanks to the reports of several networks (THR, GRF, STR, NEIC, LDG). The different magnitudes available in the Euro-Med bulletin for the events with magnitude larger than 6 are given in table 3.

We have compared the m_b magnitudes computed in the Euro-Med bulletin with those reported by the ISC and the NEIC (figure 7). The list of events including m_b magnitude in the three bulletins is different partly due to the different data contributions. In total, around 7,000 Euro-Med bulletin events could be compared (7,170 for the ISC and 6,860 for the NEIC with 3,480 common events). The m_b estimate calculated in the Euro-Med bulletin is consistent with those of the NEIC and the ISC (figure 7). The standard deviations between the EMSC m_b estimates and the ISC or NEIC estimates are respectively 0.2 and 0.16. The scatter between EMSC and ISC m_b estimates display a minor shift of 0.1 magnitude unit (figure 7) indicating a slight overestimate of magnitude in the Euro-Med bulletin (Willemann 2000; Willemann *et al.* 2001). This could be related to the large IDC amplitude/period contribution sent to the ISC (Storchak 2004), which is included in the Euro-Med bulletin.



▲ **Figure 6.** Gutenberg-Richter cumulative distribution for m_b (triangles) and M_L (circles) magnitudes observed in the Euro-Med bulletin.



▲ **Figure 7.** Comparison of m_b magnitude computed at the NEIC, ISC, and in the Euro-Med bulletin: A histogram distribution of magnitude differences observed between the ISC (white), NEIC (grey), and Euro-Med bulletins.

EVALUATION OF THE EURO-MED BULLETIN PERFORMANCES

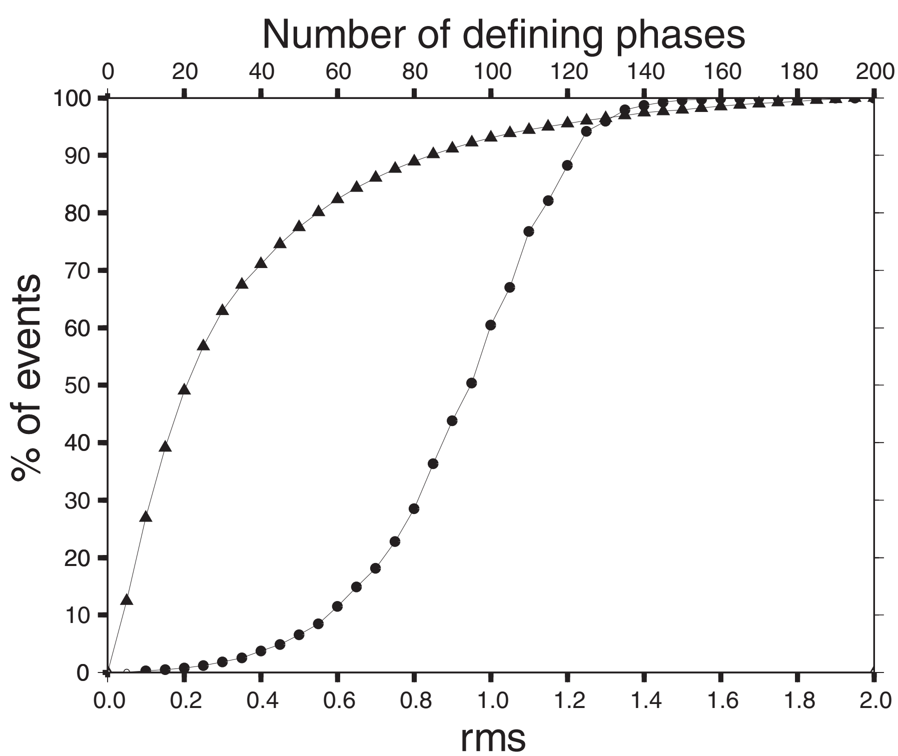
The performances of the Euro-Med bulletin can first be evaluated statistically. The number of arrivals used per event gives an indication of the phase association performance. Around 30% of the event relocations are done with more than 50 phase readings (figure 8) and generally display large improvements in comparison with the local solutions. Events relocated using fewer than 20 stations (40% of the events) are mainly small magnitude events recorded by the closest stations. Approximately 60% of the events have a RMS between 0.8 and 1.2 s (figure 8 center). The steep decrease observed after RMS 1.3 s reflects the proper selection of phases used to compute the event location (see step 5, figure 3). For events with a RMS larger than 1 s, a manual review is performed to discard phases displaying large travel-time residuals, often related to geophysically incompatible phases. Location errors, related to velocity models, can be quantified in terms of the 90% confidence region described by its mean error radius. In the Euro-Med bulletin, 90% of the events are located with an error of less than 7 km. High station coverage is obtained in the whole Euro-Med region with 65% of the events located with an azimuthal gap lower than 150° and only 10% with an azimuthal gap larger than 240° (figure 9A). The secondary azimuthal gap (*i.e.,* the maximum gap when any given station is removed from the event location) gives additional information on the location accuracy (Bondár *et al.* 2004b). The secondary azimuthal gap observed in the Euro-Med bulletin (figure 9A) is very close to the first azimuthal gap (with a maximum difference of 30°), proving that event location is robust and does not rely on a single station from a specific direction. Comparing location estimates between different catalogs is the focus of many studies on the global or local scale (Engdahl *et al.* 1998; Storchak *et al.* 2000). Variations in location between the Euro-Med bulletin and local reports were studied for some specific agencies (Godey *et al.* 2005). While a comparison of the Euro-Med bulletin with other global bulletins deserves a more extensive study, in this article we focus on a comparison with the global NEIC catalog in terms of m_b magnitude (see above) and in terms of azimuthal gap (figure 9B). This evaluation was made upon 10,600 events in the Euro-Med bulletin for which the NEIC provided data. An improvement of up to 10° in azimuthal coverage is achieved in the Euro-Med bulletin, driven by the use of additional and later contributions from Euro-Med agencies not reporting to the NEIC.

Statistical parameters only give a partial sense of the location reliability (Bondár *et al.* 2004a). To provide information about event location quality, we introduced a quality factor for each event location based on the RMS misfit, the azimuthal gap, the number of associated phases, and the error ellipse surface (described above) computed for each event location. Three different levels of quality are defined as A (higher quality) to B (intermediate quality) to C (lower quality), reflecting how the quality relates to the four characteristic parameters. The threshold values of these parameters are computed by analyzing their distribution for a set of "well-located" earthquakes.

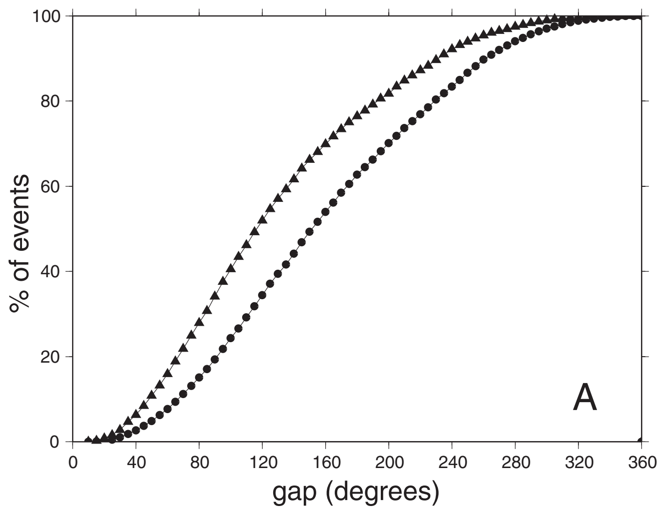
A first selection of reliable locations is done in the collected local bulletins. An event is chosen if it was recorded by the national network and if it occurred inside this network, allowing a good local azimuthal coverage. This selection was performed upon the 8,000 events occurring between 2001 and 2003 recorded by the Greek (THE), Italian (ROM), Swiss (ZUR), French (LDG), German (BGRD), Spanish (MDD) and Turkish (ISK) networks. In total 735 events were selected

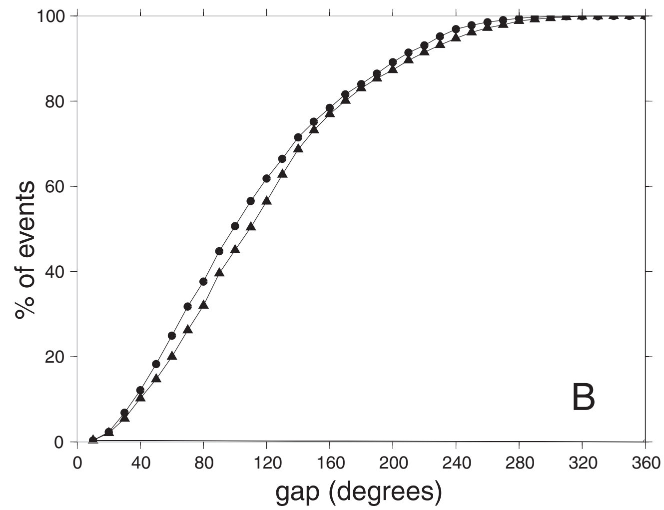
TABLE 3
List of Euro-Med events with magnitude larger than 6.

Day	Time	Latitude	Longitude	Depth	M_w	M_s	m_b	M_L	Location
26/12/2003	01:56:47.2	28.5332	59.2736	33.0		6.6	5.8		Southern Iran
29/07/2003	05:31:35.6	36.0684	–10.2620	66.4			5.3	6.0	Off-coast of Gibraltar
21/05/2003	18:44:22.8	37.0233	3.7070	30.0	6.8		6.2	5.6	Algeria, Boumerdes
01/05/2003	00:27:04.5	39.0099	40.5600	16.4	6.4		5.5		Eastern Turkey
27/01/2003	05:26:22.2	39.4977	39.8921	8.0	6.1		5.5		Eastern Turkey
01/09/2002	17:15:00.3	14.4442	51.8862	10.0	6.0		5.3		Eastern Gulf of Aden
22/06/2002	02:58:21.2	35.5538	49.0753	14.7	6.5		6.3		Western Iran
03/02/2002	09:26:44.7	38.6586	30.8822	20.0	6.0		5.7		Western Turkey
03/02/2002	07:11:28.8	38.5934	31.2890	10.0	6.5		5.7		Western Turkey
22/01/2002	04:53:50.8	35.5376	26.8286	100.0	6.1		6.1		Crete
25/11/2000	18:10:43.7	40.1512	49.9318	8.8	6.5	6.3	6.3		Eastern Caucasus
26/07/2001	00:21:36.3	39.0536	24.2620	10.0	6.5		6.0		Aegean Sea
21/06/2000	00:51:47.4	64.0412	–20.7168	17.1	6.5	6.6	6.1		Iceland
17/06/2000	15:40:40.8	64.0936	–20.3550	8.8	6.8	6.6	5.7		Iceland
06/06/2000	02:41:54.2	40.5346	32.8472	51.5	6.1	5.6	5.5		Turkey
21/05/2000	19:58:47.2	71.1675	–8.4914	11.4	6.0	5.6	5.3		North Atlantic Ridge
07/09/1999	11:56:49.0	38.0725	23.6395	12.0	6.0	5.8	5.6		Turkey
17/08/1999	00:01:35.4	40.7538	29.9902	0.0		7.4	6.3		Turkey
06/05/1999	23:00:51.7	29.5772	51.9248	24.6	6.2		5.9		Southern Iran
04/03/1999	05:38:25.3	28.4563	57.2360	23.1	6.6		6.2		Southern Iran
12/04/1998	10:55:33.9	46.2110	13.8505	10.0	6.0		5.4		Austria
14/03/1998	19:40:31.6	30.3171	57.6557	45.2	6.6		5.6		Northern Iran



▲ **Figure 8.** RMS (circles) and defining phases (triangles) distribution for the 1998–2003 Euro-Med bulletin.





▲ **Figure 9.** Distribution of the azimuthal gap (triangles) and secondary azimuthal gap (circles) in the Euro-Med bulletin (left). Azimuthal gap comparison (right) for common events in the Euro-Med (circles) and NEIC (triangles) bulletins.

as "well-located" with magnitudes ranging from 2.6 to 6.5 and depths up to 300 km.

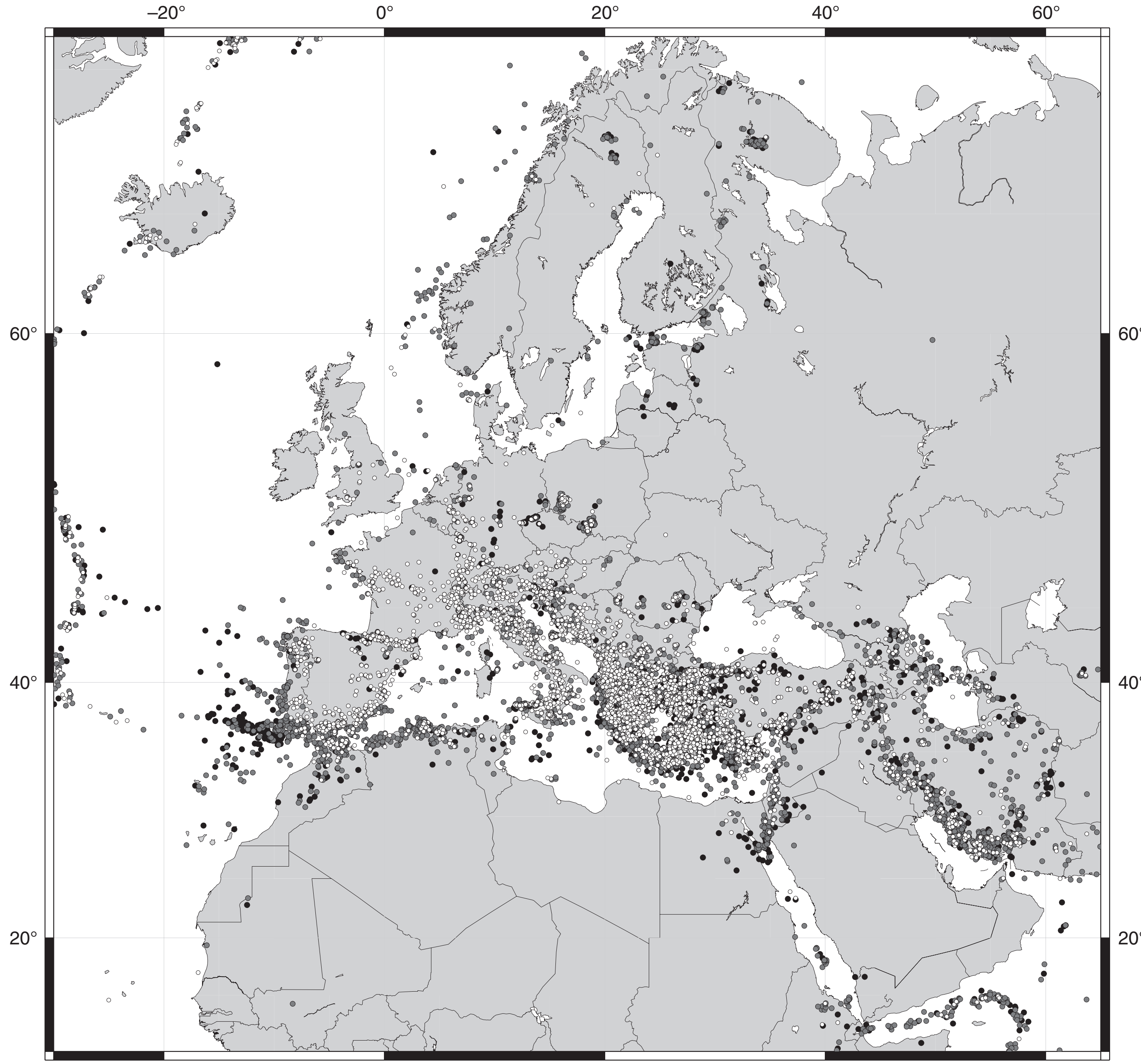
Then the EMSC source parameters are compared with the reported local information. When the difference in location is less than 10 km, the difference in time is less than 2 s, and the difference in depth is less than 10 km, the event is selected to define the A-quality parameters. In addition, we fixed a maximum azimuthal gap of 150° and a minimum of 10 phase pickings per event. The A-quality (best) are defined by the 95% limit in the RMS and ellipse surface distribution for the selected events (table 4). The parameters defining the C quality are set arbitrarily. The location errors associated with the levels of quality can be estimated to an average of 6.5 km for A quality events and 10.5 km for B quality events.

Using these quality thresholds, 46% of the relocated events in the Euro-Med bulletin are of quality A, 38% of quality B, and 16% of quality C. The distribution of events (figure 10) with higher quality relocation reflects the regions where high coverage and extensive data contributions are available: southern European countries from Portugal to Turkey and northernmost Algeria and Morocco. In addition, events occurring inland and away from the borders tend to have high-quality solutions. On the contrary, intermediate-quality events (quality B) usually are observed along borders between countries or on the coastlines, possibly reflecting inconsistencies among data contributions from different countries that use instruments of variable reliability, different location methods, or different velocity models. Poorly constrained events (quality C) are predominant in regions of extensive seismicity of low magnitude (*e.g.,* Greece, Turkey), at the edges of the Euro-Med region *(e.g.,* Strait of Gibraltar, Gulf of Aden) and in other regions where coverage is only available from one particular azimuth (*e.g.,* Iran, Morocco, the Sinaï region).

VALIDATION OF THE RESULTS

Statistical results show that the Euro-Med bulletin presents significant improvements in comparison with the local results for offshore events and in border regions. However, the expertise of the countries participating in the Euro-Med bulletin production is essential to produce a regional bulletin in agreement with the tectonics of the area. To achieve this purpose, we launched a validation procedure to identify possible errors or inaccuracies that might remain unnoticed in our own analysis (detailed information and results on this query are available at http://www.emsc-csem.org). The survey was successful, with 35 reports, and it pointed out several problems in data collection and event location that need to be accounted for in the bulletin production. The first result of the validation project was the very different evaluations of the Euro-Med bulletin from agencies in Europe (from Norway to Turkey) and in countries of Northern Africa and the Middle East (from Morocco to Syria). The large discrepancy in the answers and opinions is driven mainly by the differences in the seismological institute structures and means. Europe is densely covered by seismic stations owned by long-operating institutes. Well-maintained infrastructures and modern systems are available for data acquisition and exchange. Data from several neighboring countries often are provided for one single event, leading to an improved coverage of the European region. Overall, the Euro-Med bulletin was validated for European countries. In contrast, networks in Northern Africa or in the Middle Eastern countries have different infrastructures and the area is not as homogeneously covered. The operating systems can be slower and introduce larger delays in data acquisition, processing, and dissemination. In addition, events occurring outside a network or in a neighboring country are not always reported. As a result, for one single event, the number of recording stations can be significantly lower than if this event had occurred inside Europe. For example, significant problems have been found for the southern and eastern parts of the Mediterranean Sea that require significant corrections to improve the Euro-Med bulletin production. The problems encountered are related to two main sources: Data exchange problems that affect acquisition, dissemination delay, and data content of the local contributions; and data processing prob-

TABLE 4 Quality factor parameters and definition.							
Quality level	RMS		Number of associated phases		Azimuthal gap		Error radius
A	< 1.3 s	and	> 10	and	< 180°	and	< 3.6 km
B	1.3 to 2.5						3.6 to 12.6 km
C	> 2.5 s	or	< 10	or	> 280°	or	> 12.6 km



▲ **Figure 10.** Epicenter locations of A- (white), B- (grey), and C- (black) quality events in the Euro-Med bulletin.

lems that affect the Euro-Med bulletin production, data merging, and event location.

Several networks reported that events occurring within their areas of study were missing from the Euro-Med bulletin. The two main reasons for this are related to data availability at the time of production and the reported event selection. Some data can be missing in our database due to parsing errors at the EMSC. For approximately 200 events, mainly from the Middle East, the data were reprocessed and the Euro-Med bulletin has been corrected. Data also can go missing when local networks provide their data after the bulletin production starts. Data availability has a significant impact on the content of the Euro-Med bulletin. Missing data from eastern and southern Euro-Med countries minimizes the added value and interest of the Euro-Med bulletin. However, improvements are expected in the future, with at least six contributors, in particular from the Middle East, now able to provide data with less than a six-month delay. In addition, from 2004 onward, new contributions have been received from Sweden, Malta, Tunisia, and Iraq. Events also can be missing in the Euro-Med bulletin due to the present handling of reported events. If an event is recorded and reported by only one network, no EMSC location is computed and we report the original data as sent by the local network. The only rejection criterion is that at least five stations should record this event. This criterion has proven to be too restrictive, especially in the Southern and Eastern Mediterranean region. For example, the Lebanese network owns four stations and their data sometimes are discarded when no contribution from neighboring countries is available. For the Euro-Med bulletin 2004 onward, a new procedure is implemented to ensure that each reported event epicenter lies inside the region covered by the reporting network and no limitation is set on the number of recording stations. For each network, a specific region is assigned, inside which reported locations by this network are considered reliable ("reported" event). Events occurring outside of that region are marked as "deprecated." The defined regions usually include the network country and extend over its borders by a few tens of kilometers.

Several agencies also noted the existence of ghost events, *i.e.,* events absent in their local bulletins. This problem is driven by three main sources: the present handling of reported events, the lack of event type information, and missing explosion reports. The EMSC can rely only on the information provided by the local networks to report nonseismic events. Several agencies found reports of seismic events in the Euro-Med bulletin that were actually related to quarry blast and mining activities. This mainly happens when the local network excludes explosions from the bulletin sent to the EMSC. If a neighboring country records this event and reports it to the EMSC without information on its nature, it is included as a seismic event. Following the validation procedure, several networks have now set up event type information contribution. The present procedure applied to reported events also proved to be insufficient and led to the creation of ghost events by reporting false locations from one single network. For example, the Egyptian agency reports events in the southern part of the Aegean Sea that are not recorded by the Greek and Turkish agencies. These events are distant from the Egyptian network and are possibly unrealistic; they would be marked as "deprecated" events in the new Euro-Med bulletin procedure.

To compute accurate magnitudes in the Euro-Med bulletin, amplitude and period information are necessary. Some networks mentioned problems of magnitude over-estimation. Magnitude misestimation is mainly related to station calibration problems. In particular, when a magnitude is computed using only one phase reading, its accuracy depends on the quality of the amplitude/period measurement and calibration. In the Euro-Med bulletin production from 2004 onward, magnitudes are computed when amplitudes are reported from at least three stations and manual review of these events will be performed before including them in the Euro-Med bulletin. In addition, this problem will diminish as networks from Algeria, Serbia, Romania, Israel, Lebanon, Turkey, Syria, Armenia, and Bosnia-Herzegovina are now able to provide amplitude and period information.

The second source of disagreement with the local contributors was data processing problems. Data merging and event location are performed automatically, then a manual review is done in 80% of the cases. Several networks reported wrong association of data or split events (*i.e.,* a unique event is separated into two events with close origin time). In general, these problems are related to the mathematical coherency between data that are geophysically incoherent. Most of the problems reported are relative to events of 1998–1999, before we modified the automatic procedure. Those events were studied in detail and corrected. We also received reports of several events having large location differences with the location known in the country. For some of those events, the most reliable information provided by the closest network was missing at the time of bulletin production. When necessary, corrections were applied to the Euro-Med bulletin. For 2004 onward, the bulletin production will take advantage of additional location information received from several countries including Hungary, the Netherlands, Jordan, Bosnia-Herzegovina, Georgia, Belgium, and Austria, which will provide additional constraints for event location accuracy.

PERSPECTIVES AND CONCLUSIONS

Seismological bulletins remain an important source of information for seismo-tectonic investigations. By improving the availability of local bulletins and producing a comprehensive regional bulletin, the EMSC provides an accurate additional tool to the scientific community. The Euro-Med bulletin presented here covers the period 1998–2003. The bulletin generally displays improved azimuthal coverage and phase association, particularly for events in border regions and offshore. The bulletin evaluation, an essential stage to assess its reliability, was performed by data contributors of the region through a validation process. Though the overall image of the seismicity is consistent with local seismicity knowledge and approved by most of the Euro-Med agencies, several problems were detected and the bulletin implementation was modified to improve the results. In 2006, the EMSC started operational production of its bulletin. It will take advantage of regular and fast contributions from the local networks and will include new contributions from several countries including Turkey (GBZT), Bosnia-Herzegovina (SORS), Tunisia (SBS), Iran (THE), Russia (OBN), Azores (PDA), Belarus (BELR), Ukraine (MCSM), Malta, and Iraq (ISN), as well as improved data exchange with Sweden (UPP), Spain (MRB), Saudi Arabia (SNSN), and Syria (NSSC). Several networks now provide location, event type, or amplitude/period information that will help to improve the Euro-Med bulletin.

Several modifications were adopted in the Euro-Med bulletin production after its validation. The selection of reported events has been improved and now takes into account the distance of the reporting network. Also, to facilitate the manual review of dubious events, the location results of the EMSC real-time system are used as additional information. Through the real-time system, M_w and M_s estimations from several networks are accessible and we will assess if they can be included in the Euro-Med bulletin. Finally, to ensure that all data are available at the time of bulletin production, a specific system was developed to warn each network of missing data one month before the production deadline.

In 2006, the use of several updated local velocity models provided by the local agencies and the AK135 (Kennett *et al.* 1995) global velocity model will be assessed and implemented in bulletin production. In addition, specific information including quality factor, secondary azimuthal gap, and correspondence to a reference event as defined by the criteria of Bondár *et al.* (2004a, 2004b) will be provided in the bulletin header. The operational production of the Euro-Med bulletin has started. We aim to publish an accurate bulletin for 2004 and 2005 and to close the production gap to within six months after earthquake occurrence.

ACKNOWLEDGMENTS

The Euro-Med bulletin was developed as part of the EPSI project with the support of the Commission of the European Communities under contract EVR1-CT2000-40006. Details concerning this project and its participants can be found at http://www.ingv.it/~roma/reti/epsi/index.htm.

We would like to thank the EPSI partners and all the Euro-Med bulletin contributors for their data and input for the validation project.

REFERENCES

Bondár, I., E. R. Engdahl, X. Yang, H. Ghalib, A. Hofstetter, V. Kirichenko, R. Wagner, I. Gupta, G. Ekström, E. Bergman, H. Israelsson, and K. McLaughlin (2004a). Collection of a reference event set for regional and teleseismic location calibration. *Bulletin of the Seismological Society of America* **94** (4), 1,528–1,545.

Bondár, I., S. C. Myers, E. R. Engdahl, and E. Bergman (2004b). Epicentre accuracy based on seismic network criteria. *Geophysical Journal International* **156**, 483–496.

Dercourt, J., L. P. Zonenshain, L.-E. Ricou, V. G. Kazmin, X. Le Pichon, A. L. Knipper, C. Grandjacquet, I. M. Sbortshikov, J. Geyssant, C. Lepvrier, D. H. Pechersky, J. Boulin , J.-C. Sibuet, L. A. Savostin, O. Sorokhtin, M. Westphal, M. L. Bazhenov, J. P. Lauer, and B. Biju-Duval (1986). Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics* **123**, 241–315.

Engdahl, E. R., R. D. van der Hilst, and R. P. Buland (1998). Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bulletin of the Seismological Society of America* **88,** 722–743.

Geiger, L. (1910). Herdbestimmung bei Erdbeben aus den Ankunftszeiten. *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen* **4**, 331–349.

Godey, S., R. Bossu, and G. Mazet-Roux (2005). Importance of international data exchange for earthquake location. Examples of EMSC relocation in the Aegean region. Poster presented at the International Symposium on the Geodynamics of the Eastern Mediterranean: Active Tectonics of the Aegean. 15–18 June 2005.

Husebye, E. S., and B. O. Ruud (1989). Array seismology—Past, present and future developments. In *Observatory Seismology*, edited by J. J. Litehiser. Berkeley: University of California Press, 123–153.

IASPEI New Manual of Seismological Observatory Practice (2002). Peter Bormann, ed. Potsdam: GeoForschungsZentrum Potsdam.

Jeffreys, H., and K. E. Bullen (1940). *Seismological tables.* London: British Association for the Advancement of Science, Gray Milne Trust, 50 pp.

Kennett, B. L. N., and E. R. Engdahl (1991). Travel times for global earthquake location and phase identification. *Geophysical Journal International* **105,** 429–465.

Kennett, B. L. N., E. R. Engdahl, and R. Buland (1995). Constraints on seismic velocities in the Earth from travel times. *Geophysical Journal International* **122,** 108–124.

Sipkin, S. A., W. J. Person, and B. W. Presgrave (2000). Earthquake bulletins and catalogs at the USGS National Earthquake Information Center. *IRIS Newsletter* **2000** (1), 2–4.

Storchak, D. A., A. L. Bird, and R. D. Adams (2000). Discrepancies in earthquake location between ISC and other agencies. *Journal of Seismology* **4,** 321–331.

Storchak, D. A., J. Schweitzer, and P. Bormann (2003). The IASPEI Standard Seismic Phase List. *Seismological Research Letters* **74** (6), 761–772.

Storchak, D. A., (2004). Summary of the ISC bulletin of events of 2001, 2004. Poster presented at the European Geophysical Union meeting.

Willemann, R. J. (2000). International Seismological Centre Bulletin. *IRIS Newsletter* **2000** (1), 5–7.

Willemann, R. J., and D. A. Storchak (2001). Data Collection at the International Seismological Centre. *Seismological Research Letters* **72** (4), 440–453.

EMSC
c/o LDG Bat. Sables
BP 12
91680 Bruyères le Châtel
France
godey@emsc-csem.org
(S.G., R.B., G.M.-R.)

Labaratoire de Détection Géophysique
DASE, CEA Bat. Sables
BP 12, 91680
Bruyères le Châtel,
France
jocelyn.guilbert@cea.fr
(R.B., J.G.)