GLOBAL EARTHQUAKE MODEL
working together to assess risk

PSHA input model documentation for Arctic Polar (PAR)

GEM Hazard Team

Version history

Table 1 summarises version history for the PAR input model, named according to the versioning system described here, and indicating which version was used in each of the global maps produced since 2018. Refer to the GEM Products Page for information on which model versions are available for various use cases. The changelog describes the changes between consecutive versions and are additive for all versions with the same model year.

Table 1 *– Version history for the PAR input model.*

Version	2018.1	2019.1	2022.1	2023.1	2026.1	Changelog
v2025.0.0					X	First version of GEM's model for the Arctic.

The following text describes v2025.0.0.

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1 Summary

The hazard model for the Polar Arctic region covers the Arctic Ocean North of Iceland, Europe, Russia and Canada, extending across the whole polar region.

This model, and the associated models for the Atlantic, Indian and Pacific oceans, were developed as part of the Forecasting and Communicating Earthquake Risk (FORCE) project, supported by USAID Bureau for Humanitarian Assistance (BHA). The model was built for the OpenQuake (OQ) engine by the GEM secretariat.

2 Tectonic overview

The polar region in the Northernmost latitudes includes a moderate amount of seismicity arising in the Gakkel ridge, which runs North of Iceland as a continuation of the Atlantic Mid-Atlantic ridge. Seismicity in the Gakkel ridge appears to be higher at more Southern extensions of the ridge, though this may be an artifact of recording in the very isolated far North. Outside of spreading regions, very few earthquakes are recorded at high latitudes.

This model covers the area uncovered by models for Europe (EUR), North Asia (NEA and NWA), Alaska (ALS), Canada (CAN) and Greenland (GLD), including Svalbard and Jan Mayen island.

3 Basic Datasets

This model uses the magnitude-homogenised (Appendix B.1). This catalogue merged the ISCGEM v10 catalogue (*International Seismological Centre, 2025; Storchak et al., 2013, 2015; Di Giacomo et al., 2018*), the Global CMT catalogue (*Dziewonski et al., 1981; Ekström et al., 2012*) and the comcat/ANSS (*USGS, 2017*) catalogue and includes events from 1900 - 2020, homogenised to M_W.

We also use Global Centroid Moment Tensor (GCMT) focal mechanisms from 1976-2020 (*Dziewonski et al., 1981; Ekström et al., 2012*).

4 Hazard Model

4.1 Seismic Source Characterisation

The source model uses only distributed active shallow seismicity modeled as a grid of **point sources**.

We model distributed seismicity with an approach that combines area sources with smoothed seismicity, incorporating methods from *Frankel (1995)* and *Helmstetter et al. (2007)*, with the with the source zone approach commonly used to build GEM models (see Appendix C.2). We build a source model for the crustal subcatalogue encompassed by each source zone polygon, with occurrence rates at a bin spacing of M=0.1.

First, the completeness of the catalogues is established using an automated procedure that identifies optimal windows from the catalogue. Then the catalogue is declustered to remove aftershocks and the Magnitude-Frequency (MFD) parameters are calculated for each zone. We compute the smoothed seismicity for a grid defined by h3 hexagons spanning the source polygon. The total rates expected from the MFD are then distributed according to the smoothed density, to create a spatially-varying model of seismicity.

The catalogue was declustered using the method of *Uhrhammer (1986)*. To keep the logic tree simple for this preliminary model, we include a single smoothing approach for the distributed seismicity using fixed kernel smoothing. The parameters for each source are shown in Table 2. Note that the Gakkel ridge source has a very high b-value, but this is consistent with other spreading sources. In comparison, the other sources have low b- and a-values, though this may be partly influenced by completeness issues in this region.

SZ	***a*-Value**	***b*-Value**	$M_{max,obs}$	**Description**
2	8.39343	1.5	6.8	Gakkel ridge, spreading centre
29	3.43573	0.8	5.6	Oceanic crustal source North of Gakkel ridge
30	3.60655	0.8	6.6	Oceanic crustal source North of Europe/Asia and South of Gakkel ridge

Table 2 *– Crustal source zone parameters and descriptions.*

4.2 Ground Motion Characterisation

The ground motion characterisation used available records for all oceanic events to derive a single GMC for all oceans models. Spreading and transform share one ground motion logic tree, with the GMC derived using (limited) ground-motion records for mid-ocean regions (mostly from Iceland) and following the choices of the ESHM20 model for Iceland (*Danciu et al., 2021*). For oceanic crust, two different logic trees are used depending on whether or not the zone is expected to include significant volcanism, with this classification coming from the presence or absence of volcanoes in the Smithsonian Global Volcanism Project (*2003*). In subduction regions, the ground motion logic tree was defined using records from the Guam and Mariana region. The classification of each zone is shown in Figure 1. The GMMs for each source type are shown in Table 3

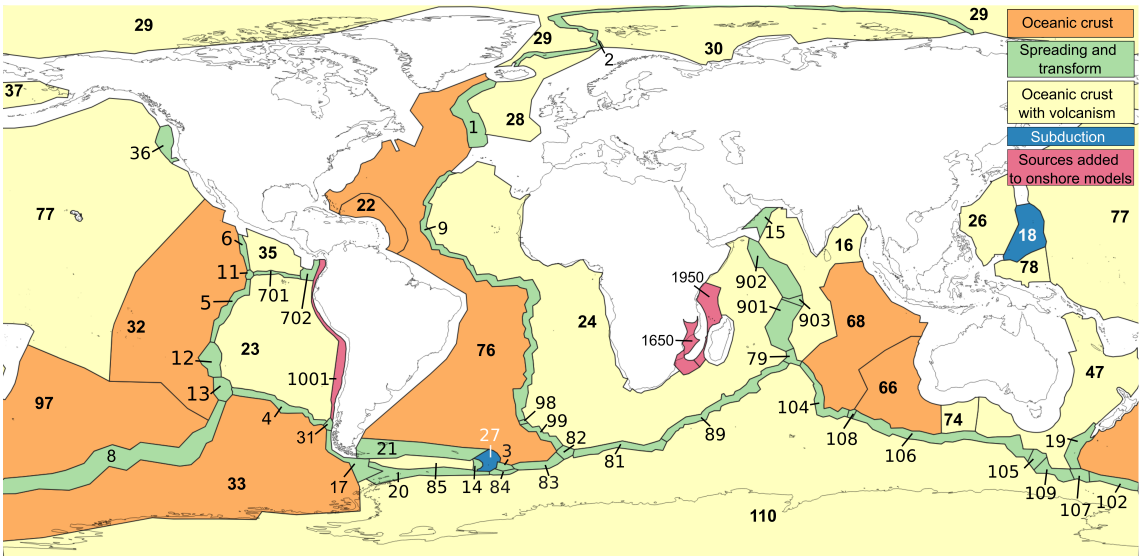

Figure 1 *– Ocean model sources coloured by ground motion tectonic region type*

Oceanic Crust without Volcanism	**Weight**
AbrahamsonEtAl2014	0.25
BooreEtAl2014	0.25
CampbellBozorgnia2014	0.25
ChiouYoungs2014	0.25
Oceanic Crust with Volcanism	**Weight**
Atkinson2010Hawaii	0.20
AbrahamsonEtAl2014RegJPN	0.20
BooreEtAl2014	0.20
CampbellBozorgnia2014	0.20
ChiouYoungs2014Japan	0.20
Spreading and Transforms	**Weight**
KothaEtAl2020ESHM20 backbone	0.50
ChiouYoungs2014	0.50

Table 3 *– GMM weights by tectonic region for the PAR model*

5 Results

Hazard curves were computed with the OQ engine for the following:

- Intensity measure types (IMTs): peak ground acceleration (PGA) and spectral acceleration (SA) at 0.1s, 0.2s, 0.3s, 0.6s, 1.0s, and 2s
- reference site conditions with shear wave velocity in the upper 30 meters (Vs30) of 760-800 m/s, as well as for Vs30 derived from a topography proxy (Allen and Wald,

2009)

Hazard maps were generated for each reference site condition-IMT pair for 10% and 2% probabilities of exceedance (POEs) in 50 yrs. Additionally, disaggregation by magnitude, distance, and epsilon was computed for the following cities: Mbabane, Maseru and Pretoria. The results were produced as csv files and bar plots for each of the following combinations:

- hazard levels for 10% and 2% POE in 50 yrs
- PGA and SA at 0.1s, 0.2s, 0.3s, 0.6s, 1.0s and 2.0s
- Vs30=800 m/s

All calculations used a ground motion sigma truncation of 5. Onshore results were computed for sites with 6 km spacing.

Visit the GEM Interactive Viewer to explore the Global Seismic Hazard Map values (PGA for Vs30=800 m/s, 10% poe in 50 years). For a comprehensive set of hazard and risk results, see the GEM Products Page.

6 References

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A GEM modelling methods

B Catalogues

Much of PSHA depends on the assumption that future seismicity will occur near observed past seismicity, and at rates that can be approximated by empirical or physical models. Thus, the early steps in PSHA include compiling and processing an earthquake catalogue. Beyond collecting instrumental and historic earthquake records, catalogues must be homogenized (expressed in uniform units), declustered (devoid of aftershocks and foreshocks), and filtered for completeness. The assumptions and uncertainties in the catalogue should be well understood by the modeler.

Most source types used in hazard models built by the GEM Secretariat use magnitude-frequency distributions (MFDs, Section D) based on seismicity. Together with ground motion prediction equations (GMPEs), MFDs govern the computed hazard levels for time frames of interest, and so their robust calculation - and thus careful preparation of the input catalogue - is critical.

Here, we describe the GEM global catalogue which contributes the majority of earthquakes used in hazard models built internally by GEM; the workflow for combining other earthquake records with the global catalogue; and the remaining steps to prepare the catalogue for rate and spatial analysis. We emphasize that while most of these steps are routinely applied outside of GEM models, the following explanations only account for our own best practices.

B.1 The GEM global catalogue

The GEM global catalogue us a homogensised catalogue combining three global catalogues: the ISCGEM catalogue (*International Seismological Centre, 2025; Storchak et al., 2013, 2015; Di Giacomo et al., 2018*), the Global CMT catalogue (*Dziewonski et al., 1981; Ekström et al., 2012*) and the comcat/ANSS (*USGS, 2017*) catalogue and includes events from 1900, homogenised to M_W. This catalogue is periodically updated with new releases of the ISCGEM catalogue and to include more recent events from GCMT and comcat.

Recent regional models developed by the GEM Secretariat use the GEM extended catalogue, augmented by data from local agencies when possible.

B.2 Processing of seismicity catalogues

B.3 Catalogue homogenization

In order to use the bulletins from multiple agencies together in statistical analyses, records must be homogenized to meet the same criteria, e.g., to use the same measure of magnitude. Usually, moment magnitude (*MW*) is selected, since it does not saturate at high magnitudes. Thus, magnitudes reported in other scales must be converted. When pos-

sible, this is done using empirical relations developed for independent local datasets, but relies on global relations when too few calibration events are available.

The homogenization methodology used to build the catalogues is described in detail in *Weatherill et al. (2016)*.

B.4 Completeness analysis

Catalogue completeness analysis accounts for the variability in instrumentation coverage throughout the catalogue duration, admitting that any catalogue is missing earthquakes beneath a magnitude threshold. This type of filtering prevents rate analysis of an incomplete catalogue - a modeling mistake that will propagate into hazard estimates. Importantly, completeness analysis must be applied to a declustered catalogue as to not confuse dependent earthquakes (such as aftershocks) with magnitude completeness.

The completeness algorithms that are applicable to *any* instrumental catalogue must depend on properties of the earthquakes, and not the stations, thus focusing on the statistics of the catalogue sample rather than the probability that a station at a known position would record an earthquake. The most common algorithmic method is by Stepp (1971), which compares the observed rate of seismicity to a predicted Poissonian rate for each magnitude, and returns a spatially constant table of time-variable magnitude thresholds. Importantly, the validity of this methodology is subject to the judgement of the user.

The Stepp (1971) is implemented in the OpenQuake Engine, and used in some steps of the modeling procedure for hazard models built by the GEM Secretariat. In other cases, we determine the completeness manually from 3D histograms that count earthquakes for magnitude-time bins, visually identifying the timings at which the occurrences rates stabilize. In recent models, we use a newly-developed approach that jointly estimates the completeness and recurrence parameters, implemented in the OQ Model Builder's toolkit (MBTK, Pagani et. al, 2026). This approach reflects the inter-dependence of these parameters.

B.5 Declustering

Catalogue declustering is applied in order to isolate mainshock earthquakes - that is, earthquakes that occur independently of each other - from a complete catalogue. The resulting declustered catalogue should therefore reflect the Poissonian rate at which earthquakes occur within a greater tectonic region. PSHA aims to model the hazard from sesimicity occurring at this background Poissonian rate.

Declustering algorithms identify mainshocks by comparing individual earthquakes to the "cluster" of earthquakes that occurred within a given proximity and time to that earthquake, choosing the largest for a given set of magnitude-dependent "triggering windows". The theory of declustering algorithms is described in detail in *Stiphout et. al., 2012*. The OpenQuake

Hazard Modeler's Toolkit provides three different windowing options: the original implementation of Gardner and Knopoff (1974), and additionally the configurations of Uhrhammer (1986) and Gruenthal (see Stiphout et al., 2012).

In subduction zones or other complex environments, we first classify the seismicity by tectonic domain (described below), and then decluster groups of domains within which we expect seismicity to interact (i.e., interface mainshocks can trigger crustal aftershocks), and then separate the deemed mainshocks into subcatalogues based on their tectonic classification. We typically use two groups: crustal, interface, and shallow slab seismicity (that beneath the interface but with intraslab mechanisms); and deep intraslab seismicity. The declustering algorithm comparing epicentral (*not* hypocentral) proximities, and thus, declustering by groups is crucial for seismicity within slab-type volumes.

B.6 Classification of seismicity

The workflow used by GEM to construct seismic source models in complex tectonic regions is dependent on the use of classified seismicity, that is, the assignment of each earthquake to a tectonic domain. Separating earthquakes in this manner allows us to compute MFDs from only the seismicity occurring within a delineated domain, thus more accurately characterizing individual seismic sources or source zones. For example, in subduction zones, we separate earthquakes occurring on the interface itself from those within the downgoing slab or the overriding plate. This allows us to model the hazard from these source types using the appropriate GMPEs.

At GEM, we classify seismicity using an procedure with similar theory to *Zhao et al., (2015)* and *Garcia et al., (2012)*, which assigns earthquakes to tectonic domains defined by the modeler. In subduction zones, earthquakes are usually categorized as crustal, interface, or intraslab based on hypocentral proximity to the Moho, and the interface and slab-top complex surfaces defined by the (Subduction Toolkit). Where subduction zones are modeled as segmented interfaces or slabs, the domains are divided accordingly. Each tectonic domain is defined by a surface and a buffer region based on general characteristics of the corresponding cross sections. The modeler provides a tectonic hierarchy that chooses among multiple assignments for earthquakes occurring within overlapping buffers of two or more domains. Usually, we specify interface superseding intraslab, and intraslab superseding crustal. Earthquakes that do not correspond to any of the defined domains are deemed "unclassified".

The classification routine includes workarounds to correct some common misclassifications, such as to seclude dominant groups of earthquakes beneath a polygon (e.g., volcanic events); to classify large magnitude earthquakes from historic catalogues only by epicenter; and the ability to manually classify earthquakes by their event IDs.

B.7 References

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C Modelling distributed seismicity

We use the term "distributed seismicity" to indicate earthquakes not clearly attributable to an individual fault source or subduction zone. To model these, we group together seismicity with common characteristics, such as focal mechanism type, strain by the same tectonic forces, rate, or 3D distribution; we then produce source models reflecting these characteristics. Here, we describe two primary source types used to model distributed seismicity.

C.1 Area Sources

Area sources consist of a statistically-determined MFD (Section D) from earthquakes occuring in a volume (usually a polygon, defined by the modeler, with depth limits), with the modelled occurrence rates distributed uniformly (equal *a*- and *b*-values) over an evenly spaced grid, and paired with a hypocenter and focal mechanism. In the OpenQuake Engine, the specified hypocentral depths and focal mechanisms can be probability distributions, or singular metrics.

C.2 Smoothed Seismicity

Smoothed seismicity is modeled similarly to area sources, but rather than using a spatially-homogeneous MFD in each source, the *a*-values vary spatially based on observed seismicity.

GEM has moved away from using traditional area sources, and predominantly models distributed seismicity with an approach that combines area sources with smoothed sesimicity, incorporating methods from Frankel (1995). We define a few source zones with internally consistent tectonics (e.g., up to a few prominent focal mechanism types, reflecting the same tectonic stresses), solve for the Gutenberg-Richter *b*-value, and then smooth the occurring seismicity onto a grid of points. This approach allows us to use larger source zones (and thus more earthquakes to compute a more robust MFDs) while still capturing spatial variability in seismicity rate.

We use the declustered crustal sub-catalogue, applying the *Stepp (1971)* completeness analysis or one based on time-magnitude density plots. Then, from the earthquakes within each source zone, we compute a double truncated Gutenberg-Richter MFD from M=5 to $Mmax,obs$ + 0.5 (bins of M 0.1), solving for *a*- and *b*-values based on *Weichert (1980)*. We classify the earthquake probability into weighted depth bins. Lastly, we assign most-likely nodal planes based on crustal earthquake focal mechanisms within the source zone based on the GCMT catalogue.

We compute the smoothed seismicity grid by applying a Gaussian filter to the clipped, declustered catalogue for each source zone, and computing the fraction of spatial seismicity rates at each grid node. These are combined with the zone MFD to compute a grid of point-by-point earthquake occurrence rates.

In areas where we also model fault sources, we prevent double counting by dividing the magnitude occurrence bins between the two source types. If there is overlap (including a buffer around the surface projection of a fault, we cut the MFDs for distributed seismicity at *Mmax*=6.5, and use the same value as *Mmin* for fault MFDs.

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D Types of MFDs

In probabilistic seismic hazard analysis (PSHA), source models require a defined occurrence rate for earthquakes of each considered magnitude, e.g., a magnitude-frequency distribution (MFD). These rates are determined either by statistically analysing the observed seismicity over instrumental and historic time scales, or-for well characterized sources—by using the fault dimensions and slip rates to model recurrence.

Regional models built by GEM use the following common approaches to characterize seismicity rates.

D.1 Gutenberg-Richter

The Gutenberg-Richter MFD allows earthquake sources to generate earthquakes of different magnitudes. *Gutenberg and Richter (1944)* were the first to develop a functional form for the relationship between earthquake magnitude and occurrence rate, resolving a negative exponential distribution:

$$logN = a - bm \tag{1}$$

$$\tag{2}$$

where *N* is the annual rate of earthquakes with *M* > *m*, *a* is the rate of all earthquakes, and *b* is the relative distribution of earthquakes among magnitudes. A higher *b*-value indicates a larger proportion of seismic moment released by small earthquakes. *a* and *b* are resolved from the available observations. Usually, *b* is close to 1.0.

D.1.1 Truncated Gutenberg-Richter

A traditional Gutenberg-Richter MFD allows for earthquakes of any magnitude, but in reality, the source in question may not be capable of producing earthquakes beyond a certain threshold. For example, fault dimensions physically limit earthquake magnitude, or the observed earthquake magnitudes saturate. To account for these constraints, a truncated MFD is used to specify a maximum magnitude (*Mmax*), simply by cutting the MFD at this magnitude. The MFD is additionally cut at a minimum magnitude ("double-truncated"), below which earthquakes are not contributing to the hazard in ways significant to engineering.

Truncated Gutenberg-Richter MFDs are commonly used in hazard models build by the GEM Secretariat. Where MFDs are produced for a source zone, such as for distributed or inslab seismicity, the upper magnitude is usually determined by adding a delta value (e.g., *MW*0.5) to *Mmax* in the earthquake catalogue or subcatalogue used to produce the MFD. This is based on the premise that the observation period is too short to have experienced a true *Mmax* earthquake.

GEM models typically use the methodology of Weichert (1985) to compute double-truncated Gutenberg-Richter MFDs for seismic source zones, which allows for the use of different observation periods for different earthquake magnitudes (e.g., a completeness threshold).

If a seismicity distribution is not explicitly available, an MFD of this form can also be computed from a seismic moment budget using strain rates, fault dimensions, and assumed magnitude ranges and *b*-values. For models built internally by GEM, we apply this to faults with available slip rates.

D.2 Characteristic

Some sources do not produce earthquakes that follow the Gutenberg-Richter distribution, but instead tend to host earthquakes of nearly the same magnitude, e.g., a characteristic earthquake. In this case, an earthquake with a moderate to high magnitude occurs more frequently than would be suggested by a Gutenberg-Richter MFD. For sources of this type, the MFD reveals more frequent occurrences concentrated around the most-likely/characteristic magnitude earthquake, for example using a boxcar or Gaussian distribution (e.g., *Youngs and Coppersmith, 1985*, or *Lomnitz-Adler and Lomnitz, 1979*).

Though the *Youngs and Coppersmith* (*1985*) MFD is technically a hybrid MFD, incorporating both a characteristic component and a Gutenberg-Richter component at lower magnitudes, it is typically often categorized as a characteristic MFD. GEM uses this MFD in a few models built in-house, such as the Philippines model, where sensitivity testing indicated that it produced a better fit to the regional seismicity than a double-truncated GR for crustal faults.

D.3 Hybrid types

Some subduction interface source models built by the GEM secretariat use a hybrid approach that combines the Gutenberg-Richter MFD with a characteristic MFD. The latter approach derives a double truncated Gaussian distribution to model occurrence of the maximum magnitude (*M*max) earthquake that an interface segment can theoretically support (herein called the "characteristic earthquake").

The magnitude and occurrence rate of the characteristic earthquake for an interface segment are based on the fault area (e.g., from the complex fault output by the Subduction Toolkit), the convergence rate, and a seismic coupling coefficient. We choose between three recent scaling relationships for subduction interfaces that compute magnitude from fault area: *Strasser et al.* (*2010*), *Allen and Hayes* (*2017*), and *Thingbaijam and Mai* (*2017*). We use published convergence rates and seismic coupling coefficients to determine the time needed to accumulate enough strain for the characteristic earthquake. The coupling parameter is often challenging, in large part due to the scarcity of land and thus GPS measurements in close proximity to subduction zones. Where no other model is available, we take values from *Heuret et al.* (*2011*) or *Scholz and Campos* (*2012*), but cautiously, as many

sometimes these values are suspiciously low (e.g., <0.1 where instrumentally recorded earthquakes *M*>8.0 have occurred.)

The characteristic MFD is combined with the Gutenberg-Richter MFD into a hybrid MFD by finding the intersection point of the two MFDs, and taking the Gutenberg-Richter occurrence rate below the intersection magnitude, and the characteristic rate above that magnitude.

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