A Tsunami Warning System for the Northeast Atlantic

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Summary

In 2006, the UK Department for Food and Rural affairs (DEFRA) commissioned the British Geological Survey (BGS) to establish a system capable of detecting and discriminating earthquakes which could pose a tsunami risk to the UK. Previous studies for DEFRA had shown that the UK risk from tsunamis is low, but not negligible. The system must be able to become part of an integrated tsunami warning process, if one is implemented in the future.

Rather than start from scratch in developing suitable earthquake detection software, the BGS chose to implement the *EarlyBird* software developed at the US NOAA West Coast and Alaska Tsunami Warning Center (Whitmore and Sokolowski, 2002). By selecting stations from seismic networks in over a dozen countries a composite network of more than 100 stations was built up that provides good coverage for our area of interest, which extends from the UK and surrounding waters to most of the North Atlantic, including offshore Portugal, the Mid-Atlantic ridge, the Caribbean, and the northeast coast of America.

The system has now been operating reliably for over a year and has detected earthquakes in most of the areas identified where potentially tsunamigenic sources could affect the UK. The detection threshold has been shown to be well below that required, considering that significant tsunamis are likely to be generated only by earthquakes of magnitude over 6.5, and response times for alert messages are good. If a tsunami warning centre is set up within the UK we are confident that the system described here would fulfil the seismic requirements. In addition such a centre would need access to real-time deep sea pressure sensors, tide gauge instruments (these aspects are under investigation by the Proudman Oceanographic Laboratory) and tsunami forecast tools as well as reliable means to disseminate warnings.

Network

More than 100 stations have been selected to make up a network that gives good coverage for the area of interest (Figure 1). Because tsunami warning requires earthquakes to be detected quickly, waveform data has to be available in near real-time, defined by a data latency (delay in availability) of less than about 2 minutes. This latency is acceptable for ocean-wide tsunami detection, where tsunami travel times are more than 30 minutes. In addition, to correctly measure the size of large earthquakes, data from broadband seismometers with a natural period of more than 100 seconds is required. Agreement has been reached with each of the operating agencies listed in Figure 1 and data is acquired by the BGS over the internet using a variety of protocols. A few of the stations used are not shown on this map as they are in the opposite hemisphere. These are included to avoid distant earthquakes being located incorrectly within our area of interest.

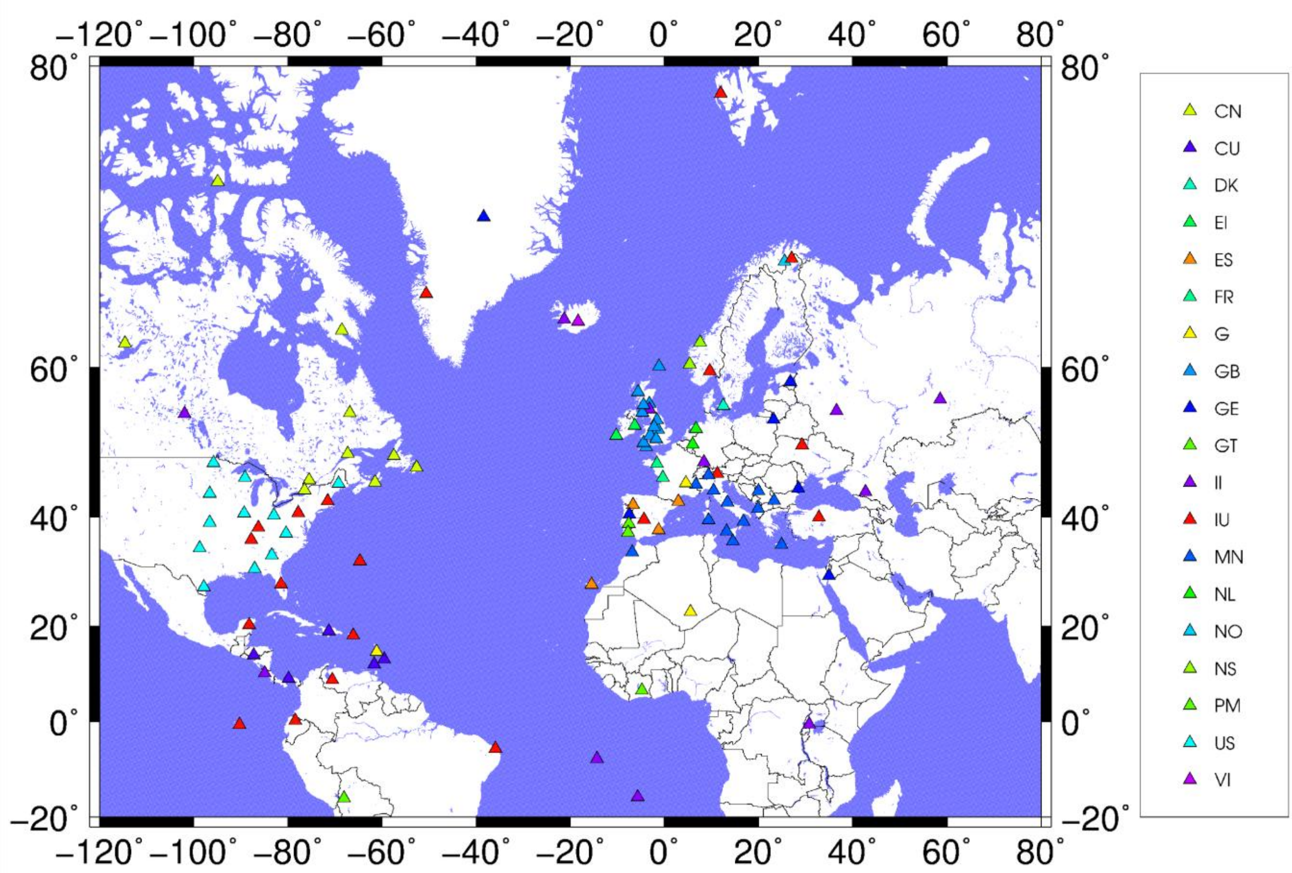


Figure 1. The network of seismic stations used for earthquake detection within *EarlyBird*. A few stations used are outside these map boundaries. The station symbols are colour-coded depending on the network operator.

Operation

EarlyBird is software specifically developed for use in tsunami warning. It rapidly processes data from many seismic stations to detect, locate and estimate the magnitude of earthquakes. It was developed at the US NOAA West Coast and Alaska Tsunami Warning Center and parts of it are also used by the Pacific Tsunami Warning Center. The software was originally written in 1980 and has been subject to continuous development since then.

EarlyBird is closely integrated with the *EarthWorm* software package (Johnson et al., 1995). *EarthWorm* is an open-source (www.isti2.com/ew), real-time seismic data processing system developed by the USGS and widely used by seismic networks worldwide. It is used by the BGS to process data from the UK seismograph network, which made *EarlyBird* particularly suitable for this project. *Earthworm* is modular, and autonomous modules import, export, process or archive waveform data. These modules communicate by generating messages in areas of shared memory known as 'rings', which other modules can read without interacting with the originating module in any other way. Modularity makes it easy to modify and add to *EarthWorm*.

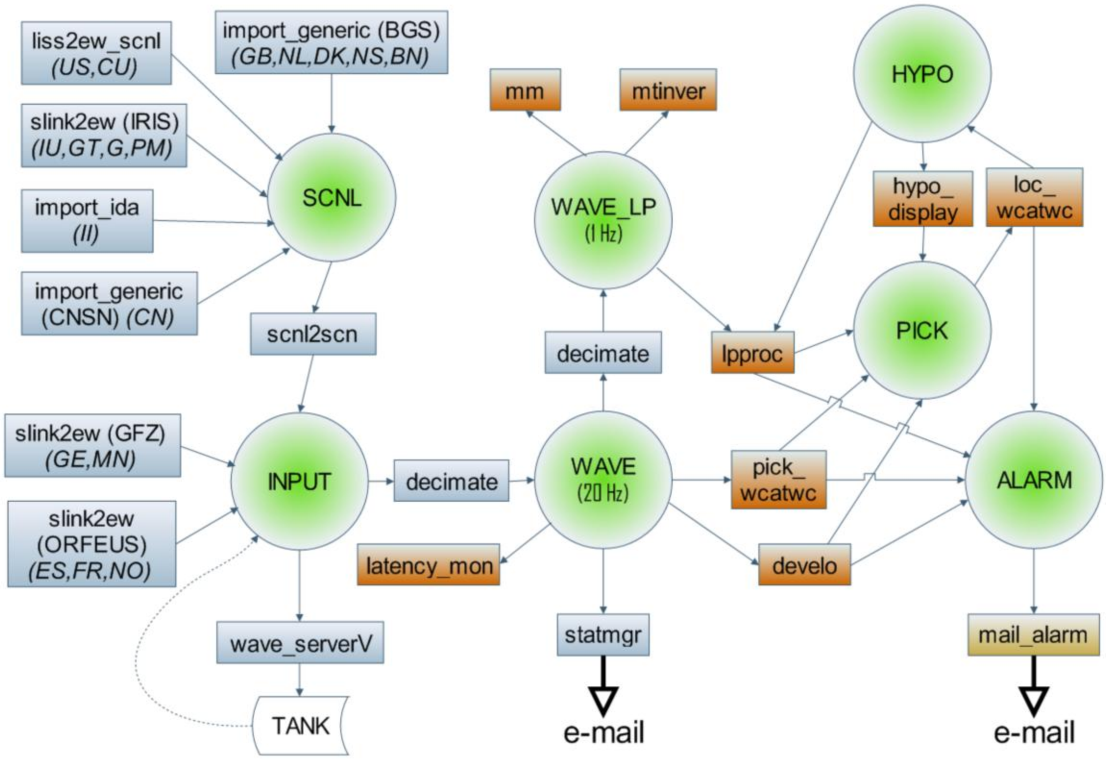
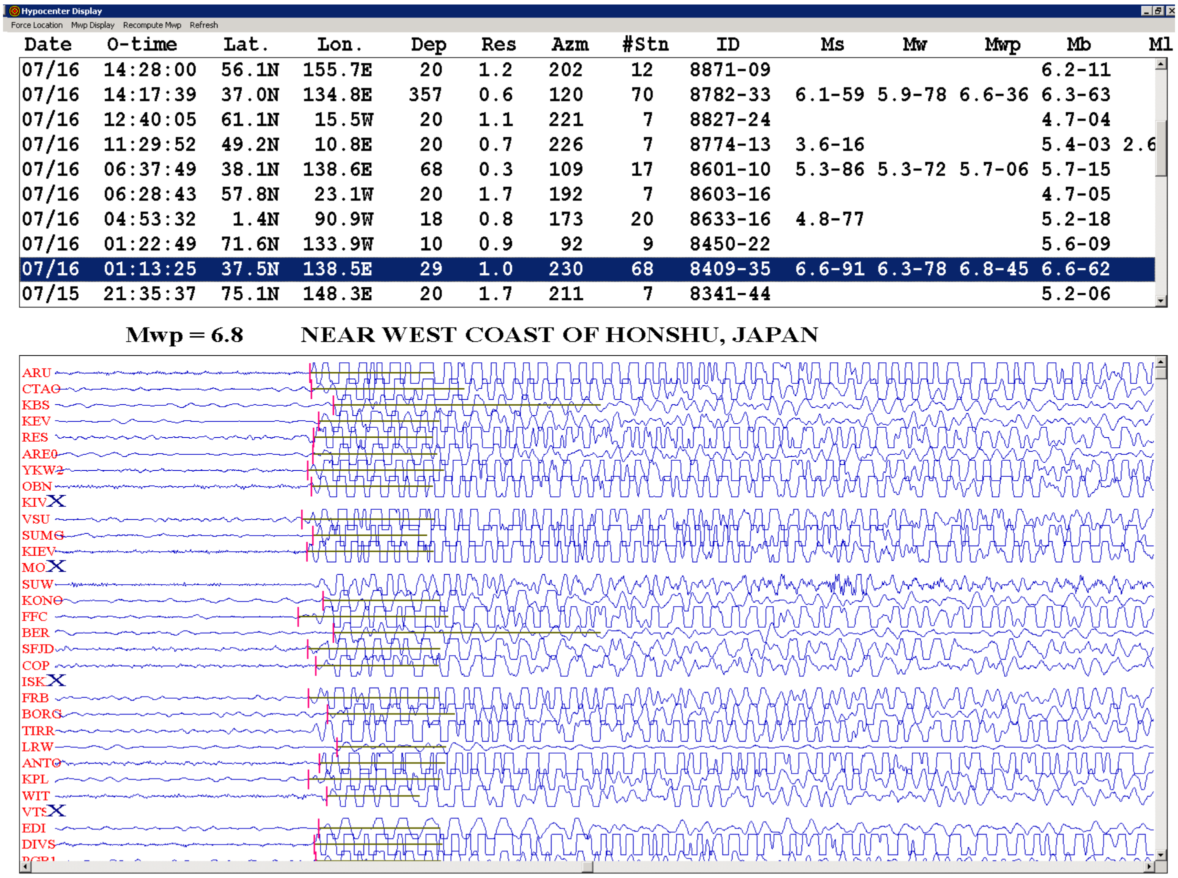


Figure 2. Flowchart of *EarlyBird* configuration implemented for this study. The rectangles indicate autonomous modules, standard *EarthWorm* modules are blue and *EarlyBird* modules are orange. Input modules are to the left of the diagram with the network codes of data being input by each module in brackets under the module name. The circles represent the areas of shared memory, called 'rings', used for inter-module communication.

EarlyBird uses the existing *EarthWorm* architecture and standard modules for importing and decimating data. It adds modules for fast real-time global data processing. These additional modules differ from standard *EarthWorm* by including graphical user interfaces, allowing an operator to inspect current data and quickly verify or amend automatic results. Figure 2 gives a schematic overview of the *EarlyBird* installation used in this study. Data is imported from a number of seismic networks using a variety of protocols and converted to a standard format. Then it is decimated to both 20 samples per second (short period) and 1 sample per second (long period). The short period data is used for initial processing, e.g. phase picks. For large events the long period data is used for magnitude and moment-tensor calculations.

EarlyBird detects earthquakes by continuously running a picking algorithm designed to detect P-wave arrivals (Veith, 1978) on each station (module *pick_wcatwc*). The picks found are grouped by arrival time and station location and once there is a sufficient number a trial location is attempted (Huang et al., 2007). Either an event is declared or the phases are released for possible inclusion in other groups. Locations are computed using Geiger's method and the *iaspei91* global travel time tables. Although location is based on a global Earth model, it works at all distances, from local to regional and distant. The depth calculated for earthquakes is not considered in subsequent automatic decisions as the trade-off between depth and origin-time makes depth values unreliable.

Once an earthquake has been located it is essential to find its magnitude to estimate the tsunamigenic potential. *EarlyBird* routinely calculates up to five different magnitudes (ML, Mb, Ms, Mm and Mwp) depending on the epicentral distance. The larger an earthquake, the more energy is released at long periods. Some of the magnitude scales (ML, Mb and Ms) only use phases with shorter periods and so saturate for large earthquakes. Thus, for larger events only Mm and Mwp reflect the size of the earthquake, and even Mwp will normally underestimate the size of earthquakes over magnitude 8. Mm or mantle magnitude (Okal and Talandier, 1989) is calculated using surface waves (period greater than 50 seconds), which arrive later than other phases and so cannot be obtained until some time after the other magnitudes. Mm is, therefore, only valuable for warnings of distant earthquakes. Mwp was specifically developed to quickly determine the size of a large earthquake and has been shown to be equivalent to moment magnitude Mw (Tsuboi et al., 1995; 1999) This makes it the most useful magnitude in the tsunami warning context. Alternative magnitudes have been developed to more accurately measure very large earthquakes (e.g. Lomax and Michelini, 2007) but so far these have not been implemented in *EarlyBird.* In practice the response to an event with a calculated magnitude of 8 would be the same as the response to one with magnitude 8.5, especially since such events are extremely rare. For smaller events, Mwp and Mm cannot be determined due to the lack of long-period energy and for these events the other magnitudes are useful.



Date	O-time	Lat.	Lon.	Dep	Res	Azm	#Stn	ID	Ms	Mw	Mwp	Mb	Ml
07/16	14:28:00	56.1N	155.7E	20	1.2	202	12	8871-09				6.2-11	
07/16	14:17:39	37.0N	134.8E	357	0.6	120	70	8782-33	6.1-59	5.9-78	6.6-36	6.3-63	
07/16	12:40:05	61.1N	15.5W	20	1.1	221	7	8827-24				4.7-04	
07/16	11:29:52	49.2N	10.8E	20	0.7	226	7	8774-13	3.6-16			5.4-03	2.6
07/16	06:37:49	38.1N	138.6E	68	0.3	109	17	8601-10	5.3-86	5.3-72	5.7-06	5.7-15	
07/16	06:28:43	57.8N	23.1W	20	1.7	192	7	8603-16				4.7-05	
07/16	04:53:32	1.4N	90.9W	18	0.8	173	20	8633-16	4.8-77			5.2-18	
07/16	01:22:49	71.6N	133.9W	10	0.9	92	9	8450-22				5.6-09	
07/16	01:13:25	37.5N	138.5E	29	1.0	230	68	8409-35	6.6-91	6.3-78	6.8-45	6.6-62	
07/15	21:35:37	75.1N	148.3E	20	1.7	211	7	8341-44				5.2-06	

Figure 3. Example of hypocenter display showing list of parameters on top and corresponding interactive seismograms for selected event at the bottom.

Once a location and magnitude have been obtained they are used to decide which alerts, if any, should be sent. For the purposes of this work, event alerts are distributed to BGS staff by email and through *SMS* to mobile phones. The earthquake detection algorithm in *EarlyBird* is designed to produce results quickly. The importance of an early alert means that the first location and magnitudes for an event can sometimes be calculated using barely sufficient data. This may be quite different from subsequently-refined solutions obtained using additional data. The importance of never failing to detect a potentially tsunamigenic earthquake means that the detection parameters chosen make it more likely that false events will be produced than that real events will be missed. These design features are mitigated by making the process interactive with input from a human operator possible at every stage. Many of the modules that make up *EarlyBird* have graphical user interfaces; Figure 3 for example shows the interactive location display. It is simple to review events and decide which of the generated alerts should be released to outside agencies. It is also possible to improve locations and magnitudes in real-time by, for example, removing or repicking phase arrivals or fixing depth. Although the current study only used *EarlyBird* in a completely automatic mode the program is designed to support 24/7 staffed operations. In an operational tsunami warning system the reviewed *EarlyBird* event can be released as a first alert. Tsunami generation can then be confirmed or not through deep sea pressure and tide gauge instruments.

Performance

EarlyBird has been in operation at the BGS since autumn 2006. Overall, the software has proven itself to be extremely robust, with no system crashes experienced. Data availability and hence detection capability can change daily as sites become unavailable and then come back online again. To ensure the required coverage it is necessary to import data from more stations than would be needed if they were all working all the time. While there have been some interruptions in data availability the overall coverage has been satisfactory at all times. The system relies entirely on internet communication. While we have experienced no problems with this, it may not be acceptable for an operational tsunami warning centre, as the loss of internet to the centre would completely stop it operating. Alternative communication could include a satellite downlink at the centre.

While the focus of earthquake detection for tsunami warning is to detect the largest earthquakes, detection of smaller events is a good indicator of how well the system is working. A comparison was carried out of *EarlyBird* and NEIC locations of earthquakes in the North Atlantic (Figure 5 and Figure 6). This comparison shows how accurate the *EarlyBird* locations are, as well as how many earthquakes of what size are being missed by the current system and how many false events are being generated. It should be noted that the NEIC locations are manually reviewed, using a wider selection of stations than are available in real time, and so should be more accurate than *EarlyBird*'s automatic locations. The EarlyBird locations used for the comparison are those included in the first alert. The time between each event and its first alert is shown in Figure 4 plotted against the distance to the nearest station contributing to that alert. As can be seen, alerts were most often received within 10 minutes of large earthquakes.

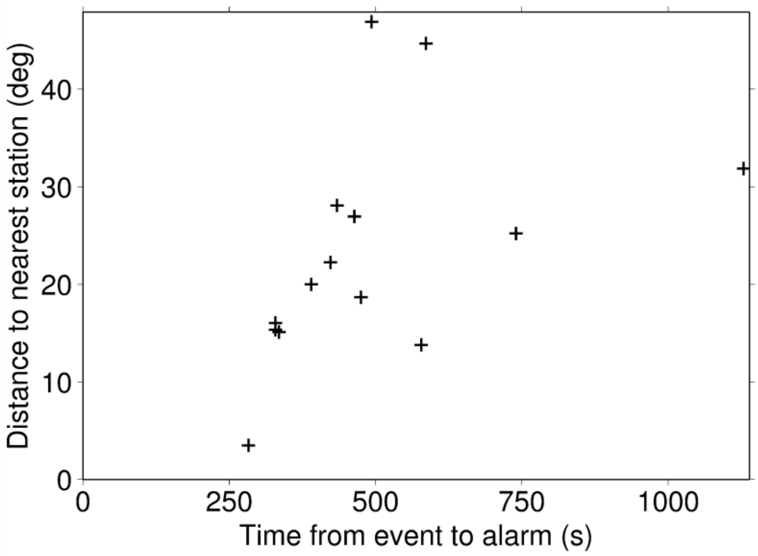


Figure 4. Time delay before alarm for events with magnitude greater than 5 plotted against the distance between the event and the nearest station contributing to the alert solution.

Figure 5 shows that a number of events below magnitude 5 are missed by *EarlyBird*. Analysis of the processing shows that this is because of difficulties in associating phases in real time when there is no nearby station. However, Figure 6 shows that above magnitude 5 *EarlyBird* performs very well. The three earthquakes missed by *EarlyBird* in Figure 6 all have magnitude 5.1 and, as earthquakes in the Mid-Atlantic are furthest away from the nearest stations, magnitude 5.1 can be regarded as the detection level throughout the monitoring region. As tsunami are expected only from earthquakes above at least magnitude 6.5 the system is operating successfully well below the required threshold. The false detections shown in both datasets are caused by unrelated phases arriving at widely spread stations within a short time-window. Recent enhancements to the EarlyBird associator have greatly reduced the number of false detections due to the association of unrelated phases (Huang et al., 2007). Even with the reduction of false detections, human review is necessary to ensure that incorrect information is not automatically released. A future tsunami warning system will require 24 hour a day monitoring.

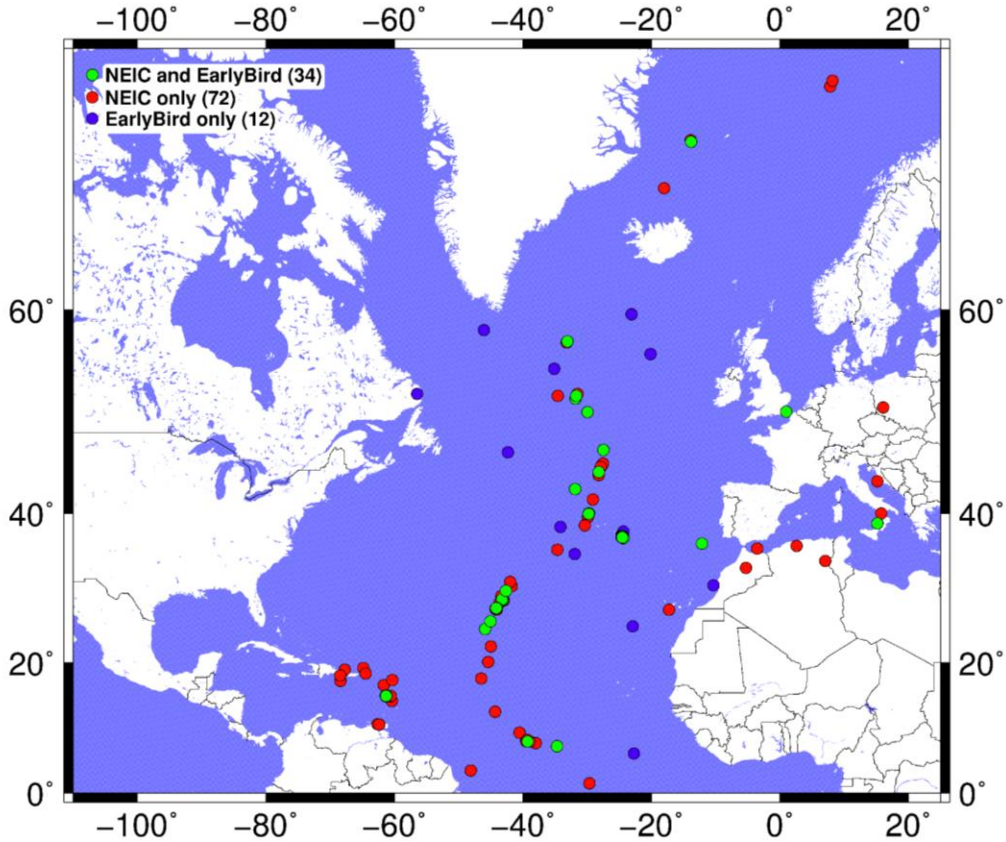


Figure 5. Comparison of events detected by *EarlyBird* and the NEIC between 1st April and 1st December 2007, with magnitude above 4.5. Events are considered to be the same if their locations are within 1 degree in space and 10 seconds in time.

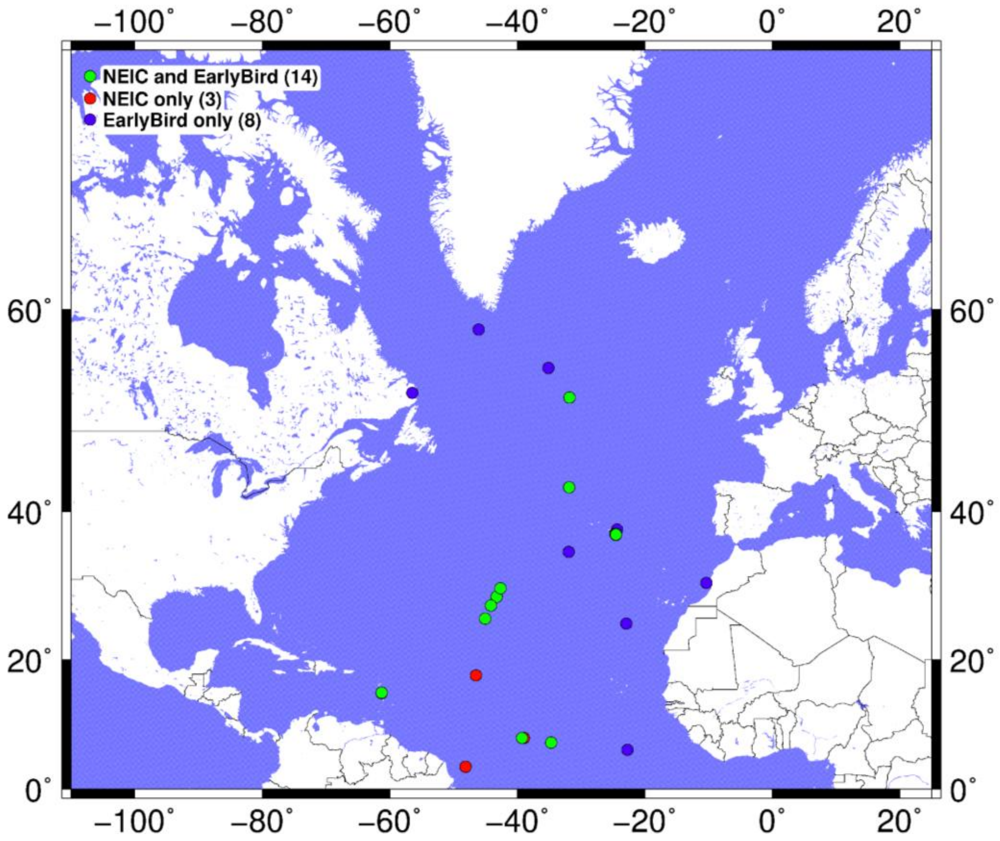


Figure 6. Comparison of events detected by *EarlyBird* and the NEIC between 1st April and 1st December 2007, with magnitude above 5. Events are considered to be the same if their locations are within 1 degree in space and 10 seconds in time.

Conclusions

The system implemented using *EarlyBird* software to automatically detect and determine the location and size of earthquakes for tsunami warning has proven to be very robust. A total of more than one hundred stations are used to provide good coverage for the area of interest. While access to data from seismic stations was reasonably easy to establish, single stations or, worse, complete networks can become unavailable for a limited time. This can have serious consequences for the detection of earthquakes, but can be mitigated by using data from networks with overlapping coverage and using more stations than necessary, to provide redundancy. The composite network used allows accurate determination of location and magnitude for all earthquakes with magnitude greater than 5.1 in the area of interest. To date *EarlyBird* has been running in fully automatic mode, providing alerts to BGS staff only. Most alerts have been from real events, but, false detections do occur. Operator interaction is vital to the reliable use of *EarlyBird*. This is, however, only one of the reasons that operation of a tsunami warning centre requires staffing 24 hours a day.

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Nacional, Spain, Instituto de Meteorologia, Portugal, Instituto Superior Tecnico, Lisbon, Portugal, KNMI, Netherlands, NORSAR, Norway and ReNaSS, France.

Maps in this article where created using GMT (Wessel, P., and Smith, W., 1998. New, improved version of Generic Mapping Tools released, EOS Trans. Amer. Geophys. U., 79, 579.)

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