INTERNATIONAL SEISMOLOGICAL CENTRE (ISC)

# 2019

# Annual Director's Report


It was another hugely productive year for the ISC thanks to the support of 68 Member-Institutions and 13 Project Sponsors and despite the local government in West Berkshire taxing the ISC at the standard business rate. To alleviate the problem, the ISC has been considering registration with the Charity Commission for England and Wales.

The data for seismic events during 2016-2019 have been added to the ISC Bulletin. The ISC Bulletin has been rebuilt and released for the period 1985-1990. The ISC continued using openly available waveforms to determine source mechanisms, based on first onset polarities, and to constrain earthquake depths, based on depth phase pickings. Smaller continental earthquakes during the 1980-1990 period and several hundreds of source mechanisms from literature have been added to the ISC-GEM catalogue. We released the ISC-EHB dataset and corresponding subduction zone cross-sections for the entire period (1964-2016). We began operating the ISC Seismological Dataset Repository.

Both the ISC download statistics and the large number of scientific research articles indicates an extensive worldwide use of ISC data.

# EXECUTIVE SUMMARY

- The ISC gratefully acknowledges generous support received from **68 Member-Institutions in 48 countries** and additional project grants (**24%** of total income) from CTBTO, USGS, BGR, FM Global, Lighthill Risk Network, US NSF, NIPR, JAMSTEC, MS&AD InterRisk as well as sponsorships from Reftek, GeoSIG, Guralp and SRC.
- The 2019 annual income exceeded the ISC's expenditure by £39,869, which partly alleviated a loss of £44,454 in year 2018.
- A comparatively small amount (£6,744) is owed for accounting year 2019 (£117,683 in 2018); we praise those ISC Members who pay their dues promptly, when invoiced.
- The local government in West Berkshire continued charging the ISC with full business rates; to alleviate the problem, the ISC has been considering registration of its non-for-profit status with the Charity Commission for England and Wales.
- At any one time, 16-19 staff members, one contractor and one member of the Earth Science Department of the University of Oxford worked at the ISC during the year.
- 913 seismic stations were registered or modified in the **International Seismograph Station Registry**.
- Within a few days after an event occurrence, the ISC collected and grouped preliminary data from 32 networks and made the **Preliminary ISC Bulletin** available to all users.
- The routine process of collecting revised bulletins from various institutions stood at 12 months behind real time; a number of agencies were not able to comply with this deadline and inadvertently hindered the ISC Bulletin analysis.
- Due to the analyst's efforts being partly diverted to the completion of the Rebuild of the historical part of the ISC Bulletin, less than 12 recent full data months were added to the Reviewed **ISC Bulletin** with ~60,000 events and ~7.7 million seismic arrivals; the entire Bulletin was enlarged by ~683,000 seismic events and ~24.3 million associated seismic arrivals.
- ~8,500 ISC focal mechanisms covering the period from 1980 to March 2017 have been added to the ISC Bulletin based on reported first motion polarities and those automatically picked by the ISC using waveforms available on-line.
- We also continued waveform picking of depth phases (global) and general seismic phases (Africa) to fill in gaps in agency reporting.
- The ISC Bulletin remains more complete than the bulletins of either NEIC or IDC.
- By the end of 2019, we were only a few data months short of completing the review of the Rebuild ISC Bulletin for the entire project period 1964-2010.

- We released two further issues of the printed **Summary of the ISC Bulletin,** which included several invited network related articles; each issue and each invited article now has its own DOI registered via the ISC's membership of CrossRef.
- The **ISC-GEM Global Instrumental Earthquake Catalogue** has been advanced to include many small continental earthquakes during 1980-1990 and several hundreds of earthquake mechanisms from scientific literature.
- References to ~2,000 scientific articles related to ~6,400 seismic events have been added to the **ISC Event Bibliography.**
- We continued operating and improving the **CTBTO Link to the ISC database** which experienced a steady stream of data requests from NDC and IDC personnel.
- The ISC database and the website mirrors at IRIS DMC in Seattle, ERI in Tokyo, LLNL in Livermore and CEA in Beijing/Xian guaranteed improved speed of access to ISC data.
- We continued updating and distributing the IASPEI Reference (**GT**) Event List and the List of **International Contacts in Seismology**.
- We released the **ISC-EHB** dataset for the entire period 1964-2016, complete with a collection of regional seismicity cross-sections; the EHB is now truly obsolete.
- Two new ISC-EHB analysts have been trained.
- We released a new ISC product - the **Seismological Dataset Repository**
- The ISC staff published several scientific articles describing the production methods and availability of the ISC datasets.
- We attended a number of international and regional scientific and industry conferences.
- We helped the University of Edinburgh to prepare and run the 2nd British Seismology Meeting (**BSM-2019**), the tradition originally devised by the ISC in 2017.
- The ISC has contributed to the work of **IASPEI** by maintaining the IASPEI website, leading several working groups and working at the IASPEI ExecCom.
- Impressive ISC data download statistics and a large number of published scientific articles using ISC data indicate a very wide and extensive use of ISC products by many researchers worldwide.

Signed, 5th May 2020

Dr. Dmitry A. Storchak
Director

# STAFF and CONTRACTORS

A total of 20 members of staff (16-19 at any one time), one contractor and one member of staff from University of Oxford worked at the ISC throughout the year, thanks to the regular Member's support and a number of additional grants given to the ISC by international institutions, public institutions and commercial companies to work on the ISC-GEM Catalogue, CTBTO Link, Station Registry and ISC Event Bibliography. Staff changes through the year are highlighted in red or light blue.

Among the staff, there were 6 Ph.D., 6 M.Sc. or equivalent, and 4 B.Sc. or equivalent degrees. The ISC staff represents 11 different countries from 4 continents. Several members of staff took part in professional meetings, travelled to international conferences and participated in professional training programmes.

ISC staff often organise sessions at scientific conferences. Several ISC staff are members of professional organizations such as IASPEI, EGU, AGU and SSA. ISC staff members are engaged in the IASPEI's Executive Committee, commissions and working groups.

## MANAGEMENT and ADMINISTRATION

**Dmitry Storchak**, Ph.D.
Director/Seismologist
*Russia/UK*

**Lynn Elms**
Administration Officer
*UK*

## SYSTEM ADMINISTRATION and WEB DEVELOPMENT

**James Harris**
*Senior System & DB Administrator, UK*

**Alfie Barber**
*Systems Administrator, UK,*
*left in August*

**Gergely Csontos**
*Web Developer, Hungary,*
*left in January*

**Oliver Rea**, B.Sc.
*Systems Administrator, UK,*
***joined in October***

## BULLETIN DATA COLLECTION and ENTRY

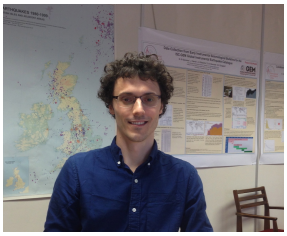
The Data Collection Officer communicates with agencies and manages routine automatic entry of reported data. The Historical and Bibliographical Data Entry Officer helps with entering paper-based data into the ISC database and maintaining the ISC Event Bibliography.

**John Eve**, B.Sc.
Data Collection Officer
*UK*

**Daniela Olaru**
M.Sc.Admin., Historical and Bibliographical Data Entry Officer,
*Romania*

## ANALYSIS TEAM: STANDARD and REBUILT BULLETINS

Ten analysts were engaged in reviewing the current ISC Bulletin. Each member of this team has an additional task either in development projects or in data collection. All of them took part in the Rebuild of the historical ISC Bulletin.



**Lonn Brown, M.Sc.**
Seismologist/ Analyst Administrator,
*Canada, left in November*

**Kathrin Lieser, Ph.D.**
Seismologist / **Analyst Administrator** / Editor of the Summary
*Germany*

**Blessing Shumba**, M.Sc.
Seismologist / Senior Analyst,
*Zimbabwe*

**Elizabeth Ayres**, B.Sc. Geog.,
Analyst/Historical Data Officer,
*UK*

**Rebecca Verney**, B.Sc.,
Analyst, 3 days a week,
*UK*

**Rosemary Hulin**, M.Phys. Geog., 3 days a week,
*UK*

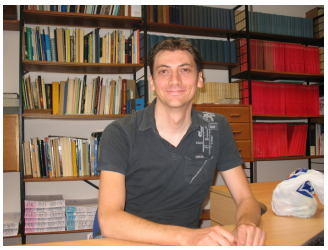
**Gharikleia Gkarlaouni, M.Sc.**,Seismologist/Analyst, *Greece*

**Peter Franek, Ph.D.**, Seismologist/Analyst, *Slovakia*

**Angeliki Adamaki, PhD**,Seismologist/Analyst, *Greece, left in July*

**Burak Sakarya**, **M.Sc**., Seismologist/Analyst, *Turkey*

## DEVELOPMENT PROJECTS



**Domenico Di Giacomo**
Ph.D.
Senior Seismologist
*Italy*

**Kostas Lentas**
Ph.D.
Seismologist/Developer
*Greece*

**Thomas Garth**
PDRA, Department of Earth Sciences, University of Oxford, part-funded by the ISC, *UK*

## CONTRACTORS

During the year, the following person also contributed to the ISC as contractor:

- **E.R. Engdahl**, Ph.D., *Boulder*, *USA*: taking leading role in preparing the ISC-EHB dataset;

# OPERATIONS

## INTERNATIONAL SEISMOGRAPH STATION REGISTRY (IR) as part of the ADSL DATABASE

The International Seismograph Station Registry (IR) allocates globally unique codes to seismic stations worldwide.

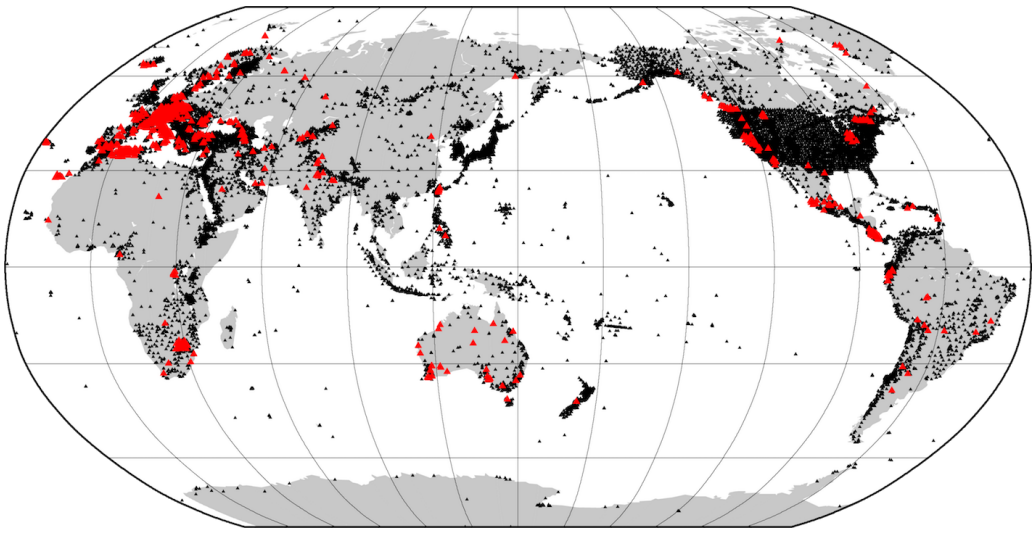


***Figure 1***. *27,451 stations, open or closed, were fully registered in the International Seismographic Station Registry at the end of 2019; parameters of 913 of those (in red) were either registered or modified during 2019.*

During 2019, the IR has been particularly improved and extended in Europe, the Mediterranean, Southern Africa, Australia, North and Central America (Fig. 1) as part of:

- regular ISC Bulletin work,
- inclusion of additional or missing datasets into the ISC Rebuilt Bulletin,
- update of the IASPEI Reference Event (GT) List and
- participation in the CTBTO initiative on Regional Seismic Travel Times (RSTT).

The ISC runs a popular web page giving an account of already registered stations as well as inviting the submission of parameters required to register a new station. Figure 2 gives an account of the IR related web searches, per country.

In fact, the IR has become part of the ADSL database (Agency.Deployment.Station.Location) which we designed and continue maintaining jointly with the NEIC. The ISC maintains the agency.deployment "ISC.IR" as a subset of ADSL. In order to use all waveform data available on-line, NEIC routinely updates the ADSL database with stations under the deployment codes equal to corresponding FDSN two-character network codes, based on

dataless mini-SEED files available at IRIS DMC. NEIC no longer needs the IR in day-to-day operations since they use waveforms of stations available on-line, usually with FDSN codes.

Now and in the future, the globally unique ISC.IR station codes will remain an exclusive source of station position information for the historical period of time. Also, the ISC.IR will continue to cover a large number of stations whose waveform data are not available to the international waveform data centres.

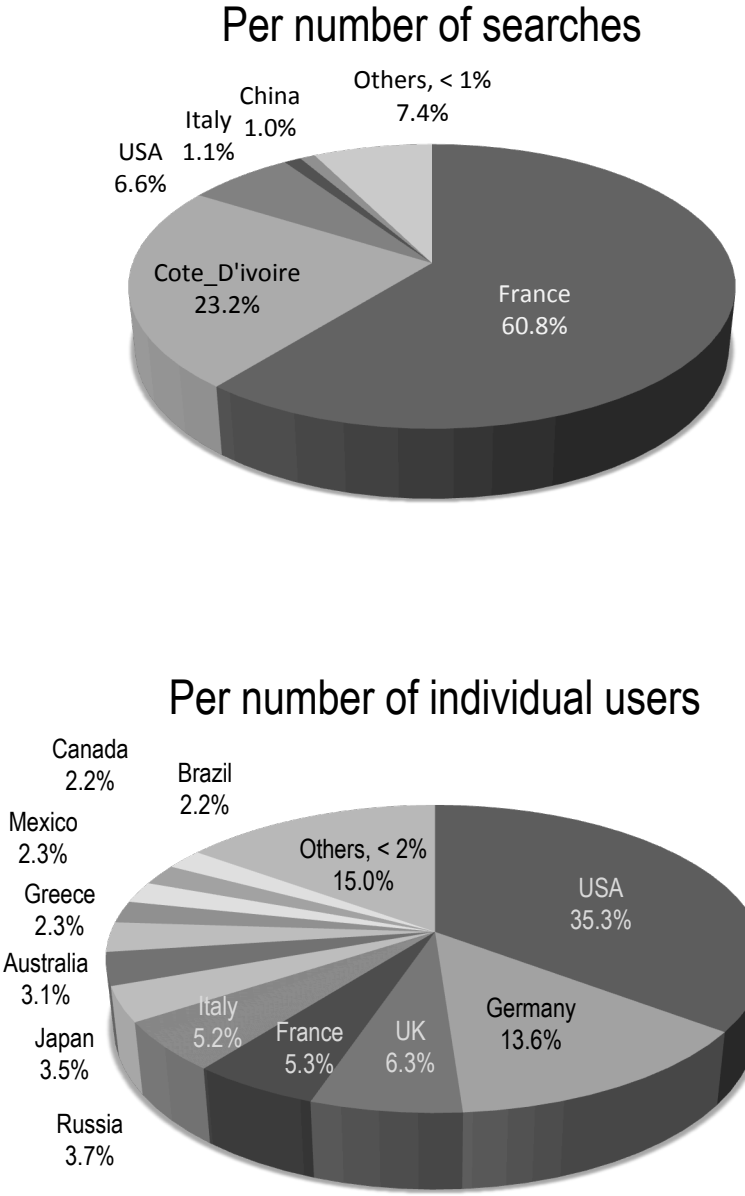



***Figure 2.*** *Per country statistics of IR web-searches; some countries may be shown here due to them housing a VPN-server through which some user-searches are made; NEIC/USGS now searches directly through the ADSL database and is not shown here.*

At present, for the majority of its standard operational activities, the ISC uses just the IR (almost equivalent to ISC.IR element of the ADSL database). In order to be able to deal with a multitude of additional stations becoming available largerly from NEIC, the ISC plans to

switch to working with the entire ADSL. To make this happen, a very large effort is required to update, test and validate almost the entire operational and web distribution computer code at the ISC. This work has begun in 2019 but progressed slowly due to major conflict with the Bulletin Rebuild project that required us to run two main ISC databases at the same time. This wasn't a good time to modify operational procedures.

Nevertheless, during 2019 we have:

- prepared for the ISC Bulletin distribution using the ISF2.1 format that includes ADSL station coding;
- studied the code of the ISC location program to see how to use it with the ADSL; potential difficulties related to ISC magnitude computation have been identified; we are therefore building plans to safeguard the ISC magnitude values from beeing skewed by data of the same station reported with different network codes or stations positioned very closely to each other;
- planned measures to be able to use the ISC-EHB software with ADSL.

Overall, the work on ADSL will continue throughout 2020-2021.

## COLLECTING PRELIMINARY NETWORK BULLETINS

The ISC continues to collect preliminary bulletin data from a large number of networks and data centres. These data are expected to have undergone at least a minimal review by local analysts. Typically, the incoming data include a preliminary hypocentre location, magnitude estimates, moment tensor solution and station arrival data, though there are large variations from agency to agency. Agencies that reported preliminary data during year 2019 are shown in Table 1.

***Table 1**. 32 agencies reported **preliminary** hypocentre determinations and corresponding arrival time data to the ISC in 2019.*

| Country | Reporting Agency |
|---|---|
| Armenia | National Survey of Seismic Protection |
| Australia | Geoscience Australia |
| Austria | Zentralanstalt fur Meteorologie und Geodynamik (ZAMG) |
| Canada | Canadian Hazards Information Service, Natural Resources Canada |
| Cyprus | Cyprus Geological Survey Department |
| Czech Republic | Geophysical Institute, Academy of Sciences of the Czech Republic |
| Denmark | Geological Survey of Denmark and Greenland |
| Egypt | National Research Institute of Astronomy and Geophysics |
| Finland | Institute of Seismology, University of Helsinki |
| France | Institut de Physique du Globe de Paris |
| France | Centre Sismologique Euro-Mediterranean (CSEM/EMSC) |
| Germany | Helmholtz Centre Potsdam, GFZ Research Centre for Geosciences |
| Germany | Landeserdbebendienst Baden-Wurttemberg |

| | |
|---|---|
| Hungary | Geodetic and Geophysical Research Institute |
| India | National Geophysical Research Institute |
| India | National Centre for Seismology, Ministry of Earth Sciences |
| Indonesia | Badan Meteorologi, Klimatologi dan Geofisika |
| Israel | Geophysical Institute of Israel |
| Italy | Istituto Nazionale di Geofisica e Vulcanologia |
| Japan | Japan Meteorological Agency |
| Kyrgyzstan | Institute of Seismology, Academy of Sciences of Kyrgyz Republic |
| Norway | University of Bergen |
| Norway | Stiftelsen NORSAR |
| Romania | National Institute for Earth Physics |
| Russia | Geophysical Survey of Russian Academy of Sciences (GS RAS) |
| Russia | Baykal Regional Seismological Centre, GS RAS |
| Russia | Kamchatka Branch, GS RAS |
| Slovenia | Slovenian Environment Agency |
| Spain | Instituto Geografico Nacional |
| UK | British Geological Survey |
| USA | NEIC, USGS |
| USA | Pacific Tsunami Warning Center |

There are 19 agencies that produce bulletins soon after an event occurrence and never return to event re-analysis unless there is a special need (Table 2). These agencies can be considered as reporting both preliminary and final bulletins at the same time.

***Table 2**. Agencies reporting final analysis results within a month of event occurrence*

| | |
|---|---|
| Australia | Geoscience Australia |
| Austria | International Data Centre, CTBTO |
| Chinese Taipei | Institute of Earth Sciences, Academia Sinica |
| France | Laboratoire de Detection et de Geophysique/CEA |
| French Polynesia | Laboratoire de Geophysique/CEA |
| Germany | Alfred Wegener Institute for Polar and Marine Research |
| Germany | GFZ Potsdam |
| Greece | National Observatory of Athens |
| Greece | University of Patras, Department of Geology |
| Ireland | Dublin Institute for Advanced Studies |
| Kazakhstan | Seismological Experimental Methodological Expedition |
| Kyrgyzstan | Kyrgyz Seismic Network |
| Macao | Macao Meteorological and Geophysical Bureau |
| Mexico | Centro de Investigacion Cientifica y de Educacion Superior de Ensenada |
| New Zealand | Institute of Geological and Nuclear Sciences |
| Norway | Stiftelsen NORSAR |
| Poland | Institute of Geophysics, Polish Academy of Sciences |
| Portugal | Instituto Geofisico do Infante Dom Luiz |
| Switzerland | Swiss Seismological Service |

Notably, the availability of data from the IDC/CTBTO bulletin (REB) stayed as agreed with CTBTO – seven days after formal release of each REB data day. This is essential since the ISC is the only channel through which academic research scientists can get regular uninterrupted access to the REB event and station recording parameters (not original bulletins) except for the most recent 10-14 days. In line with CTBTO's formal conditions of release, the ISC is not allowed to make the original REB bulletins openly available.

## BUILDING the PRELIMINARY ISC BULLETIN

Preliminary hypocentre solutions and station arrivals are grouped in the ISC database with corresponding solutions from other agencies and made available through the standard ISC Bulletin search procedure within a few hours of receipt. For each event an output includes several hypocentre solutions reported by various agencies, all reported source mechanisms and magnitude estimates as well as corresponding station arrival data. Event headers include logo images of each reporting agency and, by clicking on the logo, Preliminary ISC Bulletin users can get further information from each agency directly.

Almost all events with magnitude 5 and above and many of smaller magnitudes are reported within the first week. Further reports beyond one week add information to already reported large and moderate events and also inform about smaller events.

This process is there to fill the gap between the event occurrence and the time when the final Reviewed ISC Bulletin becomes available. It presents an attempt to consolidate the effort of many data centres and networks to make their data available internationally in good time. At this stage the ISC does not compute or publish its own event solutions. This service is not intended for use by the media or civil protection agencies. It is designed to be used by seismologists to receive as much information as possible in one single format from one single source and then to get access to details using the links provided to the original data reporters.

No later than one year after each seismic event occurrence, the preliminary data from agencies are substituted with their final, revised versions; this is well before the ISC analysts make their final review of the ISC Bulletin. The ISC hypocentre solutions are still based only on the revised set of bulletin parametric data given by each reporting institution.

## COLLECTING REVISED NETWORK BULLETINS

The standard ISC data collection pulls together revised bulletins from agencies (network data centres and single observatories) around the world up to 12 months behind real time. This delay gives the majority of data contributors enough time for reviewing and finalising their bulletin data before submission to the ISC.

*Appendix 1* lists 139 agencies that contributed revised seismic bulletins to the ISC during the calendar year 2019. It is important to note that among them this time is only one regional data concentrator, the NEIC/USGS, which in fact represents a number of US-based networks. Sadly, the East and South Africa Regional Seismological Working Group (ESARSWG) that

usually contributes a coordinated collection of local bulletins from 9 countries (*Ethiopia, Eritrea, Kenya, Malawi, Mozambique, Tanzania, Uganda, Zambia and Zimbabwe)* has failed to meet and produce their bulletins for data year 2017.

The ISC no longer receives seismic bulletins from the European-Mediterranean Seismological Centre (EMSC). All available bulletin contributions from this region arrive at the ISC directly from individual institutions.

Figure 3 shows countries and agencies that contributed revised bulletins for various months and years, directly or indirectly (via other agencies), during 2019. Figure 4 shows those agencies that reported data for the data months that the ISC reviewed during 2019. This collection is generally more complete (see the improvement in Cote D'Ivoire, Cuba, Madagascar, Morocco, Nicaragua, Pakistan, Saudi Arabia, Sudan, Sweden) due to the effort of the Data Collection Officer and the Director to obtain missing agency data before the analysis at the ISC begins.

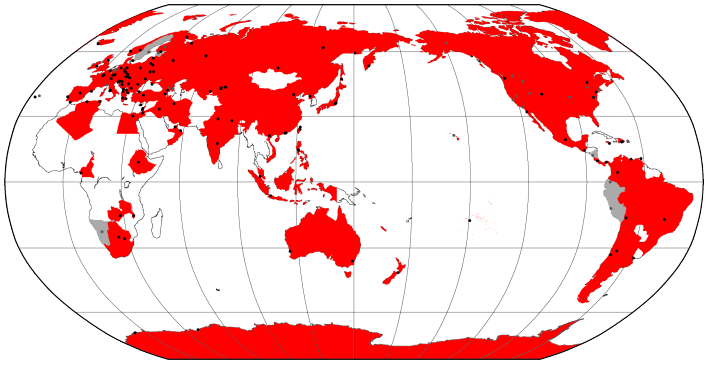


***Figure 3**. Agencies (black dots) and corresponding countries (in colour) that reported revised bulletins during 2019; red/grey colours indicate direct/indirect contributions.*

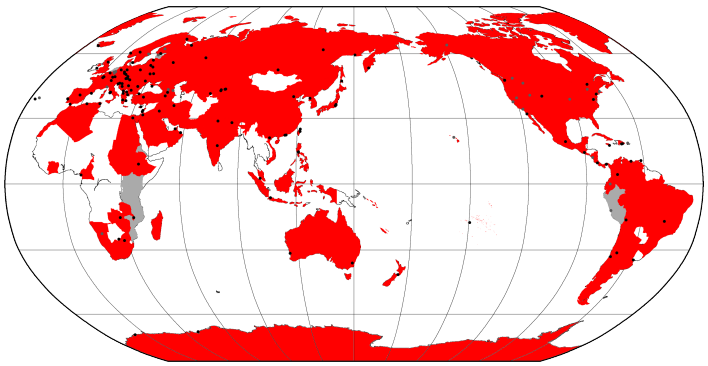


***Figure 4**. Agencies and corresponding countries that reported revised bulletins for the data months reviewed by the ISC in 2019: June 2016 – May 2017.*

The ISC Bulletin is progressively updated with each network report coming in. Preliminary network contributions are substituted with final reviews. New events are built, merged or split with every new report coming to the ISC by e-mail and processed either automatically or manually by the ISC Data Collection Officer, who is working remotely from his home office in Scotland. The Analyst Administrator and the Data Collection Officer regularly review the status of data collection and contact various agencies to avoid reporting gaps. The Director helps to address urgent and difficult cases.

## BULLETIN REVIEW

When the time comes, one month's worth of data is pulled into a separate database and a set of automatic procedures are run to produce automatic ISC event locations and magnitude determinations for those events that are large enough to be reviewed by the ISC seismologists. The threshold criteria are complex yet almost all events of magnitude 3.5 and larger are reviewed.

The ISC seismologists/analysts review approximately 10-20% of all events formed in the ISC database by the automatic procedures. Although this review misses smaller events, it makes the most used part of the ISC Bulletin accurate and trustworthy. The accuracy of *ak135*-based ISC solutions and magnitude estimates, and proper grouping of reported information between the events in the Bulletin is under constant scrutiny. The ISC analysts also review the correctness of automatic association of reported station arrivals to events, reported arrival's phase identification and travel-time residuals.

All analysis work is done using the Visual Bulletin Analysis System (VBAS). We were able to correct various small issues in the original version. We are planning to improve it further, where possible. A major upgrade would require employing an additional programmer, skilled in Java. Unfortunately, there are no extra funds available for this at this moment.

Throughout 2019, the Analysis Team varied between 9.2 (at start of the year) and 7.2 members (end of the year). This variability was caused by one resignation for personal reasons in the middle of the year and the Team leader, Lonn Brown taking a PhD post in his home country at the end of the year. The responsibility for administering the group was transferred to Dr Kathrin Lieser, who by that time had four years experience with the Team.

During 2019, the Team was conducting the review of the standard current ISC Bulletin as well as the Rebuilt ISC Bulletin for the period 1985-2010. In fact, in the second half of 2019, the priority and most resources were directed at the Rebuild project, with just two analysts performing the analysis of the standard ISC Bulletin. As a result the lag in the reviewed ISC Bulletin availability behind real time has increased (Fig.5).

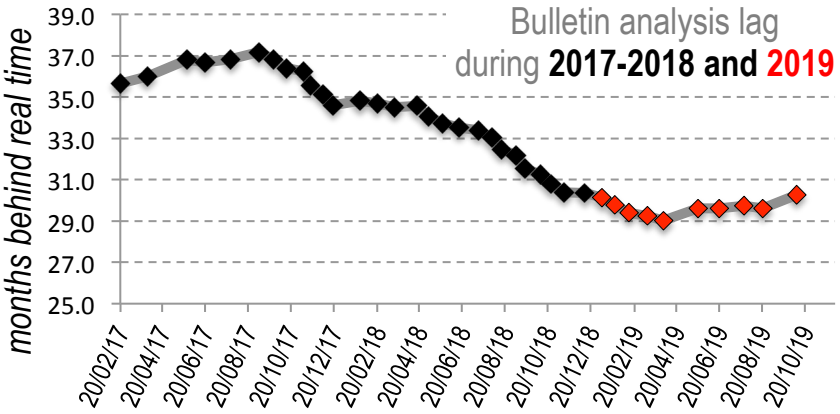



***Figure 5**. The lag in availability of the Reviewed ISC Bulletin in months behind real time.*

In addition, members of the team were involved in other projects such as the ISC-EHB bulletin, Event Bibliography, ISC-GEM catalogue, automatic amplitude measurements from waveforms and production of the printed/electronic Summary of the ISC Bulletin, including its statistical analysis.

As a result, during 2019, the Analysis Team fully reviewed only **eight** complete data months of the recent ISC Bulletin with **four** data months receiving partial review. In total this covered data from June 2016 - May 2017. The analysts were working with a marginally lower number of seismic events compared to the average number during the previous five years (Fig. 6). Nevertheless the number of associated phases reviewed by analysts was on the increase (see numbers below) as new stations and networks were set up and corresponding data reported to the ISC. By design, VBAS helped to alleviate this problem.

During the calendar year 2019 (*2018*), ~60,000 *(~76,000)* reviewed events with ~7.7 *(~8.8)* million associated phases were added to the reviewed part of the Bulletin by the ISC analysts. Overall, the Bulletin (both reviewed and un-reviewed) was enlarged with ~683,000 (~613,000) events and ~24.3 (~20.3) million associated phases.

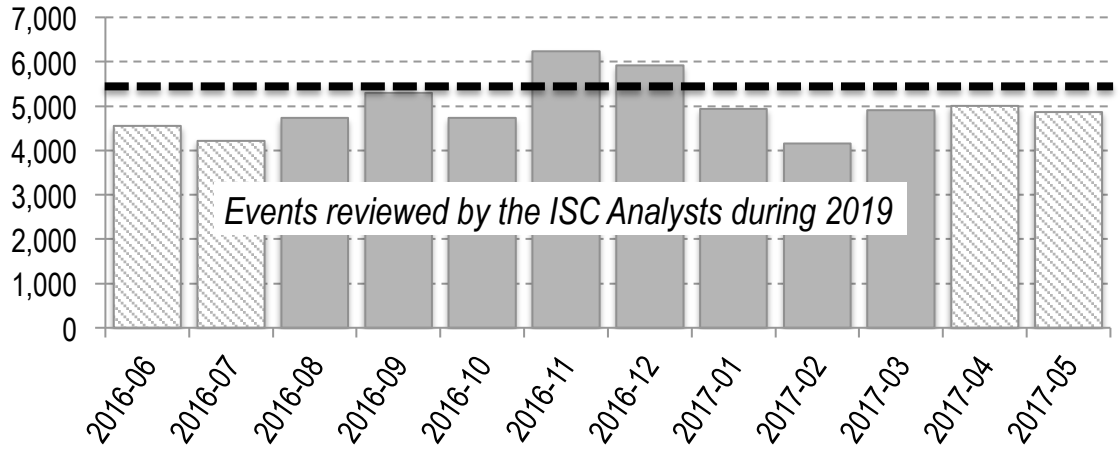



***Figure 6**. Monthly number of seismic events in the Reviewed ISC Bulletin analysed during 2019; the solid colour represents those data months that were fully completed during 2019; the dashed line shows the average monthly number during the preceding 5 years.*

The result of the ISC work can be seen when comparing Figures 7 and 8. A fuzzy picture of the originally reported seismicity sharpened by the Reviewed ISC Bulletin.

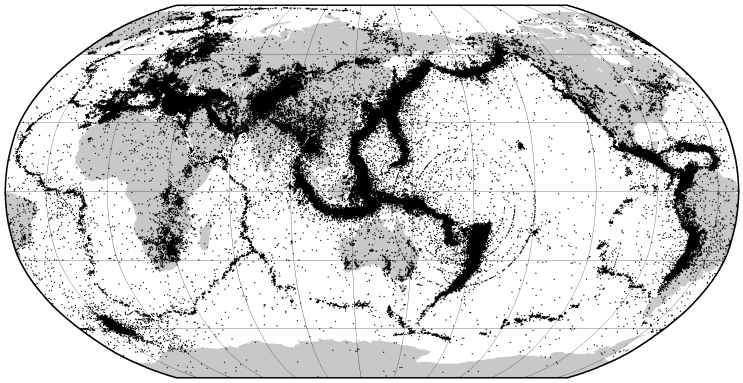


***Figure 7**. All hypocentres reported by individual networks (June 2016 – May 2017).*

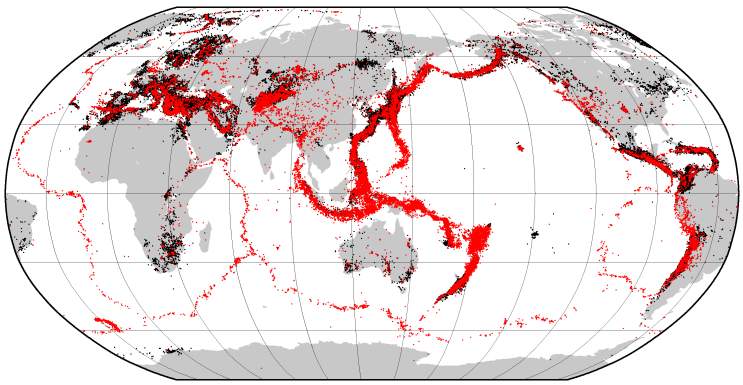


***Figure 8**. Primary hypocentres in the ISC Bulletin (black) in the period (June 2016 – May 2017); in red are the reviewed events.*

Figure 9 demonstrates the diversity of seismic phases included in the ISC Bulletin.

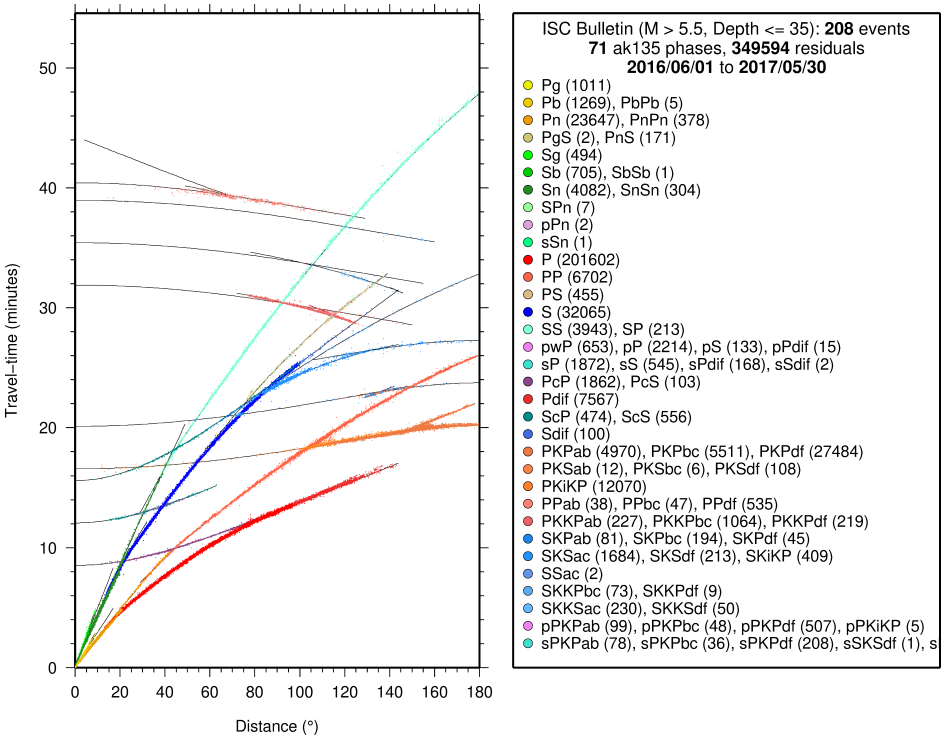



***Figure 9**. The travel-time graph and associated table show the statistics of various seismic phases generated by large shallow events reviewed by the ISC analysts during 2018; depth <=35 km and magnitude above 5.5 are shown.*

## GENERAL STATISTICS of the ISC BULLETIN

The ISC Bulletin and the ISC database grow by the day in both seismic event (earthquake or explosion) numbers (Fig. 10) and reported seismic wave arrival times and amplitudes of seismic waves recorded at stations registered in the IR (Fig. 11). Please note that, compared to the Directors Report 2018, the numbers on these graph have been taken after the ISC Bulletin has been fully rebuilt for the period 1964 to 2010. This would have seen the event numbers and especially the phase numbers rise as a result of additional bulletin data from permanent and temporary networks given to the ISC and integrated into the ISC Bulletin.

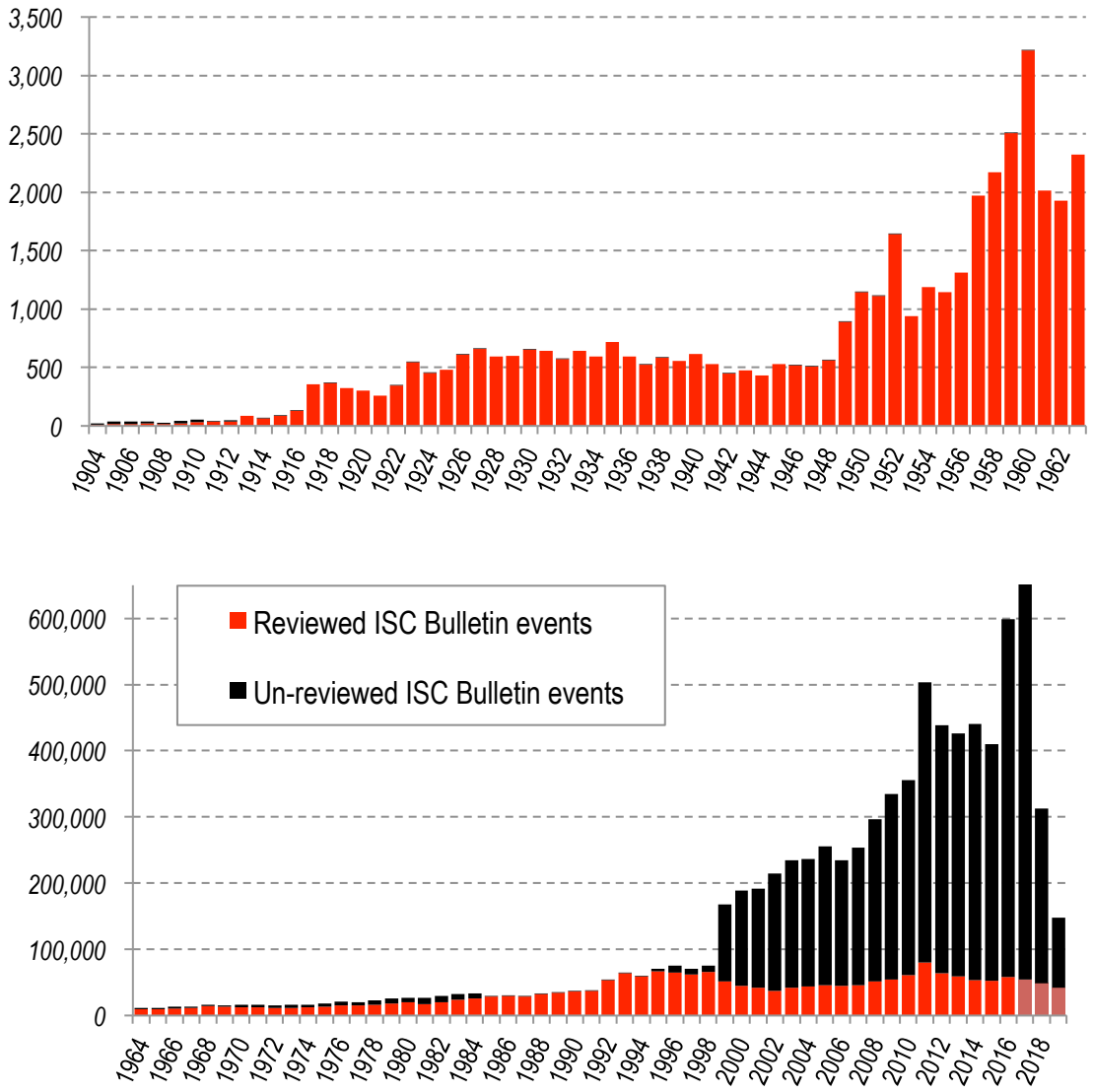



***Figure 10***. *Timeline of the annual number of reviewed and un-reviewed (small) events in the ISC Bulletin; the total height of each column represents the annual number of all seismic events in the ISC Bulletin; note different scale used for events before and after 1964; "Reviewed" events beyond June 2017 are those intended for review.* Numbers as of March 6, 2020

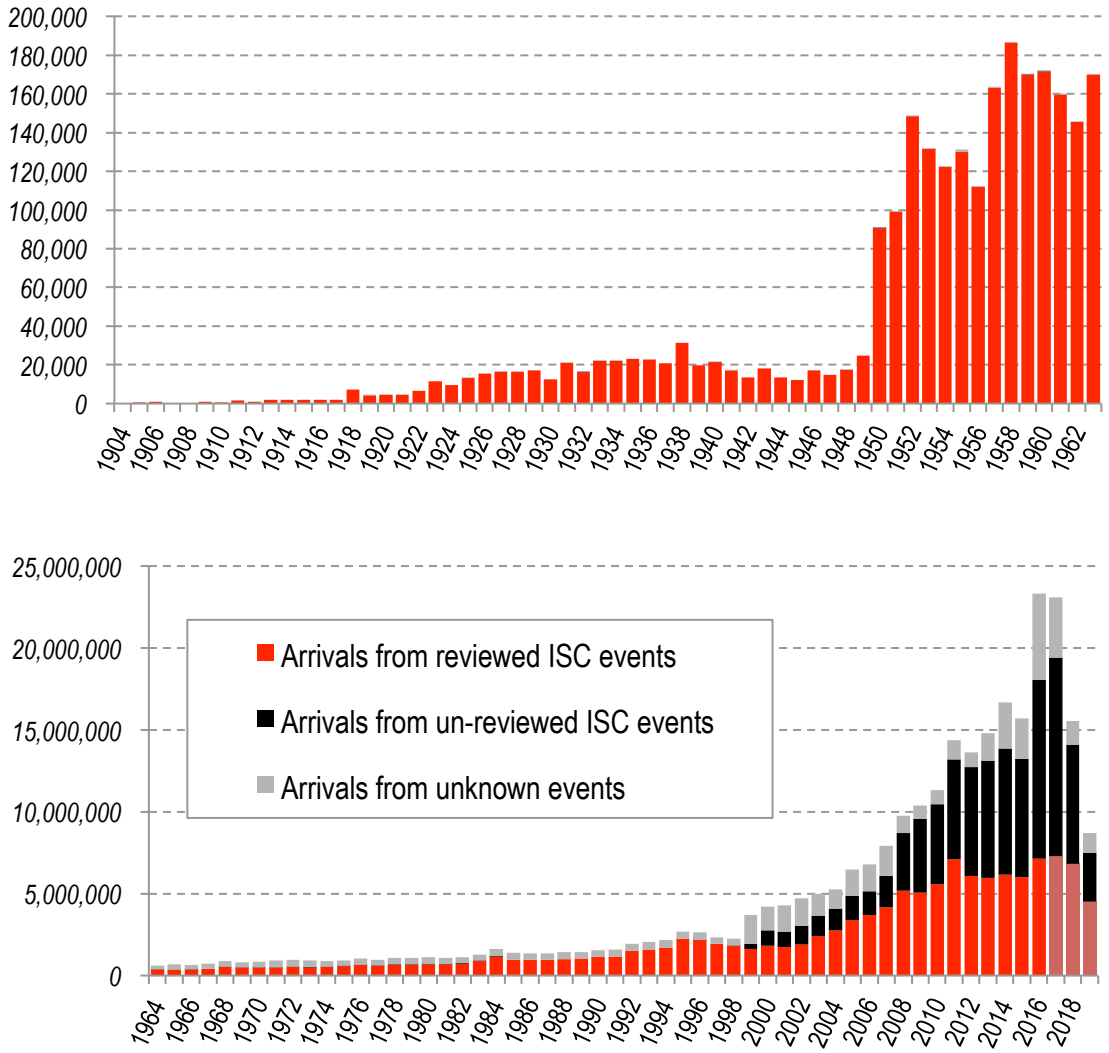



***Figure 11**. Timeline of the annual number of seismic arrivals associated with both reviewed (red) and un-reviewed (black) events in the ISC Bulletin, as well as those arrivals in the ISC database that are not associated to any known event (grey); the total height of each column represents the annual number of all seismic arrivals in the ISC database; note different scales used for events before and after 1964; "reviewed" events beyond June 2017 are those intended for review.* Numbers as of March 6, 2020

Figure 12 demonstrates the comparative magnitude completeness of the ISC Bulletin and bulletins of NEIC/USGS and IDC/CTBTO. The ISC Bulletin appears to be more complete globally than NEIC or IDC by at least half a unit of magnitude. The NEIC's current global operational magnitude cut-off threshold is 4.5. Smaller events are routinely included only for US territories. Thus, the ISC Bulletin is more complete by definition. The IDC is unlikely to use many more seismic sites/arrays than they use at present because the exact IMS network station positions are a fixed part of the Comprehensive Test Ban Treaty. Hence, the Bulletin of the ISC is likely to stay more complete than that of either NEIC or IDC.

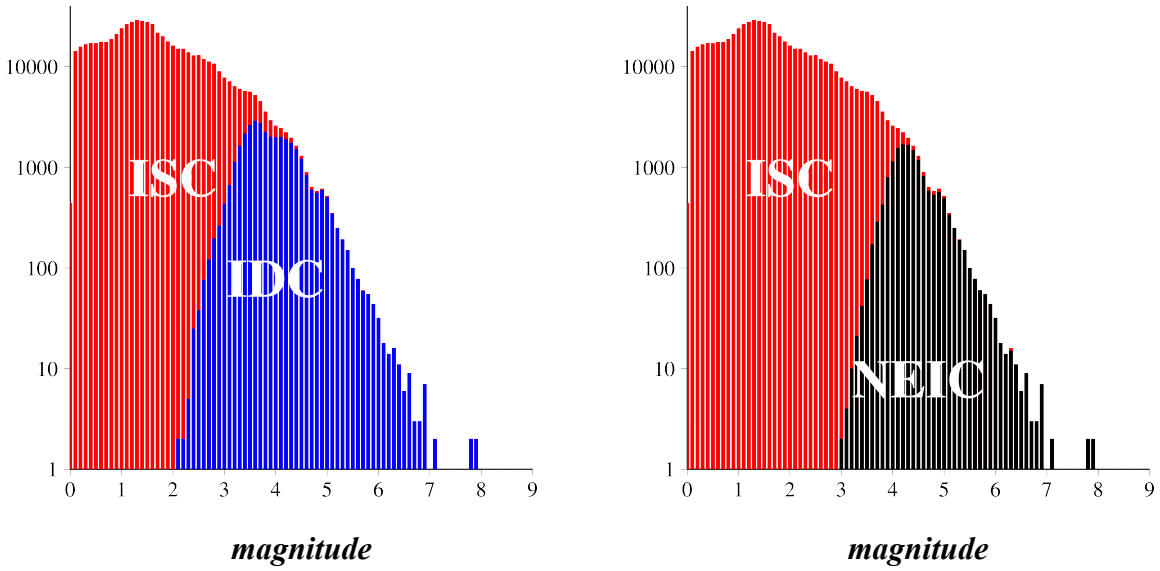



***Figure 12**. Number of seismic events of different magnitude in the ISC, IDC/CTBTO (left) and NEIC/USGS (right) bulletins during the June 2016 - May 2017 period.*

The ISC Bulletin is used by a large number of researchers worldwide. The number of bulletin web searches in 2019 more than doubled compared to 2018; it is in the order of 6 searches per minute (Fig. 13). The above number doesn't even include searches through the ISC mirror databases at ERI, CTBTO, LLNL or CEA. Neither does it include individual user searches based on flat bulletin files downloaded by some users from the ftp-site.

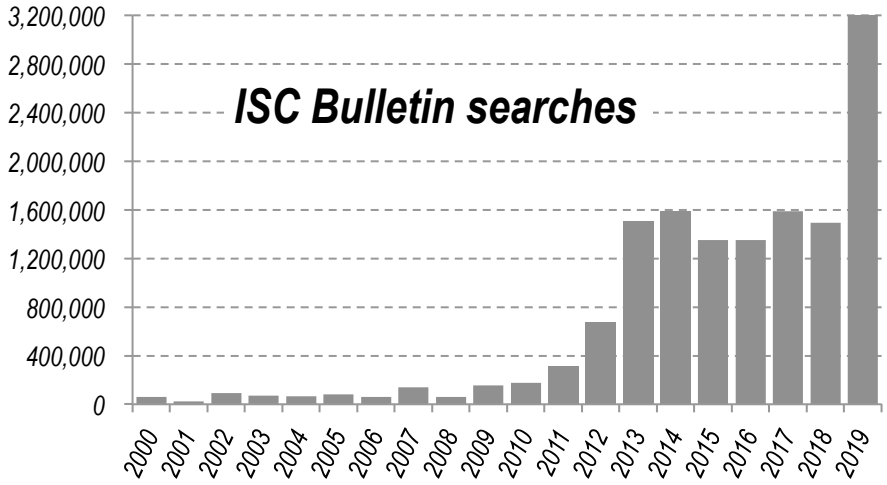



***Figure 13**. The annual number of ISC Bulletin searches made by website users during 2019, the search numbers averaged **six per minute**.*

Figure 14 shows the multinational character of the ISC Bulletin search users.

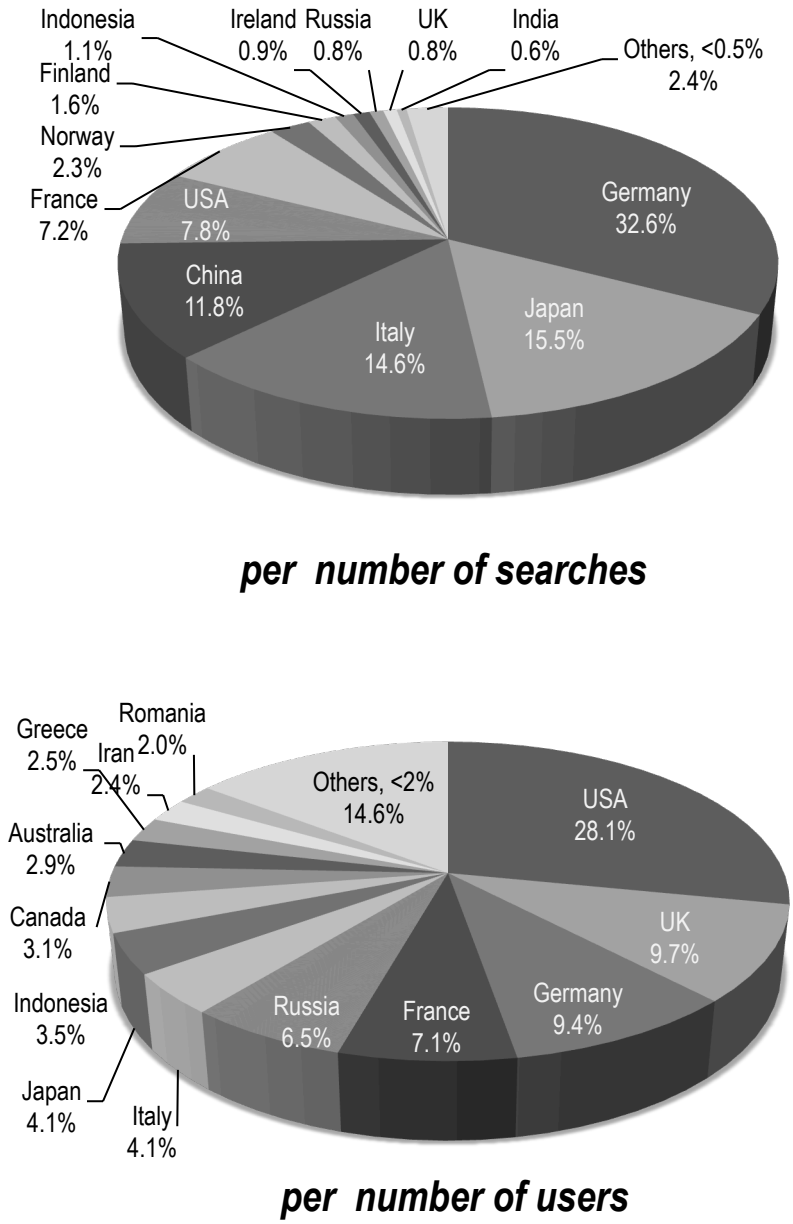



***Figure 14**. International usage of the ISC Bulletin in 2019: per number of searches (top) and per number of individual users (bottom).*

The above statistics include the use of the ISC mirror website at IRIS DMC, but not bulletin searches made from mirror-sites at ERI in Tokyo and LLNL in Livermore. Where reliably known, we have removed the numbers related to web crawlers.

Currently, the website searches give output in three major formats: ISF1.0 (International Seismic Format), QML (QuakeML) and CSV (comma separated variables). Figure 15 shows that the total number of searches in QML exceeds those of ISF and CSV combined. The QuakeML searches though, are performed by fewer users who tend to run automated queries that request larger volumes of data. It therefore appears that all three formats are popular and need to be maintained in the future.

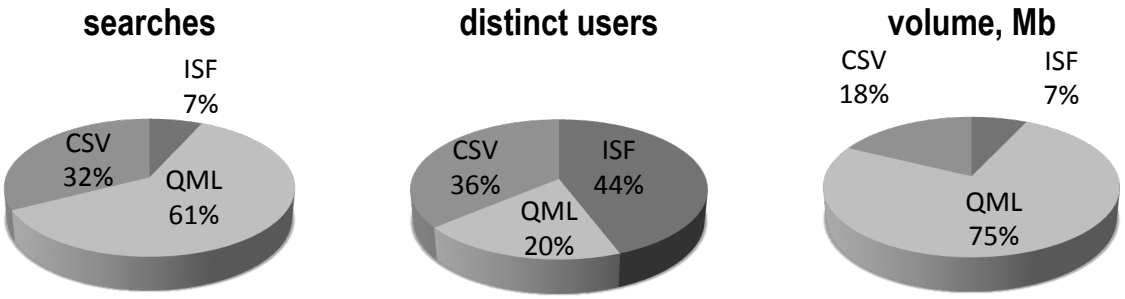



***Figure 15**. Distributions of the number of ISC Bulletin searches, distinct users and overall volume of data taken per output format.*

## PRINTED SUMMARY of the BULLETIN of the ISC

Each volume of the *Summary of the Bulletin of the ISC* covers six months of data. The Summary is prepared at the ISC, printed by *Cambrian Printers* in Wales and posted to ISC Members and paying customers within approximately two months after the relevant period of ISC data becomes available to users. Within a few months the Summary becomes openly available on the web.

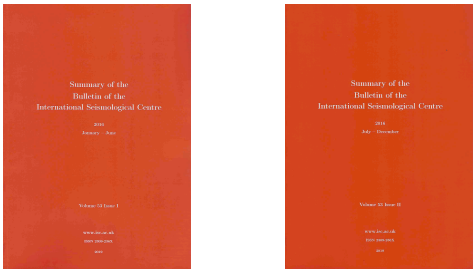


***Figure 16**. The first and second issues of the printed Summary of the Bulletin of the ISC for data year 2016 were published during 2019.*

During 2019, we published two issues covering the period from January-December 2016 (Fig. 16). The following topics were covered:

- The ISC (Mandate, History, Evolution of the Bulletin, Member Institutions, Sponsors, Data Contributors, Staff)
- Operational Procedures (data collection, grouping, association, thresholds, location, magnitude determination, review, history of operational changes)
- IASPEI Standards
- Summary of Seismicity (for every 6 months)
- Invited articles on the history, status and procedures used at:
    a. ***National Data Center*** in Kazakhstan
    b. ***National Seismological Service*** in Mexico
    c. ***National Seismic Network*** in Turkey
- Statistics of Collected Data

- Overview of the *ISC Bulletin*
- Leading Data Contributors
- Advertisements for instrument producers – Sponsors of the ISC

The invited network description articles become associated with general information available for each agency contributing to the *ISC Bulletin*.

As a book publisher, the ISC charges no Value Added Tax (VAT) on its printed products yet VAT on all goods and services that it buys from other suppliers can be reclaimed.

## IASPEI REFERENCE EVENT LIST (GT)

The International Seismological Centre maintains the IASPEI database of Reference Events (earthquakes and explosions, including nuclear) for which epicentre information is known with high confidence (to 5km or better, GT5) with seismic signals recorded at regional and/or teleseismic distances (Fig.17a,b). It should be noted that the depth of these events is not known to the same level of accuracy as the epicentre.

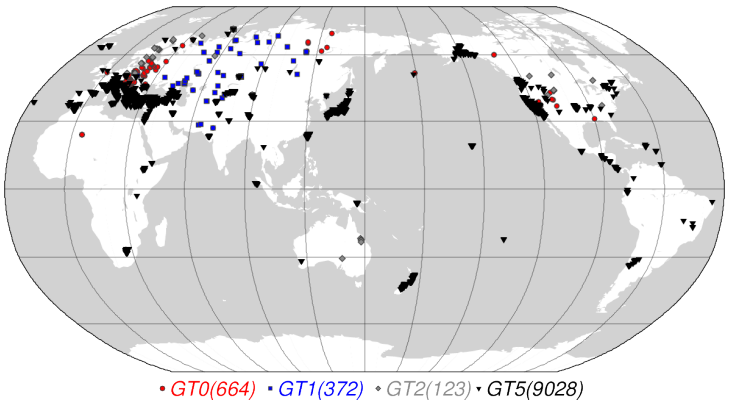



***Figure 17a.*** *The IASPEI List contains seismic events during 1959-2017 for which epicentre information is known with high confidence (to Xkm or better (GTX))*

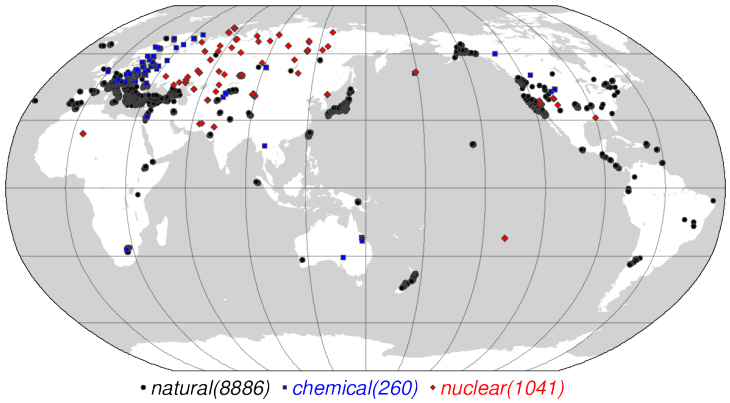



***Figure 17b.*** *The IASPEI List contains natural earthquakes as well as chemical and nuclear explosions.*

The global effort of collecting and validating GT events is coordinated by the CoSOI/IASPEI working group on Reference Events for Improved Location which includes Bob Engdahl, Eric Bergman, István Bondár, Keith McLaughlin and Kostas Lentas.

The GT database of 10,187 reference events (1959-2017) and 1,275,806 station arrival times facilitates better visualization of the Earth's structure, better modelling of velocities of seismic waves, more accurate travel time determinations and increased accuracy of event locations.

The ISC users are able to search this database at the ISC website and receive GT locations and corresponding ISC locations along with station arrival data available for each event. A cross-link to the ISC Bulletin is provided for users to go between ISC and GT databases.

At the end of the analysis of each ISC Bulletin data year, we add new events to the Reference Event List. During 2019, 604 events were added or updated (Fig. 18).

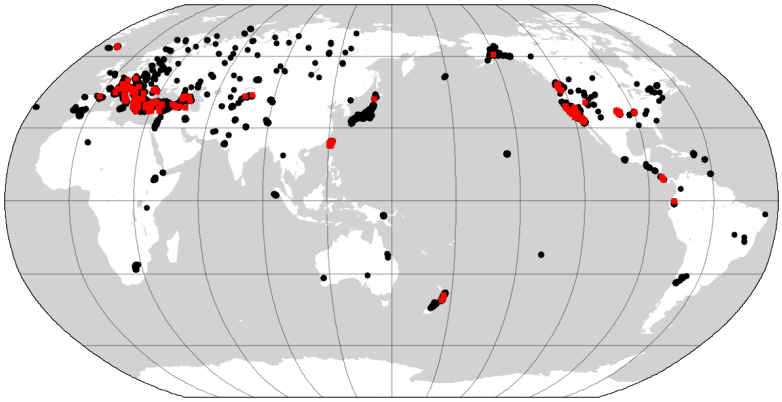


***Figure 18.*** *Events (in red) updated or added to the IASPEI Reference Event List during 2019*

## ISC EVENT BIBLIOGRAPHY

The ISC Event Bibliography (Di Giacomo *et al*., 2014) facilitates an interactive web search for references to scientific publications linked to both natural and anthropogenic events that have occurred in the geographical region of their choice based on earthquake (location, time, etc.) and/or publication parameters (author, journal, year of publication, etc.). The output is presented in a format accepted by major scientific journals. For most recent publications the results include the DOI that allows direct access to scientific articles from corresponding journal websites.

References are collected and linked to events in the ISC database based on the titles and abstracts of scientific publications found in the electronic indexes provided by scientific journals as well as references collected during work on the ISC-GEM Catalogue.

Figure 19 illustrates 1,955 articles related to 6,404 events that were added to the Event Bibliography during 2019. A large proportion of this work for the 20$^{th}$ century benefitted from the bibliographical efforts bringing reliable earthquake source mechanisms and moment tensors into the ISC-GEM catalogue.

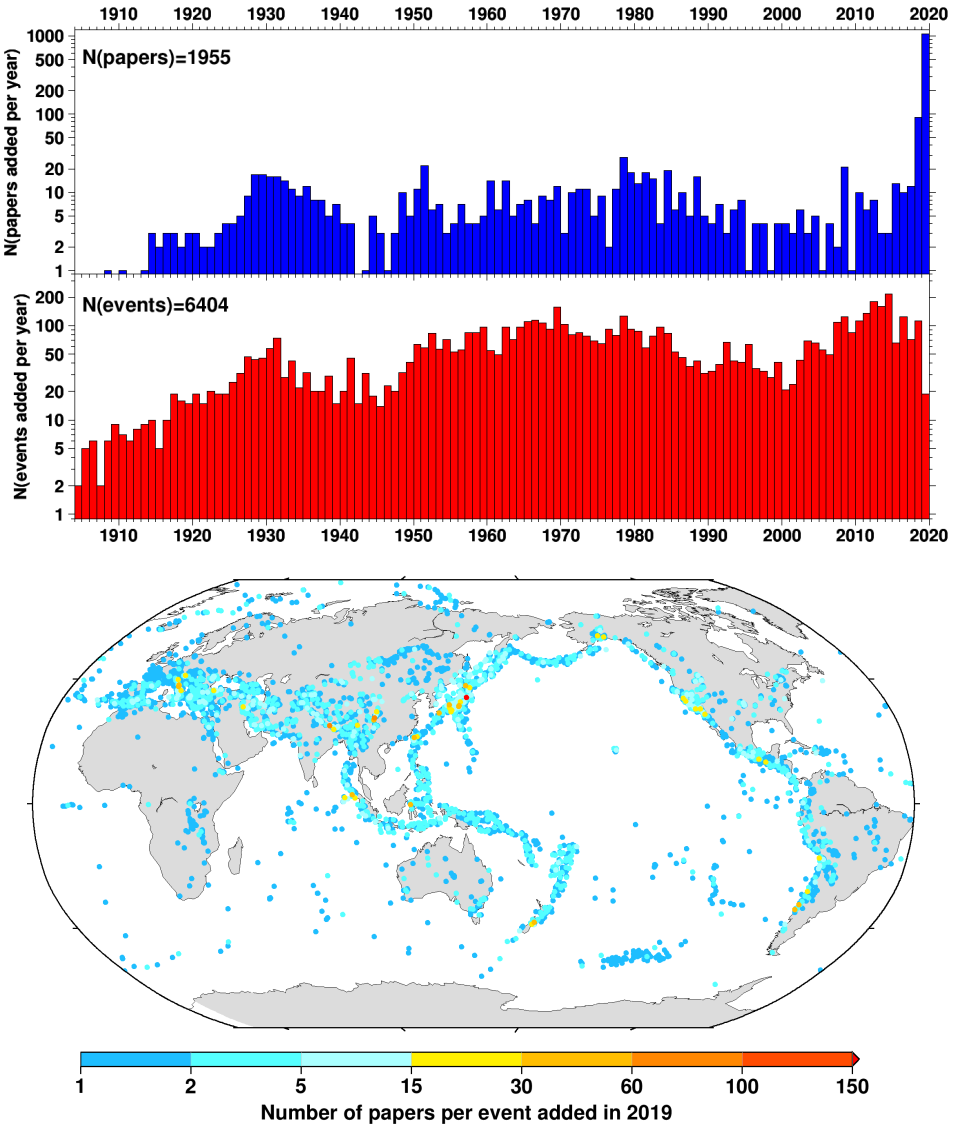



***Figure 19**. Annual numbers and the map of 6,404 seismic events related to 1,955 scientific articles added to the ISC Event Bibliography during 2019.*

## SEISMOLOGICAL CONTACTS

The objective of this project is to maintain up-to-date information on the network of scientific institutions, seismologists and geophysicists, especially in the developing countries (Fig. 20), willing to serve as scientific points of contact for:

- Seismologists and Geophysicists in other countries,
- Governments,
- Charitable, Response and Relief organizations,
- Media.

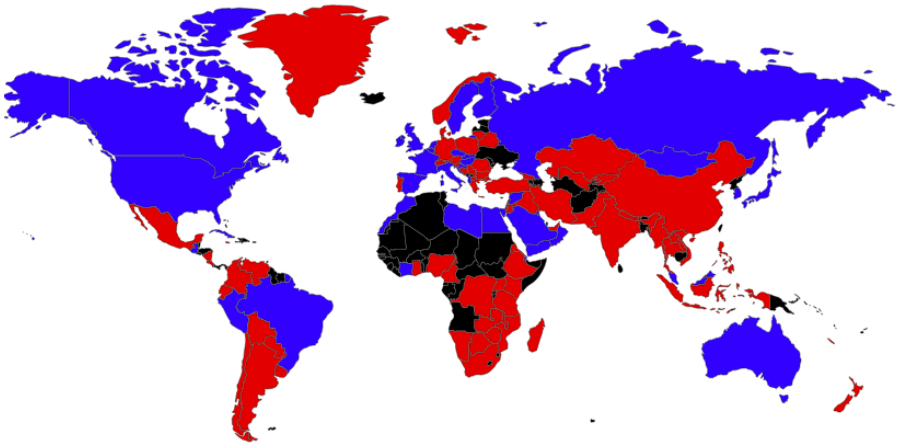


***Figure 20**. Seismological Contacts webpage; in **red** are countries in which institutes and individual staff members are willing to share information and serve as a local point of contact; in **blue** are countries for which we have information about operating geophysical organisation(s); in **black** are countries for which we do not hold any information.*

## ISC WEB and FTP SITES

In 2019, the ISC website experienced ~12.5 million hits which is 37% higher than in 2018. The majority of the ISC web data are distributed through the main ISC website and the mirror at IRIS DMC in Seattle. The load balancer automatically directs users queries to the least busy server.

The use of the ISC ftp site in 2019 has almost doubled again compared to the previous year. The ftp-site is used for downloading pdf copies of the printed ISC Bulletins and Summaries, the ISC Bulletin in FFB and ISF formats, the ISC-EHB bulletins and the text version of the IR station list. Figure 21 demonstrates worldwide interest in ISC data.

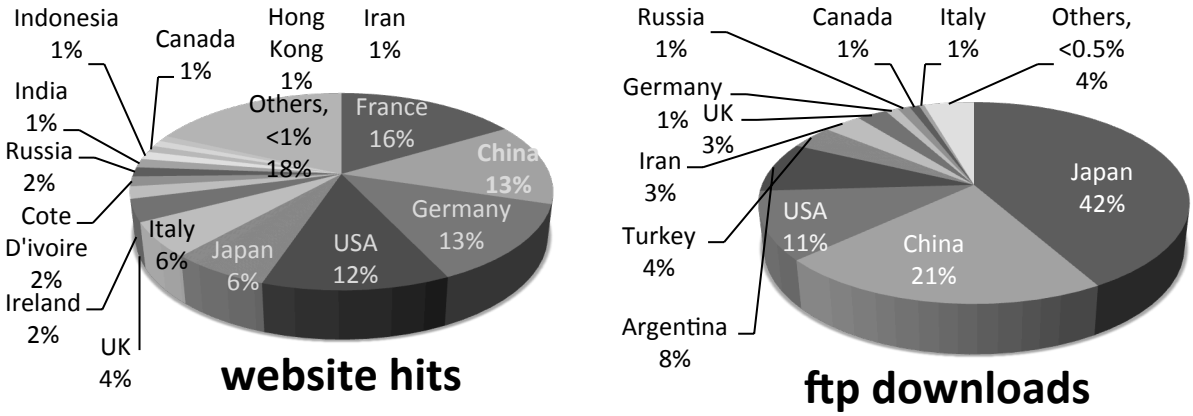



***Figure 21**. Per country statistics of **downloads from the ISC website and ftp-site***

## ISC DATABASE, WEBSITE BACKUP and MIRRORS

The ISC continued maintaining one of it's servers at the IRIS DMC in Seattle in order to hold a mirror of the ISC database and the ISC website. This was done with assistance from DMC and US NSF in order to achieve a general ISC data back-up and fall-over facility in case of a breakdown of services at the ISC itself as well as to spread the load on the ISC internet line and give ISC users faster access to data.

The mirror has been operational since 2011. The database in Seattle is updated with approximately an hour time lag. The load balancer evenly distributes the load on the ISC website, including the user searches, between the server at the ISC in Thatcham and the server at DMC in Seattle. Users no longer need to know the exact web address in Seattle and are generally no longer aware which server is addressing their request.

In addition, the IRIS DMC is able to use the database, when required, to serve DMC archive users with event-based selection of waveform data.

Other mirrors of the ISC database are maintained by the Earthquake Research Institution (ERI) of University of Tokyo to serve the research community in Japanese universities, by the Lawrence Livermore National Laboratory (LLNL) to serve users from nuclear test monitoring laboratories in the US and a database mirror and website installed in Beijing and Xian by the China Earthquake Administration (CEA) to help numerous Mandarin speaking seismologists to obtain more intuitive access to the ISC data.

# DEVELOPMENT PROJECTS

## ISC BULLETIN REBUILD

The value of the ISC Bulletin is subject to adhering to uniform procedures over a long period of time. Nevertheless, essential changes in the ISC procedures have occurred (Fig. 22):

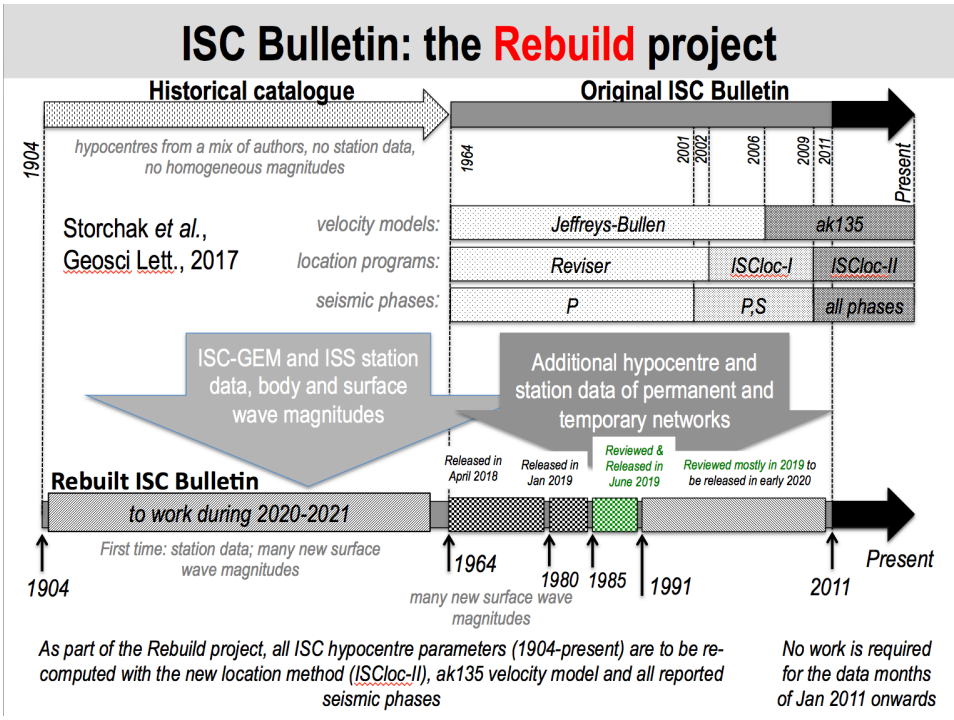



***Figure 22**. The overall plan and current status of the ISC Bulletin Rebuild project (updated figure from Storchak et al., 2017)*

- The *ak135* velocity model (Kennett *et al*., 1995) has been used since 2006 superseding the *JB* travel times (Jeffreys and Bullen, 1940).
- A new event Locator based on a different approach was introduced from data year 2009 (Bondar and Storchak, 2011).
- Throughout ISC history different sets of seismic phases were used for location: P and (from 2001) S with other *ak135* phases from 2009.
- Latitude and longitude error estimates were computed before Oct 2002, followed by full error ellipses later on.
- Procedures that determine which reported events require relocation by the ISC were also changed in 1999, 2005 and 2006.

We are currently rebuilding the ISC Bulletin using current ISC procedures to guarantee homogeneity throughout its entire period by:

- Renaming the ISC phase identifications in line with the IASPEI standard (Storchak *et al.* 2003, 2011; Schweitzer *et al.,* 2019);

- re-computing all ISC hypocentres and event magnitudes with uncertainties;
- soliciting, obtaining and integrating essential additional datasets that were not available at the time of the original ISC Bulletin production;
- performing essential integrity and consistency checks, quality control and correction.

The ISC analysts review events with considerable departures of main hypocentre parameters from the original ISC solutions as well as events with unacceptable travel time residuals at individual stations. They also review those events where the only hypocentre is that of the ISC and events where there was no ISC hypocentre in the past.

During the first half of 2019, we completed the review of seismic events within the period 1985-1990, substituted the old data in the main ISC database with those rebuilt and released to users, as part of general search, in June 2019, just before the IUGG Assembly in Montreal. Here we show figures for the 1988-1990 period, similar to those in Storchak *et al.* (2017).

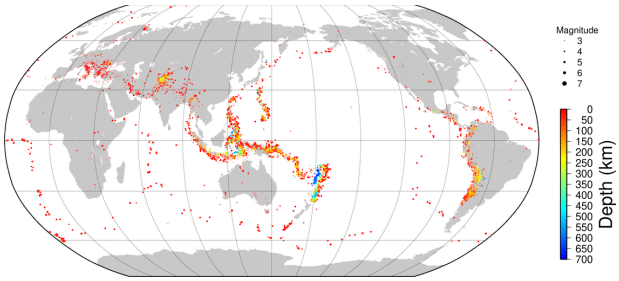



***Figure 23**. Poorly located or phantom events discarded from the ISC Bulletin (1985-1990).*

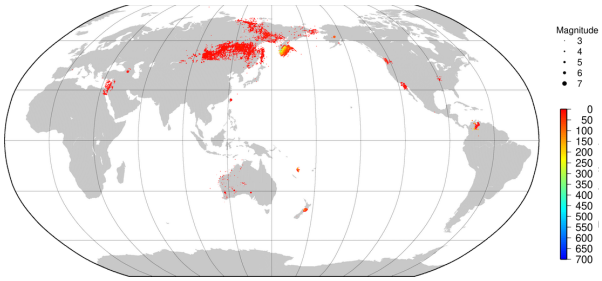



***Figure 24**. New events added to the ISC Bulletin (1985-1990).*

We performed the overall review of events in the Bulletin by removing poorly constrained and phantom events (Fig. 23) as well as adding new events from previously unavailable datasets (Fig.24). New stations are shown on Figure 25. A large number of seismic arrival times have been added to the Bulletin, whilst the numbers of additional stations continued to grow (Fig. 26).

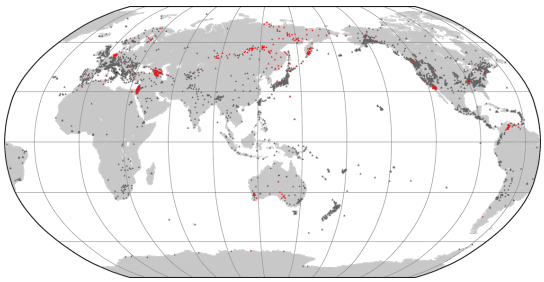


***Figure 25**. The existing and new (red) stations in the Rebuilt Bulletin during 1985-1990.*

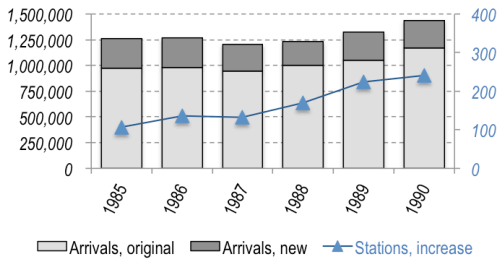



***Figure 26**. Comparative numbers of original and new seismic arrivals and the growth in station numbers during 1985-1990.*

Considerable changes have taken place in the magnitude area (Fig. 27). Many one or two station based ISC *mb* and *MS* magnitudes have been deleted whilst the rest of the magnitudes were recomputed using a much more robust technique that is used by the ISC today.

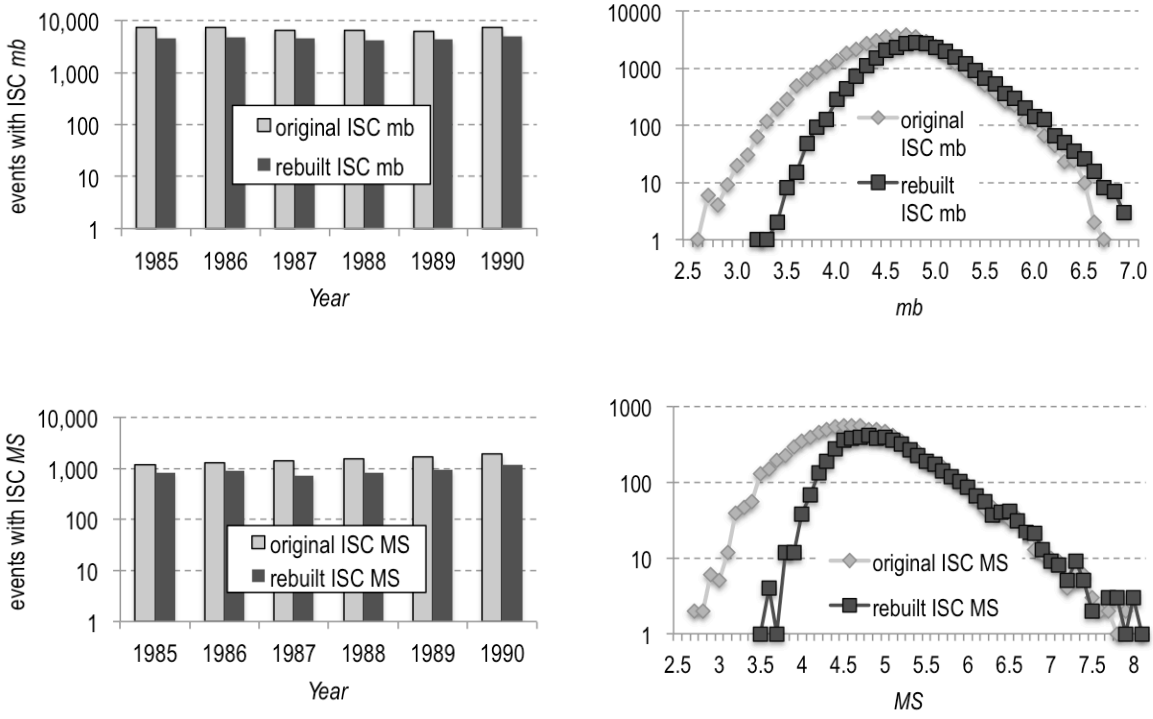



***Figure 27****. Comparison of the annual number (left) and the magnitude frequency distribution (right) of the ISC mb (top) and ISC MS (bottom) in the original and the rebuilt ISC bulletins during 1985-1990.*

Figure 28 shows the statistical differences between the original and rebuilt ISC magnitudes. It appears, that the rebuilt *mb* is 0.08 larger, on average, than the original *mb*. The rebuilt *MS* is 0.06 larger than the original *MS*. These differences appear larger during the period 1985-1990, compared to the entire rebuilt period (1964-2010). We shall investigate this issue next year when preparing a scientific publication on the entire rebuilt period.

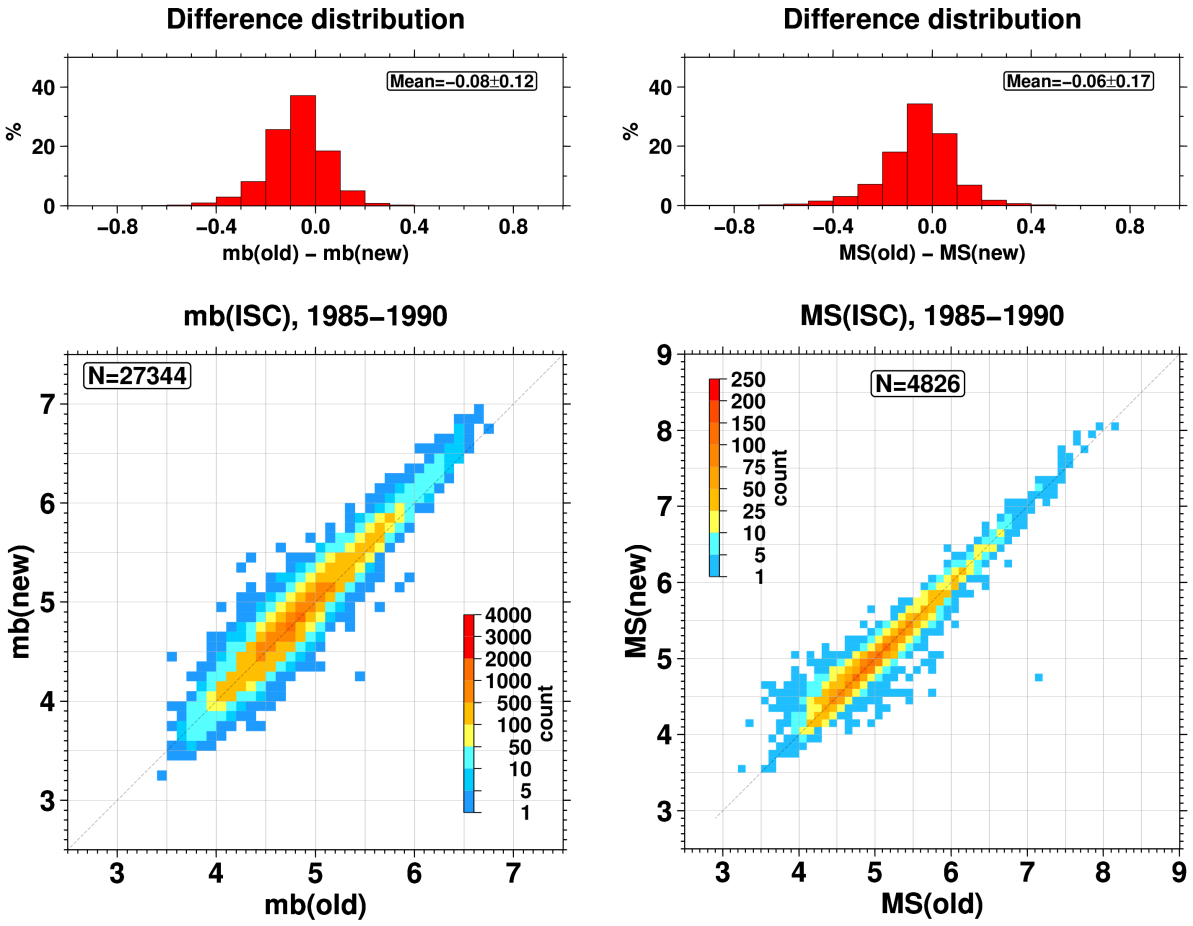
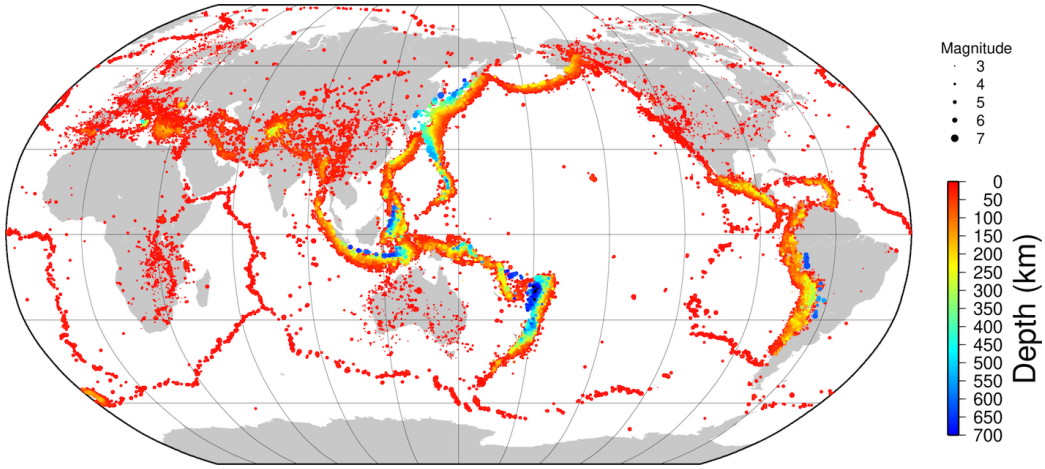



***Figure 28***. *Statistical differences between the original and rebuilt ISC mb (left) and MS (right) during the 1985-1990 period.*

Figure 29 shows the changes in location of seismic events that have taken place with the introduction of the Rebuilt ISC Bulletin.



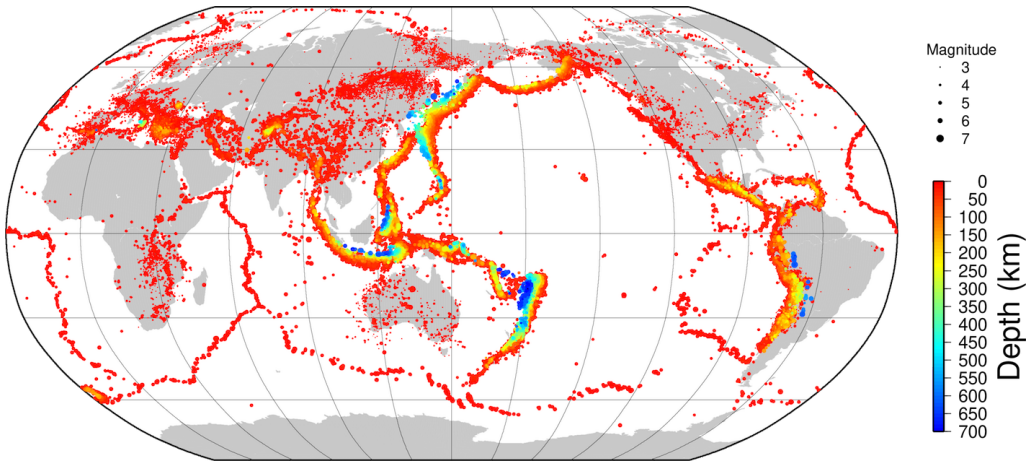



***Figure 29**. Before / after maps that demonstrate the changes in the Rebuilt ISC Bulletin during the 1985-1990 period.*

In the second half of 2019, we continued the review of the 1991-2010 period. With the approval of the Executive Committee, a large part of our analytical resources were diverted from the standard concurrent bulletin analysis to the Rebuild project. With the exception of just a few data months and final integrity checks, the analysis was largely complete by the end of 2019. The release to users took place in February 2020, which is outside the scope of this annual report.

Our plan for early 2020 is to release the entire 1964-2010 period and, by the end of 2021, to reinvent the ISC Bulletin for the 1904-1963 period, based on the data available in the ISC-GEM database account.

As a result, the entire extended ISC Bulletin (1904-present) will be relocated based on the same location procedure, *ak135* velocity model and magnitude computation techniques that are used in the ISC Bulletin production today.

## COMPUTING EARTHQUAKE FOCAL MECHANISMS at the ISC

We are now computing fully automatic focal mechanisms of recent earthquakes, combining directions of first motions reported to the ISC with auto-picked first motions from waveforms available at IRIS, EIDA, etc. We focus on moderate to large earthquakes ($mb^{ISC} \geq 4.5$) in the reviewed ISC bulletin and especially on earthquakes with no previously reported source mechanisms. For the historical period, we placed no magnitude restriction and computed mechanisms for all events where adequate collection of station polarity reports was available. For this work we took advantage of the HASH algorithm to compute focal mechanisms (Hardebeck and Shearer, 2002) and FilterPicker source code to automatically determine the polarities of first motions (Lomax *et al*., 2012). The entire procedure is described in scientific paper published by Lentas (2018) and Lentas and Harris (2019).

During 2019, the ISC on-line Bulletin was upgraded with 8,595 ISC focal mechanisms covering the period from 1980 till March 2017 (Fig. 30). This work was timed to coincide

with the release of the portions of the Rebuilt ISC Bulletin and will continue in both historical and current time periods.

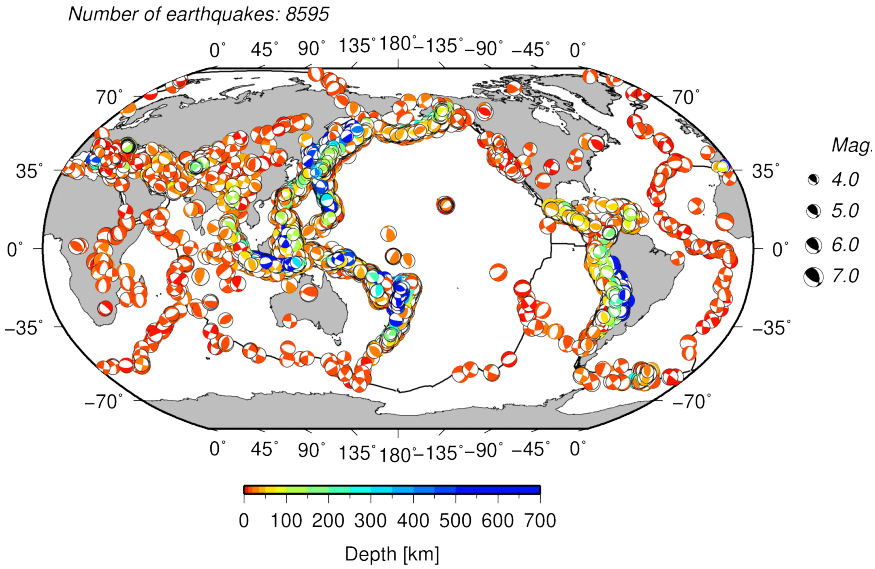



***Figure 30**. Map of earthquakes for which the source mechanisms were computed by the ISC and made available through the on-line bulletin.*

## IN-HOUSE WAVEFORM PICKING for USE in the ISC BULLETIN

From 1964, the ISC's mission was based on re-using the seismogram (waveform) arrival time measurements (picks) made by many tens of observatories and data centres. In recent years, the ISC used reported arrival times of ~8.5 thousand stations worldwide. The ISC does not have sufficient staff capacity to obtain those picks from waveforms, even if these waveforms were always available. We nevertheless feel that the value and quality of the ISC Bulletin would have been compromised if we didn't act in two particular areas.

Depth phases such as pP, sP, pPKP, sPKP etc. are crucial for constraining the hypocentre depth of many moderate earthquakes in the ISC Bulletin that occur away from close monitoring stations. During the last 10-14 years though, we have observed a steady decline in the number of depth phase reports. Fig. 31 shows the monthly statistics of these reports for the three largest reporters of depth phases: National Earthquake Information Center (NEIC/USGS), International Data Centre (IDC of CTBTO) and Geophysical Survey of Russian Academy of Sciences (GS RAS). Consultations with the three agencies have shown that we can't expect the numbers to improve in the short term.

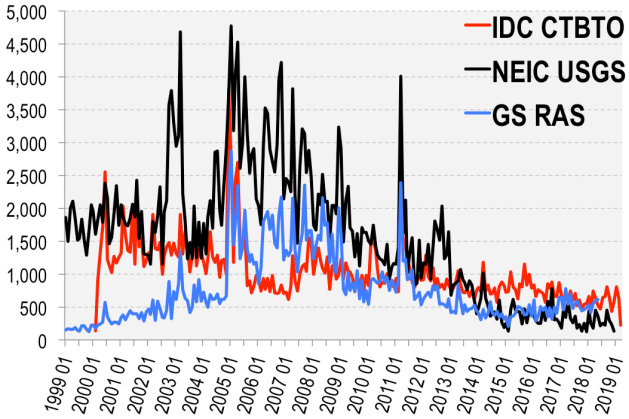



***Fig. 31.*** *Steady decline in the monthly number of depth phase (pP, sP, pPKP, ...) arrival time reports by the three largest reporters of this information to the ISC.*

Since 2018, we set aside a small fraction of analyst resources to deal with the problem. One or two ISC analysts are spending one day per week picking the depth phases on waveforms available from IRIS DMC for earthquakes with $mb^{NEIC} \geq 4.8$. We time this activity so that the results can be used during the routine production of the ISC Bulletin and reviewed by the ISC analysts. An example of such work is shown on Fig. 32.

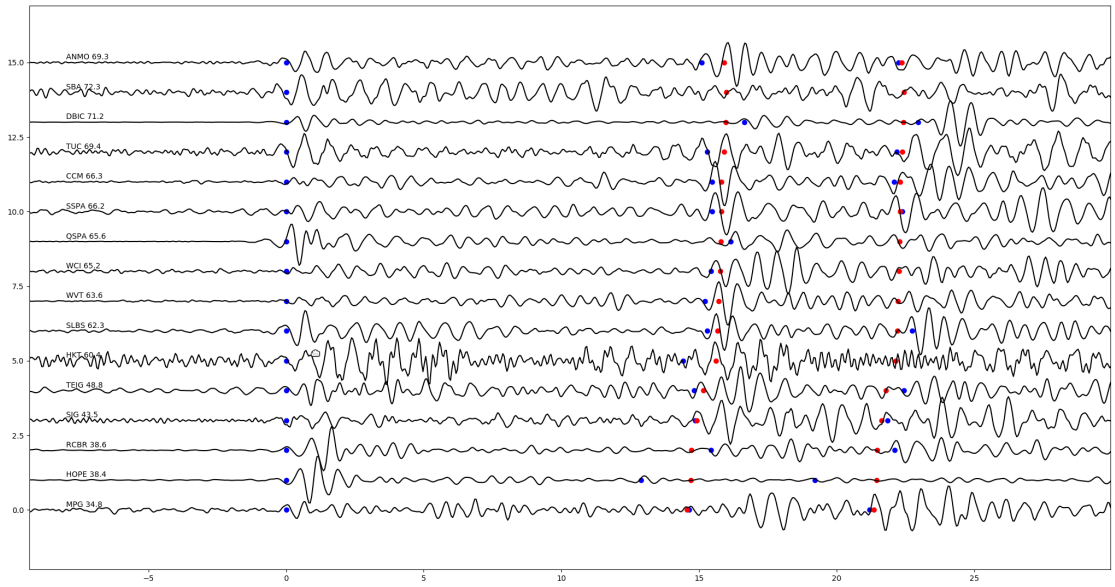



***Fig. 32****. An example of picking depth phases by the ISC analysts using the SEISAN (Havskov et al., 1999, 2010, 2020) for mb 5.2 earthquake in Northern Chile; blue/red dots indicate measured/theoretical arrivals of depth phases for the ak135 model against ISC solution.*

Depth phases for 1,179 earthquakes that occurred during the period from June 2016 till May 2017 were added to the ISC Bulletin. Figure 33 shows 793 events for which this information was crucial, i.e. the depth would have otherwise had to be fixed to the area's default. Figure 34 shows the worldwide distribution of 159 stations used and their comparative input. As expected, stations in quiet regions of Australia, Antarctica and Kazakhstan provided the largest input.

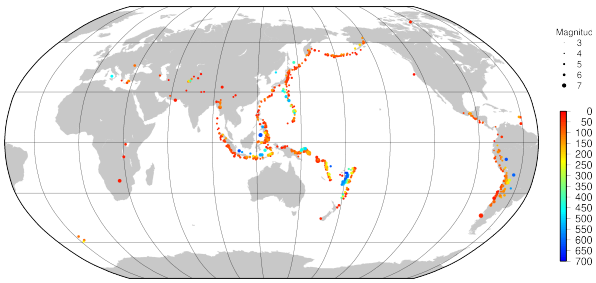


***Fig. 33**. The map of 793 events where additional ISC pP/sP picks were critical to constrain the ISC event depths.*

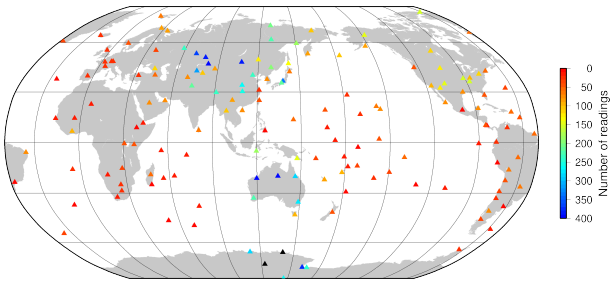



***Fig. 34**. Waveforms of 159 stations were used by the ISC to deliver the missing pP/sP picks; relative contributions are shown by colour.*

We plan to continue with this effort and train a further two members of the Analysis Team to be able to do this work in the future.

We also continued picking waveforms of the Africa Array to compensate for the unfortunate lack of permanent observations on large parts of this continent. We include these picks in the routine production of the ISC Bulletin.

## ISC SEISMOLOGICAL DATASET REPOSITORY

Just before the IUGG Assembly in Montreal, we released a new supplementary ISC service that allows individual researchers or groups to submit seismological datasets that they wish to be openly available to the scientific community for a long period of time.

This service (International Seismological Centre, 2019) will assist a positive trend in scientific publishing to require article authors to make the original research data openly available so that their conclusions can be both tested and used by other researchers.

The examples of acceptable datasets include but not limited to:

- Event catalogues/bulletins
- Results of earthquake source studies
- Results of structure studies
- Velocity models
- Notable earthquake observations
- Seismological computer code

We do not envisage storing raw waveforms as this role falls within the mission of other data centres.

This long-term secure repository of seismic datasets includes all necessary metadata such as a DOI, author contact information, affiliation, relevant scientific publication and date of submission as well as associated information such as comments, formats, positions of relevant seismic stations etc.

The ISC shall obtain the DOI for each submitted dataset via CrossRef.

The ISC Repository is an open facility that has good potential to serve geophysicists for a very long time. This facility is likely to be recognised by scientific journal editors as one of the legitimate independently maintained places for depositing author processed datasets to satisfy editorial board requirements on open access to data.

The Repository received nine eligible submissions by the end of 2019. George Choy was the first registered author with the USGS source parameters catalogue (1987-2013), listing broadband depths, focal mechanisms, radiated energy and energy magnitudes (Choy, 2019).

## ISC-EHB (1964-2016) RELEASED

The original EHB dataset served as a groomed version of the ISC Bulletin. It was a valuable tool for global and regional seismicity studies and tomographic inversions. Teleseismically well-constrained events were selected from the ISC Bulletin and are relocated using the EHB location algorithms (Engdahl *et al*., 1998) to minimise errors in location (particularly depth) due to assumed 3D Earth structure. The EHB algorithm incorporated a specific phase identification algorithm for teleseismic depth phases (pP, pwP, sP, PcP) as well as using PKiKP, PKPdf, PKPbc and PKPab.

The original **EHB** stopped in 2008, and since then the volume and quality of bulletin data at the ISC has significantly improved. We have used these enlarged and improved data, updated the event selection, data preparation and processing, and relocation procedures to produce a cleaner and more robust **ISC-EHB** dataset (Weston *et al*., 2018), using the advantages of both the ISC (Bondar and Storchak, 2011) and EHB location techniques.

During 2019, together with E.R. Engdahl of University of Colorado Boulder, we applied the ISC-EHB approach to events in the 1964-1999 period and year 2016 to complement the 2000-2015 period, released during 2018. The entire dataset (1964-2016) has now been released along with updated cross-sections through the majority of subduction regions of the globe. This dataset has made the original EHB truly obsolete.

The ISC-EHB dataset has great potential to reveal complicated structures (Fig. 35). It is available from the ISC website along with **cross-section plots** for a large number of seismic regions. A second scientific article was prepared during the second half of 2019 and finally published in early 2020 (Engdahl *et al*., 2020).

The entire EHB/ISC-EHB dataset contains 170,550 seismic events from 1964 to 2016. During 2019, Dr Engdahl also trained two seismologists/analysts at the ISC who will be able to carry this project forward. We shall incrementally extend this dataset forward as part of routine operations, based on the progress in production of its original source of data - the Reviewed ISC Bulletin.

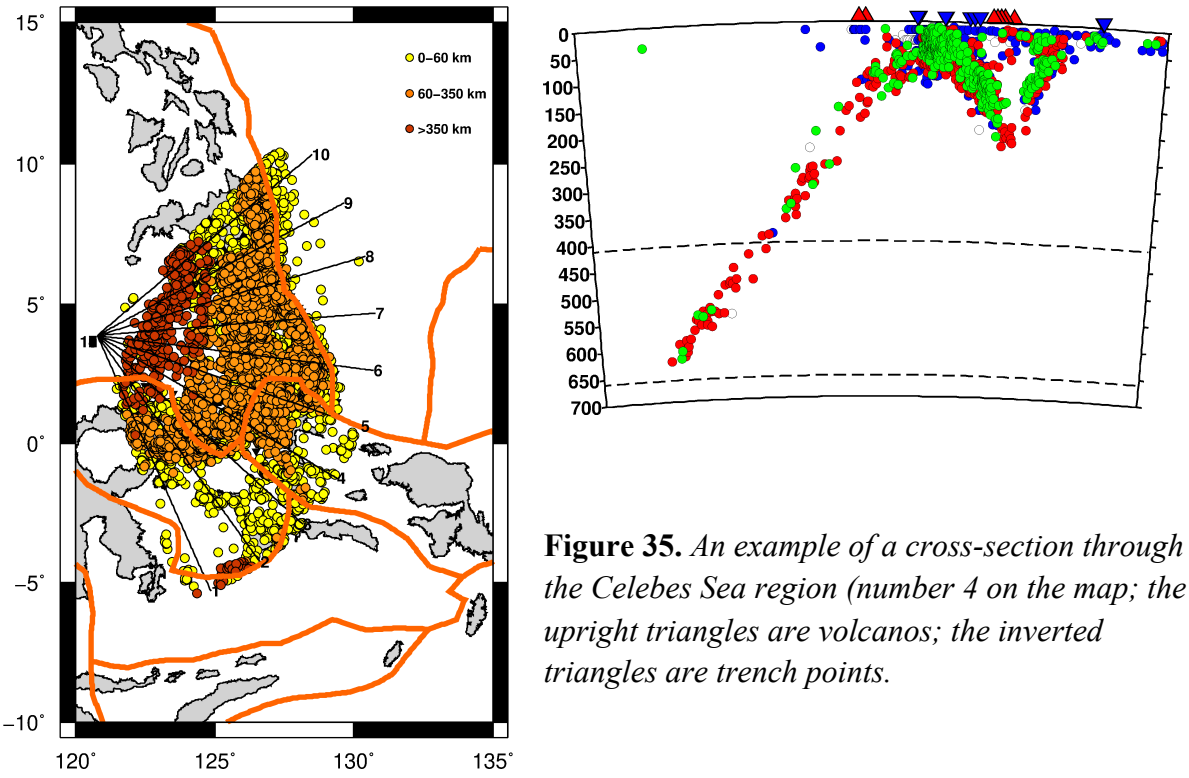



**Figure 35.** *An example of a cross-section through the Celebes Sea region (number 4 on the map; the upright triangles are volcanos; the inverted triangles are trench points.*

## ADVANCEMENT of the ISC-GEM CATALOGUE

The ISC-GEM Global Instrumental Catalogue was originally requested and funded by the GEM Foundation. The catalogue is widely used for modelling seismic hazard on a regional and global scale. In addition, the catalogue is also used as an authoritative reference and a starting point in regional studies in South America, Africa and Asia. The catalogue also has a multidisciplinary use in a wide range of other areas such as studies of global seismicity, tectonics, earthquake hazard forecasting, rapid determination of hazard etc (Storchak *et al.*, 2015). Moreover, during the ISC-GEM project, we digitised a large volume of basic station observation data which can now be used by individual researchers for historical earthquake studies.

Notably, the ISC-GEM catalogue forms the basis of the USGS's ComCat Catalog (ANSS Catalog) before 1970.

The popularity of ISC-GEM has grown over the years. An average of ~14.8 downloads per day were recorded in the last 54 months and an average of ~17.4 - during 2019 alone (Fig. 36).

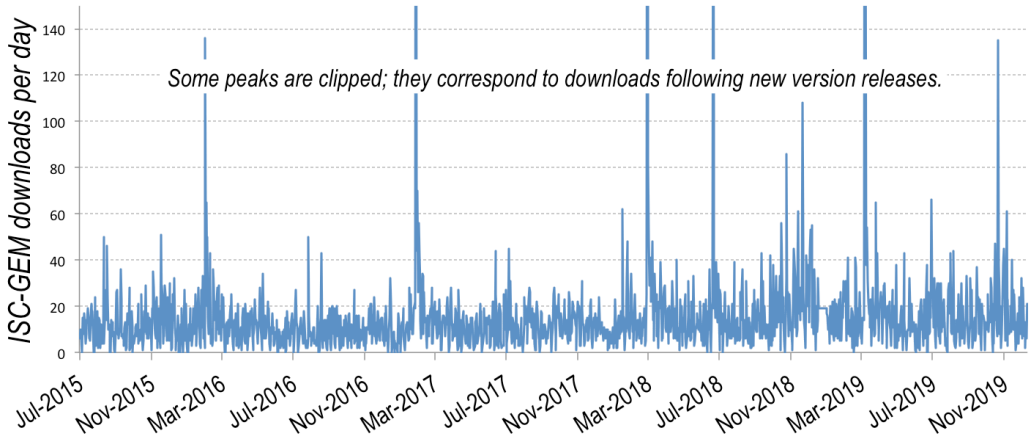



***Figure 36**. During the last 54 months, the ISC-GEM catalogue has, on average, been downloaded ~15 times per day.*

The ISC-GEM catalogue was first released in January 2013 (Storchak *et al.*, 2013). Unlike the ISC Bulletin, the ISC-GEM catalogue was built for use in seismic hazard and risk assessment. The catalogue covers ~110 years of global seismicity and includes:

- hypocentres computed (Bondar *et al.,* 2015) using *ak135* velocity model (Kennett *et al*., 1995), using a combination of the EHB technique (Engdahl *et al*., 1998) and the new ISC locator (Bondár and Storchak, 2011), based on the original station arrival time reports (Di Giacomo *et al*., 2015a);
- magnitudes expressed in $M_W$ scale (Di Giacomo *et al*., 2015b, Lee and Engdahl, 2015;
- formal uncertainties and quality given for both hypocentre and magnitude determinations.

The original ISC-GEM catalogue covered the period 1900-2009 with the magnitude cut-off thresholds dictated by the size of the original funding available at the time and the need to finish the original project in just over two years:

- 1900-1917: M≥7.5
- 1918-1959: M≥6¼
- 1960-2009: M≥5.5

As a result of work under the *Extension* project (Di Giacomo *et al.*, 2018), the improved cut-off thresholds were as follows:

- 1904-1917: M≥6¼
- 1918-2015: M≥5.5

Year 2019 was the 2nd year of the *Advancement* project. We further dropped the cut-off magnitude to $M_W$ 5.0 in the continental areas during 1980-1990 and 2016 (Fig. 37).

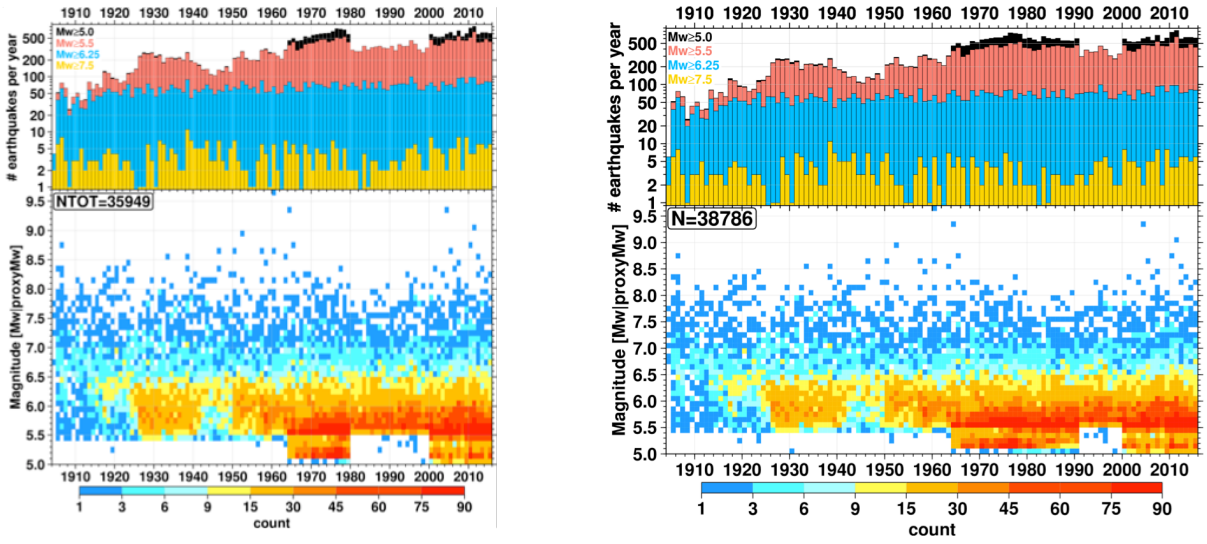



***Figure 37**. Annual number (top) and magnitude distribution (bottom) of earthquakes above a certain magnitude in ISC-GEM Ver.6 (at the end of Year 1 of the Advancement project, left) versus Ver.7b at the end of Year 2 of the Advancement project (right).*

We also continued with the large task of searching through the scientific literature for studies of fault mechanisms of past earthquakes before 1976 when the Global CMT project (Ekström *et al*., 2012) began. The results are shown in Figure 38.

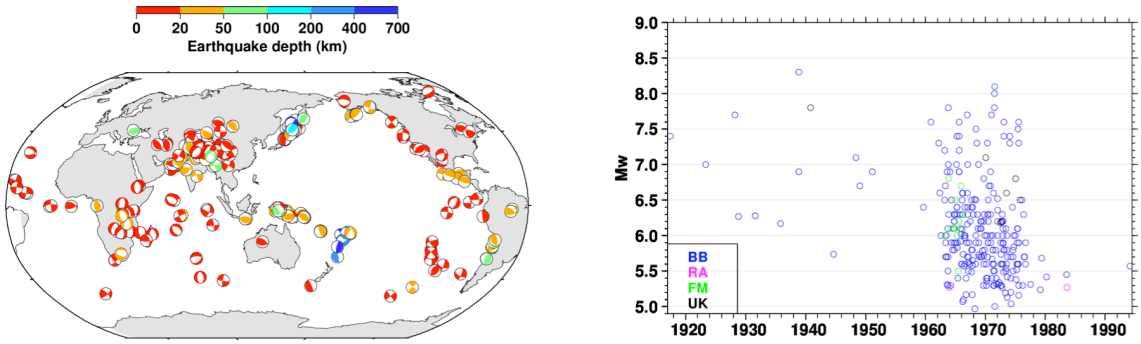



***Figure 38**: Left: 273 earthquakes with source mechanisms from literature, colour-coded by depth. Right: timeline colour-coded by type of source mechanism: broadband (BB); relative amplitudes (RA); first motion polarities (FM); unknown (UK).*

In addition, we made further improvements to ~100 earthquakes already listed in the 1960s and 1970s by updating the magnitude and/or location. We also investigated the possibility of filling gaps in reports of certain long-term stations, mostly in Central Asia.

## PROBABILISTIC STF, MT and DEPTH INVERTIONS

In 2017, Dr Tom Garth joined the ISC and Department of Earth Sciences, University of Oxford of which he is a formal employee. His appointment is jointly funded by the ISC (⅔) and Prof. Karin Sigloch's ERC grant (⅓). He has a desk at both the ISC and in Oxford.

During 2019, Tom Garth has continued developing the new ISC source time function (STF) product. We aim to provide moment tensor (MT), source time function (STF) and depth constrains for moderate magnitude earthquakes ($M_W$ 5.8 – 7.2) globally, along with a full assessment of the inherent uncertainty in each of these parameters. As previously outlined, the code uses teleseismically observed body waves to solve the STF and MT. As the arrivals include surface reflected depth phases, with their characteristic sensitivity to source depth, the method has the potential to add new depth resolution to shallow earthquakes (<40 km depth) in remote areas, and complimentary depth resolution to moderate depth earthquakes (40 – 300km) where depth phases picking can also add resolution. The work has involved:

- adapting the codes to the 'high through put' (*CondorHTC*) cluster that has been set up at the ISC for this purpose;
- building the data workflow around the code that has been developed during this project, with the aim of making the process as automated and reliable as possible;
- testing the methodology and workflow on a broader set of example earthquakes, fixing the bugs that were illuminated, as well as developing the methodology and codes to steer away from the short falls that were discovered.

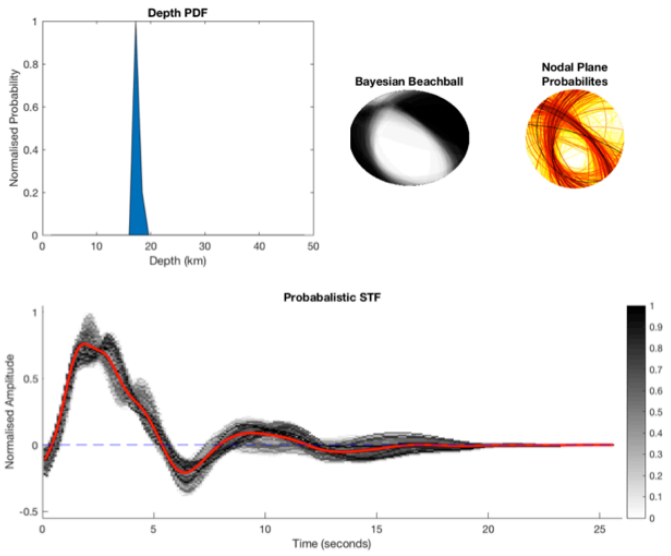



***Figure 39**: Example of the probabilistic STF and moment tensor inversion; **top left:** depth probability density function; **top middle:** Bayesian beach ball, with dark colours representing a high probability of a positive first motion at the represented take-off angle; **top right:** heat map of potential nodal planes, with more probable nodal planes represented by darker reds; **bottom**: representation of the plausible set of STFs, with darker colours representing more probable solutions. The red line represents the average STF.*

In addition, an outline of the methodology and initial testing results were presented at the British Seismological Meeting (BSM, September 2019), and at invited departmental seminars in Cambridge (Bullard Lab Geophysics seminar, November 2019) and Oxford (Brown Bag seminar, October 2019). An example of the results produced by this code is shown in Fig. 39.

In this work, Tom Garth has been building on the work of the project partner Prof. Karin Sigloch (University of Oxford) (Sigloch and Nolet, 2006; Stahler and Sigloch, 2014; 2016).

It is expected that at the end of the 3-year PDRA post, Tom Garth will be able to join the ISC as a full member of staff responsible for earthquake location and other developments.

## CTBTO LINK to the ISC DATABASE

In 2008, the UK Foreign and Commonwealth Office (FCO) awarded the ISC with a three-year grant to set up a dedicated and secure link to the ISC database for the CTBTO PTS and National Data Centres (NDC). The FCO provided 90% of the total funding with GEUS (Denmark), NORSAR (Norway), FOI (Sweden) and University of Helsinki (Finland) complementing it with 2.5% each. From April 2011, the funding of the project was taken over by CTBTO. The current contract runs from April 2015 until March 2020. A new annual contract was signed to start in April 2020 with four possible annual extensions.

During 2019, we maintained a dedicated server at the ISC that held a mirror version of the ISC database. The dedicated web-based software package designed, maintained and upgraded by the ISC for this service allowed users from the Provisional Technical Secretariat and National Data Centres for CTBTO to query the ISC database in ways specific to the nuclear test monitoring community. The software package includes four types of bulletin searches: area based, REB event based, GT event based and IMS station based through the wealth of parametric information in the ISC database.

The objective is to provide the capability for NDCs to perform various analysis such as:

- assessing historical seismicity in a specific region;
- putting an event of interest into context with the seismicity of the surrounding region;
- examination of observations reported by non-IMS stations;
- comparison of hypocentre solutions provided by various agencies;
- relocating an REB event based on user selected arrival times available in the ISC database using the *ak135* 1-D model with optional RSTT regional velocity model;
- investigation of station histories and residual patterns of IMS or IMS surrogate stations.

We developed an interface for selecting waveforms of non-IMS stations for REB events from the IRIS DMC, EIDA and GeoNet archives. For recent REB and GT events, this interface:

- allows selection of stations by distance / azimuth to the REB epicentre;
- shows the number of stations, for which waveforms are available at all three archives;
- exhibits pre-prepared images of selected waveforms, filtered and un-filtered with theoretical first arrivals indicated on top of the waveform images;
- offers a form to request part of a waveform, based on absolute or relative theoretical arrival times of required seismic phases or on group velocity of surface waves;
- triggers a request to waveform archives; as a result, users receive required waveforms by e-mail in the SEED format.

Figure 40 shows user activity on the Link by both PTS/CTBTO and NDCs.

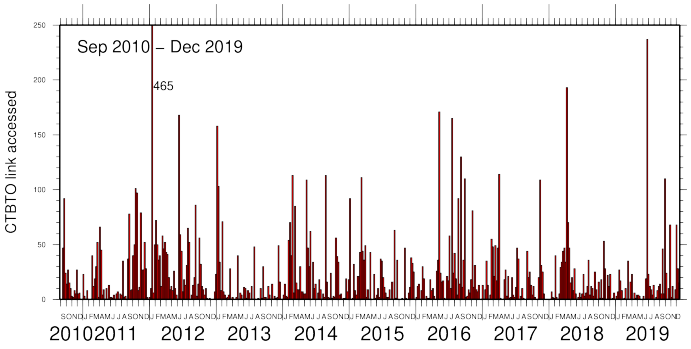



***Figure 40**. The Link to the ISC database mirror is provided to the NDCs through the IDC secure website. The figure shows the healthy stream of user activity.*

This project also benefits the ISC and the ISC users.

- The ISC development staff acquired relevant skills and experience during this project. The advances made under this project are gradually implemented to improve the open ISC web services. For example, the station histories now form an essential part of the International Seismograph Station Registry, available from the ISC website.
- In particular, experience of downloading, quality checking and processing waveforms on an industrial scale helps the ISC's efforts towards making its own automatic waveform measurements to further improve the quality of the ISC Bulletin.
- The ISC and its Bulletin users have speedy access to the REB Bulletin which is now available in **daily batches within 7-14 days after an event occurrence** as opposed to 6-12 months in the past (Fig. 41).
- Many NDCs are run by institutions that are either Members or Reporters of data to ISC.
- Several NDC's either became ISC Members or increased their financial contributions, based on the added value of the ISC services.

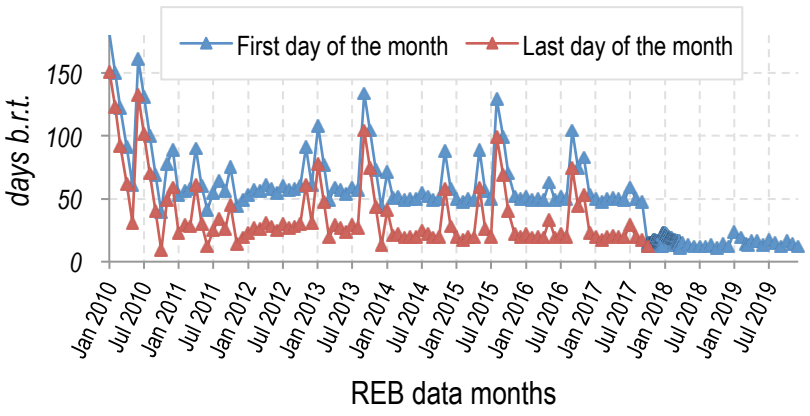



***Figure 41**. The availability of data from the ISC REB bulletins (not REB itself) to general ISC Bulletin users (days behind real time) has considerably improved as an indirect result of routine operation of the CTBTO Link; reporting of daily instead of monthly batches made any day of a data month available at the ISC much sooner.*

It also has to be noted that although the use of software created under this project is open only to the monitoring community, the actual data used by them are exactly the same as used by all ISC users: the *ISC Bulletin*, *GT List*, the *ISC-EHB* bulletin and the *International Seismograph Station Registry*.

# FINANCE

The detailed financial statements of the ISC for 2019 were audited by Wilkins Kennedy Chartered Accountants (Newbury, UK). These statements present the state of the ISC's financial affairs as at 31st December 2019.

## INCOME

In 2019, the ISC had a total income of £936,962.

The ISC received **£713,428** of contributions from 68 Member Institutions in 48 countries, which, unlike in 2018, included a full 12 months of NSF award. We were pleased to welcome the following new Members:

- Observatorio Nacional **(ON)**, *Brazil*;
- National Institute of Geophysics, Geodesy and Geography **(NIGGG)**, *Bulgaria*;
- Texas Seismological Network **(TexNet)**, *USA*;
- University of Utah Seismograph Stations **(UUSS)**, *USA*.

Grants for special projects and general sponsorship totalled **£223,686**, which is ~24% of the total income.

Traditionally, the income also includes the revenue from sales of the Bulletin Summary book, reduced by the cost of the book and DVD-ROM production and postage, which in 2019 amounted to a **loss of £2,401**.

We received a further **£2,249** in interest on our bank accounts.

At the end of year 2019, £6,744 had yet to be paid by Members. At the time of writing this report £4,320 had been received, leaving £2,424 outstanding. This is an outstanding result, compared to 2018, when the £117,683 had yet to be paid by Members at the year's end. We praise those Members who make an effort to pay membership invoices promptly.

## EXPENDITURE

As much as 80% of ISC expenditure was committed to personnel costs, which reflects the continuing rise in pension costs. The staff costs include salaries, pension contributions, and recruitment of new staff. The ISC salaries continue to follow the scales adopted in 2015 and approved by the Executive Committee. Each January, with the approval from the Chairs of the Governing Council and the Executive Committee, we increase the staff salaries in line with the annual inflation index (CPI), published by the UK Office of National Statistics.

Building maintenance costs increased by approximately 3% as compared to 2018. Staff travel and computer costs decreased by ~10%. As in previous years, staff travelled to attend conferences and increase the profile of the ISC, take part in project meetings and also to seek new data and future funding.

The cost of the PDRA position at the University of Oxford, supported by the ISC (66.66%), was £40,349, which this year was charged by the University with four quarterly invoices.

A total of £4,299 has been treated as bad debt. This corresponds to one unit of unrecovered membership subscription for two years from INPRES (San Juan, Argentina) who informed the ISC of their unfortunate decision to withdraw due to financial difficulties.

The exchange rate between UK £ and US $ / Euro changed throughout the year. Taking into account the timings of individual incoming and outgoing transactions, the ISC experienced a loss of £2,171 on foreign currency exchange in 2019.

Additionally, the increased expenditure reflected a loss of the 80% relief granted by West-Berkshire Council (local authority) to the ISC as a non-profit organization in the past. As a result, the ISC is charged ~£15,000 per annum instead of ~£3,000 formerly charged. Negotiations with the local Council and HMRC to reinstate the discount have proven lengthy and frustrating, despite the support from our accountant's charity specialists. It turned out that the only way to reinstate the Council's support was to obtain formal registration of the ISC's not-for-profit (charitable) status with the Charity Commission for England and Wales. With approval from the Executive Committee, a lawyer from Lester Aldridge LLP has been commissioned to help with identifying the most appropriate way of registering the ISC status with the Charity Commission.

## RESERVES

In understanding that all missing contributions will be paid, the ISC's income during 2019 exceeded its expenditure by £39,869, which partly compensated a loss of £44,454 made in 2018. As a result the total reserves, comprising cash in the bank, value of building and land, money owed to the ISC (debtors) minus money the ISC owes (creditors) have increased to **£846,256**; this includes money ear-marked for on-going projects.

The Contingency Fund still stands at £30,000 in accordance with the wish of the ISC Governing Council. The ISC General Reserve stands at £816,256.

## CASH FLOW

The cash flow in Fig. 42 shows receipts and expenditure using dates when transactions were recorded at the bank and the bank balances where US Dollars and Euros are converted to Sterling using the exchange rate at the end of each month.

Due to the size of its General Reserve serving as a safety cushion, the ISC was fortunate not to experience problems with its cash flow in 2019. This may change in the future if Members and Sponsors do not provide funds in time.

Here we would like to thank once again those member-Institutions that make their annual fee payment promptly and accurately when invoices are sent at the beginning of each year.

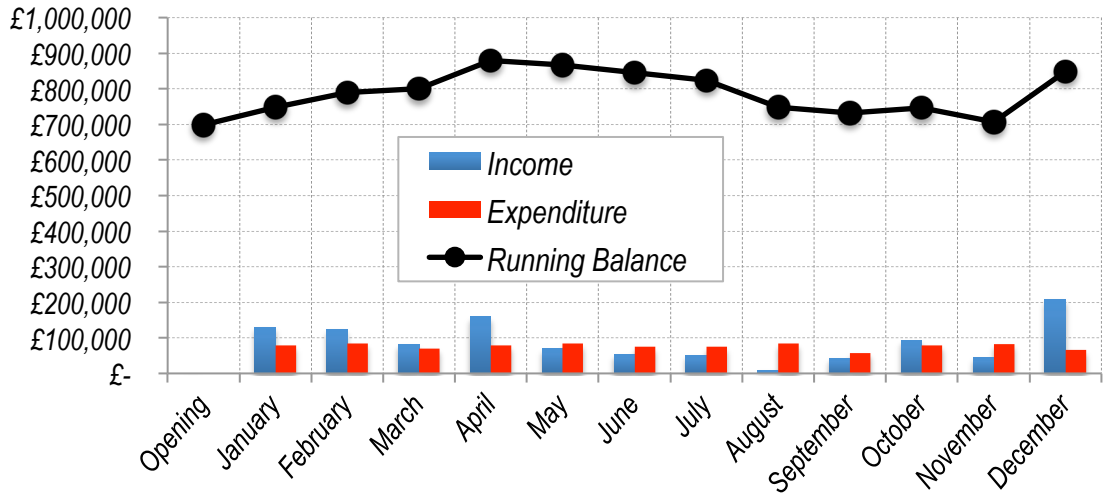



***Figure 42.*** *Income/Expenditure and running cash balance at the end of each calendar month during 2019.*

# SCIENTIFIC COMMUNITY AWARENESS

## VISITORS to the ISC

The following geophysicists visited the ISC premises in Thatcham during the year:

- Dino Bindi, GFZ, Potsdam, ***Germany***
- Angelo Strollo, GFZ, Potsdam, ***Germany***
- Elefteria Papadimitriou, Aristotle University of Thessaloniki, ***Greece***
- Vassilis Karakostas, Aristotle University of Thessaloniki, ***Greece***
- Ken Kawabe, MS&AD Interrisk, Tokyo, ***Japan***
- Wataru Echizenya, MS&AD Interrisk, Tokyo, ***Japan***
- Hannah Elms, Victoria University, Wellington, ***New Zealand***
- Jose A. Jara, ICGC, Barcelona, ***Spain***
- Antoni M. Silva, ICGC, Barcelona, ***Spain***
- Cassandra Bailly, Guralp, ***UK***
- Marie Balon, Guralp, ***UK***
- Sadie de Clercq, Guralp, ***UK***
- Tim Craig, University of Leeds, ***UK***
- Harsh Gupta, NGRI, Hyderabad, ***India***
- Bob Engdahl, University of Colorado Boulder, ***USA***
- Rengin Gok, LLNL, ***USA***
- Rob Mellors, LLNL, ***USA***

- Michael Pasyanos, LLNL, ***USA***
- Doug Dodge, LLNL, ***USA***
- Neill Symons, LANL, ***USA***
- Michael Begnaud, LANL, ***USA***
- Scott Phillips, LANL, ***USA***
- Ellen Syracuse, LANL, ***USA***
- G. Andrew Erickson, LANL, ***USA***

## CONFERENCES, MEETINGS, WORKSHOPS, TRAINING COURSES

To establish a tradition, we helped the University of Edinburgh to organise and run the 2nd British Seismology Meeting (BSM2019). The 1st BSM was organised by the ISC in 2017. The next BSM2021 is scheduled to take place in Cambridge.

Members of the ISC staff presented at the following conferences, meetings and workshops:

- EGU Meeting, Vienna, ***Austria***
- CTBTO WGB-52 meeting, Vienna, ***Austria***
- CTBTO Science and Technology Conference, Vienna, ***Austria***
- CTBTO WGB-53 meeting, Vienna, ***Austria***
- 3rd Brazilian Seismology Symposium, Vinhedo, ***Brazil***
- IUGG Assembly, Montreal, ***Canada***
- 20Y Chi-Chi Earthquake, Taipei, ***Chinese Taipei***
- EPOS Seismology Workshop, Grenoble, ***France***
- AG Seismology, Rastatt, ***Germany***
- International Seismology School, GS RAS, Chisinau, ***Moldova***
- ORFEUS Board of Directors meeting, Lisbon, ***Portugal***
- Complex Geophysical Monitoring of Far East, Petropavlovsk, ***Russia***
- Africa Array Workshop, Johannesburg, ***South Africa***
- NDC-RSTT Workshop, Chiang Mai, ***Thailand***
- Publishers Workshop, CrossRef and British Library, London, ***UK***
- British Seismology Meeting 2019, Edinburgh, ***UK***
- EPOS Workshop on Anthropogenic Hazards, Keele, ***UK***
- Impact Forecasting Revealed, Aon Benfield, London, ***UK***
- Future of Passive Seismic Acquisition, Cambridge, ***UK***
- UK SEDI meeting, UCL, London, ***UK***
- Deep Earthquakes, RAS, London, ***UK***
- WRN Earthquake Seminar, London, ***UK***
- SSA Meeting, Seattle, ***USA***
- AGU Meeting, San Francisco, ***USA***

## ISC STAFF VISITING OTHER INSTITUTIONS

Often with the help of the hosting institution, members of the ISC staff visited and, where appropriate, gave a presentation to the staff of:

- Instituto Dom Luiz, University of Lisbon, ***Portugal***
- The Portuguese Institute for Sea and Atmosphere (IPMA), Lisbon, ***Portugal***
- British Library, London, ***UK***
- The University of Edinburgh, Edinburgh, ***UK***
- British Geological Survey, Edinburgh, ***UK***
- IDC/CTBTO, Vienna, ***Austria***
- IRIS Data Management Center, Seattle, **USA**
- Pacific Northwest Seismic Network (PNSN), University of Washington, Seattle, **USA**
- Royal Society, London, ***UK***
- Natural Environment Research Council (NERC), Swindon, ***UK***
- University of Oxford, Oxford, *UK*
- University of Cambridge, Cambridge, ***UK***
- Geophysical Survey, Russian Academy of Sciences (RAS), Obninsk, **Russia**
- University of the Witwatersrand, Johannesburg, **South Africa**
- Geological Survey, Ottawa, ***Canada***
- Nanometrics, Kanata, ***Canada***
- Institute of Geology and Seismology, Chisinau, ***Moldova***
- Milestii Mici Seismic Station, Milestii Mici, ***Moldova***
- Institute of Earth Sciences, Academia Sinica, Taipei, ***Chinese Taipei***
- Kamchatka Branch, Geophysical Survey, RAS, Petropavlovsk, ***Russia***
- WDC-B, Geophysical Centre, Russian Academy of Sciences, Moscow, ***Russia***
- Institute des Sciences de la Terre, Universite Grenoble Alpes, Grenoble, ***France***
- Chiang Mai Array facilities, Chiang Mai, ***Thailand***
- China Earthquake Networks Center, Beijing, ***China***
- Institute of Geophysics, China Earthquake Administration, Beijing, ***China***
- TAIDE Enterprise Co, Zhuhai, ***China***
- Guangdong Earthquake Administration, CEA, Guangzhou, ***China***

## ISC PRIZES: UNIVERSITY OF OXFORD

Several years ago the ISC established a small annual Prize in Mathematics and Geophysics (£200 and traditional ISC coffee mug) for the best first year student at the Earth Science Department of its home institution – the University of Oxford.

In 2018, the prize was given to Ms Marjolaine Briscoe, the student with the best exam results in Mathematics and Geophysics. By awarding this prize the ISC hopes to attract University of

Oxford students to take note of the ISC services right from their first year, support the ISC in the future and perhaps even help the ISC in fulfilling its mission.

## SCIENTIFIC PUBLICATIONS BY ISC STAFF

The ISC staff published several scientific articles during 2019 to fulfil a general strategy of making the ISC standards, procedures and services transparent to users. This also helps to keep an improved historical record of how the ISC data were put together at different times.

Lentas, K., Di Giacomo, D., Harris, J., and Storchak, D. A., 2019. The ISC Bulletin as a comprehensive source of earthquake source mechanisms, Earth Syst. Sci. Data, 11, 565-578, https://doi.org/10.5194/essd-11-565-2019

Lentas, K. and Harris, J., 2019. Enhanced performance of ISC focal mechanism computations as a result of automatic first-motion polarity picking optimization, J. Seismol., 1141-1159, https://doi.org/10.1007/s10950-019-09862-x.

Schweitzer J., Storchak D.A., Borman P., 2019. Seismic Phase Nomenclature: The IASPEI Standard. In: Gupta H. (eds) Encyclopedia of Solid Earth Geophysics. Encyclopedia of Earth Sciences Series. Springer, Cham, https://doi.org/10.1007/978-3-030-10475-7

Wang, K., Brown, L., Hu, Y., Yoshida, K., He, J., and Sun, T., 2019. Stable forearc stressed by a weak megathrust: Mechanical and geodynamic implications of stress changes caused by the M=9 Tohoku-Oki earthquake. J. Geophys. Res.: Solid Earth, 124,

https://doi.org/10.1029/2018JB017043

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# APPENDIX 1: STANDARD BULLETIN REPORTERS

139 institutions in 88 countries reported reviewed seismic bulletin data to the ISC during 2019. This number also includes the ISC itself, which now produces depth phase arrival times, polarities of first motions and event source mechanisms in addition to the traditional set of hypocentre solutions and magnitudes.

| | |
|---|---|
| Albania | The Institute of Seismology, Academy of Sciences of Albania |
| Algeria | Centre de Recherche en Astronomie, Astrophysique et Geophysique |
| Argentina | Universidad Nacional de La Plata |
| Argentina | Instituto Nacional de Prevencion Sismica |
| Armenia | National Survey of Seismic Protection |
| Australia | Geoscience Australia |
| Australia | Curtin University |
| Austria | International Data Centre, CTBTO |
| Austria | Zentralanstalt fur Meteorologie und Geodynamik (ZAMG) |
| Belgium | Royal Observatory of Belgium |
| Bolivia | Observatorio San Calixto |
| Bosnia and Herzegovina | Republic Hydrometeorological Service, Seismological Observatory, Banja Luka |
| Botswana | Botswana Geoscience Institute |
| Brazil | Instituto Astronomico e Geofisico |
| Bulgaria | Geophysical Institute, Bulgarian Academy of Sciences |
| Cameroon | Seismological Observatory of Mount Cameroon |
| Canada | Canadian Hazards Information Service, Natural Resources Canada |
| Chile | Centro Sismologico Nacional, Universidad de Chile |
| China | China Earthquake Networks Center |
| Chinese Taipei | Institute of Earth Sciences, Academia Sinica |
| Chinese Taipei | CWB |
| Colombia | Red Sismologica Nacional de Colombia |
| Costa Rica | Seccion de Sismologia, Vulcanologia y Exploracion Geofisica |
| Croatia | Seismological Survey of the Republic of Croatia |
| Cyprus | Cyprus Geological Survey Department |
| Czech Republic | The Institute of Physics of the Earth (IPEC) |
| Czech Republic | Geophysical Institute, Academy of Sciences of the Czech Republic |
| Czech Republic | Institute of Geophysics, Czech Academy of Sciences |
| Denmark | Geological Survey of Denmark and Greenland |
| Dominican Republic | Observatorio Sismologico Politecnico Loyola |
| Dominican Republic | Universidad Autonoma de Santo Domingo |
| DPRK | Korea Earthquake Administration |
| Egypt | National Research Institute of Astronomy and Geophysics |
| Ethiopia | University of Addis Ababa |
| Finland | Institute of Seismology, University of Helsinki |
| France | Centre Sismologique Euro-Mediterranen (CSEM/EMSC) |

| | |
|---|---|
| France | Institut de Physique du Globe de Paris |
| France | Laboratoire de Detection et de Geophysique / CEA |
| France | EOST / RENaSS |
| French Polynesia | Laboratoire de Geophysique/CEA |
| Georgia | Institute of Earth Sciences/ National Seismic Monitoring Center |
| Germany | Alfred Wegener Institute for Polar and Marine Research |
| Germany | Bundesanstalt fur Geowissenschaften und Rohstoffe |
| Germany | Seismological Observatory Berggiesshubel, TU Bergakademie Freiberg |
| Germany | Geophysikalisches Observatorium Collm |
| Germany | Helmholtz Centre Potsdam GFZ German Research Centre For Geosciences |
| Germany | Landeserdbebendienst Baden-Wurttemberg |
| Greece | National Observatory of Athens |
| Greece | Department of Geophysics, Aristotle University of Thessaloniki |
| Greece | University of Patras, Department of Geology |
| Guatemala | INSIVUMEH |
| Hong Kong | Hong Kong Observatory |
| Hungary | Geodetic and Geophysical Research Institute, Hungarian Academy of Sciences |
| Iceland | Icelandic Meteorological Office |
| India | National Geophysical Research Institute |
| India | National Centre for Seismology of the Ministry of Earth Sciences of India |
| Indonesia | Badan Meteorologi, Klimatologi dan Geofisika |
| Iran | Tehran University |
| Iraq | Iraqi Meteorological and Seismology Organisation |
| Ireland | Dublin Institute for Advanced Studies |
| Israel | The Geophysical Institute of Israel |
| Italy | MedNet Regional Centroid - Moment Tensors |
| Italy | Istituto Nazionale di Geofisica e Vulcanologia |
| Italy | Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) |
| Jamaica | Jamaica Seismic Network |
| Japan | Japan Meteorological Agency |
| Japan | National Research Institute for Earth Science and Disaster Prevention |
| Japan | National Institute of Polar Research |
| Jordan | Jordan Seismological Observatory |
| Kazakhstan | National Nuclear Center |
| Kazakhstan | Seismological Experimental Methodological Expedition |
| Kyrgyzstan | Kyrgyz Seismic Network |
| Kyrgyzstan | Institute of Seismology, Academy of Sciences of Kyrgyz Republic |
| Latvia | Latvian Seismic Network |
| Lebanon | National Council for Scientific Research |
| Lithuania | Geological Survey of Lithuania |
| Macao | Macao Meteorological and Geophysical Bureau |
| Malawi | Geological Survey Department Malawi |
| Malaysia | Malaysian Meteorological Service |
| Mexico | Centro de Investigacion Cientifica y de Educacion Superior de Ensenada |
| Mexico | Instituto de Geofisica de la UNAM |

| | |
|---|---|
| Moldova | Institute of Geophysics and Geology |
| Montenegro | Seismological Institute of Montenegro |
| Nepal | National Seismological Centre, Nepal |
| New Zealand | Institute of Geological and Nuclear Sciences |
| North Macedonia | Seismological Observatory Skopje |
| Norway | University of Bergen |
| Norway | Stiftelsen NORSAR |
| Oman | Sultan Qaboos University |
| Panama | Universidad de Panama |
| Philippines | Philippine Institute of Volcanology and Seismology |
| Philippines | Manila Observatory |
| Poland | Institute of Geophysics, Polish Academy of Sciences |
| Portugal | Instituto Dom Luiz, University of Lisbon |
| Portugal | Instituto Portuges do Mar e da Atmosfera, I.P. |
| Portugal | Sistema de Vigilancia Sismologica dos Azores |
| Republic of Belarus | Centre of Geophysical Monitoring of the National Academy of Sciences of Belarus |
| Republic of Crimea | Inst. of Seismology and Geodynamics, V.I. Vernadsky Crimean Federal University |
| Romania | National Institute for Earth Physics |
| Russia | Baykal Regional Seismological Centre, GS SB RAS |
| Russia | Federal Center for Integrated Arctic Research |
| Russia | Institute of Environmental Problems of the North, Russian Academy of Sciences |
| Russia | Kola Regional Seismic Centre, GS RAS |
| Russia | Kamchatkan Experimental and Methodical Seismological Department, GS RAS |
| Russia | Mining Institute of the Ural Branch of the Russian Academy of Sciences |
| Russia | Geophysical Survey of Russian Academy of Sciences |
| Russia | North Eastern Regional Seismological Centre, GS RAS |
| Russia | Sakhalin Experimental and Methodological Seismological Expedition, GS RAS |
| Russia | Yakutiya Regional Seismological Center, GS SB RAS |
| Serbia | Seismological Survey of Serbia |
| Slovakia | Geophysical Institute, Slovak Academy of Sciences |
| Slovenia | Slovenian Environment Agency |
| South Africa | Council for Geoscience |
| Spain | Instituto Geografico Nacional |
| Spain | Institut Cartografic i Geologic de Catalunya |
| Spain | Real Instituto y Observatorio de la Armada |
| Switzerland | Swiss Seismological Service (SED) |
| Syria | National Syrian Seismological Center |
| Trinidad and Tobago | Seismic Research Centre |
| Tunisia | Institut National de la Meteorologie |
| Turkey | Disaster and Emergency Management Presidency |
| Turkey | Kandilli Observatory and Research Institute |
| U.S.A. | Experimental (GSETT3) International Data Center |
| U.S.A. | The Global CMT Project |
| U.S.A. | IRIS Data Management Center |
| U.S.A. | National Earthquake Information Center |

| | |
|---|---|
| U.S.A. | Pacific Northwest Seismic Network |
| U.S.A. | Pacific Tsunami Warning Center |
| U.S.A. | United States Geological Survey |
| Ukraine | Main Centre for Special Monitoring |
| Ukraine | Subbotin Institute of Geophysics, National Academy of Sciences |
| United Arab Emirates | Dubai Seismic Network |
| United Kingdom | British Geological Survey |
| United Kingdom | International Seismological Centre |
| Uzbekistan | Institute of Seismology, Academy of Sciences |
| Venezuela | Fundacion Venezolana de Investigaciones Sismologicas |
| Vietnam | National Center for Scientific Research |
| Zambia | Geological Survey Department of Zambia |

# APPENDIX 2: ISC DATA in RESEARCH PUBLICATIONS

This list is a result of a special effort to put together a collection of scientific papers published during 2019 that used ISC data. The list is by no means exhaustive. The ISC has become such a familiar name that many researchers sadly fail to reference their use of the ISC data.

To track publications that use one or more of the ISC dataset and services, we set up automatic alerts with Google Scholar for scientific papers that refer to ISC. The Google Scholar alerts return matches with different ways to refer to the ISC as normally done by authors, such as "International Seismological Centre", "International Seismological Center", "ISC-GEM", "ISC-EHB" and "EHB" + "seismic". No doubt many more references can be found by using different search phrases. Below are the bibliographic references to the ~280 works in year 2019 as gathered by Google Scholar. The references to articles published in journals are listed first, followed by the references to other types of publications (e.g., chapters in books, reports, thesis, websites). The references are sorted by journal name. The vast majority of the references below belong to journal articles.

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