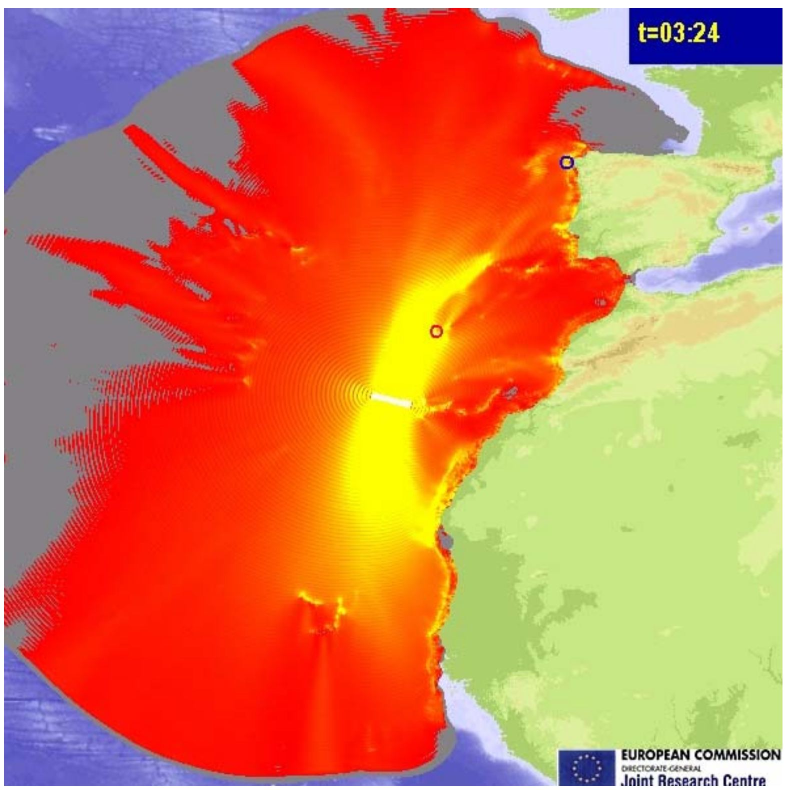
JRC Scientific and Technical Reports

The JRC Tsunami Assessment Modelling System

A. Annunziato



EUR 23063 EN - 2007

JRC EUROPEAN COMMISSION

Institute for the Protection and Security of the Citizen

The Institute for the Protection and Security of the Citizen provides research-based, systems-oriented support to EU policies so as to protect the citizen against economic and technological risk. The Institute maintains and develops its expertise and networks in information, communication, space and engineering technologies in support of its mission. The strong cross-fertilisation between its nuclear and non-nuclear activities strengthens the expertise it can bring to the benefit of customers in both domains.

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
Address: Via Fermi 1
E-mail: alessandro.annunziato@jrc.it
Tel.: +39 0332 789519
Fax: +39 0332 785584

http://ipsc.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

JRC41997

EUR 23063 EN
ISSN 1018-5593

Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

Table of Content

1 Introduction 4
2 The JRC Tsunami Assessment Tool 5
2.1 Fault length.... 5
2.2 Water level increase at epicenter.... 6
2.3 Fault direction 9
2.4 Calculation space initialization 10
2.5 Tsunami propagation.... 11
2.5.1 Generals.... 11
2.5.2 Shallow water propagation model.... 12
2.6 Identification of relevant locations.... 13
2.7 The JRC-SWAN interface.... 13
3 Calculations execution 16
3.1 Automatic calculations.... 16
3.2 Calculations Refinement 20
4 Actuations of the JRC Tsunami Assessment Tool 23
4.1 Kuril Island event, 15/11/2006.... 24
4.2 Solomon Island Event 26
5 Pre-calculations or On-line calculations ?.... 29
6 Future developments 31
7 Conclusions 34
8 References 35

Appendix A - Example of call and response of the JRC Tsunami Tool 36
Appendix B - Travel Time Model.... 37
Appendix D – Kuril Island Event Report.... 39
Appendix E - Detailed Timeline for the Kuril Island Event 47
Appendix F - Solomon Island Event Report 48
Appendix G - Detailed Timeline and PTWS Bulletins for Solomon Islands Event 52

1 Introduction

As a consequence of the 26th December Tsunami the European Commission JRC developed a model for the evaluation of the wave propagation time of hypothetical Tsunamis. This model [1], connected with an automatic earthquake data collection system, allows the prediction in real time of the propagation time of a tsunami wave. The model, active since March 2005, allowed to predict the behaviour of all the recent Tsunami occurred after its starting date. The model has also been included in the Global Disaster Alerts and Coordination System [2] (GDACS) to anticipate the wave arrival time in the case of an earthquake with the potential to result in a tsunami. Alerts via SMS, email and fax are sent by this system to registered users.

However that model is only able to predict the time at which the Tsunami wave arrives on the coast, but it is unable to predict the Tsunami height. The objective of the current report is the presentation of a new Tsunami model which can be integrated with the existing early warning software which can calculate the tsunami height.

When an earthquake occurs and generates a Tsunami the following mechanisms are occurring:

1. subsidence faults movements can result in rising part of the earth and lowering the opposite section (a seismic horizontal movement does not generally determines a Tsunami)
2. the water above the fault rises of the same quantity (slip)
3. a pulse wave is generated
4. the wave may travel thousands of km in the ocean reducing its height due to energy distribution on a larger surface. Focusing mechanisms, due to reflections of the bathymetry or of the coasts may influence the wave height.
5. an increase of the height (shoaling effect) and a reduction in width and speed occurs as the tsunami approaches the shore

The Tsunami wave prediction can be performed according to the following:

a) evaluate the earth deformation caused by the earthquake and impose an initial water displacement as initial condition of the calculation
b) calculate water wave movement
c) evaluate the run-up and estimate the impact to the coast

Our objective has been to create fast running models to be used in early warning systems, by making, when possible, simplifications in order to keep the overall running time as minimum as possible.

This report describes the JRC Tsunami Assessment Tool, which is a complex computer arrangement whose objective is to predict a Tsunami's behaviour when minimal parameters are known, which is the condition when an earthquake is firstly measured. Therefore knowing the position of the earthquake (lat/lon) and the Magnitude of the event, the programme will calculate the fault characteristics, the Tsunami generation and displacement, and the identification of the location on the coast which will be most likely affected.

2 The JRC Tsunami Assessment System

The JRC Tsunami Assessment System integrates in a single programme several components that are needed in order to fully evaluate the Tsunami as a consequence of an earthquake event.

The JRC-SWAN programme evaluates the fault length, height and direction (which will influence the initial water displacement), initializes the calculation space, performs the travel time propagation calculation, verifies at each step if there are locations reached by the wave, updates the visualization and animation files. The programme can run in manual interactive mode and in automatic standby mode.

2.1 Fault length

The analysis of past earthquakes indicates that it is possible to recognize a relation between the fault length and the magnitude of the earthquake, as indicates the figure below [3].

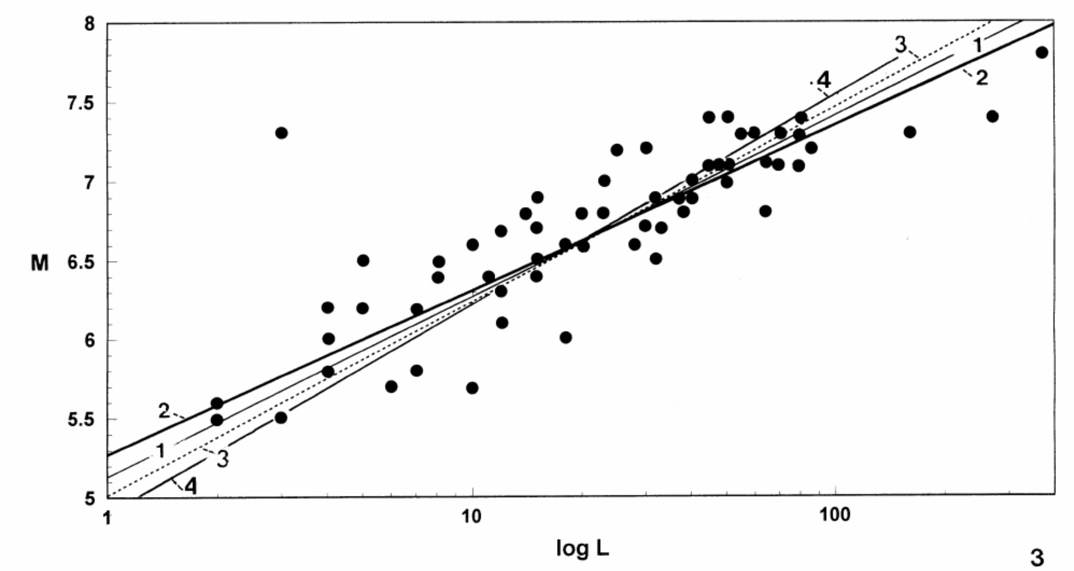


Fig. 1 – Relation between fault length and magnitude

Several interpolation models exist for the evaluation of the fault length. Most of these models are of the following form:

Log (L) = A Mw + B

With L length in km, Mw is the earthquake magnitude and A and B two constants which determine the length of the fault. These constants are extremely sensitive because solving the above equation, the length has the expression on the right as an exponent of 10.

Taking, as an example [3] A=0.82 and B=-4.09, it is possible to see that

Mw=9 > L=1938 km

Reducing the Magnitude to 8.5 the length becomes 758 km.

In the Sumatra case (8.9), the Length of the fault was about 1000 km, So the above equation can be a good starting point for the evaluation of the fault length.

In the following we will adopt the formulation by Ward [4], with A=0.5 and B=-1.8, which gives a value of 501 with a magnitude of 9. The two models become equal for a magnitude about 7.

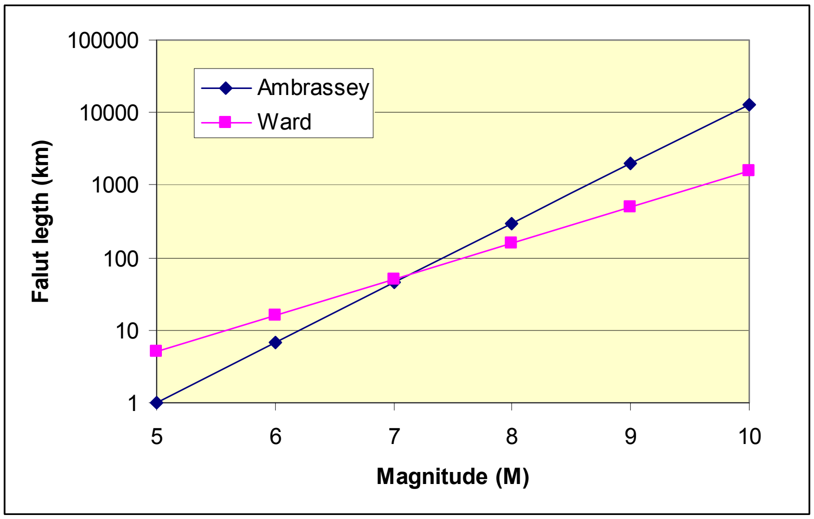


Fig. 2 - Relation between magnitude and fault length: comparison of two models

Above magnitude 7 they can represent a maximum and minimum fault size.

The knowledge of the fault length allows the avoidance to consider a point source. In the case of the 26 December 2004 Tsunami, this had a great influence because the calculations performed with the earthquake epicenter were very different from the real case in which a 1000 km fault caused a concentrated behavior and different travel times.

2.2 Water level increase at epicenter

As the earth is moving by L, determined in
the previous subchapter, an increase of the water level occurs. The level increase is proportional to the fault length. Ward proposes a simple expression for the water level increase (slip) as Du=2 10^{-5} L, with Du in km, multiplied by 1000 to have it in m.

Mw	L (km)	W (km)	Du (m)
6.5	28	8	0.56
7	50	14	1.00
7.5	89	25	1.78
8	158	44	3.17
8.5	282	79	5.64
9	501	140	10.02
9.5	891	250	17.83
10	1585	444	31.70

This means that a 9 magnitude earthquake determines an increase of 10 m in the water level.

When the water rises by x m, it is possible to have different patterns:

- part of the water rises and part decreases
- the water increases in all directions of the same quantity (full rise)

The longitudinal water distribution can be
- follows a regular pattern (cosinus)
- have a flat pattern

Any of this type of initial condition will create a different wave pattern in terms of form of the wave. Applications of different initial conditions will be presented in the next chapters.

In order to compare the different types of initial conditions an equivalent amount of water is considered to be moving each time.

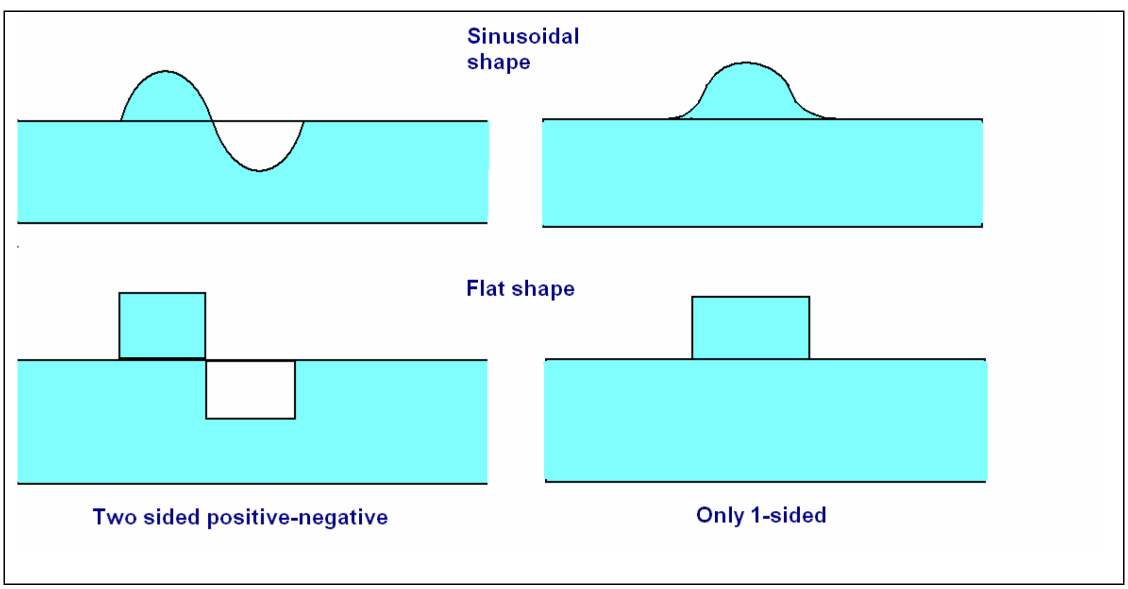


Fig. 3 – Water initial conditions

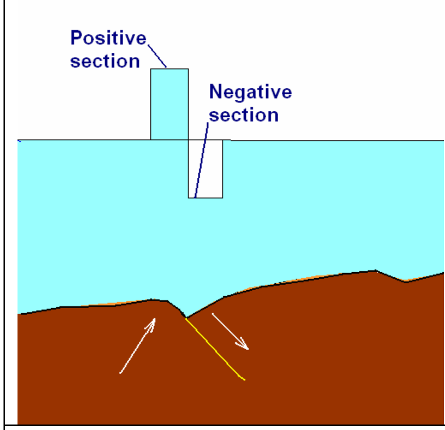
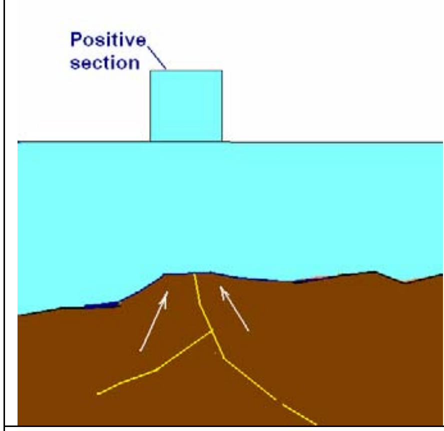
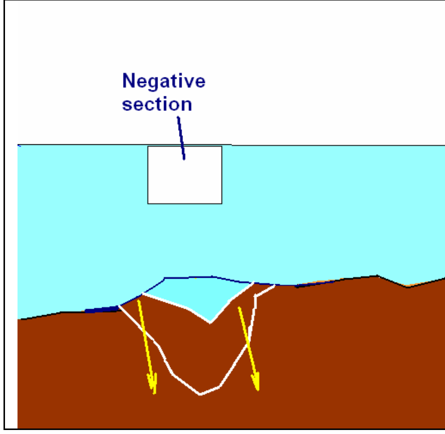
	There are two sections, one positive, one negative, caused by the insertion of one section under another (subduction). Typical of this type is the subduction zone in Indonesia, where the 2004 Tsunami occurred. The positive or the negative sections can be in opposite (positive on the right).
	Only a positive section exists. This is due to the contact of two plates moving against each other.
	Collapse of an underwater volcano may result in an initial negative section

Fig. 4 – Different types of wave initial condition

2.3 Fault direction

The earthquake faults generally occur following existing faults directions which identify the Tectonic Plates. The known faults lines are indicated in Fig. 5.

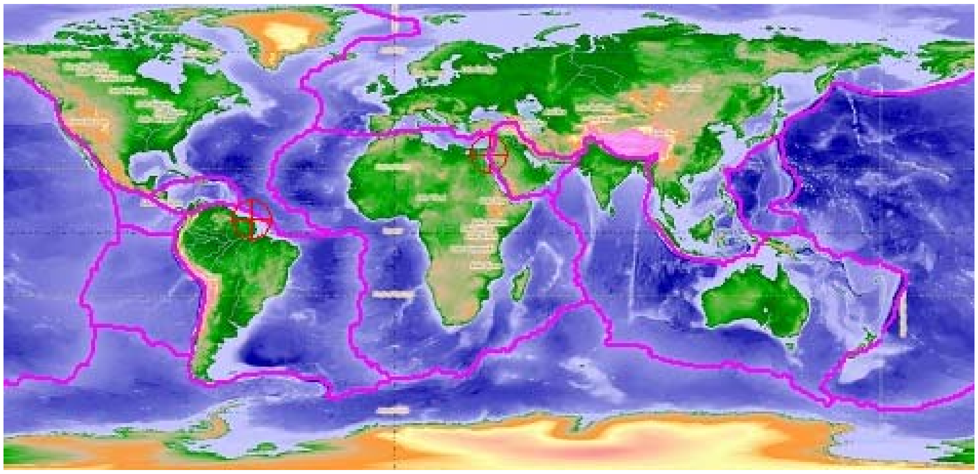


Fig. 5- Tectonic plates and major fault lines

When an earthquake occurs at a generic location X,Y the programme searches the closer fault line and assigns the fault direction as parallel to that fault line.

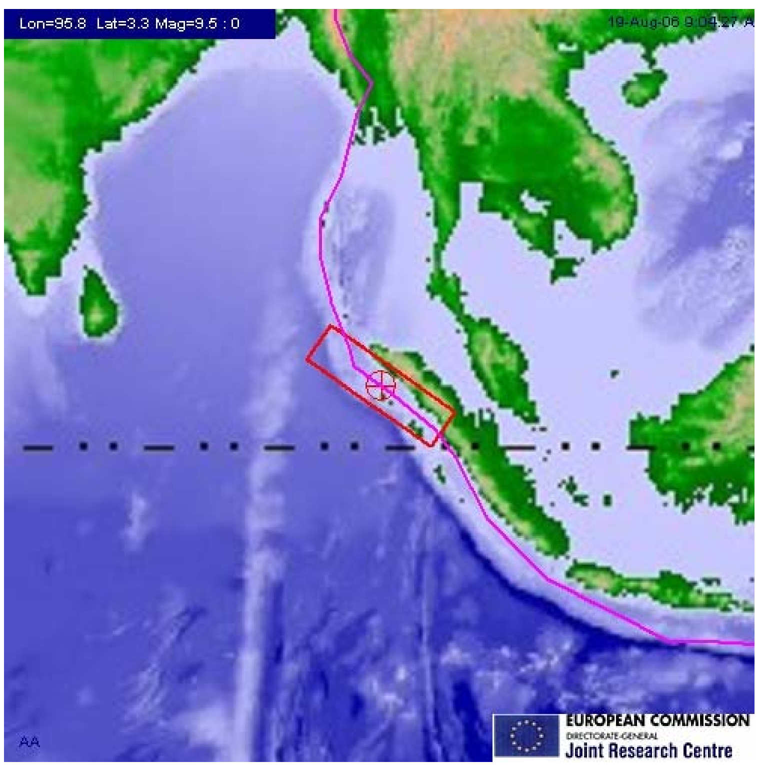


Fig. 6 - Creation of the fault direction and width

In some cases this choice may lead to errors in the correct identification of the fault location. In the case of the Tsunami in the Indian Ocean for instance, the epicenter was in the lower part of the fault and the fault was extending about 1000 km in the north, due to a progressive rupture. This method would instead position the fault symmetrically respect to the epicenter; as a first approximation it may be acceptable. Shortly after the event, there is no other available information to judge the correct position of the fault.

2.4 Calculation space initialization

The base bathymetry is the 2 min dataset, known as ETOPO-2. In some areas however the bathymetry has been improved, as in the Caspian Sea, where very coarse data were present.

The programme redefines the bathymetry according to the required cell size. If the required cell size is smaller than 2 min (about 220 km) the new bathymetry is obtained creating a new grid and interpolating each point using the 4 adjacent data points. If the cell size is greater than 2 min the same procedure is used, even if, most probably a better solution would be a surface interpolation and averaging.

In case an automatic calculation is performed, the programme selects a bathymetry size according to the following logic:

1. determination of the fault width and length, as indicated in chapter Fault length2.1
2. evaluation of the maximum cell size, considering that the minimum size (width) has to be represented at least by 10 cells. The width of the calculation as 5 times the fault length but limited to have a maximum grid of 600x600 and thus accordingly determined
3. evaluation of the depth at the epicenter and calculation of the wave velocity
4. determination of the maximum calculation time considering the wave velocity and the assumed with size

Example: M 7.5 earthquake

Fault length=89 km
Fault width=24 km
Max cell size= 24 * 180 * 60 / (10 * 3.1415 * radius) = 1.30 min

[earth radius=6340 km]

WidthMax=1.1 Max(5 * FaultLenght* 180 / (radius * 3.1415), batmax / 60 * 300)
=1.1 max(4,6.6) = 7.26 min = 800 km

Assuming a depth of 1460 m, the wave velocity is 431 km/h, thus the maximum calculation time is

T= 800/431=1.9 = 1 h 54 min

If the depth is lower, 500 m, the velocity is lower, 252 km/h and thus the calculation time longer, 3h 18 min.

Therefore the cell size depends strongly on the magnitude of the earthquake. The greater the magnitude the greater is the cell size and the calculation domain size.

2.5 Tsunami propagation

2.5.1 Generals

The dynamic of the Tsunami propagation in the ocean has already been included in the model in terms of wave speed and timing. It is now interesting to evaluate how the initial height of the Tsunami reduces as it propagates in the ocean.

If a Tsunami of initial height H_o propagates from a point source and a constant water depth is considered, the wave amplitude at distance R is proportional to the inverse of the distance and proportional to the initial height

$$H \propto H_o R^{-1}$$

This means that the height cannot be higher than the initial height and reduces along the distance.

Taking into account the motion equations it is possible to see that the height is initially proportional to a value between 0.5 and 1 (Ward).

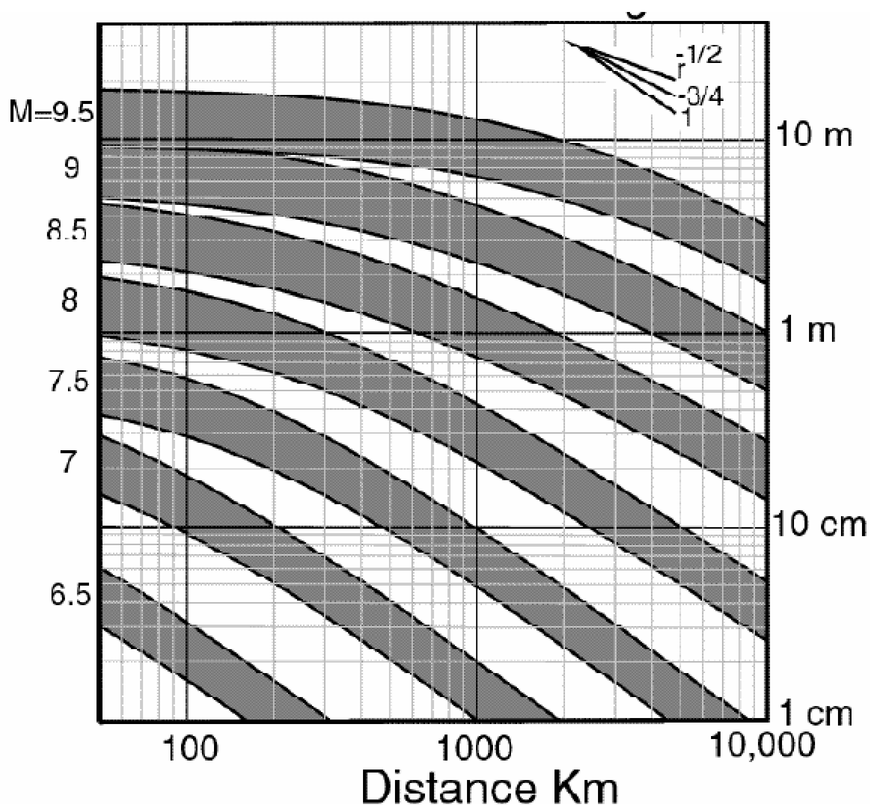


Fig. 7 – Relation between magnitude and height at various distances

In theory using the above correlations to express the wave height reduction as the Tsunami propagates in the ocean.

However after some attempts to use easy relations as the one above as connected with the wave propagation model, it has been decided to use the complete shallow water equations because there are so many different situations that it is not possible to consider all the variations. A typical example is an isle around which the wave is propagating and in which the term “distance from the epicenter” loses its meaning because is the distance in straight line or the distance along the path ?

2.5.2 Travel Time Propagation model

The travel time propagation model is based on the integration of the wave propagation velocity along radial directions starting from the contour of the prospected fault line. It runs quickly (less than 30 sec) and allows a first estimate of the time available for any recovery action. The details of this model are present in

The model is independent of the magnitude since only the wave propagation velocity is calculated. However an estimate of the Tsunami probability needs to account for the magnitude, the position of the fault, the earthquake depth, the local history etc. A risk analysis based on historical earthquake driven Tsunamis, their associated earthquake magnitudes, depths and sheer moments is currently underway. The aim is to associate a numerical estimate of the Tsunami probability to first reported earthquake data..

2.5.3 Shallow water propagation model

In order to express the Tsunami propagation it is possible to use the shallow water equations in the form proposed by C. Mader coded into the SWAN code.

The model uses the mass and momentum conservation equations in 2 dimensions, with the approximation of constant velocity along the height. This theory is valid when the ratio wave length over the water depth is low. Therefore for Tsunami calculations, considering about 4000 m as maximum depth, when the wave length is several times the depth (i.e. 10 times) so when the wave length is greater than 40 km.

Mass conservation equation

$$\frac{\partial H}{\partial t} + \frac{\partial\left[(D+H)U_x\right]}{\partial x} + \frac{\partial\left[(D+H)U_y\right]}{\partial y} = 0 \qquad (1)$$

Momentum conservation

$$\begin{aligned} \frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_y}{\partial y} - FU_y + g\frac{\partial H}{\partial x} &= -\frac{1}{\rho}\frac{\partial P}{\partial x} + A^{(x)} \\ \frac{\partial U_y}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_y}{\partial y} + FU_x + g\frac{\partial H}{\partial y} &= -\frac{1}{\rho}\frac{\partial P}{\partial y} + A^{(y)} \end{aligned} \qquad (2)$$

Where D is the water depth (under water is positive depth, mountains are negative depths), H is the local water level, U_x and U_y are the velocities in the two directions, P is the pressure derivative, which is express as water level difference, and A contain tide generating forces.

The above equations are integrated over control volumes and finite difference equations are obtained. The original code by Mader in Fortran Language has been rewritten in C and connected with a Visual Basic driver into the SWAN-JRC code.

The integration grid is obtained by the available bathymetry. Typically a Tsunami propagation analysis is performed with a bathymetry grid of 20 min (36 km at the equator); local analyses are calculated with 2 min (3.6 km). Run-up calculations, to evaluate the flooding extent, need to be performed with even higher resolutions (i.e. 150-200 m, or 4.5 to 6 sec).

2.6 Identification of relevant locations

In order to identify if a location is stuck or not by a tsunami wave and with which height the following procedure is adopted. At each calculation time step a check of every point of the calculation grid is performed. If the height of the wave is greater than 80% of the depth (h/d>0.8) or if the height is positive and the depth positive (water on the earth), a check is performed of all the locations at a distance of 5 km from the grid center. These locations are assigned the wave height calculated for that cell. The procedure is repeated for each calculation cell.

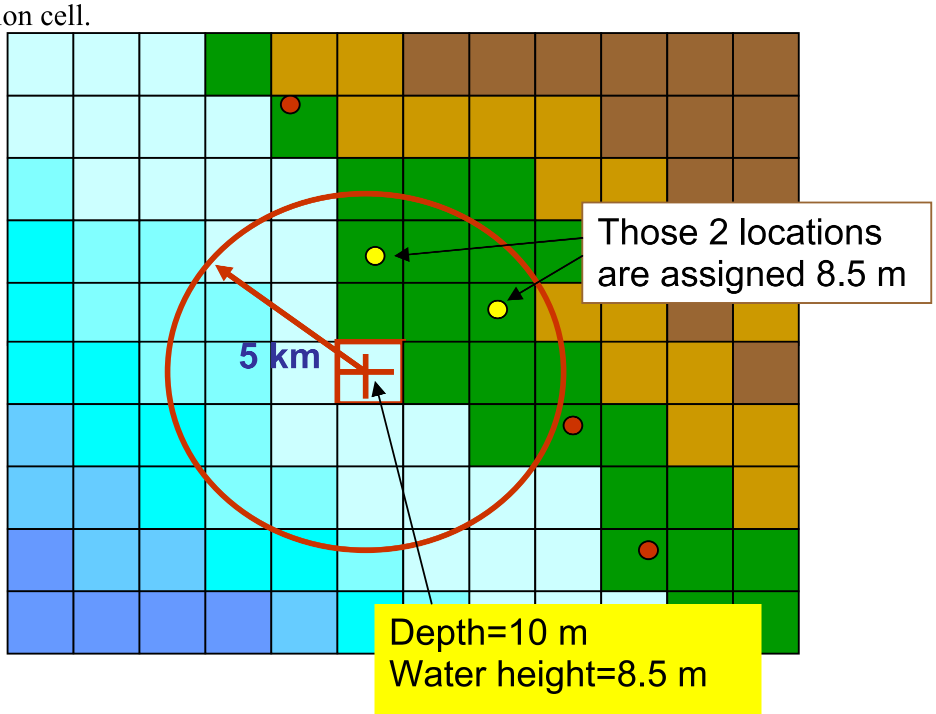


Fig. 8 – Identification of locations

The database for identifying the locations includes about 700 thousands cities around the world.

2.7 The JRC-SWAN interface

Very often the difficulty to use some computer programmes is represented by the user interface which is difficult to use and not easy to perform several sensitivity analyses.

In order to make the programme user friendly a user interface has been developed. This is in the form of a Windows programme which allows to establish and change all the initial conditions. It is also possible to change the form of the fault and its shape.

The programme con work in manual mode or in automatic mode. When in automatic mode, it continuously checks if a new calculation is to be done. If yes it initializes autonomously and produces output files, animation files and presentation files so that are directly published in internet with no human intervention.

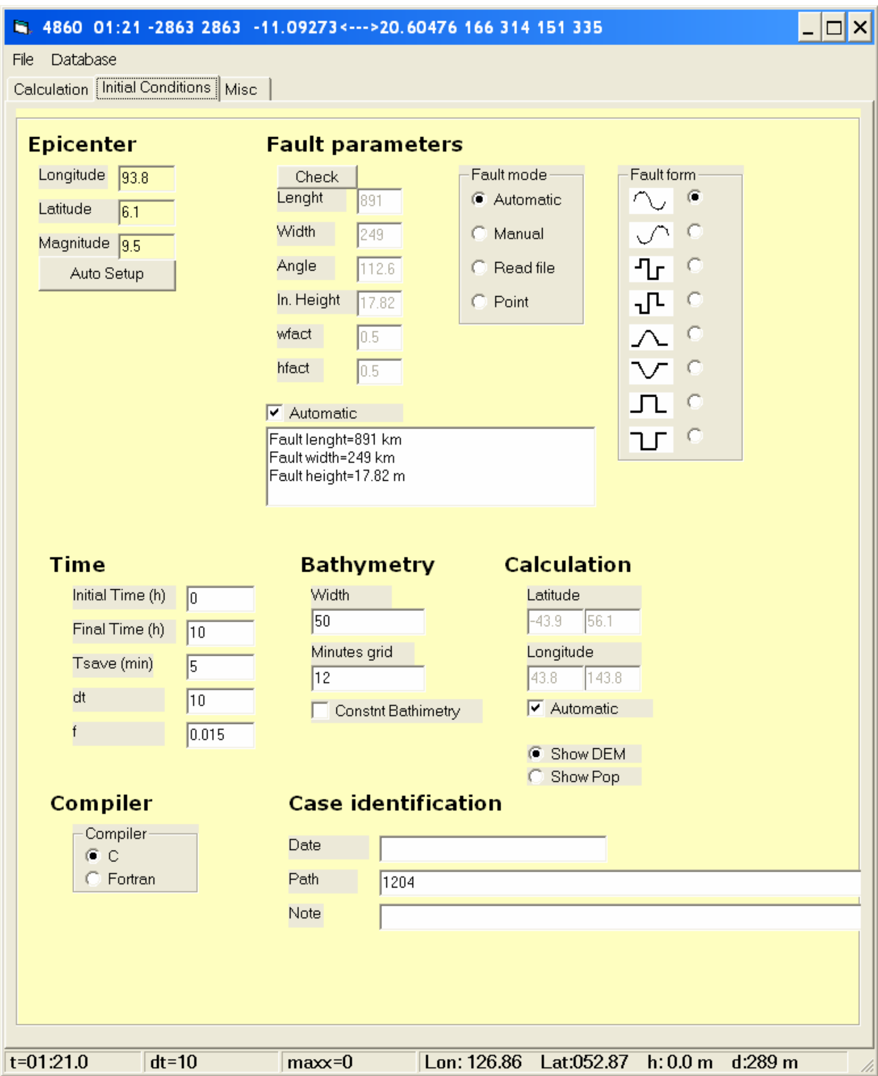


Fig. 9 -User interface to establish the initial conditions of the calculations

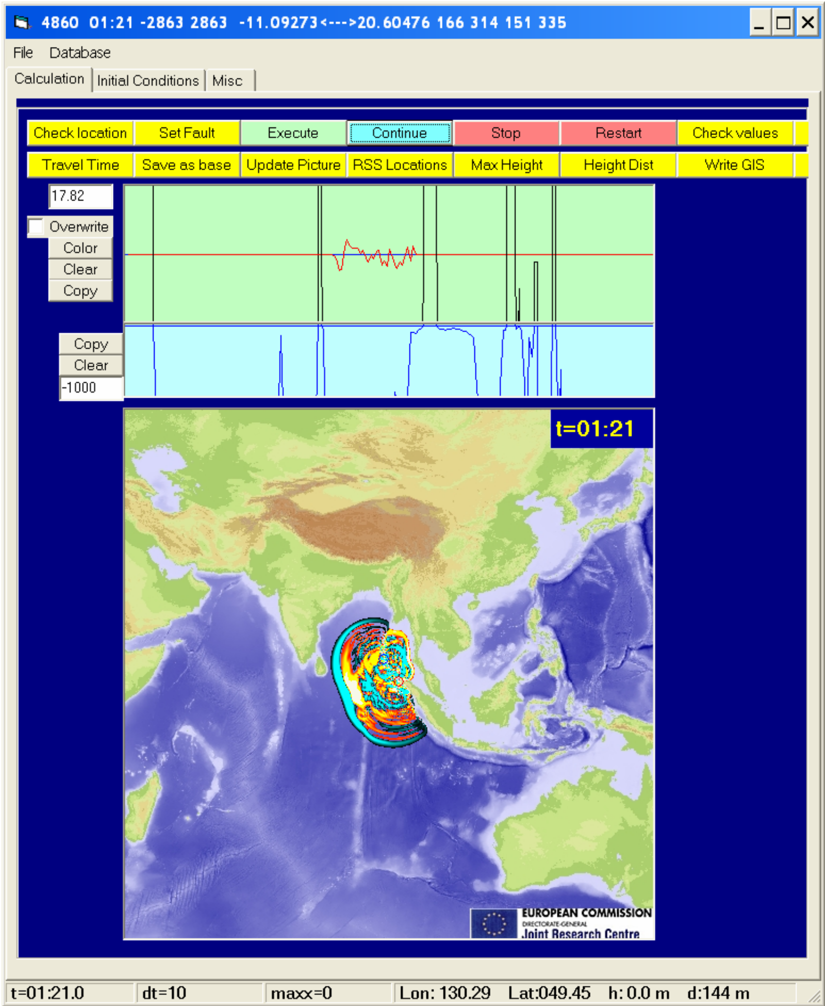


Fig. 10 – Calculation output window

3 Calculations execution

3.1 Automatic calculations

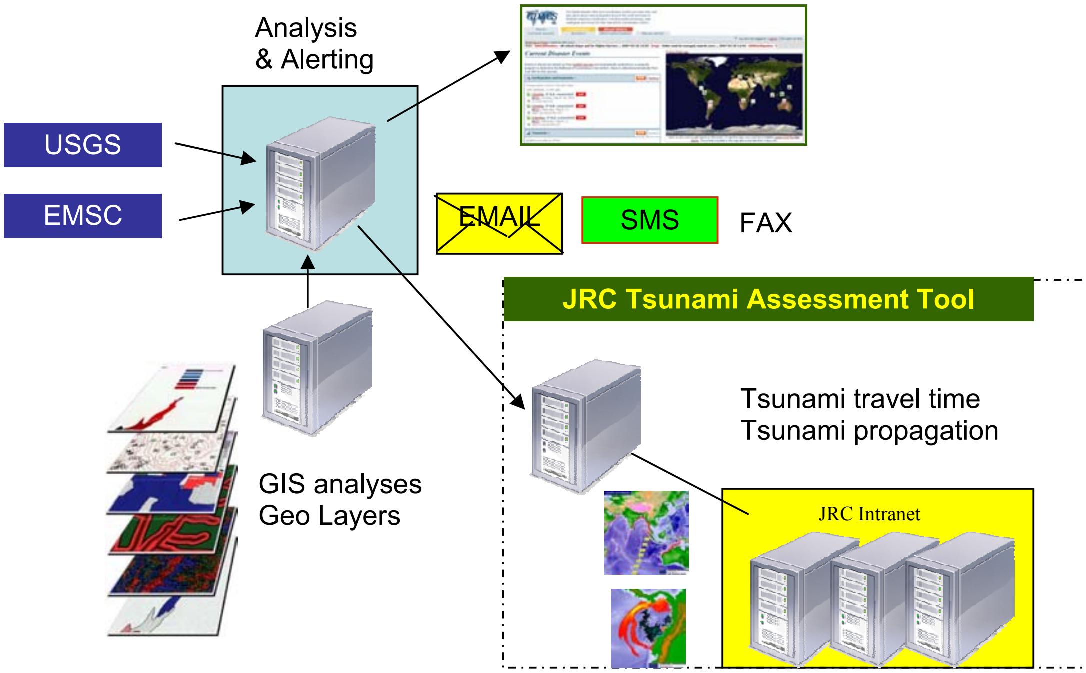


Fig. 11 – Architecture of the Global Disasters Alerts and Coordination System and relation with the Tsunami Assessment Tool

The JRC Tsunami assessment tool is part of the Global Disasters Alerts and Coordination System (GDACS), a joint United Nations (OCHA) and Commission (ECHO, ENV, JRC) system. GDACS does not make physical observation (like deep sea observations or seismographs). Instead, it picks up such information from seismological organizations, through web protocols and performs additional processing such as overlaying information with population density. GDACS aims at controlling the information flow after the disaster, including fast alerts, updated news, satellite maps and needs and relief related information.

When a new event is detected by the seismological sources (USGS, EMSC), an evaluation of the event is performed to estimate the importance of the event from humanitarian point of view. If the event is relevant automatically the system sends out alerts (email, SMS, fax) to the registered users. The information is published on the GDACS web site in real time.

In the case of an earthquake event occurring under water and of magnitude greater than 6.5, the JRC Tsunami Assessment Tool is invoked and a new calculation is requested. The current arrangement foresees 1 collection server in the DMZ zone which can serve the calculations input/output in internet and 3 execution server in the JRC intranet. When a new calculation is to be performed one of the 3 servers picks up the required initial conditions and begins the calculation. In the meantime the other 2 servers are in standby, waiting for additional requests.

The reasons for multiple execution servers are the following:

1. possibility that two events occurs at very short time interval each other and a new calculation is required (on 25/3/2007 two earthquakes in Vanuatu and Japan occurred at 1 min each other).
2. often events are redefined in terms of position or magnitude and therefore a new calculation should be performed
3. possibility to perform systematic calculations within a range

The calculations are all stored in a database and a file system. This means that if a new calculation is requested with the same parameters of one already present in the database this calculation is offered by the system as result of the analysis. The current settings is that a new calculation is performed if the difference in latitude or longitude or magnitude is greater than 0.1 (degrees or Richer scale value). This is a quite stringent requirement but it allows to have exactly the right calculation for the requested case.

The system works with the method of the web service. It means that if a system (GDACS or any other client) needs a calculation for a certain location (latitude/longitude 28.86/-19.73, magnitude 8.2), it has to perform a call to a specific internet address such as:

http:// cmd.asp?CMD=SET_CALC&eqid=LP001&evDate=01/12/2007
&**mag=8.2**&**lat=28.86**&**lon=-19.73**&location=off-shore Canary Islands&Client=Manual

The system will respond with an xml file containing several information including:

- the initial conditions of the fault (length, width, orientation, height)
- the output parameters:
  - travel time image
  - locations where to find the output images and files
  - list of locations affected

Appendix A reports the complete file in answer to the indicated request. If the required calculation is already present in the database the stored calculation is offered to the user; if not a new calculation is performed.

Soon after the receipt of the request one of the execution servers will start the job and the calculation initiated. About every 5 minutes, updates of the running calculation are published at the internet location indicated. The following figure represents the update after 11 min of calculation time. It is possible to note the indication of the locations with the predicted height at each location and the time of the maximum height and the height

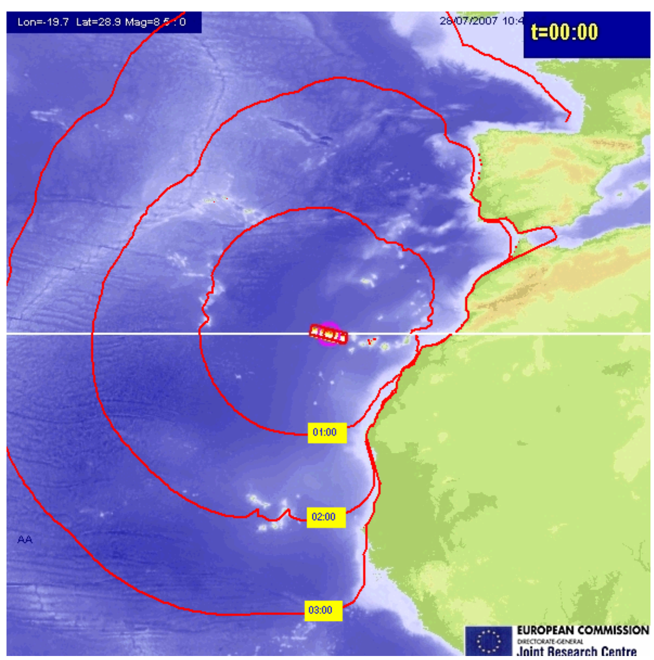


Fig. 12 – Travel time image calculated for the Canary Island case

distribution.

A typical calculation takes about 30 minutes to be completed. However the closer the location, the quicker it appears in the updated page. So, for instance in the case considered above, the location San Sebastian de a Gomera, which is reached in 20 minutes the evaluation takes less than 1 minute; San Pedro da Cadeira (Portugal), reached at 2h 36’, is shown after 10 minutes of calculation.

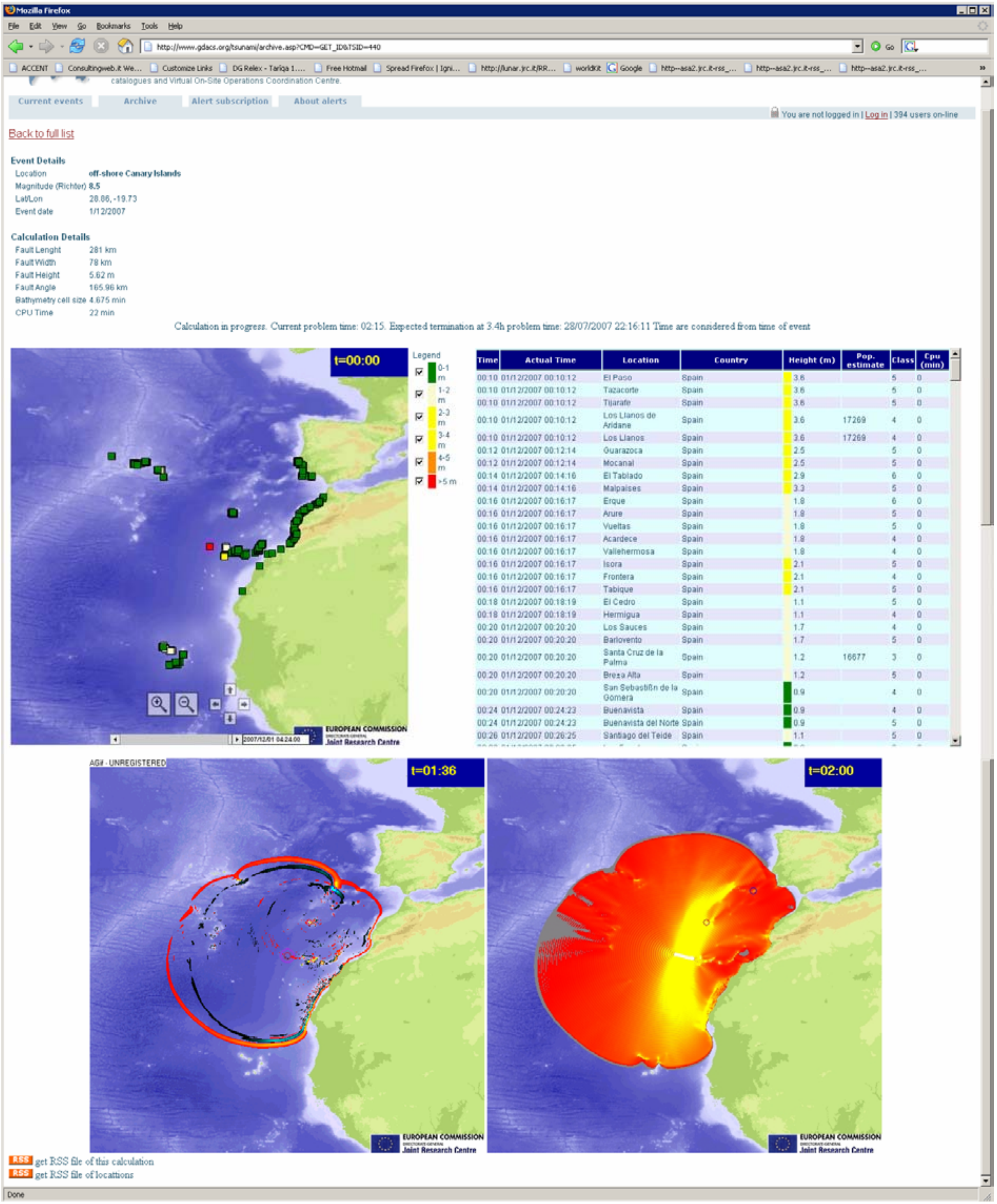


Fig. 13 –Overall output of the JRC Tsunami Assessment System

Time	Actual Time	Location	Country	Height (m)	Pop. estimate	Class	Cpu (min)
00:10	01/12/2007 00:10:12	El Paso	Spain	3.6		5	0
00:10	01/12/2007 00:10:12	Tazacorte	Spain	3.6		5	0
00:10	01/12/2007 00:10:12	Tijarafe	Spain	3.6		5	0
00:10	01/12/2007 00:10:12	Los Llanos de Aridane	Spain	3.6	17269	4	0
00:10	01/12/2007 00:10:12	Los Llanos	Spain	3.6	17269	4	0
00:12	01/12/2007 00:12:14	Guarazoca	Spain	2.5		5	0
00:12	01/12/2007 00:12:14	Mocanal	Spain	2.5		5	0
00:14	01/12/2007 00:14:16	El Tablado	Spain	2.9		6	0
00:14	01/12/2007 00:14:16	Malpaises	Spain	3.3		5	0
00:16	01/12/2007 00:16:17	Erque	Spain	1.8		6	0
00:16	01/12/2007 00:16:17	Arure	Spain	1.8		5	0
00:16	01/12/2007 00:16:17	Vueltas	Spain	1.8		5	0
00:16	01/12/2007 00:16:17	Acardece	Spain	1.8		4	0
00:16	01/12/2007 00:16:17	Vallehermosa	Spain	1.8		4	0
00:16	01/12/2007 00:16:17	Isora	Spain	2.1		5	0
00:16	01/12/2007 00:16:17	Frontera	Spain	2.1		4	0
00:16	01/12/2007 00:16:17	Tabique	Spain	2.1		5	0
00:18	01/12/2007 00:18:19	El Cedro	Spain	1.1		5	0
00:18	01/12/2007 00:18:19	Hermigua	Spain	1.1		4	0
00:20	01/12/2007 00:20:20	Los Sauces	Spain	1.7		4	0
00:20	01/12/2007 00:20:20	Barlovento	Spain	1.7		5	0
00:20	01/12/2007 00:20:20	Santa Cruz de la Palma	Spain	1.2	16677	3	0
00:20	01/12/2007 00:20:20	Bre±a Alta	Spain	1.2		5	0
00:20	01/12/2007 00:20:20	San Sebastißn de la Gomera	Spain	0.9		4	0
00:24	01/12/2007 00:24:23	Buenavista	Spain	0.9		4	0
00:24	01/12/2007 00:24:23	Buenavista del Norte	Spain	0.9		5	0

Fig. 14 – Detail on the list of locations with indication of locations and population estimates

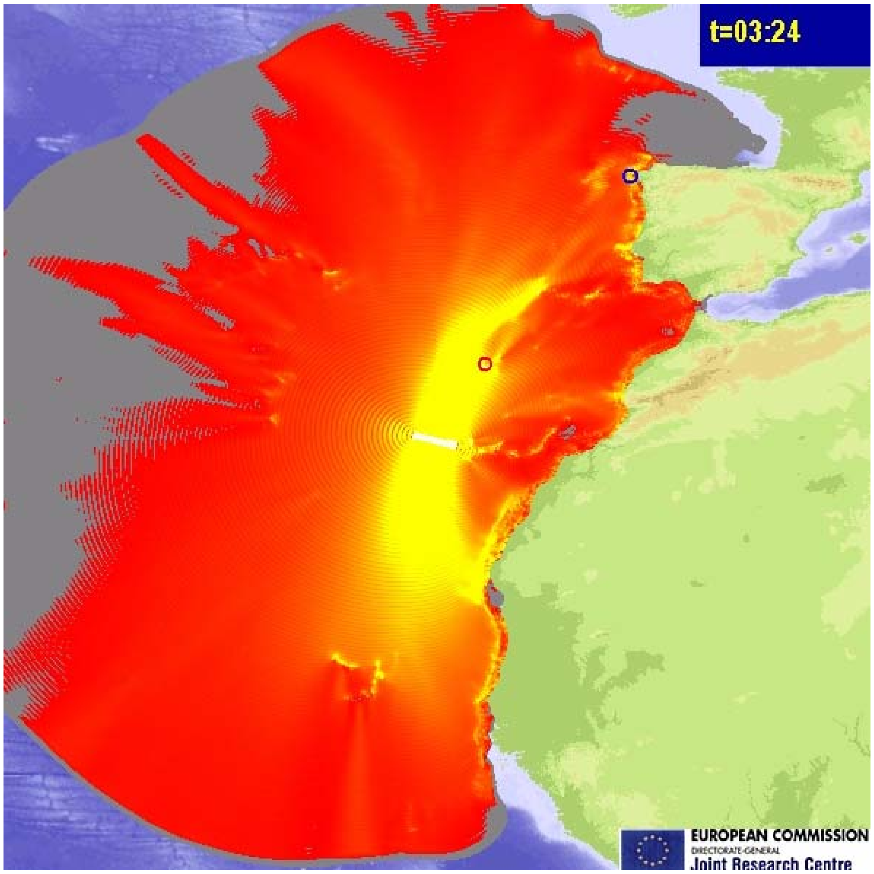


Fig. 15 – Final height distribution for a M 8.2 earthquake occurring off-shore Canary Islands

The list of locations with the wave travel time after the event and the actual time, the wave height and the population estimate is updated as soon as the calculation progresses in the model result page (Fig. 14). The final form of the calculation is indicated in Fig. 15, which shows the maximum height in any location.

3.2 Calculations Refinement

It is important to note that this initial automatic calculation may not be correct for locations very close to the epicenter, because in order to keep the CPU time low, the bathymetry assumed for the calculation is rather coarse (see 2.4). In the previous example, the system would assume

Calculation width[1] = 46 degrees
Bathymetry size[2] = 4.7 min

corresponding to a 601x601 grid.

Refining the calculation and using 2 minute bathymetry the grid size becomes 1832x1832 and the cpu time increases. However the heights calculated in the various positions are higher,

[1] Size of the calculation space centered on the epicenter (latitude from lat-23 to lat+23 and longitude from lon-23 to lon+23).
[2] Size of each calculation node

because a much better resolution of the physical problem is obtained. As an example, we perform a comparison with two locations, one close and one far from the epicenter:

The closest location identified by the automatic calculation is Tazacorte (the cyan arrow in the figure below) which has a value of 3.6 m, while S. Sebastian de la Gomera (the yellow arrow), which is shadowed by the Gomera Island, and the maximum calculated height is 0.9 m. The calculation with the higher resultion (2 min) is 5.6 m on Tazacorte on Santa Cruz Island, and 1.3 m for S. Sebastian de la Gomera. Further reduction of the bathymetry size would still increase the maximum height at such a short distance. It was already demonstrated in validation calculations performed on a Nicaragua case that the maximum height is reached for a size of 0.5 degrees and further reductions have no effect.

For far distances, instead the difference is not so large, for instance Boavista, Portugal is reached after 2h:36’ with a height of 1.3 m with the automatic calcualation and 2h:32’, height 1.7 m with the higher resolution calculation. The drawback of the higher resolution calculation is that it takes 13 min to calculate with the automatic and 33 min with the manual case.

	4.7 min resolution (automatic)		2 min resolution	
	Time (hh:mm)	Height (m)	Time (hh:mm)	Height (m)
Tazacorte	0:10	3.6	0:08	5.6
S. Sebastian de la Gomera	0:20	0.9	0:18	1.3
Rogil, Portugal	2:06	0.7	2:08	1.0
Boavista, Portugal	2:36	1.3	2:32	1.7

Fig. 16 - Canary Island locations

Therefore it is important, after an initial automatic calculation, to perform further verifications and eventually repeat the calculations with better local resolution if the epicenter is very close to the coast. A possible solution to this could be to launch at the same time two calculations, one with a high resolution and a small width, to evaluate close locations and another one with a coarser resolution and a larger width, to estimate far distances.

In the end, however the initial calculation was able to identify correctly the affected locations, even the closer ones. The height evaluation for closer locations needs further refinements; this could be achieved as outlined above.

4 Actuations of the JRC Tsunami Assessment System

The Tsunami Assessment Tool is operational since November 2005

#	Location	Magnitude	Depth	Date	CPU time	Note
1	Kuril Islands	M 8.3	30 km	15/11/2006	22 min	**0.4 mt Tsunami** reached Japan, Hawaii and California
2	China	M 7.2	2 km	26/12/2006	28 min	No Tsunami generated
3	Kuril Islands	M 8.2	10 km	13/01/2007	40 min	**Small Tsunami generated**
4	Indonesia	M 7.2	10 km	21/01/2007	22 min	**Small Tsunami generated**
5	[Vanuatu]	M 6.9	35 km	25/03/2007	23 min	**Small Tsunami generated**
6	Japan	M 7.3	50 km		48 min	**Small Tsunami generated**
7	Solomon Island	M 8.1	10 km	01/04/2007	22 min	**10 mt Tsunami**, about 200 persons dead
8	Papua New Guinea	M 6.9[3]	20 km	01/07/2007	25 min	No Tsunami generated[3]
9	Honshu	M 6.6	55 km	16/07/2007	34 min	**0.5 m Tsunami** on Japanese coasts, damages from the earthquake
10	Honshu	M 6.8	314 km	16/07/2007	38 min	No Tsunami generated
11	Vanuatu	M 7.3	144 km	01/08/2007	35 min	No Tsunami generated
12	Sakhalin	M 6.9	39 km	02/08/2007	30 min	**0.3 m Tsunami generated**
13	Indonesia	M 7.5	289 km	08/08/2007	60 min	No Tsunami generated

Since the start of the operations the actuation of the system was requested 13 times (as 8/8/2007). In 8 cases real Tsunamis were generated, in 3 cases the earthquake depth was too high to generate a Tsunami (>100 km), in 1 case the initial magnitude of 6.9 was later lowered to 5.7, in 1 case there was no tsunami even if the earthquake depth was very shallow (2 km). Therefore assuming no Tsunami below 100 km (a modification that will be done in the next release of the system), and excluding the case of wrong initial magnitude, out of 12 cases 11 would have been correctly calculated by the JRC system, which is an extremely good result.

An analysis has been done on the time of issuing of the various PTWS bulletins and the execution of the calculations for two events: Kuril Island (15/11/2007) and Solomon Island event (01/04/2007). The reason for choosing these two events is that the first one can be identified as a long distance Tsunami, since traveled up to Japan, Hawaii and California. The second one is instead a more localized event.

[3] This earthquake was initially classified 6.9 by GEOFON, finally reduced to 5.7

4.1 Kuril Island event, 15/11/2006

On 11/15/2006 11:14:01 AM UTC an earthquake of magnitude 8.3 struck the unpopulated Kuril Islands between Russia and Japan (Lon: 153.22 Lat: 46.68). The earthquake triggered a relatively small tsunami (with wave heights up to 50cm), which reached mainly Japan, Russia but it was detected also in Hawaii, California coasts and South America. No casualties were reported.

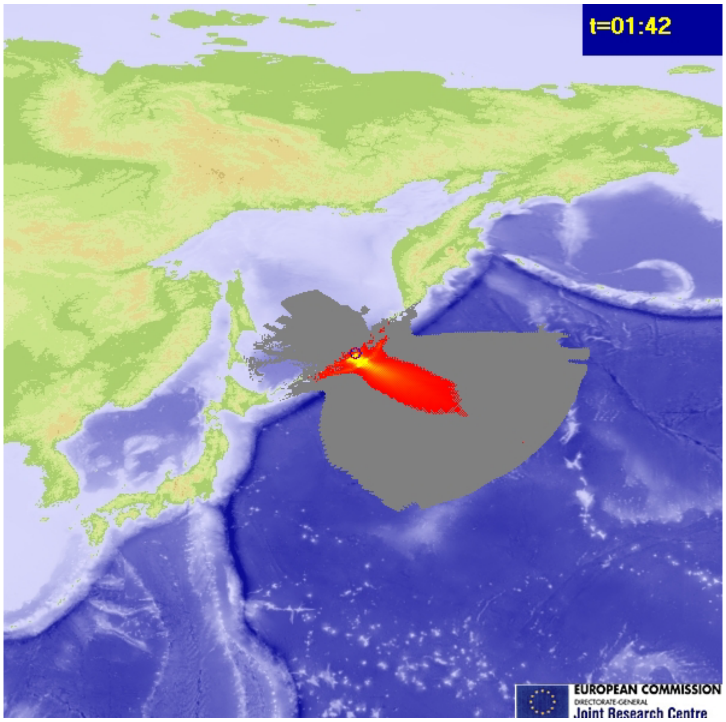
Calculations of tsunami wave height were automatically initiated with the JRC SWAN model. Results were updated on the dedicated web site every 10 minutes. The model predicted a maximum height of 40 cm in Japan arriving at 1h 30 min; in reality a wave of about 30 cm arrived at 1h 22 min, according to Japanese measurements.

The highest predicted height was 6.6 m to occur on the inhabited Islands (Fig. 17).

The calculation, initiated when the notification occurred, 17 min after the event, and was completed in 30 min thus, related to Japan, there were still 43 minutes available for early warning.

This is the timeline of the events actuation

0	11:14:15 UTC M7.7 earthquake Kuril Islands
16’	1st PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated)
17’	JRC-SWAN calculation starts
47’	JRC-SWAN calculation ends, locations identified with 0.4-0.5 m height maximum
1h	Magnitude revised to M 8.1 2nd PTWS message generated (“**it is not known if a Tsunami was generated**”)
1h 1’	New JRC-SWAN calculation started
1h 16’	JRC-SWAN predicts Hokkaido, Japan reached 0.1 m at 1:30
1h 22’	JRC-SWAN predicts Oishi, Japan, reached at 2 h, 0.12 m
1h 30’	Hasahi Hokkaido reached by the wave, 0.3 m
2h 3’	3rd PTWS bulletin, indicating that “**a Tsunami was generated**” and that two locations in Japan were reached by the wave
3h 44’	4th PTWS bulletin, indicating that also Alaska was reached by the wave, 0.2 m



The image below was produced at the end of the first calculation, when the known magnitude was 7.7. Already this image was showing very clearly that the direction of the energy distribution was such that a major wave on Japan was not expected.

Also the image indicates that great amount of energy is directed towards Hawaii, which indeed were reached several hours after by waves up to 1 m.

The results of the revised calculation are indicated in the figure below which shows the various locations reached by the wave. It is interesting that one remote location (Kostochko) was reached by a 6.6 m wave. Analysis of the satellite images in the area allowed concluding that indeed an important wave reached that coasts. Appendix C reports the bulletin on the event published by JRC the day after the event.

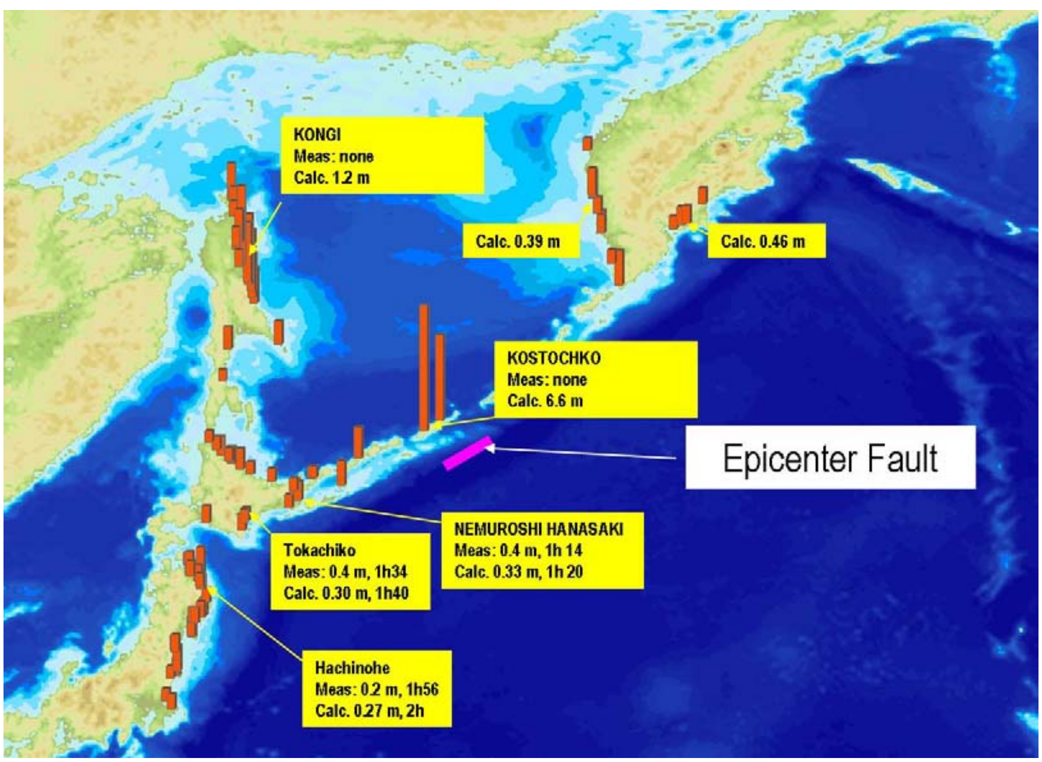


Fig. 17 – Distribution of the predcted and measured after the Kuril Island event of 15/11/2006

Fig. 18 - Satellite image on the coast on Kuril Islands showing that a section of the vegetation was taken out as a result

of the Tsunami inhundation.

The analysis of this event indicates that in this case of long distance Tsunami the information was produced rather quick, well in advance respect to the time the wave reached the first populated areas (Japan). The timings are comparable with the ones of PTWS. The use of these calculations could have allowed to issue bulletins indicating that no major problems were expected on Japanese coasts.

4.2 Solomon Island Event

On Sunday 1 April 200 7 at 20:39 UTC, an underwater earthquake of magnitude 8.1 caused a tsunami of several meters to hit the Solomon Islands. More than 10 people have been reported killed and thousands affected or injured. The international community was put on standby and offered help through OCHA. Australian beaches were evacuated.

JRC systems detected the event 16 minutes after the event, i.e. as soon as it was published by the United States Geological Survey. The event was calculated to be a Red Alert and over 3000 alerts were sent out.

0	20:40:00 UTC M7.7 earthquake Solomon Islands
15’	1st PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated)
16’	JRC-SWAN calculation starts with 7.7 magnitude
17’	JRC-SWAN identified the following locations in less than 1 minute of calculation: Hofovo, 3.2 m, Harai 3.1 m, Vanikuva 3.1 m, Judaea 3.1 m, Au 3.1 m, Kunji 3.3 m, Pienuna 1.5 m, etc. All these locations are calculated to be hit in less than 5 min.
41’	JRC-SWAN calculation completed, calculated values: Harsi 1.9 m, Vanikuva 2.2 m, Kunji 1.5 m, Honiara 0.1 m (predicted to be hit at 54’) etc

52’	2nd PTWS message generated (“**it is not known if a Tsunami was generated**”, arrival times indicated), revised magnitude to **8.1**
53’	Second JRC-SWAN calculation initiated
54’	JRC-SWAN new estimates of locations in less than 1 min: Ganongga 3.5 m, Pienuna 3.5 m, Mundimundi 1.8 m, Paramata 1.8 m, Iringgila 1.4 m, Lunga 1.6 m, Vella Lavella I 1.5 m, Eghelo 3.7 m, Mburuku 3.7m etc.
57’	Honiara reached by 0.15 m wave (measurement)
1h 5’	Second JRC-SWAN calculation (with higher magnitude) completed (Honiara predicted to be reached at 48’ with 0.3 m)
1h 59’	3rd PTWS message, confirmation of the Tsunami, measurements in Honiara reported (0.15 m, at 57’)

Other 5 PTWS messages follow with additional locations measurements, but none of these indicate high wave values (Manus 9 cm, Vanuatu 15 cm, Cape Ferguson 11 cm) because the measurement locations were not close to the epicenter and not in line with the greater energy track (see the orange dots in Fig. 19).

The JRC-SWAN calculations were available already at least at the time of the second PTWS message, indicating about 3.3 m wave height in Kunji. Thus the availability of this calculation tool could have been useful in identifying the extent of the possible affected areas, once the Tsunami would have been confirmed by the far measurement points.

It is interesting to note that, although the first PTWS message was issued 15’ after the event, the email was received at JRC only after 2h 31’. At least one media source reported that the GDACS alert arrived while the Pacific Tsunami Warning Centre did not issue any alert message[4].

[4] MICHAEL FIELD - Fairfax Media (http://www.stuff.co.nz/4013314a12.html), initially wrote: “The Pacific Tsunami Warning Center in Hawaii has not issued any warnings but the European Union/United Nations Global Disaster Alert and Coordination System says a tsunami is a high risk.”. The text of the article was then modified.

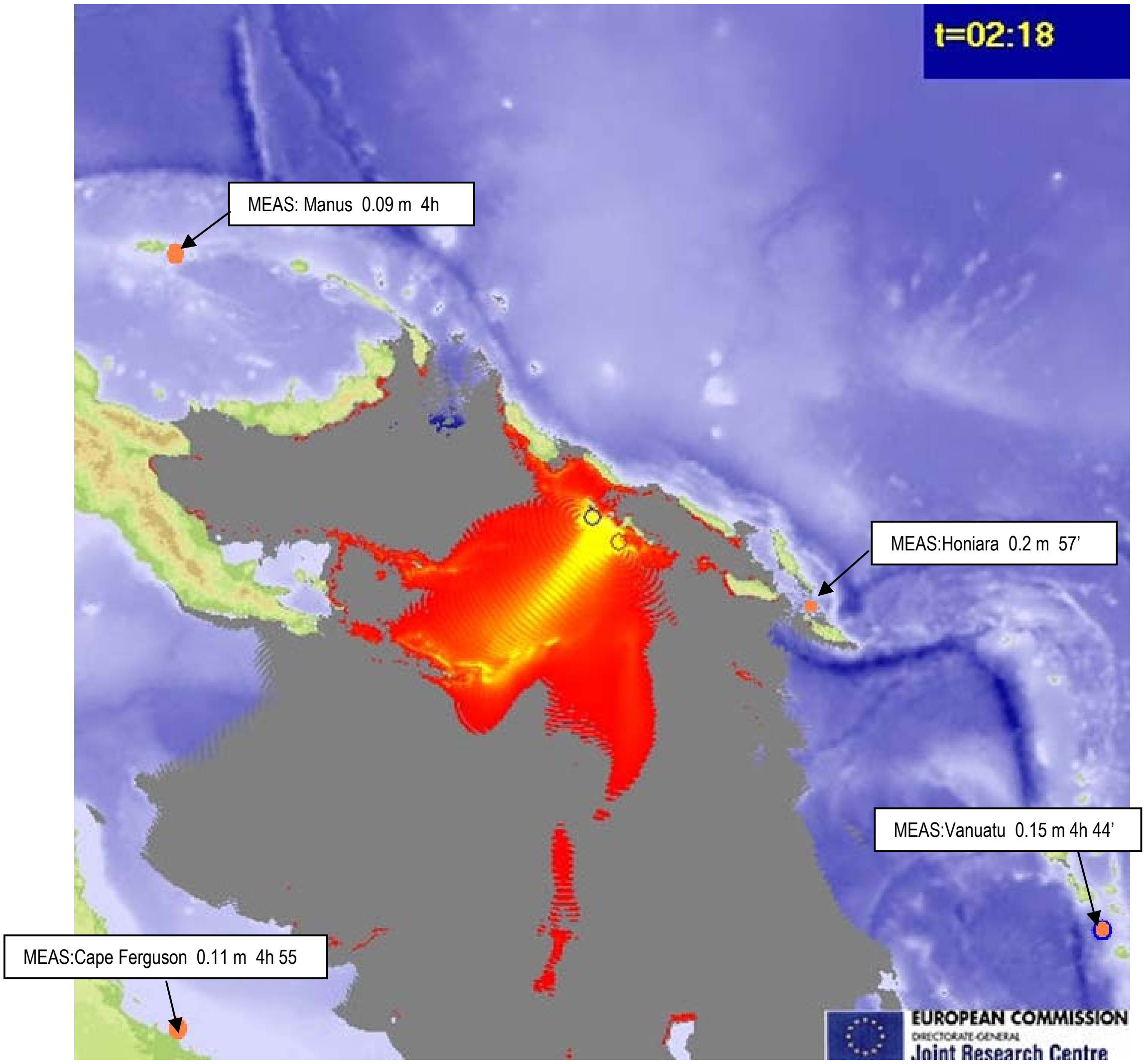


Fig. 19 – Solomon Island Event. In orange the positions of the water height measurements indicated in the PTWS messages

5 Pre-calculations vs On-line calculations?

The execution of the calculations takes some time which may be not acceptable if the results of the calculations may be important to issue an alert (early warning system calculation), immediately or soon after the occurrence of an event. An alternative strategy could be to run a number of calculations in order to cover any possible location in the world. It is easy to show however that this is not a viable solution because it would be necessary to perform one calculation every 0.1 degrees (11 km) and for each magnitude.

Considering the whole earth and a 70% water coverage of the earth, the number of initial locations at every 0.1 degrees are, without considering magnitude variations would require:

$360 \times 180 / 0.1^2 \times 70\%$ = **$4.5\ 10^6$ runs**

The space requirements of the generated data would be 8 Mbytes/ run : **38 Tbytes**

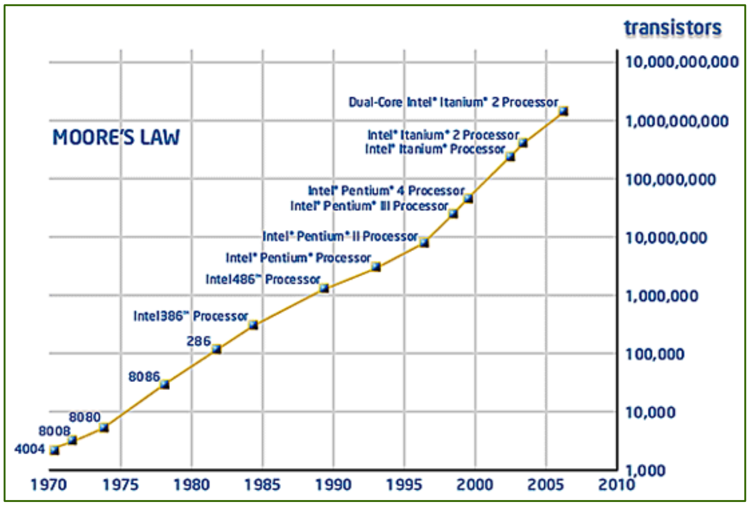
The execution time would be 30 min/run: **258 years cpu**

It could be possible to increase the size of the calculation grid to 0.5 degrees (55 km) instead of 0.1, thus allowing a greater error in the initial location of the earthquake. In this case there would be $1.8\ 10^5$, with a reduction of 250 times and 1 year of cpu time, which is more reasonable. It is however necessary to consider that various magnitudes should be accounted because varying the magnitude the length and width of the fault increases. The figure below illustrate a possible uniform grid for the Mediterranean sea. This is a 0.4 degrees grid, including 1084 points. Calculating magnitudes ranging from 6.5 to 9.5 every 0.25, it would imply 13000 calculations and a total CPU time of 9 months and would generate 101 GBytes of data.

Another important advantage of the on-line calculations is the possibility to upgrade the model without the need to re-run all the thousands of calculations or perform calculations with more than 1 model for comparison purposes.

Fig. 20 – Uniform calculation grid for the Mediterranean sea

Another argument in support to the on-line calculation is the fact that the computer speed increases constantly over the years. In the last 5 years the computing power increased by a factor greater than 10. This means that in 5 years from now it could be possible to perform in 3 minutes the same calculation that now is performed in 30 minutes !



A disadvantage of the on-line calculation is that the system must be ready to execute the calculations at any time. The failure probability should be reduced as much as possible by increasing the number of execution servers. At the moment JRC is using 3 servers but we intend to increase them to 5.

6 Future developments

6.1 Grid calculations

Although the JRC approach has a preference for the on-line calculation method, it could be useful to have ready calculations for the areas which are vulnerable from historical tsunami point of view.

We would define a grid which covers only these areas and initiate the calculations on these areas only. The calculations will be performed at every 0.5 degrees with magnitude range of 0.25. When a new calculation will be requested and the location fits in the defined grid (minimum distance from a calculation performed, with the distance defined as

$$d=((lat-lat_0)^2+ (lon-lon_0)^2+(mag-mag_0)^2)^{0.5}$$

an initial estimate of the calculation is offered and at the same time a new calculation with the required values is started. In such a way, the user may have immediately an estimate of the values that he will expect on the coast, with the availability of a more refined calculated values within 30-50 minutes.

1. given a new calculation request at lat_0, lon_0, mag_0
2. select the calculation with the closer distance from the epicenter and define the ratio required initial height/calculated height to correct the results and offer this preliminary result on-the-spot
3. start a new calculation with the correct values of lat_0, lon_0, mag_0

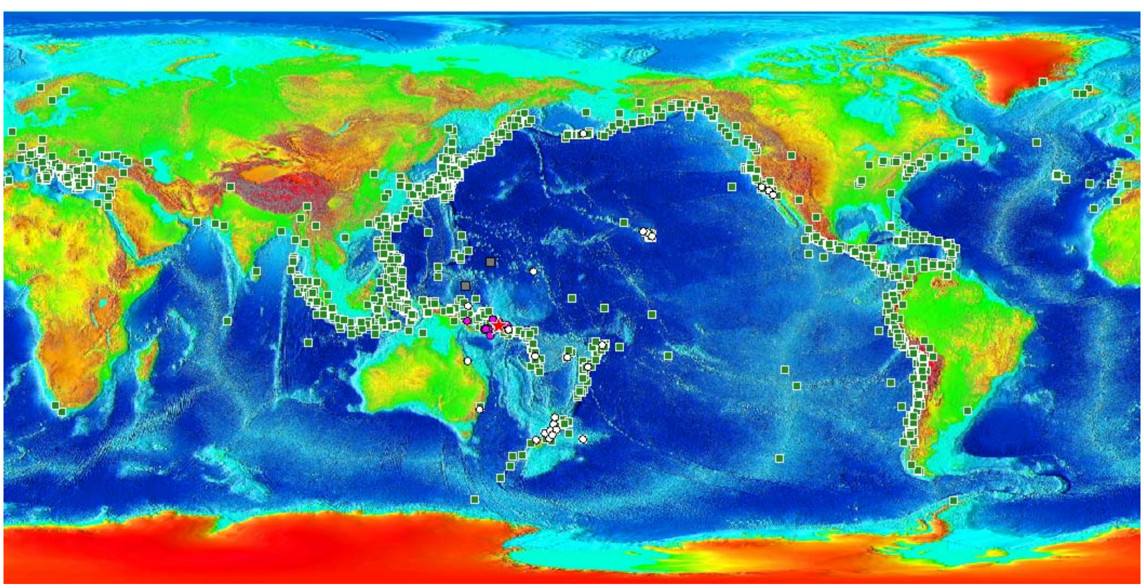
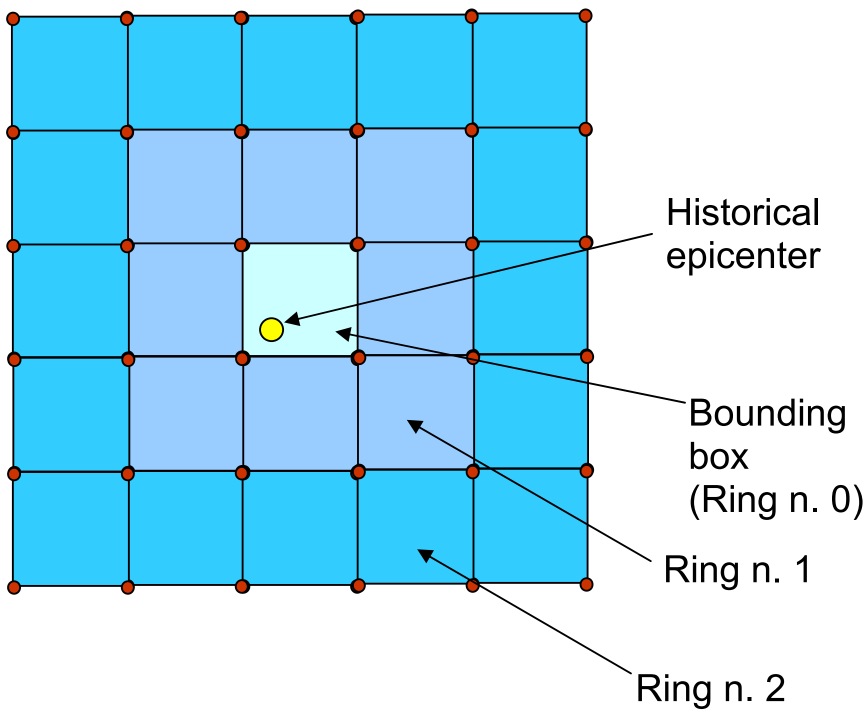


Fig. 21 - Historical database of Tsunamis in the world (source NOAA, NGDC database)

In order to reduce the amount of needed calculations for the areas that are potentially tsunami prone, a reduced calculation grid has been defined. For every historical Tsunamis source (each square in the above figure), the bounding grid points have been determined using a 0.5 degrees grid. In order to cover possible different locations a number of additional "rings" have been defined. No ring entails having 4 calculation points (bounding box), 1 ring involves 16 calculation points, 2 rings entails 36 calculation points and so on.



The number of resulting epicenters grid points N quickly increases with the second power of the double the number of rings n $N=N_{box}\,(2\,(n+1))^2$. In reality there may be points on land and these will not be calculated.

0 ring (bounding box)	1598
1 ring	4223
2 rings	7159
3 rings	**10185**
4 rings	18039

Increasing the number of rings, reduces the probability that a new earthquake epicenter falls **out** of the calculation grid. Reducing the grid size, reduces the precision (distance) of the requested point to the available points but the number of calculations increase. We will start the 3 rings calculations on a grid of 0.5 degrees (10185 points) and a magnitude of 8 as an average magnitude. Each magnitude would imply to recalculate all the 10185 data points.

Considering that each calculation imply 30 minutes cpu time and 8 Mbytes storage space, means to spend 7 months on 1 computer or 1 months on 7 computers and occupy 80 Gbytes per set of magnitude calculation. In theory every magnitude should be calculated. One could assume calculating from M 6.5 to M 9.5 every 0.25, that means 12 set of magnitude calculations (1 year using 7 computers). These calculations have not yet been started.

6.2 Models improvement

6.2.1 Fault Generation

A model which needs to be refined is the fault generation model which is too simple. In collaboration with the University of Cachan a new model for earth deformation and definition of the initial calculation condition is in preparation and will eventually be integrated in an enhanced JRC model.

6.2.2 Propagation models

It will be useful to have more propagation models in the system in addition to the SWAN code. The TUNAMI code by prof. Imamura has been also included but it has not yet been converted to C,

7 Conclusions

Several computer codes for simulating the Tsunami behavior have been developed woldwide. None of them however has been designed in order to respond automatically and quickly with the limited information available within minutes after an earthquake event which may cause a Tsunami and publish, while it is still running, the results on the web.

The JRC Tsunami Assessment Modelling System is a complex series of computer codes, procedures and computers set-up to respond in about 30 minutes to any request coming from Early Warning Systems, such as the Global Disaster Alerts and Coordination System (GDACS) or the LiveMon[5], both developed and operated by JRC.

The Tsunami Assessment Modelling system, developed in a simpler form (travel time) soon after the Tsunami event of 2004, has been greatly improved with the inclusion of a model to calculate the wave height. The revised system is now fully operational and performs automatic calculations whenever requests from the early warning systems are received.

In the meantime a scenario pre-calculation activity is being performed in order to produce a large database of possible cases which are shown immediately when an event occurs, during the on-line calculation activity; these pre-calculated scenario calculations, started in September 2007 should be completed by March-April 2008 and will be operationally connected with the GDACS system or any other early warning system, if necessary.

[5] LiveMon is a simplified version of the Global Disasters Alerts and Coordination Systems developed to be used as informatic tool in Natural Disasters Situation Centers.

References

[1] Annunziato A., 2005. DEVELOPMENT AND IMPLEMENTATION OF A TSUNAMI WAVE PROPAGATION MODEL AT JRC. Fifth International Symposium on Ocean Wave Measurement and Analysis. WAVES 2005, Madrid 3-7 July 2005

[2] T. DE GROEVE - *Global Disaster Alert and Coordination System: More Effective and Efficient Humanitarian Response* - In: The 14th TIEMS Annual Conference 2007 Book of Proceedings, Hotel "Medena", Trogir, Croatia, pages 324-334, Hydrographic Institute of the Republic of Croatia (Publ.), Split - JRC40031

[3] N.N. Ambraseys, J.A. Jackson – 'Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region' – Geophysics Journal International (1998, 133, 390-406

[4] S. Ward – 'Tsunamis' – Encyclopedia of Physical Science and technology – Academic Press

[5] C. Mader – "Numerical modeling of water waves" – CRC Press – ISBN 0-8493-2311-8

Appendix A - Example of call and response of the JRC Tsunami Tool

Request:
http:// cmd.asp?CMD=SET_CALC&eqid=LP001&evDate=01/12/2007
&**mag=8.2**&**lat=28.86**&**lon=-19.73**&location=off-shore Canary Islands&Client=Manual

Response
<?xml version="1.0" encoding="ISO-8859-1"?>
<rss version="2.0" xmlns:icbm="http://postneo.com/icbm/" xmlns:dc="http://purl.org/dc/elements/1.1/" xmlns:asgard="http://asgard.jrc.it" xmlns:gdas="http://www.gdacs.org" xmlns:geo="http://www.w3.org/2003/01/geo/" xmlns:glide="http://glidenumber.net"><channel>
<query><![CDATA[cmd=GET_LAST]]></query><item>
<title>(M 8.5) off-shore Canary Islands</title>
<description>SWAN Calculation requested by Manual</description>
<pubDate>Fri, 12 Jan 2007 0:0 UTC</pubDate>
<evDate>1/12/2007</evDate>
<link><![CDATA[?CMD=GET_ID&TSID=440]]></link>
<geo:lat>28.86</geo:lat>
<geo:long>-19.73</geo:long>
<mag>8.5</mag>
<ID>440</ID>
<client>Manual</client>
<SWAN_ID>0</SWAN_ID>
<URL_Base>http://tsunami.jrc.it/model/swan/Reports/440/</URL_Base>
<DIR_Base>\\139.191.1.18\g$\inetpub\wwwroot\tsunami\model\swan\Reports\440\</DIR_Base>
<status>waiting</status>
<location>off-shore Canary Islands</location>
<eqID>LP001</eqID>
<gdas:country>off-shore Canary Islands</gdas:country>
<updateDate>7/28/2007 10:29:07 AM</updateDate>
<StartingTime></StartingTime>
<EndingTime></EndingTime>
<dc:subject>EQ_White</dc:subject>
<execution_server></execution_server>
<CPU_Time>0</CPU_Time>
<initialConditions>
<Fault><Lenght>0</Lenght>
<Width>0</Width>
<Height>0</Height>
<Form></Form>
<Mode></Mode>
<Angle>0</Angle>
</Fault>
<Bathym>0</Bathym>
<dtMax>0</dtMax>
</initialConditions>
<outputs>
<status_HTML>http://tsunami.jrc.it/model/swan/Reports/440/calcstatus.htm</status_HTML>
<image_anim_gif>http://tsunami.jrc.it/model/swan/Reports/440/outres1.gif</image_anim_gif>
<image_distr_jpg>http://tsunami.jrc.it/model/swan/Reports/440/P1_MAXHEIGHT_END.jpg</image_distr_jpg>
<TravelTime_jpg>http://tsunami.jrc.it/model/swan/Reports/440/TravelTime.jpg</TravelTime_jpg>
<TravelTime_status_HTML>http://tsunami.jrc.it/model/swan/Reports/440/calcstatusTT.htm</TravelTime_status_HTML>
<case>0</case>
<response></response>
</outputs>
</item>
</channel></rss>

Appendix B - Travel Time Model

The aim of this model is to rapidly estimate travel times of a potential Tsunami. 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

. $v = \sqrt{g\ d}$

where v is the wave velocity (m/s), g the gravitational costant (m/s2) 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 epicenter and evaluating, step by step, the local velocity and integrating the velocity to get the wave position. The distance from the epicenter at time t_{req}, is a function of the angle α and can be calculated integrating the above equation:

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

s is the generic coordinate along a radius starting from the epicenter. 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, see Figure B-1.

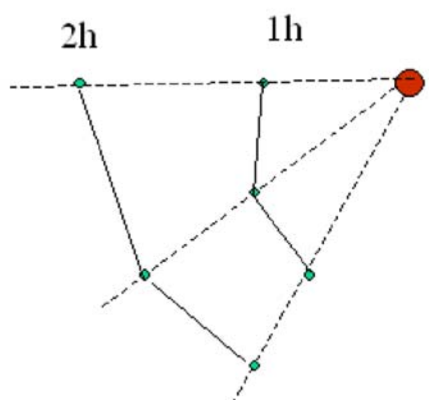


Figure B-1 – Logic for the propagation model

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 epicenter, 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 extremely sensitive to the bathymetry, which therefore has to be specified very 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 epicenter in a 1000 m location depth. We are using the ETOPO5 data, defined at each 5 minute and we intend to improve it with a 2 minute data for a better local response.

The model, applied to the epicenter of 26th December (long: 95.78, lat: 3.3) gives the response indicated in Figure B-2. The calculation is compared with the calculation performed by NOAA with the MOST model (Titov, 2004), Fig. B-3. The agreement is excellent. The only differences are related to the fact that the MOST model adopt a large initial event while the JRC a point source. The calculated times are also in very good agreement with the reported times of arrival of the waves in the various locations.

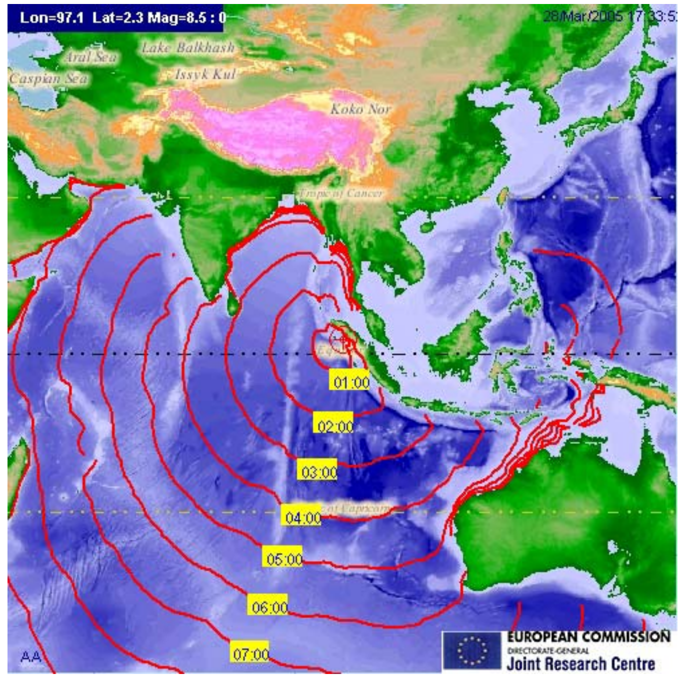


Fig. B-2 – Travel times for the 2004 Tsunami

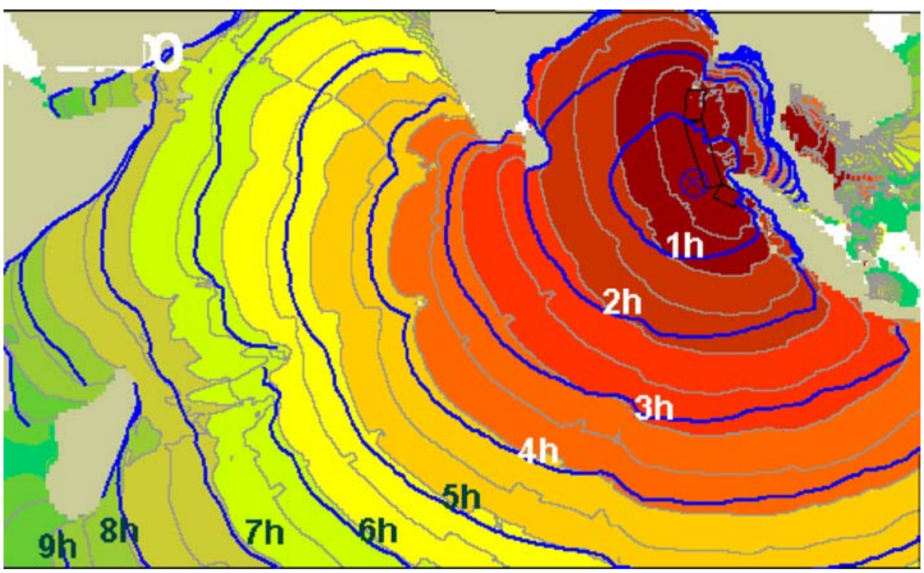


Fig. B-3 – Comparison of the JRC Travel Time Model with the MOST code

Appendix C – Kuril Island Event Report

A. Annunziato, C. Louvrier, T. De Groeve, Z. Kugler – 28/11/2006

GDACS Report on the Tsunami near Russia and Japan, 15/11/2006

Part 1- Published 16/11/2006

Summary

On 11/15/2006 11:14:01 AM UTC an earthquake of magnitude 8.3 struck the unpopulated Kuril Islands between Russia and Japan (Lon: 153.22 Lat: 46.68). The earthquake triggered a relatively small tsunami (with wave heights up to 50cm), which reached mainly Japan and Russia[6]. No casualties were reported.

Thousands of people living along northern Japan's Pacific coast fled to higher ground, but Japan's meteorological agency withdrew its tsunami warning after about three hours. Tsunami warnings for Russia and coastal areas of Alaska also were cancelled, as were tsunami watches for Hawaii, the Philippines, Taiwan, Indonesia and several Pacific islands.

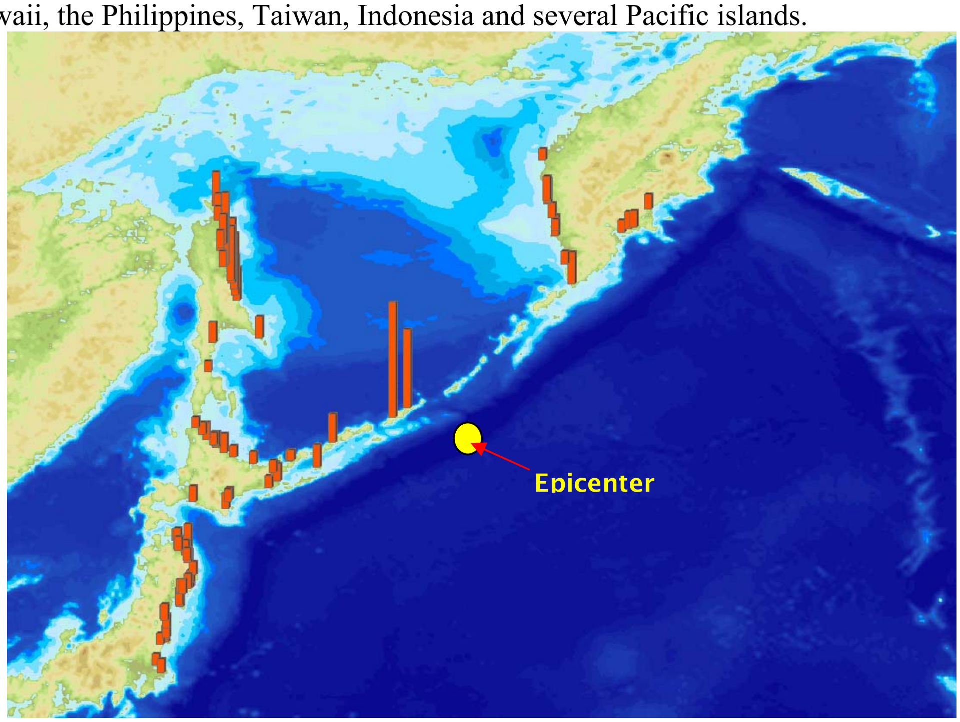


Fig. C-1 – Epicenter of the Kuril event and calculated heights

JRC issued initial alerts 19 minutes after the event. A GDACS Red alert was sent after 54 minutes when a revised magnitude became available. The GDACS system and the new JRC

[6] There are reports that the tsunami reached Hawaii (http://www.usatoday.com/news/nation/2006-11-16-hawaii-tsunami_x.htm?csp=34) with a 75cm swell on Kauai. In California, the US National Weather Service reported ocean surges from 0.3 to 2m but did not call an official tsunami warning or watch. Surges were observed from Port San Luis on the Central California coast to the Oregon border.

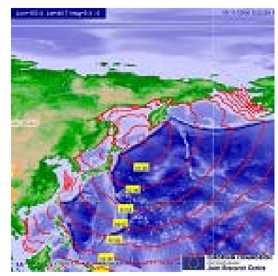
tsunami wave height model (SWAN model) performed as expected. SWAN wave height output was very accurate when compared with near real-time gauge measurements.

Earthquake and Tsunami Warning Systems

Japan issued a tsunami warning and evacuation orders. The Pacific Tsunami Warning System (PTWC) also issued tsunami warnings and watches. Gradually, warnings and watches were cancelled when more gauge information became available. The last PTWC bulletin read:

```
Sea level readings indicate a tsunami was generated. It may have
been destructive along coasts near the earthquake epicenter. For
those areas - when no major waves are observed for two hours after
the estimated time of arrival or damaging waves have not occurred
for at least two hours then local authorities can assume the threat
is passed. Danger to boats and coastal structures can continue for
several hours due to rapid currents. As local conditions can cause a
wide variation in tsunami wave action the all clear determination
must be made by local authorities.
No tsunami threat exists for other coastal areas in the pacific
although some other areas may experience small sea level changes.
For all areas the tsunami warning and tsunami watch are cancelled.
```

Both the JRC GDACS system and Tsunami system detected the event and generated the following information:



- 19 minutes after the event:
    - Tsunami propagation map and tsunami alerts based on initial magnitude (7.7). When better magnitude estimates became available from USGS, updated alerts were sent (35 minutes after the event for M7.8 and 2h56 after the event for M8.1)
    - GDACS detected the event as well but it was classified as Green alert due to initial lower magnitude
- Calculations of tsunami wave height were automatically initiated with the JRC SWAN model. Results are updated every 10 minutes.
- 54 minutes after the event:
    - GDACS earthquake and tsunami red alerts was sent as the magnitude was revised by USGS
    - GDACS web report was automatically created including the tsunami propagation map and the EMM news analysis (continuously updated).
- 1h30 after the event:
    - JRC created a GLIDE number (unique disaster identifier) for this event. This allows the GDACS portal to automatically collect information related to this event from partner websites, including ReliefWeb and UNOSAT.
    - Tsunami wave height calculations were included in the GDACS report (and continuously updated)

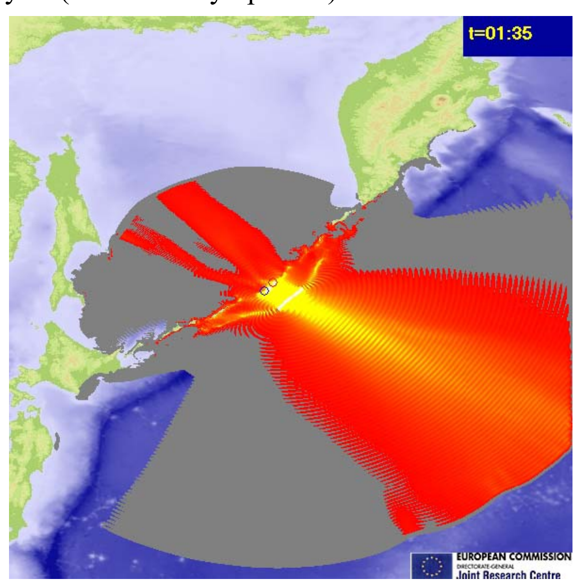
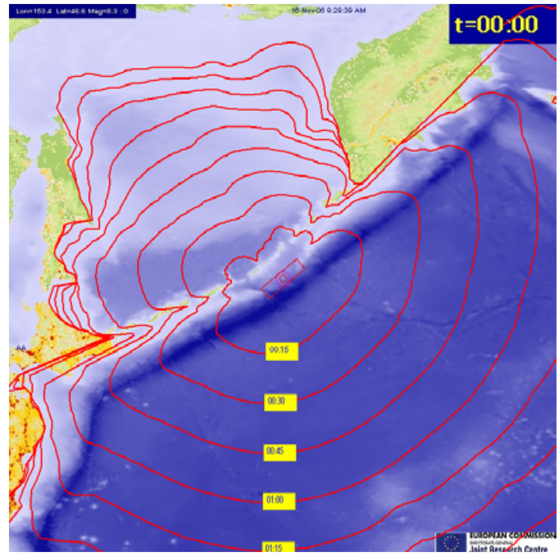


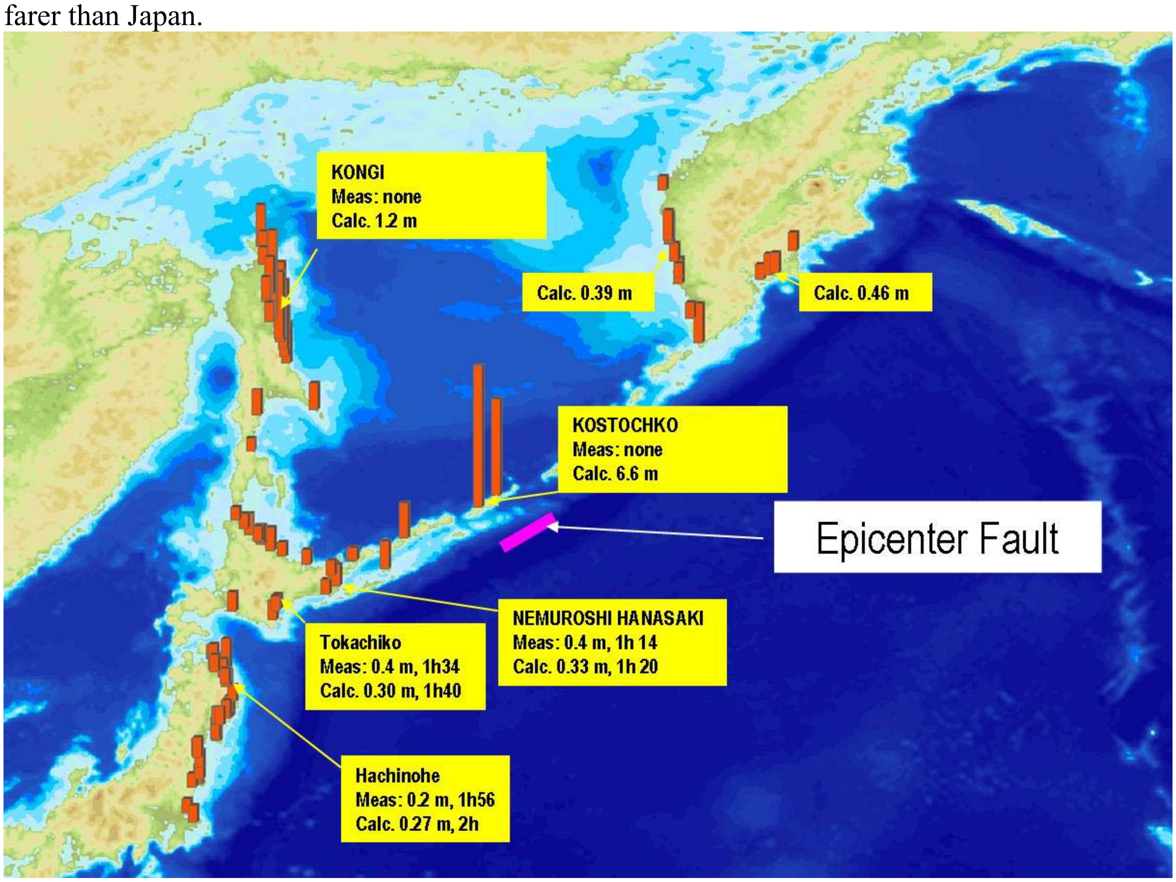
Figure C-2. Maximum wave height as calculated by JRC SWAN model.



FigureC-3- Tsunami travel time calculated by JRC model.

Evaluation of JRC information

JRC tsunami alerts went out 19 minutes after the event. GDACS alerts went out 54 minutes after the event. As gauge measurements and model outputs indicate, Japanese mainland was reached after 1h. Only some sparsely populated Kuril Islands (with maximum wave height) were reached within minutes.
Gauge wave height information available from the Japanese Meteorological Agency was compared with the SWAN model outputs and a high degree of correspondence was found. According to the model waves of over 6m should have reached the Kuril Island of Simushir. The total population of the Kuril Islands is estimated to be 30.000. There are no media reports at the time of writing on the impact of the tsunami on those islands.
The reason why in Japan no large waves were measured is, according to the model (Fig. C-2) is that most of the energy was directed orthogonally to the fault line, therefore not towards Japan but towards Hawaii, for instance, where in effect a small event occurred even if much farer than Japan.



FigureC-4 - Validation of JRC SWAN tsunami model. Estimated heights are conform with measured heights as provided by the Japanese Meteorological Service.

GDACS Report on the Tsunami near Russia and Japan, 15/11/2006

Part 2- Published 26/11/2006

Summary

On 11/15/2006 11:14:01 AM UTC an earthquake of magnitude 8.3 struck the unpopulated Kuril Islands between Russia and Japan (Lon: 153.22 Lat: 46.68). The earthquake triggered a tsunami which caused relatively small effect (with wave heights up to 50cm), which reached mainly Japan and Russia. No casualties were reported. The wave however reached also Hawaii and California with waves of about 1 m.
In the previous JRC report[7] (16 November 2006) it was shown that the calculations of the Tsunami indicated however that in proximity of the epicentre rather high waves should have been created with a maximum height of 6.6 m. No measurements are available in that area to confirm this calculation.

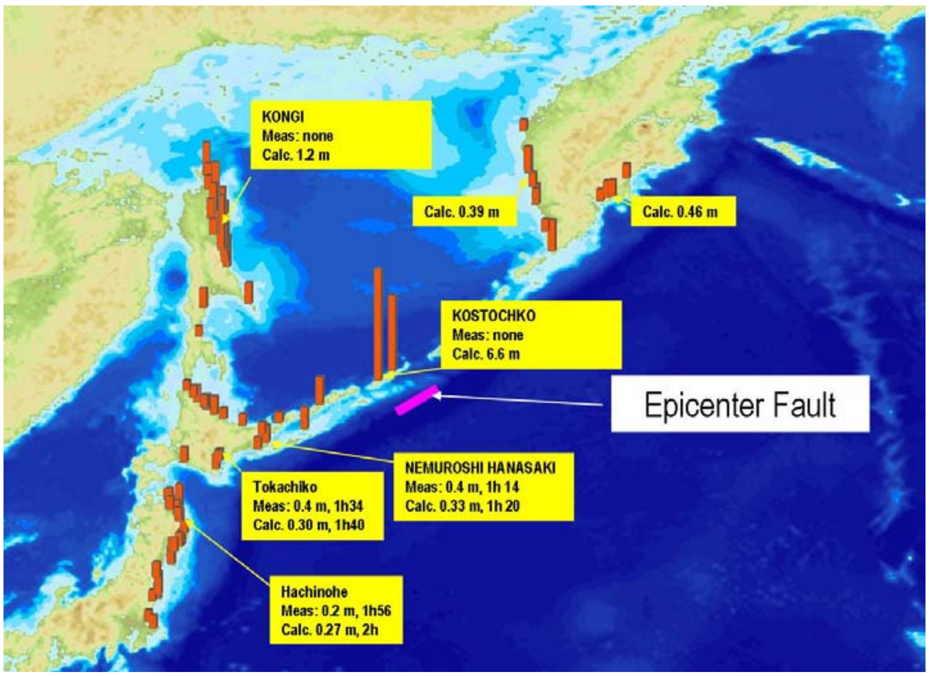


Fig. C-5 – Epicenter location

We were unable to find any single media report regarding the status of the Kuril Islands, damages on the isles or any signal of the height reached by the wave.
Nevertheless we have searched available satellite images in that area in order to see if there were some signs of the wave arrival on those coasts. The visual analysis shows strong signs that the Tsunami arrived on these coasts.

Images available on the Kuril Islands

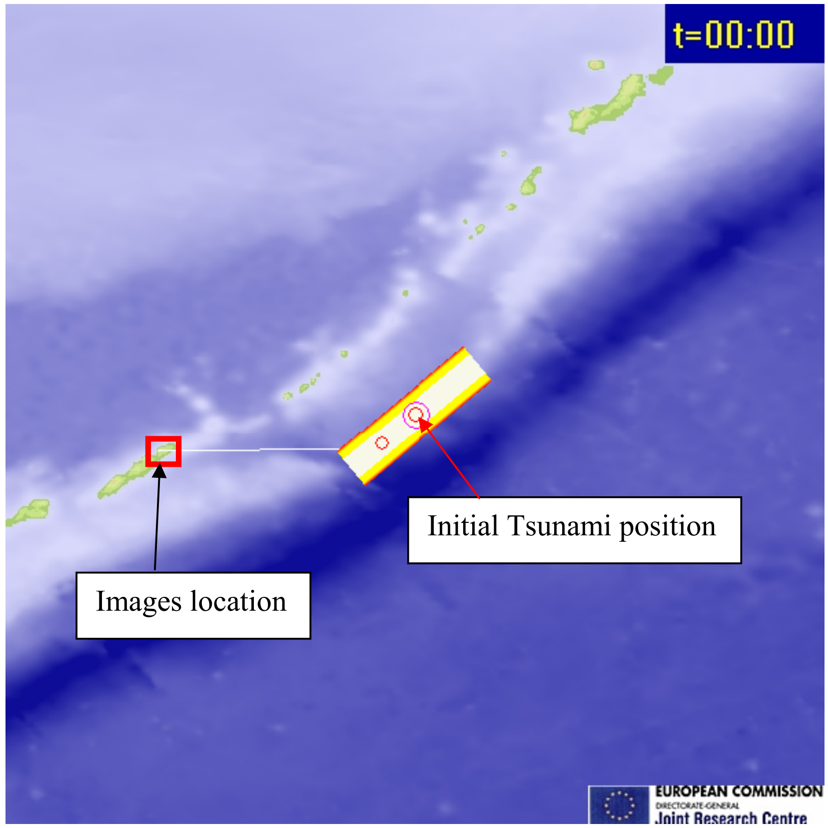
The following Quickbird (QB) cloud free DigitalGlobe images were found:

- Before the event

[7] GDACS and Tsunami Alert System Report, Tsunami near Russia and Japan, 15 November 2006 – JRC Report 16 Nov. 2006

- 6 September 2005
- 26 June 2006

- After the event
  - 20 November 2006



The images are of Urup Island, Lat=46.14, Lon=150.41.
The comparative analysis of the QB images before and after the Tsunami shows that for a distance of about 700-800 m all along the coast, there is an area without vegetation after the Tsunami event.
The experience of JRC with the analysis of the 2004 Tsunami indicates that this was an area which was probably hit by the wave.
The area appears parallel all along the coast. Draping the image in Google Earth and showing it in a 3D view with an exaggeration factor of 3 for the heights shows that the area is relatively flat before the start of the hill in the central side). It should be noted that quick look free images have been used. Maybe a better analysis could be done with the real high resolution images.
However, according to JRC calculations, the area shown in these images is not the area affected by the maximum heights. The calculations predict a maximum height of 1.6 m in area of the images. The digital elevation model we have at JRC (SRTM, 90 m resolution) is not detailed enough to quantify the amount of loss of vegetation in the images. Google Earth uses the same source for digital elevation.
The maximum heights predicted by the calculations occur on the island just in front of the Tsunami initial position; there, heights of 6.6 m were calculated. However, we did not find any very high resolution images until now. An attempt to use MODIS was unsuccessful due to the low resolution (see last images). We will search in the next days other images of that area.

Conclusions

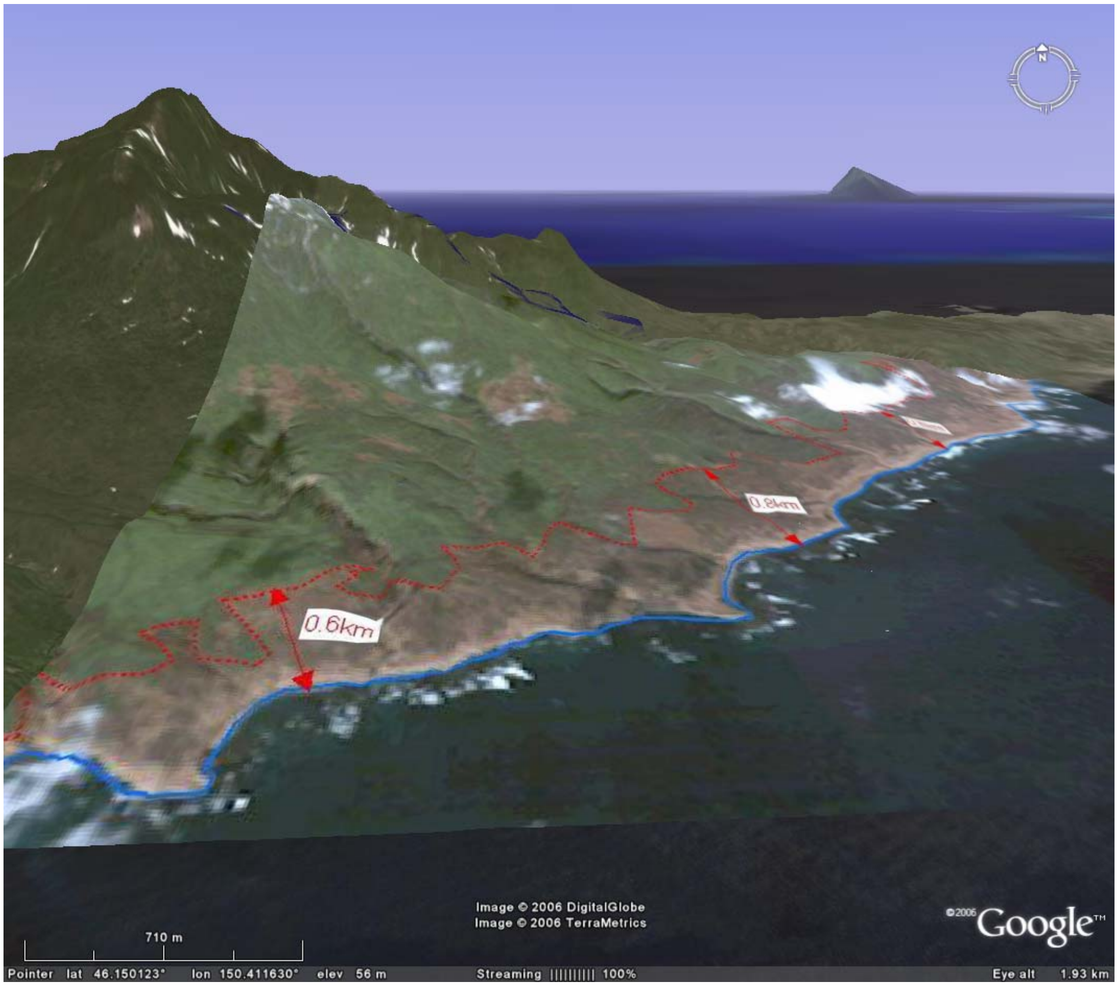
The experience gained in the analysis of 2004 Tsunami allowed us to analyse the images of an Island very close to the Tsunami initial location and allowed us to find a clear indication of the impact of the Tsunami on these coasts. The extension of the run-up in that particular island has been in the order of 600-800 m. This confirms the JRC calculations which were indicating the presence the wave in that island. The digital elevation model is too coarse to validate the quality of the calculated run-up height (1.6 m).

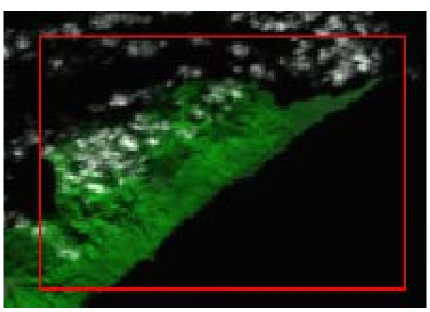
23 June 2006

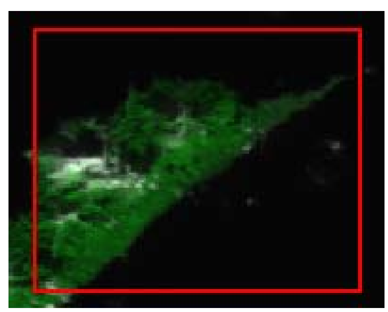
6 September 2006

Fig. C-6 – Quickbird images of Kuril Islands

20 November 2006




Before the event, MODIS images


After the event, MODIS images

Appendix D - Detailed Timeline for the Kuril Island Event

Kuril Island event, 15 Nov.2006

0	event	11:14	00:00	11:14 15/11/2006
1	**M 7.7**	11:30	00:16	**IT IS NOT KNOWN THAT A TSUNAMI WAS GENERATED.** THIS WARNING IS BASED ONLY ON THE EARTHQUAKE EVALUATION. AN EARTHQUAKE OF THIS SIZE HAS THE POTENTIAL TO GENERATE A DESTRUCTIVE TSUNAMI THAT CAN STRIKE COASTLINES IN THE REGION NEAR THE EPICENTER WITHIN MINUTES TO HOURS. AUTHORITIES IN THE REGION SHOULD TAKE APPROPRIATE ACTION IN RESPONSE TO THIS POSSIBILITY. THIS CENTER WILL MONITOR SEA LEVEL GAUGES NEAREST THE REGION AND REPORT IF ANY TSUNAMI WAVE ACTIVITY IS OBSERVED. THE WARNING WILL NOT EXPAND TO OTHER AREAS OF THE PACIFIC UNLESS ADDITIONAL DATA ARE RECEIVED TO WARRANT SUCH AN EXPANSION. WAVE ARRIVAL TIMES follow
SWAN	M 7.7	11:31	00:17	Swan calculation starts Russia, Sarychevo: 0.4 m
			00:27	End of SWAN calculation Noother major location identified
2	**M 8.1**	12:14	01:00	**IT IS NOT KNOWN THAT A TSUNAMI WAS GENERATED**. THIS WARNING IS BASED ONLY ON THE EARTHQUAKE EVALUATION. AN EARTHQUAKE OF THIS SIZE HAS THE POTENTIAL TO GENERATE A DESTRUCTIVE TSUNAMI THAT CAN STRIKE COASTLINES NEAR THE EPICENTER WITHIN MINUTES AND MORE DISTANT COASTLINES WITHIN HOURS. AUTHORITIES SHOULD TAKE APPROPRIATE ACTION IN RESPONSE TO THIS POSSIBILITY. THIS CENTER WILL CONTINUE TO MONITOR SEA LEVEL DATA FROM GAUGES NEAR THE EARTHQUAKE TO DETERMINE IF A TSUNAMI WAS GENERATED AND ESTIMATE THE SEVERITY OF THE THREAT.
SWAN	M 8.1	12:15	01:01	Swan calculation starts with higher magnitude
		12:20	01:16	Swan predicts Hokkaido, Japan reached 0.1 m at 1:30
		12:22	01:18	Swan predicts Oishi, Japab, reached at 2 h, 0.12 m
EXP		**12:43**	**1:29**	**Japan, Hanasaki Hokkaido, 0.3 m**
EXP				Japan, Kushiro, 0.25 m
3	Confirm	13:17	02:03	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- ------ ----- HANASAKI HOKKAIDO 43.3N 145.6E 1243Z 0.30M 64MIN KUSHIRO HOKKAIDO 43.0N 144.3E - 0.25M - SEA LEVEL READINGS INDICATE A TSUNAMI WAS GENERATED.
4	New meas	14:58	03:44	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- ------ ----- HANASAKI HOKKAIDO 43.3N 145.6E 1243Z 0.30M 64MIN KUSHIRO HOKKAIDO 43.0N 144.3E - 0.25M - SHEMYA ALASKA 0.20M - AMCHITKA ALASKA 0.08M -

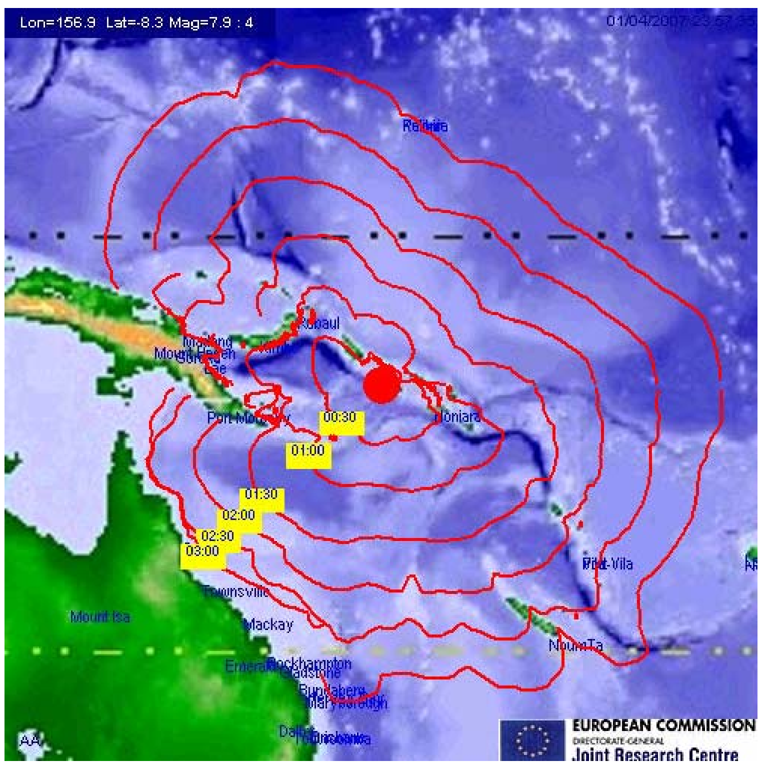
Appendix E - Solomon Island Event Report

GDACS Report on Earthquake and Tsunami in Solomon Islands

Sunday 1 April 2007

On Sunday 1 April 2007 at 20:39 UTC, an underwater earthquake of magnitude 8.1 caused a tsunami of several meters to hit the Solomon Islands. More than 10 people have been reported killed and thousands affected or injured. The international community was put on standby and offered help through OCHA. Australian beaches were evacuated.

JRC systems detected the event 16 minutes after the event, i.e. as soon as it was published by the United States Geological Survey. The event was calculated to be a Red Alert and over 3000 alerts were sent out. At least one media source reported that the GDACS alert arrived before the alert of the Pacific Tsunami Warning Centre.



Seismic event

After the initial shock 18 aftershocks with magnitude higher than 5.0 occurred nearby until the time of writing (16:00 on 2 April 2007). While only the initial shock was strong enough to generate a significant tsunami, the other earthquakes can have caused (further) damage on land, particularly to structures that were already damaged from the initial shock.

		Magnitude	Source	Event time
1		5.5	NEIC	2 Apr 2007 12:35:00 PM
2		6.1	EMSC	2 Apr 2007 12:02:00 PM
3		5.9	EMSC	2 Apr 2007 10:49:00 AM
4		5.3	NEIC	2 Apr 2007 7:16:00 AM
5		5.4	EMSC	2 Apr 2007 7:16:00 AM
6		5.7	EMSC	2 Apr 2007 4:11:00 AM
7		5.1	EMSC	2 Apr 2007 1:49:00 AM
8		5.4	EMSC	2 Apr 2007 1:36:00 AM
9		5.1	EMSC	2 Apr 2007 12:10:00 AM
10		5.4	EMSC	1 Apr 2007 11:25:00 PM
11		5.2	EMSC	1 Apr 2007 11:09:00 PM
12		5.9	EMSC	1 Apr 2007 10:57:00 PM
13		5.2	EMSC	1 Apr 2007 10:41:00 PM
14		5.4	EMSC	1 Apr 2007 10:29:00 PM
15		5.7	EMSC	1 Apr 2007 9:45:00 PM
16		5.6	NEIC	1 Apr 2007 9:26:00 PM
17		6.0	EMSC	1 Apr 2007 9:15:00 PM
18		6.7	EMSC	1 Apr 2007 8:47:00 PM
19		8.0	NEIC	1 Apr 2007 8:39:00 PM

GDACS evaluated the alert to be Red, based on the tsunami probability. A detailed report with potentially affected population was emailed 24 minutes after the event and was available on the GDCAS website, along with media monitoring and a GIS analysis of the area.

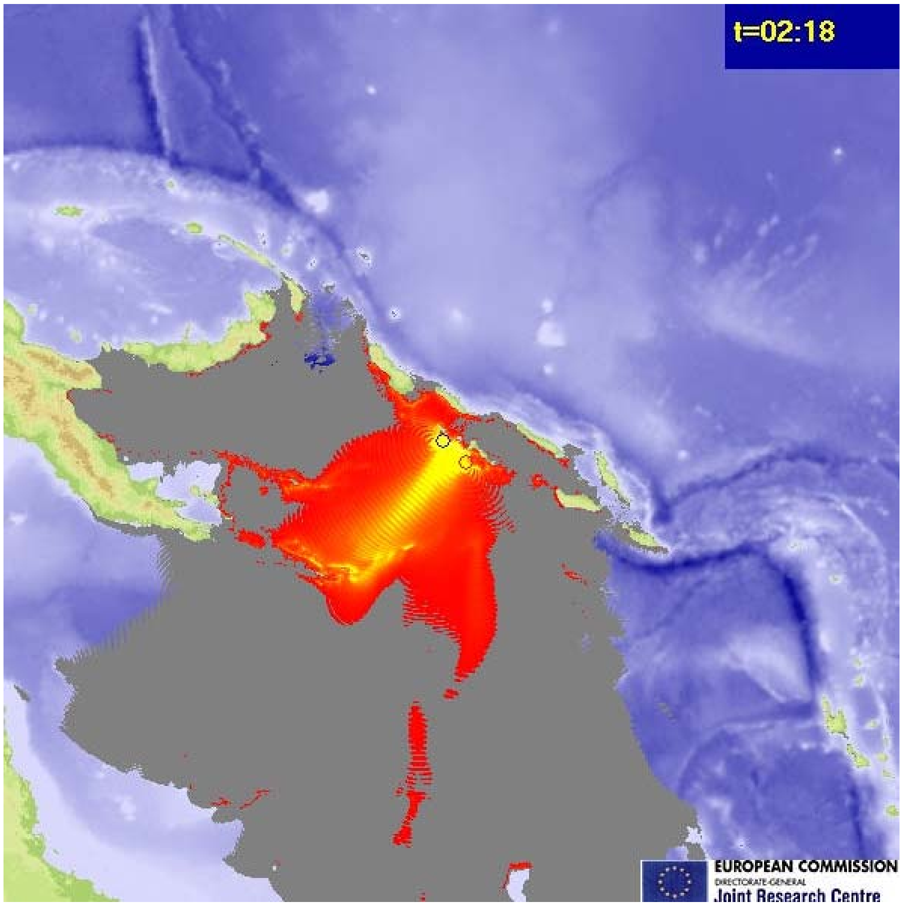
Tsunami event

The JRC Tsunami model immediately listed (16 minutes after the event and within 1 minute after the publication by USGS) the potentially affected populated places in Solomon Islands and Papua New Guinea, and published a tsunami travel time map on the GDACS website.

Subsequently, the JRC SWAN model was activated, which took 19 minutes to complete the wave height propagation model. The model calculated maximum tsunami wave heights of 3.2m in Kunji and 2.7m in Vanikuva and Harai in the Solomon Islands. For Papua New Guinea, the maximum calculated wave height was 70cm.

The tsunami was calculated to have reached shore within 3 min utes. Since the first alerts (PTWC and GDACS) were only sent out after 16 minutes they came too late to warn local population. However, several other areas in Solomon Islands and in Papua New Guinea were reached by smaller waves, but after 16 minutes.

New Zealand's Ministry of Civil Defence says the tsunami was 14cm high in Honiara and 11cm high in Vanuatu, to the south east.



Alert sequence

	UTC	Delay after event	Delay after publication by USGS	
Event	20:40:04			
PTWC alert	20:55	15min	0min	
Detected on USGS site from JRC	20:57:02	16min	1min	
Alerts sent by GDACS and JRC tsunami warning system	21:03 to 21:19	24min to 40min	9 min	1933 emails, 1249 SMS and 69 faxes sent
JRC SWAN calculation completed	21:20	40min	25min	
Human moderated alert by WAPMERR (partner of GDACS)	21:25 (overestimated damage) and 23:00 (more accurate assessment)	46min, 2h21min		
PTWC alert received at JRC	21:35	2h31min		
USGS email alerts received at JRC	22:35	3h31min		

Email alerts were sent out both by the Pacific Tsunami Warning Center and GDACS at about the same time (16 minutes after the earthquake). However, emails are not delivered immediately and they are received with often over 2h of delay. As a consequence, at least one media source [1] reported having received GDACS alerts before PTWC alerts.

Virtual OSOCC activation

The international disaster response community started activity on the GDACS Virtual OSOCC around 21:44 UTC (about 1 hour after the event).

[1] MICHAEL FIELD - Fairfax Media (http://www.stuff.co.nz/4013314a12.html), initially wrote:

> "The Pacific Tsunami Warning Center in Hawaii has not issued any warnings but the European Union/United Nations Global Disaster Alert and Coordination System says a tsunami is a high risk. "

Later, the text was updated to:

> "The Pacific Tsunami Warning Centre has issued a tsunami warning for numerous Pacific countries in cluding the Solomons, Papua New Guinea, Indonesia, Vanuatu and Australia. The centre said a tsunami watch is in force for New Zealand along with other Pacific nations like Fiji and the Cook Islands."

Appendix F - Detailed Timeline and PTWS Bulletins for Solomon Islands Event

Solomon Islands event, 1 Apr. 2007

0	event	20:40	00:00	1 apr 2007 20:40
1	M 7.8	20:55	00:15	IT IS NOT KNOWN THAT A TSUNAMI WAS GENERATED. THIS WARNING IS BASED ONLY ON THE EARTHQUAKE EVALUATION. AN EARTHQUAKE OF THISSIZE HAS THE POTENTIAL TO GENERATE A DESTRUCTIVE TSUNAMI THAT CAN STRIKE COASTLINES IN THE REGION NEAR THE EPICENTER WITHIN MINUTES TO HOURS. AUTHORITIES IN THE REGION SHOULD TAKE APPROPRIATE ACTION IN RESPONSE TO THIS POSSIBILITY. THIS CENTER WILL MONITOR SEA LEVEL GAUGES NEAREST THE REGION AND REPORT IF ANY TSUNAMI WAVE ACTIVITY IS OBSERVED. THE WARNING WILL NOT EXPAND TO OTHER AREAS OF THE PACIFIC UNLESS ADDITIONAL DATA ARE RECEIVED TO WARRANT SUCH AN EXPANSION.
SWAN	M 7.7	20:56	00:16	Starts SWAN calculation n.1
		21:20	00:41	JRC-SWAN Calculation completed Last SWAN calculated values Harsi 1.9 m Vanikuva 2.2 m Kunji 1.5 m Honiara 0.1 m etc
2	M 8.1	21:32	00:52	IT IS NOT KNOWN THAT A TSUNAMI WAS GENERATED. THIS WARNING IS BASED ONLY ON THE EARTHQUAKE EVALUATION. AN EARTHQUAKE OF THIS SIZE HAS THE POTENTIAL TO GENERATE A DESTRUCTIVE TSUNAMI THAT CAN STRIKE COASTLINES NEAR THE EPICENTER WITHIN MINUTES AND MORE DISTANT COASTLINES WITHIN HOURS.
SWAN		21:33		New SWAN Calculation
	EXP	21:37	00:57	Honiara 0.15 m
	SWAN ENDs	21:45		End SWAN calculation: Judaea 3.5m, Au 3.5 m, Vanikuva 3.5 m, Kunji 3.5 m
3	Confirm	22:39	01:59	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY HONIARA 15CM ZERO-TO-PEAK OBSERVED AT 21:37 GMT SEA LEVEL READINGS INDICATE A TSUNAMI WAS GENERATED.
4	New meas	2/4 00:13	03:33	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- --------------- ----- HONIARA SB 9.4S 160.0E 2235Z 0.14M = 0.5FT 70MIN VANUATU VU 17.8S 168.3E 2351Z 0.11M = 0.4FT 26MIN
5	New meas	2/4 1:17	04:37	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- --------------- ----- HONIARA SB 9.4S 160.0E 2308Z 0.20M = 0.6FT 62MIN VANUATU VU 17.8S 168.3E 2351Z 0.12M = 0.4FT 26MIN
6	New meas	2/4 1:58	05:18	MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- --------------- ----- MANUS PG 2.0S 147.4E 0040Z 0.09M = 0.3FT 40MIN VANUATU VU 17.8S 168.3E 0114Z 0.14M = 0.5FT 28MIN HONIARA SB 9.4S 160.0E 2308Z 0.20M = 0.6FT 62MIN
7	New meas	2/4 3:26		GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- --------------- ----- PORT KEMBLA AU 34.5S 150.9E 0244Z 0.05M = 0.2FT 14MIN VANUATU VU 17.8S 168.3E 0124Z 0.15M = 0.5FT 22MIN CAPE FERGUSON AU 19.3S 147.1E 0135Z 0.11M = 0.4FT 12MIN MANUS PG 2.0S 147.4E 0040Z 0.09M = 0.3FT 40MIN HONIARA SB 94S 160.0E 2308Z 0.20M = 0.6FT 62MIN
8	New meas	2/4 4:05		GAUGE LOCATION LAT LON TIME AMPL PER ------------------- ----- ------ ----- --------------- ----- KINGS WHARF FJ 18.1S 178.4E 0207Z 0.04M = 0.1FT 38MIN PORT KEMBLAO AU 34.5S 150.9E 0244Z 0.05M = 0.2FT 14MIN VANUATU VU 17.8S 168.3E 0124Z 0.15M = 0.5FT 22MIN CAPE FERGUSON AU 19.3S 147.1E 0135Z 0.11M = 0.4FT 12MIN MANUS PG 2.0S 147.4E 0040Z 0.09M = 0.3FT 40MIN HONIARA SB 9.4S 160.0E 2308Z 0.20M = 0.6FT 62MIN

European Commission

EUR 23063 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen
Title: The JRC Tsunami Assessment Modelling System
Author(s): A. Annunziato
Luxembourg: Office for Official Publications of the European Communities
2007 – 54 pp. – x cm
EUR – Scientific and Technical Research series – ISSN 1018-5593

Abstract
This report describes the JRC Tsunami Assessment Tool, which is a complex computer arrangement whose objective is to predict a Tsunami's behaviour when minimal parameters are known, which is the condition when an earthquake is firstly measured. Therefore knowing the position of the earthquake (lat/lon) and the Magnitude of the event, the programme will calculate the fault characteristics, the Tsunami generation and displacement, and the identification of the location on the coast which will be most likely affected.

How to obtain EU publications

Our priced publications are available from EU Bookshop (http://bookshop.europa.eu), where you can place an order with the sales agent of your choice.

The Publications Office has a worldwide network of sales agents. You can obtain their contact details by sending a fax to (352) 29 29-42758.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

EUROPEAN COMMISSION

Publications Office
Publications.eu.int