EARTHQUAKE LOCATION ACCURACY IN THE ARABIAN-EURASIAN COLLISION ZONE

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ABSTRACT

An extensive and high-quality data set of earthquake locations, many of them calibrated to $GT5_{90}$ levels of accuracy, is being compiled for the region that expresses the continental collision between the Arabian and Eurasian plates, with the primary goal of obtaining improved resolution of the crustal and upper mantle velocity structure through tomographic imaging. A specialized multiple event relocation algorithm is used to calibrate clusters of earthquakes, using several kinds of calibration data, including near-source seismic observations, InSAR data on source location and mechanism, and mapped faulting. Although our data set of calibrated locations (880 events in 21 calibrated clusters) is substantial, compared to what is available for most other regions of the Earth, it is still small in comparison with the full catalog of earthquake locations (~26,000 events) in the region which can be used for tomographic studies. Our strategy is to use the observed arrival times from GT5 events set to study regions in which the ray path coverage is dense enough, and to use these calibrated travel times for validation in regions for which it is necessary to use arrival time data from uncalibrated sources for tomography. In addition to providing data sets for tomography, the calibrated earthquake locations provide insight into the performance of permanent seismic networks that monitor the region. The location accuracy of two global networks and two regional networks, is investigated by comparing their locations with the calibrated locations (the subset of 684 events meeting $GT5_{90}$ criteria) determined in this project. Earthquake locations in this region which are based on regional and teleseismic arrival time data are systematically biased to the southwest and have a 90% location accuracy of 18-23 km, with the lower value achievable by applying limits on secondary azimuth gap. The two regional seismograph networks achieve a 90% accuracy level of 22 and 36 km, respectively. One regional network actually operated as a set of independent subnetworks until 2006 and suffers from a very imbalanced distribution of stations, such that the 90% level of accuracy exceeds 100 km during that time. In broad terms, location accuracy in the region using 1-D travel time models and single event location procedures, is presently limited to about 20 km at the 90% level of accuracy (i.e., $GT20_{90}$). The tendency for routinely-determined epicenters to be biased to the south can be explained as a consequence of the fact that there are far more seismic stations in the northern hemisphere, relative to the study region, and that the true travel times are larger than the theoretical ones, yielding positive travel-time residuals. The inversion for location tends to push an event further away from the bulk of seismic stations, i.e., to the south.

OBJECTIVES

This research has the goal of developing in-country datasets that can be used to improve ground-based monitoring capabilities in the study region, in particular by providing information needed to develop and test more accurate travel time models for seismic phases that propagate in the crust and upper mantle in the region that expresses the continental collision between the Arabian and Eurasian plates. The main thrust of this project is developing high quality data sets for tomography. The research presented here, however, deals with an assessment of the current level of location accuracy in the region of interest from several permanent seismic networks.

As part of this project we are conducting detailed analyses of clusters of earthquakes with a multiple event relocation method that has been developed to determine calibrated locations that meet or exceed $GT5_{90}$ levels of accuracy. The success of this analysis usually depends on the availability of near-source data, such as temporary deployments of seismometers for aftershock studies and geological field work after large earthquakes. In-country data sets therefore play a critical role in this kind of analysis. In the region of interest we have developed 21 calibrated earthquake clusters, containing 880 events; 684 of these events qualify as $GT5_{90}$ locations. We compare the epicenters (we do not consider focal depth or origin time) reported in two global seismic catalogs and two regional seismic catalogs with the GT5 locations to gain an understanding of the average level of location accuracy of different networks and also to reveal any evidence for systematic mis-location. All locations in this study, for the multiple event relocation analysis used to determine GT5 locations or the catalogs used for comparison, are based on 1-D Earth models, although the models may differ from cluster to cluster and from catalog to catalog.

The global catalogs considered in this study are those of the International Seismological Centre (ISC) and a version of the well-known EHB catalog (Engdahl et al., 1998) that has been carefully reviewed for the region of interest. The two regional catalogs are those published by the International Institute for Earthquake Engineering and Seismology (IIEES) and the Iranian Seismological Centre (IRSC). The IRSC is contained within the Institute of Geophysics of the University of Tehran. The IIEES catalog is based on data from the Iranian National Seismic Network (INSN), consisting of 16 broadband (Güralp CMG-3T seismometers, Güralp digitizers), real-time satellite-telemetered stations. Most stations have been installed since 2000. The IRSC catalog is based on data from the Iranian Seismic Telemetry Network (ISTN). The ITSN consists of 73 three-component short-period (Kinemetrics SS-1), digital, telemetered stations organized in 10 subnetworks. Timing corrections, based on GPS, are applied at the subnetwork recording centers. The earliest installations, for the Tehran and Tabriz subnetworks, occurred in 1995. Until 2006 the subnetworks operated largely autonomously, producing their own bulletins. Since then, all subnetwork data are transmitted to the IRSC where a national bulletin is prepared. The IRSC and IIEES catalogs used for this study can be considered almost completely independent, each utilizing only data from their own network and their own location procedures. In recent years the IRSC has sometimes included a few readings from the IIEES network to improve azimuthal coverage.

RESEARCH ACCOMPLISHED

Calibrated Earthquake Clusters

Our method of determining ground-truth quality calibrated locations is based on multiple event analysis, for which we use the Hypocentroidal Decomposition (HDC) algorithm described by Jordan and Sverdrup (1981). The code has been extensively modified to incorporate features that are relevant to the calibrated location problem, especially in the area of incorporating empirical (data-derived) estimates of arrival time uncertainty, and the results have been extensively tested through intercomparisons with other methods of location (e.g., Rodi et al., 2002, Bondár et al., 2008) and with GT0 data sets. Details have been discussed in previous presentations over the past decade. The calibration process itself can be done in two ways (categorized as “direct” and “indirect”), as discussed in previous presentations, but it almost always depends on near-source observations that can constrain the epicenter (or other hypocentral parameters) of at least one event in the HDC cluster. Near-source seismic observations are required to minimize the unknown biasing effect of using theoretical travel times in the location algorithm that do not adequately reproduce the travel times of seismic phases in the crust and upper mantle of the source region.

This requirement generally means using arrival time data only at distances inside the Pg/Pn crossover distance. Because HDC analysis tightly constrains the relative locations of all events in the cluster, the entire cluster can be shifted in space and time to best fit the available calibration data from near-source observations.

The 21 calibrated earthquake clusters used in this study are shown in Figure 1. The statistics of the calibrated clusters are presented in Table 1.

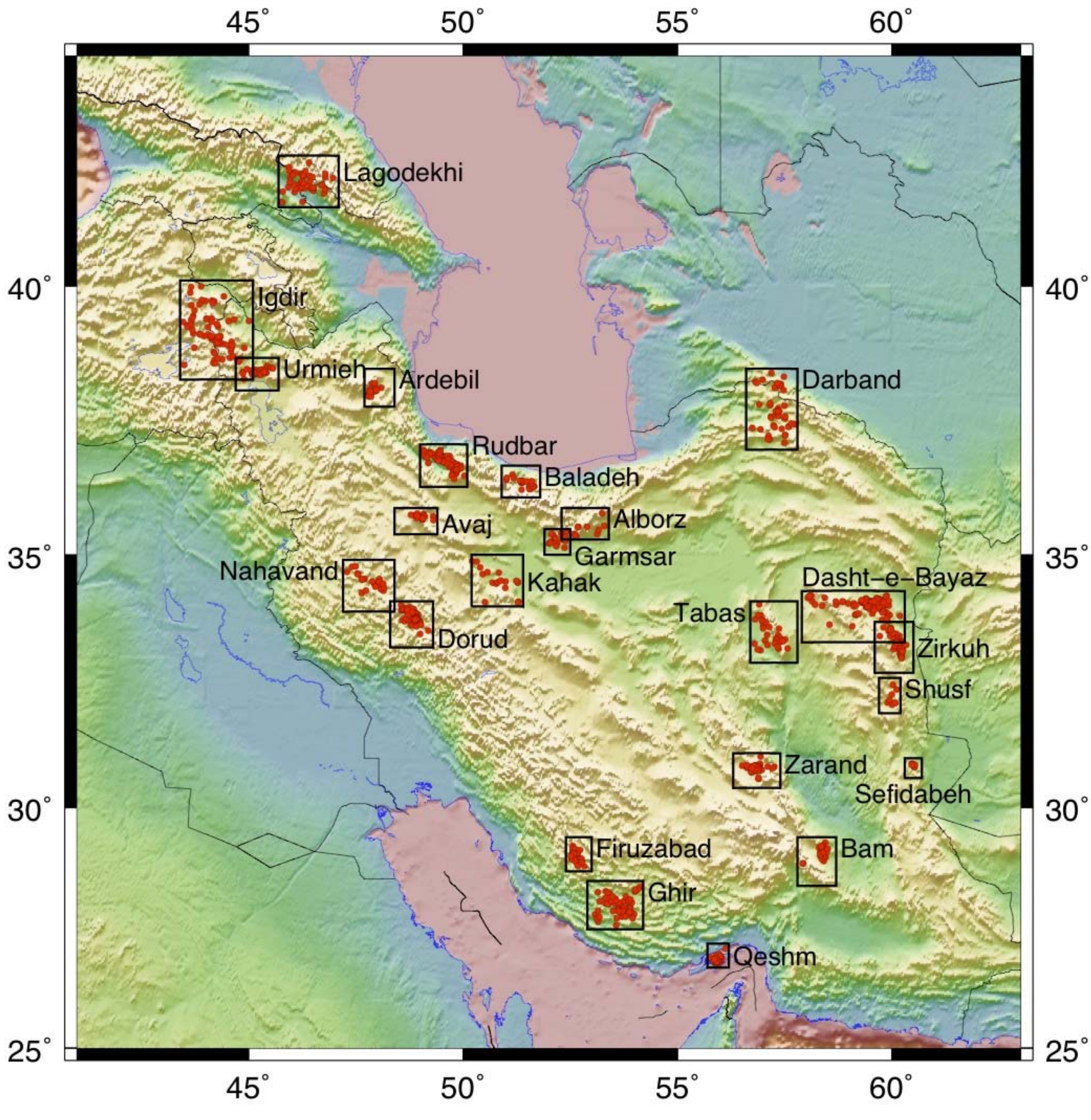

Figure 1. Locations of earthquake clusters whose locations have been calibrated using near-source data.

Table 1. Earthquake clusters for which a calibration analysis was made. "GT5" and "GT3" are the number of events that qualify as $GT5_{90}$ or better and $GT3_{90}$ or better. "Direct" and "Indirect" indicate different methods of calibration (see text). "Cal. Level" is the level of uncertainty of the calibration process, in km. "Seismic" is the number of seismic calibration events used for calibration. "InSAR" is the number of InSAR analyses or instances of mapped faulting used for calibration. "OT" indicates that the origin time is calibrated.

Name	Events	GT5	GT3	Direct	Indirect	Cal. Level	Seismic	InSAR	OT
Alborz	11	11	11	•		1.6			•
Ardebil	19	16	0	•		3.6			•
Avaj	17	16	1		•	4.3	1		•
Baladeh	25	23	20	•		2.2			•
Bam	31	18	2		•	3.2	1	1	•
Darband	44	41	17	•		2.9			•
Dasht-e-Bayaz	101	44	0		•	4.7	3	3	•
Dorud	80	77	63	•		1.8			•
Garmsar	16	16	15	•		1.3			•
Ghir	67	51	23		•	2.8	2	1	•
Igdir	71	47	1	•		3.1			•
Kahak	18	17	9	•		2.6			•
Lagodekhi	44	36	19	•		2.4			•
Qeshm	93	89	20	•		3.3			•
Rudbar	81	78	58		•	1.8	3		•
Sefidabeh	7	7	6		•	3.1	1	1	•
Shusf	7	4	1		•	4.1		1	
Tabas	30	14	2		•	4.4	2		•
Urmieh	26	25	0	•		3.5			•
Zarand	49	44	7		•	3.1	1	1	•
Zirkuh	43	10	0		•	5.1	2		•
Total	880	684	275	11	10				

Location Accuracy of Regional Networks

IIEES

The IIEES catalog has been published since July 2004 and is based on arrival time data only at INSN stations, which have increased in number from 13 in July 2004 to 16 in September 2007. The IIEES catalog contains 188 events that are also contained in our set of $GT5_{90}$ events. Most (160) of the events occurred since the beginning of 2005 when network operations became routine. For each match, we have calculated the distance and azimuth of the IIEES location with respect to the $GT5_{90}$ location. These vectors are shown in Figure 2a.

The median mislocation is only 5.1 km, showing that many IIEES locations are quite accurate. Based on median mislocation, the IIEES catalog would be rated the most accurate of the catalogs analyzed. However the distribution is quite long-tailed and a significant number of IIEES locations have large mislocations (Figure 3a). At the 90% level, IIEES locations are accurate at about 22 km. The statistics of the mislocations for the IIEES catalog are summarized in Table 2.

IRSC

Because the ISTN is organized in 10 subnetworks, the detection and location capability is quite variable, geographically. Moreover, the IRSC did not publish a unified "network" catalog until the beginning of 2006. Prior to then, locations are published for the individual subnetworks, based in most cases only on the data of that subnetwork. Thus there are many cases of multiple subnet locations of the same event. Subnet locations can be quite accurate for events inside the network, but the majority of IRSC locations before 2006 are for the case when the event is outside the network. It is well known that this inevitably leads to large errors in location. For this reason we have split the IRSC catalog into two parts for comparison with our $GT5_{90}$ locations:

- IRSC1: 538 events prior to 2006. All subnetwork solutions for the same event are retained.
- IRSC2: 82 events since 2006.

The mislocation vectors for the IRSC1 and IRSC2 data sets are shown in map view in Figure 2 and histograms of the mislocation distances is shown in Figure 3. The median mislocation for IRSC1 and IRSC2 is 31.3 and 19.6 km, respectively (Table 2), confirming our expectation that pre-2006 locations will be less accurate is strongly confirmed. At the 90% level, the location accuracy of the IRSC1 and IRSC2 is 123 and 36 km, respectively.

Even the recent IRSC2 catalog is significantly less accurate than the IIEES catalog. While some of the difference may be attributed to smaller sample size for IRSC2 which is based mainly on events from two calibrated clusters (Figure 2), we believe that the main factor is the unbalanced distribution of the ISTN stations. Because the stations are grouped tightly into subnetworks, the effective number of stations for location in many parts of the region is far less than the total number of stations would imply, and the distribution of those subnetworks does not provide adequate azimuthal coverage for many seismic source regions. Recently, the IRSC has begun incorporating some readings from INSN stations in their processing, and this should help improve location accuracy, as should the recent installation of new stations in the east and southeast of the country.

It is ironic that the ITSN, which has been the most important source of phase arrival data for many of our calibration studies, itself provides the least accurate locations of any of the networks considered.

Location Accuracy of Global Networks

ISC

The ISC catalog contains 501 of the events in common with our $9GT_{50}$ data set. 12 of the missing events occurred later than the most recent ISC Bulletin available at the time of analysis (June 2006); the remainder are smaller events which depend on data from the regional networks to obtain a stable solution. Mislocation vectors are shown in Figure 2, and a histogram of mislocation distances is shown in Figure 3. The median mislocation is 10.6 km (Table 2). At the 90th percentile, the location accuracy is about 23 km, about the same as the IIEES.

EHB-Iran

The "EHB-Iran" catalog for this comparison is based on our carefully-reviewed catalog of the region of interest, not the standard EHB catalog that is widely distributed. The 546 events considered are those that meet a secondary azimuth gap of 180° or better, based on all available arrivals from the ISC, PDE, and regional networks. Secondary azimuth gap is the largest azimuth gap filled by a single station. They have been located with the standard EHB methodology using all arrivals. In contrast, the "standard" EHB catalog is based on arrivals only at teleseismic distances (> 28°). Based on the 90% level of accuracy, the EHB-Iran catalog provides the lowest level of location bias (18 km) of the four networks examined (Table 2), although the median mislocation of 9.1 km is not as good as that of the IIEES catalog. The map and histogram of mislocations are shown in Figures 2d and 3d, respectively. The fact that the EHB-Iran catalog has fewer events with very large mislocations than any of the other catalogs is primarily due to the selection criterion on secondary azimuth gap.

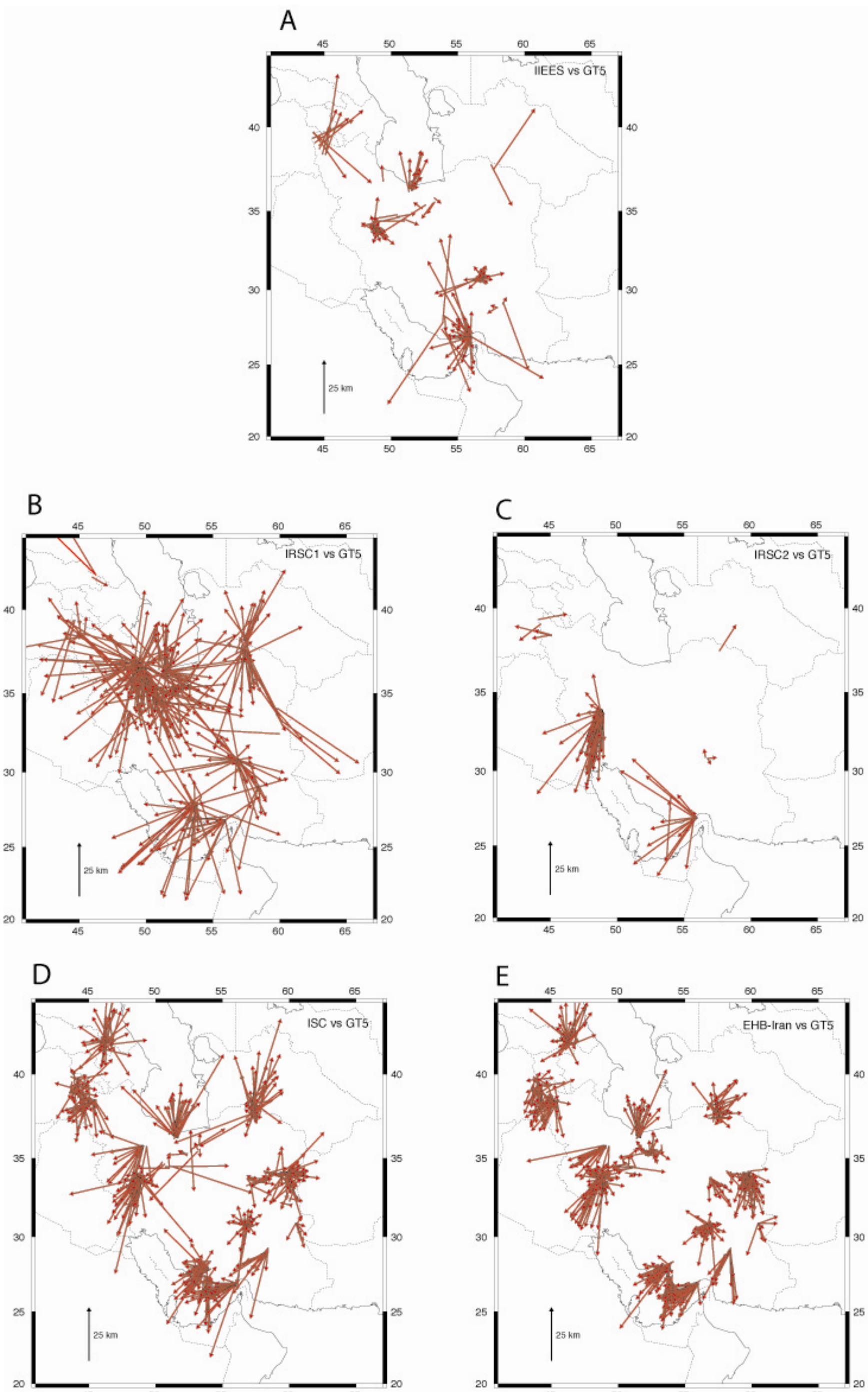

Figure 2. Mislocation vectors for locations for different catalogs, in comparison with corresponding GT5 locations. Only vectors with length less than 50 km are plotted.

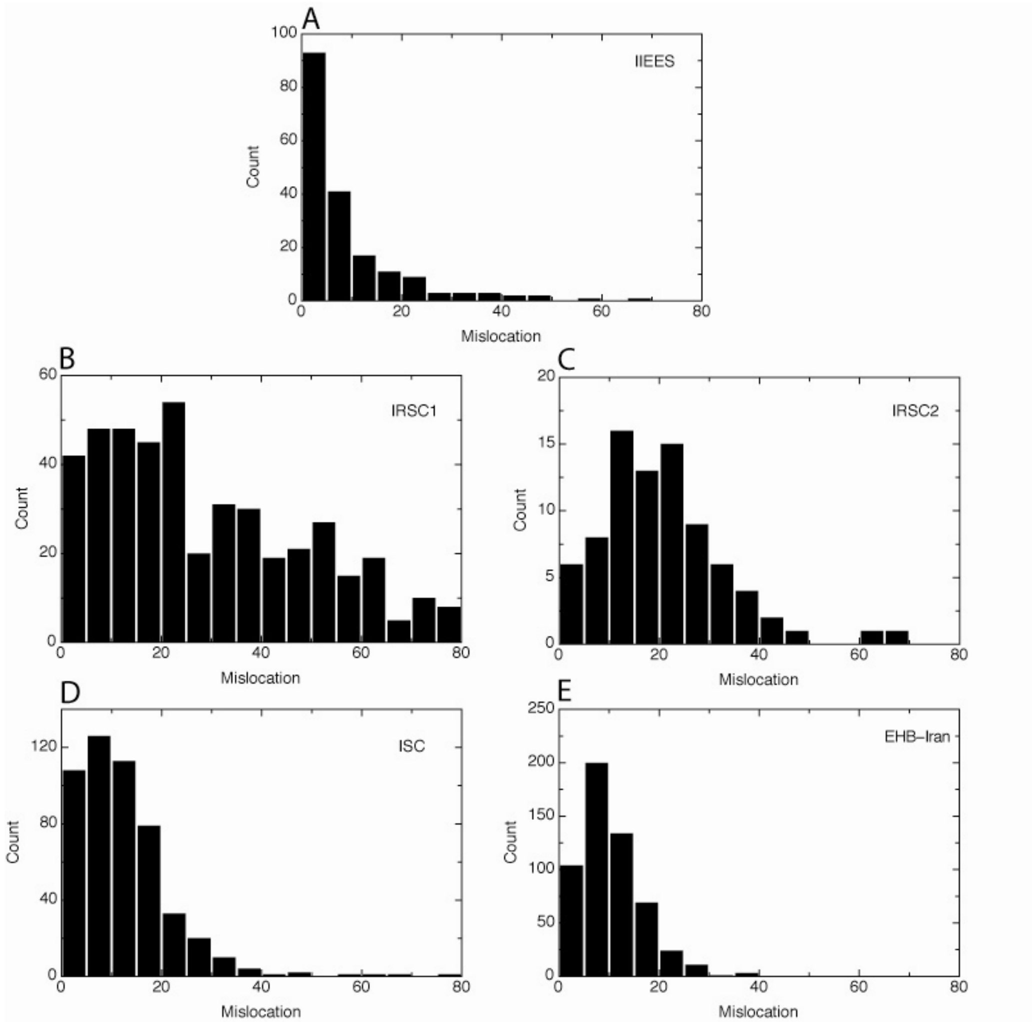

Figure 3. Histograms of mislocation distances of the different catalogs relative to the GT5 data set.

Table 2. Statistics of mislocation vectors of several seismic networks compared with the set of corresponding GT5 locations.

	# Samples	Median (km)	Mean (km)	90% (km)	Max (km)
IIEES	188	5.1	10.1	22	87
IRSC1	538	31.3	49.3	123	275
IRSC2	82	19.6	21.0	36	67
ISC	501	10.6	12.6	23	170
EHB-Iran	546	9.1	10.3	18	38

Azimuthal Bias in Locations

To explore the possibility of a systematic direction of location bias, we made sector plots of the mislocation vectors for each catalog (Figure 4). All the networks considered exhibit a tendency for systematic bias in certain directions, driven by the convolution of station geometry with the distribution of seismicity in the region, and scaled by the appropriateness of the travel time model used for location.

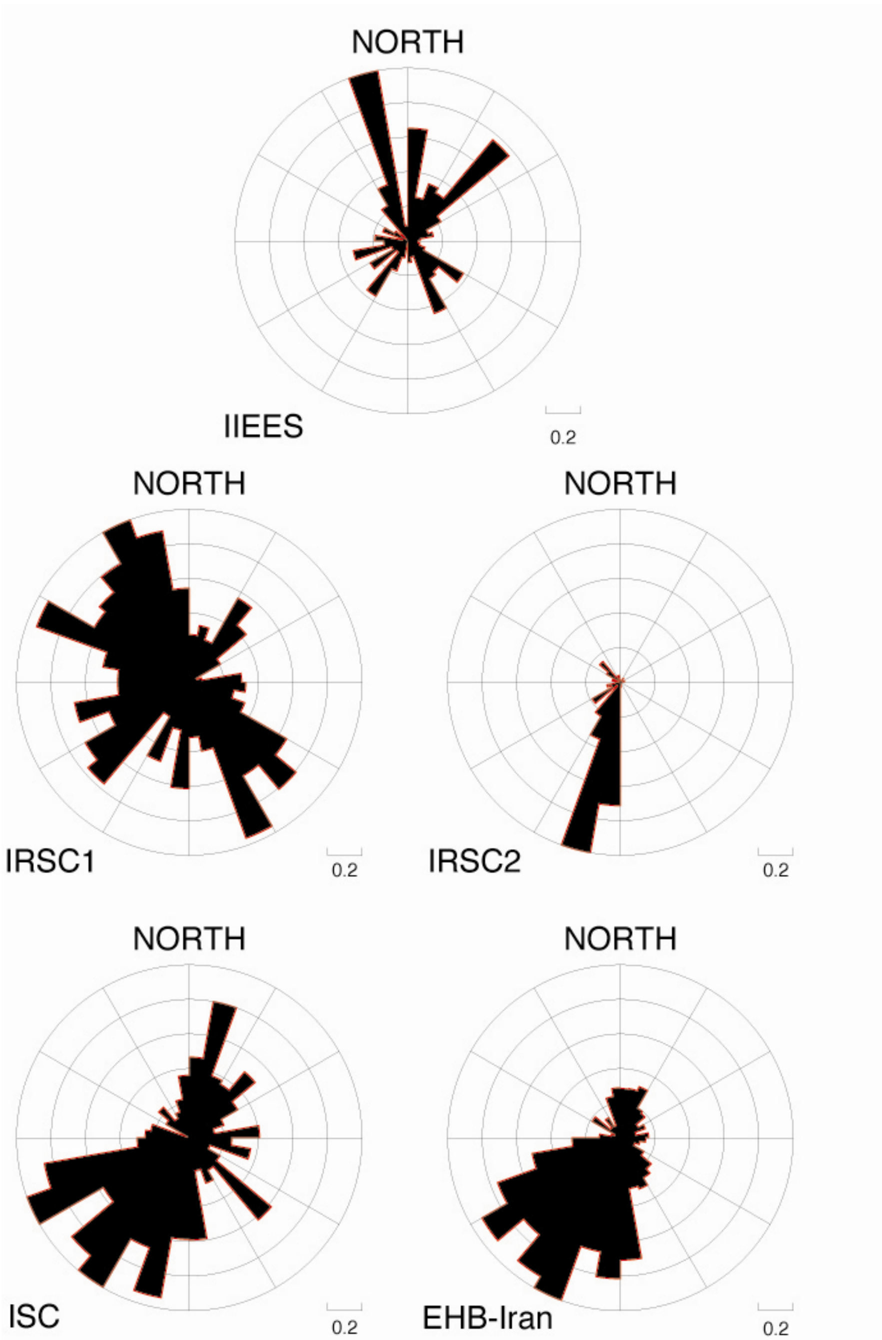

Figure 4. Sector diagrams of the azimuth of mislocation for the different catalogs. Sectors are 30° in azimuth.

The number of mislocation vectors in each sector is normalized to the most populous sector.

The IIEES catalog tends to be biased to the north, and probably represents a tendency for epicenters to be pulled toward the bulk of the stations. The IRSC1 (pre-2006, subnetwork solutions) catalog shows a strong NW-SE trend for mislocations. It may be that this pattern is the sum of two patterns such as is seen for the IIEES catalog, dominated by the frequent seismic activity in the NW-SE trending Zagros region. Some subnetworks of the ISTN see more events to the northwest and some see more events to the southeast. The sector plot for the IRSC2 catalog (post-2006) is dominated by a single calibrated cluster (Dorud), for which IRSC locations were systematically too far south, but this should not be taken to represent the performance of the ISTN network in all parts of the region. The two catalogs (ISC and EHB-Iran) that are based largely on teleseismic and far-regional phase readings both exhibit a strong tendency to mislocate events to the southwest. This is especially true of the EHB-Iran catalog, from which the grossest consequences of poor azimuthal coverage and large outlier readings have been removed. What remains is a signal that is the result of a significant and regionally-consistent departure of real Earth structure in the study region from that assumed in the theoretical travel-time model used for location. All EHB-Iran locations are based on the ak135 model (Kennett et al., 1995); all ISC locations in this comparison are based on the Jeffreys-Bullen tables (ISC has recently begun using ak135).

In broad terms the systematic direction of mislocation can be summarized as a consequence of the fact that there are far more seismic stations in the northern hemisphere, relative to the study region, and that the true travel times are larger than the theoretical ones, yielding positive travel-time residuals (Figure 5). The inversion for location tends to push the event further away from the bulk of seismic stations, i.e., to the south. The EHB-Iran catalog simply ignores the worst cases of poor azimuthal distribution, but it cannot correct the fundamental imbalance of global station distribution.

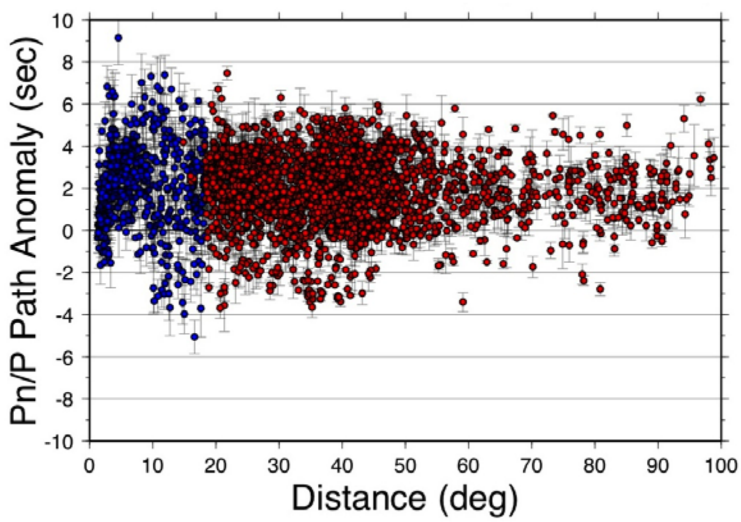

Figure 5. Empirical path anomalies for Pn (blue) and P (red) phases for $GT5_{90}$ events in the study region, calculated as the difference between the observed travel time of the phase arrival from a calibrated location (including origin time) and the theoretical travel time calculated with the ak135 velocity model. On average over the entire epicentral distance range, ak135-derived travel times are about 2 seconds faster than the travel times derived from calibrated locations.

CONCLUSIONS AND RECOMMENDATIONS

880 earthquakes in 21 clusters have been analyzed using a multiple event relocation technique for calibrated locations that remove most of the systematic bias in single-event locations done with regional and teleseismic data. 684 of these calibrated events have location uncertainties that qualify them as $GT5_{90}$ or better. By comparing these

locations with those from the catalogs of global and regional networks (all of which are based on 1-D Earth models), we investigate the location accuracy of those networks in the region. Earthquake locations in the study region which are based on regional and teleseismic arrival time data (ISC and EHB) are systematically biased to the southwest and have a 90% location accuracy of 18-23 km, with the lower value achievable by applying limits on secondary azimuth gap. Iranian seismograph networks have operated both as regional networks (IIEES and the IRSC since 2006) and local networks (IRSC prior to 2006). The IIEES catalog achieves the best location accuracy in this category, with a 90% accuracy level of 22 km. The IRSC network, even in recent years, when all the subnetwork data have been combined, suffers from a very imbalanced distribution of stations and achieves a 90% level of accuracy of 36 km. When IRSC subnetworks are used independently to locate earthquakes, as was typically the case prior to 2006, location accuracy at the 90% level exceeds 100 km. The IIEES catalog has a systematic location bias towards the north. The data for the IRSC catalog are inadequate for an analysis of systematic mislocation directions. In broad terms, location accuracy in the study region using 1-D travel time models and single event location procedures, is presently limited to about 20 km at the 90% level of accuracy (i.e., $GT20_{90}$). These results emphasize the importance of developing improved velocity models for the region which can more reliably predict seismic travel times at regional distances. The data set of calibrated earthquake locations assembled for this study has exceptional value as a validation tool for such efforts.

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