Existing Earthquake Catalogs

PAGER-CAT is a composite earthquake catalog that has been developed entirely from published or online databases and reports. No new information has been derived in its compilation. However, for the first time, it brings together information from a range of sources in a comprehensive, easy to use digital format. Here we describe some of the key global earthquake catalogs compiled by recognized data centers and independent researchers that were considered for our studies. We restrict this review and the initial version of PAGER-CAT to global earthquake catalogs that are openly available in digital format.

USGS Preliminary Determination of Epicenters

Since 1940, the USGS National Earthquake Information Center (NEIC) and its predecessors at the Coast and Geodetic Survey, have produced its monthly publication; the *Preliminary Determination of Epicenters*, or PDE (NEIC, 1970; Sipkin and others, 2000). The NEIC routinely produces near-realtime solutions for earthquakes magnitude 5.0 and greater worldwide within 20 minutes of their occurrence. The monthly PDE is the archival USGS earthquake catalog containing locations, magnitudes, phase arrival times, and amplitude measurements for these and smaller earthquakes located by the NEIC and contributing U.S. regional and foreign networks. The monthly PDE is typically available six months in arrears and is available via ftp at ftp://hazards.cr.usgs.gov/pde/ or as an online search at http://neic.usgs.gov/neis/epic/epic_global.html. Multiple magnitude types are reported from both the NEIC and other contributors, including, moment magnitudes derived from NEIC body-wave moment-tensor solutions since 1981 (Sipkin, 1986). Since the late 1960's, the PDE has also included preliminary descriptions of earthquake impact and casualties, which are generally obtained from media reports or, more preferably, official sources (e.g., local or national government officials, humanitarian agencies, emergency managers, etc.). With the advent of modern communication networks, estimates of earthquake impact are more readily available than they were even a decade ago. Consequently, the quality of impact reports in the PDE has improved. This is also true for the quality of earthquake locations with the ongoing expansion of global seismograph networks, in addition to improved earthquake location techniques. The impact reports in the PDE are heavily referenced in other earthquake bulletins. However, one drawback of PDE the archive is that it is not often updated to reflect new information after publication.

International Seismological Centre Bulletin

The International Seismological Centre (ISC) and its predecessor, the International Seismological Summary, has published its monthly Bulletin since 1918 (available at http://www.isc.ac.uk/). The ISC bulletin is the authoritative international archive for hypocentral locations and phase picks. It contains all the locations and picks in the PDE plus data contributed from hundreds of other regional and global networks. In fact, it is because of the ISC's authoritative role that the USGS continues to refer to its final bulletin publication as "preliminary". The ISC's reviewed earthquake origins are typically available about two years in arrears and are intended to be as comprehensive as possible. The ISC identifies, on average, about 10,000 events per month of which approximately 40% of these require manual review (International Seismological Centre, 2001). For each event relocated by the ISC, phase picks and origin estimates contributed by other agencies are listed, in addition to the refined estimate as calculated by the center (Adams and others, 1982). An earthquake's felt effects and any unusual scientific features are also described if these data are contributed to the ISC. Impact reports from the PDE are routinely included in ISC bulletins.

Engdahl, van der Hilst and Buland Catalog (EHB)

The Engdahl *et al*. (1998) earthquake catalog comprises over 100,000 events and aims to be complete to M_W 5.5 and above. Smaller, well-recorded earthquakes and all those with CMT solutions are also included. The EHB catalog contains data from 1964 to 2005 and is periodically updated. Engdahl *et al*. (1998) use phase picks published by the ISC, but also use improved algorithms to identify additional depth and secondary phases, and employ the improved ak135 Earth velocity model (Kennett and others, 1995). They obtain significantly lower, and better constrained average residuals in phase arrivals than residuals reported by ISC. Further evidence for the quality of the locations is seen in improved tomographic delineation of whole Earth structure, in particular, subduction zones (Engdahl and others, 1998).

Centennial Catalog

The Centennial Catalog compiled by Engdahl and Villaseñor (2002) is an enhanced EHB catalog that ranges from 1900 through September 2007 (at time of writing) . It assembles the authors' preferred earthquake locations and magnitudes using a combination of literature searches and relocation using the Engdahl *et al*. (1998) method. From 1900 to 1963, the Centennial Catalog contains large magnitude earthquakes of $M \geq 6.5$, and $M \geq 5.5$ thereafter. The catalog includes a preferred magnitude from a variety of sources. However, it does not include any earthquake impact or casualty information.

Global Centroid Moment Tensor Database

The Global Centroid Moment Tensor (GCMT) Database, formerly known as the Harvard CMT (HRV) catalog has produced centroid moment tensor (CMT) solutions since 1976 (Dziewonski and others, 1981; Ekström and others, 2005). The group routinely calculates CMT solutions with a three-to-four day delay for events of about M_W 5.5 and above. They publish their final monthly catalog, including events of about M_W 5.0 and above, about four months in arrears (Global CMT Project, 2006). The GCMT catalog is available online at http://www.globalcmt.org. The solutions published by the GCMT database program have been calculated employing a systematic approach, with only minor modification, since its inception. The GCMT methodology uses long-period seismic waves and consequently only saturates for magnitude 9+ earthquakes.

National Geophysical Data Center's Significant Earthquake Database

The National Geophysical Data Center's (NGDC) Significant Earthquake Database provides a listing of historical earthquakes throughout the world that range in date from 2150 B.C. to the present. The events are gathered from scientific and scholarly sources, regional and worldwide catalogs, and individual event reports (e.g., Dunbar and others, 1992). Events included in the database must meet at least one of the earthquake source or impact criteria outlined by Dunbar *et al*. (1992). Earthquake source information for recent historical events in the NGDC database is obtained from the PDE (Dunbar and others, 2003). An advantage of the NGDC catalog is that information regarding earthquake impacts can be updated once more detailed information becomes available. Occasionally this catalog may also separate earthquake shaking-related fatalities (i.e., from building collapse) from those fatalities caused by secondary earthquake effects (e.g., tsunami or landslides). Separating secondary earthquake effects from shaking effects is important if we wish to develop fatality models for earthquake ground shaking only.

Historical Tsunami Database

The Historical Tsunami Database (HTD), hosted by the NGDC, provides a catalog of tsunami events from 2000 B.C. to the present (Dunbar, 2007) and is available online at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml. Although this database does not have any additional information about the earthquake source beyond that in the catalogs described above, it is useful in indicating the occurrence of tsunami hazards where other catalogs may not. Tsunami observations may be described in some earthquake catalogs. However, the systematic reporting of tsunami observations, in addition to other secondary hazards, is not the primary purpose of these catalogs and tsunami information may sometimes be omitted. An important attribute of this catalog is that tsunami deaths are separated from the total earthquake deaths where this information is available. Moreover, the HTD also indicates the run-up height for many tsunami events. This may enable us to make some judgment on the severity of the tsunami relative to that of ground shaking effects so that we can be more inclusive of minor tsunami events into for ground shaking loss models. For example the 1989 Loma Prieta, California earthquake generated a 40 cm tsunami observed in Monterey Bay (Ma and others, 1991) that did not contribute significantly to losses. However, due to its occurrence, it is flagged as a tsunami event.

Utsu Deadly Earthquakes Catalog

The Utsu catalog (e.g., Utsu, 2002) compiles a list of deadly historical earthquakes from 1500 through 2006 (available online at http://iisee.kenken.go.jp/utsu/index_eng.html). The data have been compiled from various accounts, earthquake catalogs, research articles, and reports on global and regional earthquakes. The majority of the fatality estimates are identical to those published in the PDE (83% from 1973 to 2006). However, the Utsu catalog has the advantage of being more retrospective and can be updated more readily over time. The Utsu catalog generally does not differentiate between fatalities caused by earthquake shaking and those caused by secondary effects (e.g., landslide, tsunami or fire). Cause of death from secondary effects may be flagged in the comments, but there is generally no indication on the contribution of these modes of deaths relative to the total deaths.

Emergency Events Database

The Emergency Events Database (EM-DAT) is maintained by the Centre for Research on the Epidemiology of Disasters at the University of Louvain (Belgium). It is a global, multi-hazard (e.g., earthquake, cyclone, drought, flood, volcano, extreme temperatures, etc.) database of human impacts and economic losses (e.g., Hoyois and others, 2007). The database often provides a more complete overview of earthquake-related injuries and other human impacts (e.g., the number of homeless) than other earthquake catalogs. In addition, it tends to include more detailed information on financial losses and foreign aid contributions. Since this compilation concentrates on the effects of disasters, the earthquake source parameters provided in the EM-DAT are not always of high quality and are often absent, incomplete, or erroneous. Furthermore, where the impact of an earthquake spans political boundaries, database entries are often subdivided by country. If the user desires a complete summary of an earthquake's impact, these records must be aggregated. Some effort to associate EM-DAT attributes to events with poor epicenters, or multiple entries has been done manually for key events within PAGER-CAT.

Selecting Preferred Earthquake Attributes

Below we outline the basic logic used to evaluated preferred PAGER-CAT attributes; particularly hypocentral locations, magnitudes, and human casualty information. Some of the logic for evaluating our preferred parameters may appear subjective. However, all information considered in PAGER-CAT is also retained as provided in its native catalog so that users can modify PAGER preferred parameters for their specific needs. The PAGER parameters are the preferred values based on our assessment of the input catalogs. Consequently, these values should be treated by users with some scrutiny.

Hypocenter

We use the updated Centennial Catalog earthquake origin as the preferred origin for all earthquakes since it uses more sophisticated location techniques than that used by the PDE, particularly for older events (see catalog description above). A semi-automated algorithm associates Centennial Catalog locations to our primary earthquake list of PDE events (from 1973) using origin time, epicentral location and magnitude as the association criteria. Since the magnitudes reported in the different catalogs vary considerably, we employ a relatively large magnitude window of ± 1.5 magnitude units, a 30 second time window, and an initial location window of ± 1 degree for latitude and longitude. If no corresponding event was found in the Centennial catalog using the default search criteria, the location window was extended to ± 2.5 degrees. If still no corresponding event is found, we retain the location and origin time of the primary PDE catalog as the preferred origin. Alternatively, if multiple earthquakes were found within the query, they will be listed onscreen and the operator must then select the appropriate Centennial Catalog event to associate to the PDE origin. This was usually intuitive since earthquake origin times from the two catalogues usually only differed by a few seconds (i.e., less than ± 5 sec). For those events in the PDE where we could not associate a Centennial Catalog origin, we repeat the process above, but use the original EHB catalog which is more inclusive of lower magnitude earthquakes than the Centennial Catalog. The subsequent hierarchy for obtaining preferred hypocenters is:

1. Centennial Catalog
2. EHB
3. PDE

It should be noted that both the Centennial Catalog and EHB catalog share the same fields in PAGER-CAT since they share the EHB location technique (except when labeled otherwise for older earthquakes). In the period from January 1973 through September 2007 (last Centennial Catalog update available), 95.1% of the events within the PDE with a preferred magnitude of M 5.5 and greater could be associated to a corresponding EHB hypocenter and origin time.

Magnitude

Where available, we use moment magnitude (Hanks and Kanamori, 1979) as the PAGER preferred magnitude type. Sipkin (1986) notes that moment tensors reported by the NEIC can have systematic biases for large earthquakes ($M_W > 7.3$) relative to the GCMT method. Since we are primarily concerned with the magnitudes of large, deadly earthquakes in the development of PAGER-CAT, we use the GCMT (or its predecessor, Harvard CMT) M_W solutions as our preferred source of magnitude. We use the same search criteria for the GCMT and HRV catalogs as for the EHB catalog outlined above. If the GCMT M_W cannot be associated, the NEIC M_W is used, when available. If neither the GCMT nor PDE catalogs provide an M_W estimate, we allow for the assignment of M_W from other sources obtained through independent research. This, by default, is the preferred magnitude, but is only ever assigned when GCMT or NEIC M_W are not available. For earthquakes that have no M_W estimates, we use the Centennial Catalog preferred magnitude prior to 1973, and the PDE thereafter. Below we outline the logic used in assigning our preferred magnitude M;

1. Other magnitude source (rarely assigned)
2. GCMT M_W (operator code: HRV, GCMT)
3. NEIC M_W (from PDE – operator code: GS)
4. PDE preferred magnitude (from PDE and may be M_S, m_b, M_L or unknown – multiple operator codes)
5. Centennial Catalog preferred magnitude (may be M_S, m_b, M_L , M_J, or unknown – multiple operator codes)

Mechanism

We assign the style of faulting (reverse slip, strike slip, or normal slip) from the plunge of the *P*- and *T*-axes of the focal mechanism from the GCMT catalog using the following conditions:

- Reverse faulting (RS): *T*-axis plunge > 45°
- Normal faulting (NS): *P*-axis plunge > 45°
- Strike-slip faulting (SS): *T*-axis plunge ≤ 45° and *P*-axis plunge ≤ 45°

Casualties

Catalogs that include casualty (death or injury) information are attributed to PAGER-CAT using similar approaches to those used for the earthquake source information. Assignment of PAGER-CAT preferred casualty numbers follows a complex hierarchy. Because some earthquake loss catalogs provide detailed information for a specific earthquake effect, this must be considered among all other information prior to assigning casualty numbers. Assigning preferred casualty numbers follows the logic below for total number of deaths, injuries and homeless:

- Use information from other source (input manually)
- If Utsu ≠ PDE, use Utsu
- PDE
- NGDC
- EM-DAT
- HTD

The logic for assigning preferred shaking deaths are essentially the same as above, but rely on additional conditional logic when secondary effects are observed. The subsequent logic for picking preferred shaking deaths is as follows:

- Use information from other source (input manually)
- PDE shaking
- If HTD tsunami < HTD total and no landslide flags, use HTD total – HTD tsunami
- If maximum tsunami wave height ≤ 1 m and no landslide flags
    - Utsu
    - NGDC total
    - EM-DAT

Where possible, any obviously erroneous values contained in these casualty fields, they are reviewed and edited manually.

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