Modelling Disaster Impact for the Global Disaster Alert and Coordination System

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ABSTRACT

The Global Disaster Alert and Coordination System, jointly developed by the European Commission and the United Nations, combines existing web-based disaster information management systems with the aim to alert the international community in case of major sudden-onset disasters and to facilitate the coordination of international response during the relief phase of the disaster. The disaster alerts are based on automatic hazard information retrieval and real-time running of impact models. This paper describes impact models for earthquakes, tsunamis and tropical cyclones.

Keywords

Earthquakes, tsunami, tropical cyclones, volcanoes, disaster alert, international response

INTRODUCTION

The Global Disaster Alert and Coordination System (GDACS) is a web-based platform that combines existing web-based disaster information management systems with the aim to alert the international community in case of major sudden-onset disasters and to facilitate the coordination of international response during the relief phase of the disaster.

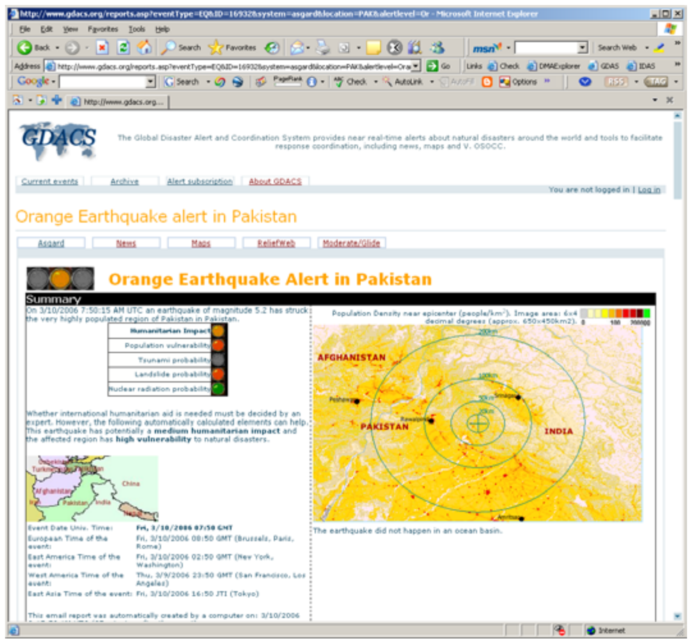
GDACS is jointly developed by the European Commission Joint Research Centre and the United Nations Office for Coordination of Humanitarian Affairs (OCHA). Other participating organisations are the Humanitarian Early Warning Service (hosted by the World Food Programme), UNOSAT. GDACS systems process data collected from The United States Geological Survey National Earthquake Information Centre, the European-Mediterranean Seismological Centre (EMSC), GEOFON Programme of the GFZ Potsdam, the French Réseau National de Surveillance Sismique (RENASS), the Hawaii University IFA/SOLAR lab (for tropical cyclones) and the Southwest Volcano Research Centre.

In essence, GDACS is not a system. It is a set of elements that allow system integration. GDACS comprised of the following elements:

- A set of standards to ensure interoperability between existing alert and response coordination systems,
- A set of working procedures to ensure predictability and reliability of information creation and exchange during crisis response,
- Stakeholders that commit to provide related information according to the GDACS standards for data exchange and GDACS working procedures.

However, a GDACS portal has been built at the Joint Research Centre to demonstrate how a GDACS system can look like. The portal is available at http://www.gdacs.org. It has integrated GDACS compliant information sources and offers a way to register for the alert services by email, fax, SMS and/or RSS as provided by GDACS components.

GDACS intends to collect two types of information: events alerts and coordination information. The United Nations OCHA is currently making key coordination systems GDACS compliant, including the ReliefWeb and the Virtual On-Site Operations Coordination Centre. OCHA is therefore largely responsible for the coordination section of GDACS. Event alerts, on the other hand, are currently provided by HEWS[1] and by JRC. HEWS staff monitors floods and droughts based on field reports and news and makes these available as a GDACS compliant feed. The JRC has created novel software, called Asgard, to automatically monitor events, run impact models, generate reports and alert levels and disseminate this information to humanitarian decision makers. Currently, JRC is using Asgard to monitor earthquakes, tsunamis, tropical storms and volcanoes (although for the latter only nearby population is calculated). Note that generating the alert is only one function of Asgard. Asgard also creates automatic maps, lists critical infrastructure nearby (nuclear installations, airports), assesses probability of secondary effects (landslides or tsunamis) and automatically collects the international news related to the event for three weeks after the event.



Disaster alerts are different than event alerts. Not every natural hazard event is a humanitarian disaster for obvious reasons: either no population is near or the scale of the event is too small for disrupting society.

This document presents the methods used for generating disaster alerts. The basic principle is to obtain operational models. Often, parts of the phenomenon can be modelled accurately (e.g. earthquake intensity field), while another part is vague (destruction of houses). In such cases, it does not make sense to use complex models in the first part, because the ultimate result ("Is it a disaster or not?") will only be as accurate as the least accurate model in the chain of models. More often accurate models exist but the data needed to run them is missing. Again for example for earthquakes, earthquake engineers have designed accurate models of building collapse, given the construction materials of the building. But this data is not available on a global scale.

In this paper we do not attempt to discuss the most advanced models in each of the disaster type fields. However, we try to indicate if better models exist and why we are or are not using them. It will become clear that simple models often have a satisfactory and reliable result.

EARTHQUAKES

Because earthquakes cannot be predicted routinely with enough lead time to safeguard people and infrastructure, they are one of the most devastating natural disasters. Unlike other sudden-onset disasters, there is no lead time. Therefore, it is important for the humanitarian aid community to be alerted shortly after the earthquake occurred about the potential humanitarian impact.

Earthquakes disrupt society in several ways: casualties (people are killed and injured in collapsing houses); loss of shelter (many building types, in particular in poorer regions of the world, are not earthquake resistant and are completely destroyed); destruction of roads, bridges, railroads and other transportation infrastructure; damage of high risk infrastructure such as nuclear plants or hydrodams; secondary effects: tsunamis, landslides.

[1] Humanitarian Early Warning Service. An early warning service provided by the UN Inter Agency Standing Committee and developed by the World Food Programme.

While not all tsunamis are created by seismic events, most tele-tsunamis and tsunamis of high magnitude are. Therefore, tsunamis can be considered as a secondary effect of earthquakes. However, as seen in the tsunami of December 2004, this "secondary" effect can be the most important one in terms of humanitarian damage. The tsunami phenomenon is further described in the next chapter. However, tsunami alerts are integrated in the earthquake alerts as described further.

Modelling the phenomenon and its impact

In order to model the impact of an earthquake, several steps can be modelled: intensity of shaking, affected area (the area in which the intensity of shaking is large enough to cause damage to structures or casualties), affected population (the number of the people living in the affected area that suffered damage or injury), humanitarian disaster (if the needs of the affected population are significant and beyond their own control) and international humanitarian disaster (if the needs of the affected population are beyond the control of the national government).

The first two steps, calculating the intensity and the affected area, involve seismological expertise. For instance, the United States Geological Survey is now running models to produce what is called ShakeMaps (Wald *et al.*, 1999), which predict the intensity of shaking around the epicentre. ShakeMaps provide a detailed analysis of where the earthquake has most impact. Similar work has been done by Wyss (2005). Currently, JRC is not using ShakeMaps as an input for the impact models; however, this can be done in future work.

An alternative method uses an ellipsoid around the epicentre with a fixed radius (De Groeve and Ehrlich, 2004) or a radius as a function of the magnitude (Peduzzi and Herold, 2004). For the first method, a constant radius (of 50 or 100km) is a coarse approximation of the real affected area. But the impact model is not very sensitive to this variable. For the variable radius, thresholds for radius can be fixed based on magnitude for which an estimation of ground motions duration, for specific acceleration and frequency ranges, is higher on equal to one second, as described in Bolt *et al.* (1975).

Theoretically, the affected population can be estimated using earthquake statistical and engineering techniques for modelling building response and socio-economic data for modelling population movements (Shakhramanian *et al.*, 2000). However, this is complicated and needs detailed data on a global scale, which is generally not available or updated.

Moreover, calculating the affected population is not necessary to assess whether an earthquake is an (international) disaster or not. Instead, information on population density, vulnerability and coping capacity is equally or more important to assess whether an earthquake is an international humanitarian disaster or not. Regression models with few variables and calibrated on earlier humanitarian response to earthquakes can provide a model with sufficient reliability to predict earthquake disasters.

Asgard earthquake model

In 2005, Asgard used the fixed radius model with a radius of 100km. When using circular areas on global datasets, it is important to account for projections. A real circle on the earth would look more like an ellipse on the map in geographical projection. Not taking into account projections generally leads to population underestimation of 5 to 10% in Europe (40 degrees latitude).

Currently, the evaluation of the potential humanitarian impact of earthquakes considers (1) earthquake magnitude (in units reported by source), (2) earthquake depth, (3) population within 100km of epicentre (Pop_{100}), and (4) national population vulnerability. Elements 1 and 2 are scraped from seismological sources, while elements 3 and 4 are automatically calculated by a geographical information system (GIS) based on epicentre location (latitude and longitude), the Landscan 2003 population dataset (ORNL, 2003) and ECHO's Global Needs Assessment (GNA) indicator (Billing and Siber, 2003), a composite indicator for vulnerability and coping capacity.

The formula for the threshold is calculated as follows. This formula was established based on statistical analysis and minimization of omission and commission errors of historical earthquake disasters (De Groeve and Eriksson, 2005).

First, the alert score is calculated:

P = sqrt ($\log_{10}$ (Max (Pop_{100} / 80000, 1)))
If Pop_{100} > 80000 (the cut off population threshold), then P is the square root of the 10 logarithm of Pop_{100}/80000. This means that we assume an exponential relationship between impact and population, with a cut off of 80000 people within an area of 31415.6 km^2, or a population density of about 2.5 people per km^2.

M = Max (magnitude - 4.5, 0)
If the magnitude is above 4.5, then M is the magnitude - 4.5. This means that we do not consider earthquakes of a magnitude lower than 4.5. Further, we assume – for strong earthquakes – a linear relationship between impact and magnitude.

V = GNA Index for closest country (a value between 0 and 3)
If GNA is missing, then V defaults to 0.6. The GNA is a combination of 9 socio-economic and historical indicators[2] that are computed based on ranking and classification. The value (between 0 and 3) is not a quantitative value, but qualitative value.

These factors are combined and weighted as follows:

$$\textbf{draft\_alert\_score} = (P * M * V^{1.5}) / 3$$

This formula gives a higher weight to the vulnerability of the country, therefore emphasizing that prepared and rich countries with good building standards that can be enforced can better cope with earthquakes than other countries. Equivalent earthquakes are more likely to be a disaster in vulnerable countries.

Subsequently, the draft alert score is modified according to the following empirical rules:

- If the magnitude is less than 6, no red alerts can be issued. In other words, if the *draft alert score* is larger than 2, it is set to 2.
- If the earthquake occurred more than 100km deep, the *draft alert score* is reduced by 1.
- If the earthquake occurred deeper than 300km, the *draft alert score* is set to 0, or a green alert.

In order to account for tsunamis, if the earthquake occurs under water the alert score is set to 2 (Orange) if the earthquake magnitude is above 7 and to 3 (Red) if the magnitude is above 7.5.

Finally, the alert score is transformed into an **alert level** according to the following thresholds:

- **Red**: > 2 – high likelihood of international humanitarian disaster
- **Orange**: > 1 and ≤ 2 – medium likelihood of international humanitarian disaster
- **Green**: ≤ 1 – low likelihood of international humanitarian disaster

This method ensures an appropriate classification of earthquakes. The appropriateness has been assessed in two independent ways. First, a qualitative assessment was done using the satisfaction of the international humanitarian response community with the alert frequency and level. Based on interviews and feedback with OCHA, ECHO and other GDACS users, the current thresholds are satisfactory. Secondly, a quantitative analysis (De Groeve and Eriksson, 2005) of 621 earthquakes causing death in the past 20 years shows that 65% (405/621) were classified correctly, with 7% (41/621) omission errors and 28% (175/621) commission errors. However, the assessment was made using the number of people killed and/or injured by earthquakes, with an arbitrary assignment of alert classes as follows: Green fewer than 10 people killed, Orange fewer than 100 people killed, Red more than 100 people killed. The JRC model does not predict a number of people killed, but the overall humanitarian impact (for which no hard data has been collected to date yet) and therefore this quantitative assessment is limited in value.

TSUNAMIS

Tsunamis are large waves caused by, among other sources, under water earthquakes. They can be local (affecting only the nearest coast) or tele-tsunamis, which affect all land on the ocean's basin (sometimes up to 8000 km far).

[2] Human Development Index, Human Poverty Index, natural disaster prevalence, conflict prevalence, internally displaced persons, refugees, child malnutrition, child mortality and official development aid (see Billing and Siber, 2003).

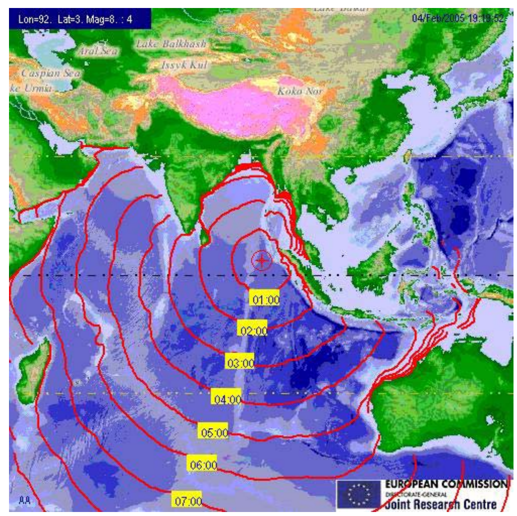
Damage is caused by the huge mass of water behind the initial wave front which floods coastal area destroying building by the speed of the flow.

The actual height of a tsunami wave in open water is often less than one metre. The energy of a tsunami passes through the entire water column to the sea bed, unlike surface waves, which typically reach only down to a depth of several meters. The wave travels across the ocean at speeds from 500 to 1,000 km/h. As the wave approaches land, the sea shallows, with two effects: the wave slows down and the wave-front becomes steeper and taller.

Tsunami models should describe both the propagation and the height of the tsunami waves. While the propagation is relatively well defined with bathymetry and initial conditions, the wave height is dependent on the actual movement of the ocean crust as a result of the earthquake. If there is no vertical movement of the crust, even the strongest earthquake is unlikely to generate a tsunami. So while it is difficult to predict if an earthquake will generate a tsunami, it is easier to predict when it will not: earthquakes with a magnitude below 6.5 Richter are unlikely to generate a tsunami. This logic is captured in the earthquake alert score described earlier in the text.

Asgard propagation model

No complete tsunami model is available in Asgard, but a model for the evaluation of the wave propagation has been implemented. It is triggered by the earthquake module and the results are inserted in the same report. This model, developed by JRC (Annunziato, 2005), determines the propagation time of the tsunami wave starting from the earthquake epicentre. The simulation is based on the shallow water approximation for gravity driven waves. Starting from the literature equation describing the wave propagation velocity in shallow water: $v = \sqrt{gd}$, where v is the wave velocity (m/s), g the gravitational constant (m/s^2) and d is the water depth (m), which is function of the positions (latitude and longitude), a fast running predictive model has been developed, based on the above formula and detailed bathymetry data. The calculation is performed for each angle starting from the epicentre and evaluating, step by step, the local velocity and integrating the velocity to get the wave position. The distance from the epicentre at time T_{req}, is a function of the angle α and can be calculated integrating the above equation:



$$s(\alpha, T_{req}) = \int_0^{T_{req}} \sqrt{g d(s)}\, dt$$

where s is the generic coordinate along a radius starting from the epicentre. The operation is repeated until the required time is elapsed. It is therefore possible to draw iso-time lines, which represent the position of the wave at that time. In order to take into account diffraction the model is applied recalculating at each time the wave position as if each point represent a new wave source. After having imposed an initial front (that could be coincident with a single point, the epicentre, or be elongated along a fault line), the calculation is performed considering a first propagation. Then each point of the front reached in the first step is considered as a new origin for the wave. In such a way it is possible to "round the corner" behind the isles. The model is sensitive to the bathymetry, which therefore has to be specified carefully. As an example a Tsunami initiated in a location where the depth is 200 m can have a completely different propagation time if we move the epicentre in a 1000 m location depth. We are using the ETOPO5 data (NOAA, 1988) with a resolution of 5 minutes, but we intend to improve it with a 2 minute dataset for a better local response. The model was calibrated for the Indian Ocean tsunami using reported arrival times in media and other sources. A visual comparison with other wave propagation models showed a high correlation.

Because of the short running times (less than 1 minute), a tsunami propagation calculation can be performed for each new earthquake (if it occurs in an ocean basin and if the magnitude is greater than 6.5) and the resulting images are including automatically in the Asgard earthquake reports.

TROPICAL CYCLONES

A tropical cyclone is a violent storm originating over tropical or subtropical waters, characterized by violent rainstorms and high-velocity cyclonic winds. It is a low pressure system which derives its energy primarily from evaporation from the sea in presence of high winds and low surface pressure, and condensation in convective clouds concentrated near its centre.

In the northern hemisphere, tropical cyclone winds move in a counter-clockwise spiral around a relatively calm and dry centre known as the “eye”. Assuming that the tropical cyclone is moving in a northerly direction, the region of the highest wind speeds is directly to the east of the eye. The wind speed decreases with the distance from the eye.

Tropical cyclones on the open sea cause high winds, heavy rain, and large waves. However, the most devastating effects of tropical cyclones occur when they cross coastlines, resulting in landfall effects. A tropical cyclone moving over land can produce direct damage through wind damage (typically with sustained winds in excess of 115 mph, or Category 3 of Saffir-Simpson scale) and flood damage. Floods are cause by storm surge (an abnormal rise in the water level caused by the wind and pressure forces of a tropical cyclone) or heavy rain (flooding rivers and streams). Storm surge produces most of the flood damage and drownings associated with either the storms that make landfall or the ones that closely approach the coastline. The storm surge is considered to be the most dangerous tropical cyclone hazard, as nine out of ten hurricane-related deaths are caused by drowning.

While several numerical, statistical or empirical models exist to model surge and rainfall, few are valid on a global level. Moreover, these models need precise coastal bathymetry and elevation data, rainfall measurements and other data that are not generally available on a global level. Furthermore, it has to be argued that flood and wind damage mostly occurs in the same areas: the areas affected close to the storm eye. Therefore, JRC currently only models the wind speed due to the lack of available real-time data and models.

Asgard tropical cyclone model

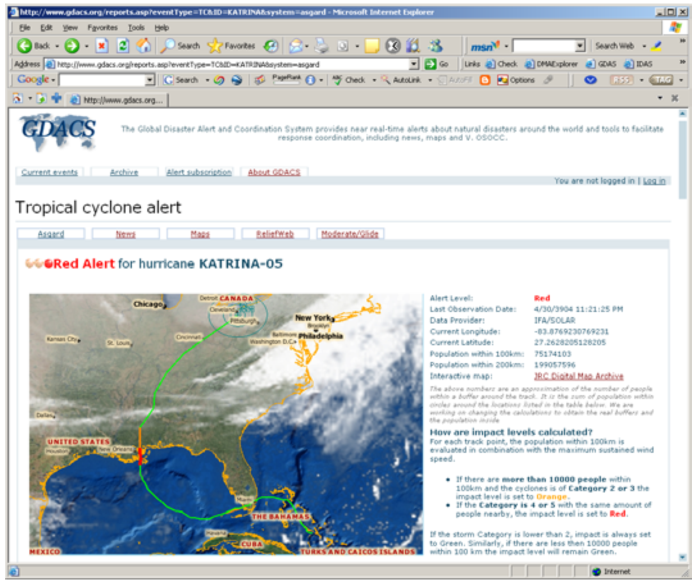
JRC has been using a simple circle model in the past few years. The affected area of the tropical storm is considered to be a circular area of 100km or 200km around the storm’s eye. While this simple approach was able to predict the impact to a certain extent, we have now moved to a more complex model that considers the wind field of the whole cyclone track. From the tracks of cyclones, the area affected by high wind speeds can be modelled taking into account central pressure, winds speed and other variables. In order to transform tracks of cyclones into wind speed surfaces our system uses a model developed by Holland (1980) and further adapted by UNEP/GRID-Geneva (Mouton and Nordbeck, 2005). For this model the following assumptions are made: the cyclone is over the ocean; the eye of the cyclone is stationary; and the surrounding winds follow a three-dimensional symmetry around a vertical axis (axisymmetric winds). The tropical cyclone surface wind field is then given by the following equation:

$$V_h(R) = \sqrt{\frac{b}{\rho} \cdot \left(\frac{R_{\max}}{R}\right)^b \cdot \left(P_{env} - P_{centre}\right) \cdot e^{-\left(R\max/R\right)^b} + \frac{R^2 f^2}{4}} - \frac{Rf}{2}$$

Where:

$V_h(R)$: Gradient wind speed at distance R from the eye (in m/s)
b: parameter that changes the shape of the radial profile
P_{centre}: Central pressure (in Pa)
P_{env}: The asymptotic environmental pressure (in Pa)
R_{max}: The radius of maximum winds (in meters) as can be seen on the curve below
R: The radius where wind speed is $V_h(R)$ (in meters)
ρ: The air density, assumed constant =1.15 kg m^{-3}
f: The Coriolis parameter =2(Earth's angular velocity)*sin(latitude) where the Earth angular velocity equals 0.0000729 radians/s.*

The pressure and wind centres do not normally coincide, and are not necessarily at the geographical centre of the hurricane eye. In fact, the wind field in tropical cyclones is rarely, if ever, symmetric. Asymmetries arise from a range of processes, including cyclone movement and external influences from surrounding weather systems. The only asymmetrical processes included in the current wind model are those arising from cyclone movement, by simply adding the translational vector to the wind field. This results in a net inflow behind the cyclone (outflow ahead), and a maximum wind on the cyclone's right hand side in the Northern Hemisphere, and on the left side in the Southern Hemisphere (Holland G.J., 1997). In practice the eye's speed intensity and direction are estimated by using the time between consecutive positions of the cyclone's eye.



In order to estimate wind speed buffers along the whole track, the first step is to calculate the wind speed profile at a certain time (corresponding to a certain position of the cyclone's eye), according to Holland's equation. The transversal buffers limits R_1 and R_2, are the right and left intervals on the line perpendicular to the track (and going through the cyclone's eye), where the wind intensity is greater than a fixed wind speed threshold V_{crit}, where V_{crit} varies according to the Saffir-Simpson (S-S) hurricane scale. These points are then connected to create a polygon of equal wind speed.

At the time of writing the described model is not yet used to produce Asgard alerts. Instead, the circle model is used and the alert level is then set using the following data: (1) hurricane magnitude (in the Saffir-Simpson (S-S) hurricane scale); and (2) population within 100km of cyclone's eye. Element 1 is scraped from specialised Meteorological Centres sources, while element 2 is automatically calculated by a GIS based on cyclone's eye location (latitude and longitude) and the Landscan 2003 population dataset. The **alert level** is established according to the following criteria: if less than 10000 people are within 100km, the alert level is set to Green; otherwise, the alert level is set to Orange is the Saffir-Simpson Category is 2 or 3 and it is set to Red if the SS Category is 4 or more.

In order to take into account the country vulnerability future work will cluster countries in high and medium vulnerable countries based on previous disasters. Early evidence (Landsea, 1999) indicates towards the use of wind speed buffer related to the S-S categories 3 to 5 for estimating the population affected in the countries with low vulnerability level (i.e. USA, Japan), and the S-S categories 1 to 5 for the countries with a high vulnerability score (i.e. Honduras, Guatemala).

The performance of the tropical cyclone alert tool was compared with a historical database of casualties (EM-DAT, 2005). If *casualties* are defined as (10 * number of dead) + number of injured, and alert classes are arbitrarily defined as Green < 100 casualties, Orange 100 to 1000 casualties and Red more than 1000 casualties, the following table summarizes the behaviour of actual Alert score model.

Table 2: Classification Error Table.

Alert level based on reported casualties	**Predicted alert score**		
	Green	**Orange**	**Red**
Green (24)	19	4	1
Orange (30)	13	10	7
Red (7)	2	2	3
Total (61)	**34**	**16**	**11**

Percentage correct: 52% (32/61), Omission: 28% (17/61), Commission: 20% (12/61)

The percentage correct is reasonable (more than 50%), but both the omission and the commission are high. In particular for Red alert the omission is high (57%). However, in most cases the omitted tropical cyclones were classified in lower classes because casualties were caused by phenomenon related to the cyclone such as heavy rain which the Asgard model does not take into account.

Table 3: Red alert omission.

Name	Countries	S-S Cat.	Dead	Injured	Casualties	Real Class	Assigned Class	Reported cause for casualties
Stan	Guatemala	1	1607	386	16456	Red	Green	Heavy rain
Muifa	Philippine	3	160	240	1840	Red	Green	Heavy rain
Talim	China	4	162	59	1679	Red	Orange	Floods and landslides
Damrey	Vietnam	2	110	28	1128	Red	Orange	Heavy rain

CONCLUSIONS

The disasters impact models described in this paper are used to generate fast and reliable alerts on the occurrences of earthquakes and tropical cyclones that require humanitarian intervention. These alerts have been consistently produced for 3 years and have helped the humanitarian aid community to act faster on earthquake disasters and prepare better for tropical cyclone disasters.

Even if the performance of the models is satisfactory at this stage, many improvements are possible. A better population dataset can improve the accuracy of the impact models significantly. The current global population dataset offers an estimate of the number of people living in every square kilometre of the earth's surface. No information about the distribution of the population related to the day time is included. Furthermore, better estimation of population vulnerability and coping capacity is essential. More than the "magnitude" of the disasters, it is the vulnerability of the population, the quality of their dwellings and the coping capacity of individuals, the society and the government that determines if a natural hazard event turns into a disaster. Better data is necessary to improve impact modelling.

For each disaster type, further modelling of the physical process will improve accuracy. JRC is currently working on a wave height model for tsunamis, integrating the variable radius affected area (Bolt *et al.*, 1975) for earthquakes and the wind speed profiles for tropical cyclones. With regards to tropical cyclones, although storm surge and high winds occur mostly in the same areas, detailed modelling of the storm surge is essential to improve alert accuracy since it accounts for 90% of tropical cyclone casualties. Moreover, existing products such as the USGS ShakeMaps should be integrated in the impact models. For coastal hazard such as tsunamis and tropical cyclones, a focus on coastal population and vulnerability – e.g. the population living below a defined elevation – can contribute significantly to better results..

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APPENDIX – DATA SOURCES

Significant earthquakes around the world are felt by seismological stations around the world. Many of these stations record earthquakes systematically and calculate and publish some physical parameters automatically on a web site. The information needed to perform an evaluation is: geographic location of the event as latitude and longitude; the magnitude in Richter scale; the depth. In order to ensure robust information gathering, Asgard collects information every 5 minutes from the following sources:

- United States Geological Survey National Earthquake Information Center (NEIC) (http://neic.usgs.gov/).
- European-Mediterranean Seismological Centre (EMSC) (http://www.emsc-csem.org/).
- GEOFON Programme of the GFZ Potsdam (http://www.gfz-potsdam.de/geofon/).
- French Réseau National de Surveillance Sismique (RENASS) (http://renass.u-strasbg.fr/).

The observations of tropical cyclones worldwide are carried out by the different Regional Specialised Meteorological Centres (RSMCs) together with six Tropical Cyclone Warning Centres (TCWCs) of World Meteorological Organisation. The different observation centres are well coordinated and they keep the first level basic meteorological information (chronological data about the geographic localisation of the cyclones and their intensity) updated on all the global tropical cyclones events. This collaboration gives a broad range of global cyclone data, but the range of reported data imply problems due to differences in data structure.

However, other sources are available for aggregated data on a global level. Asgard collects information every 10 minutes from the following source: **Hawaii University IFA/SOLAR**. Tropical storm forecasts are automatically updated every 3 hours (with increased frequency when the coastal zone is reached) from advisories received from the National Hurricane Center, the Central Pacific Hurricane Center, and the Joint Typhoon Warning Center.

The data that we use for running the model are: the successive positions of cyclone's eye; corresponding central pressure; and maximum observed sustained wind speed.