TSUNAMI QUANTIFICATION

HOW WE MEASURE THE OVERALL SIZE OF TSUNAMI (REVIEW OF TSUNAMI INTENSITY AND MAGNITUDE SCALES)

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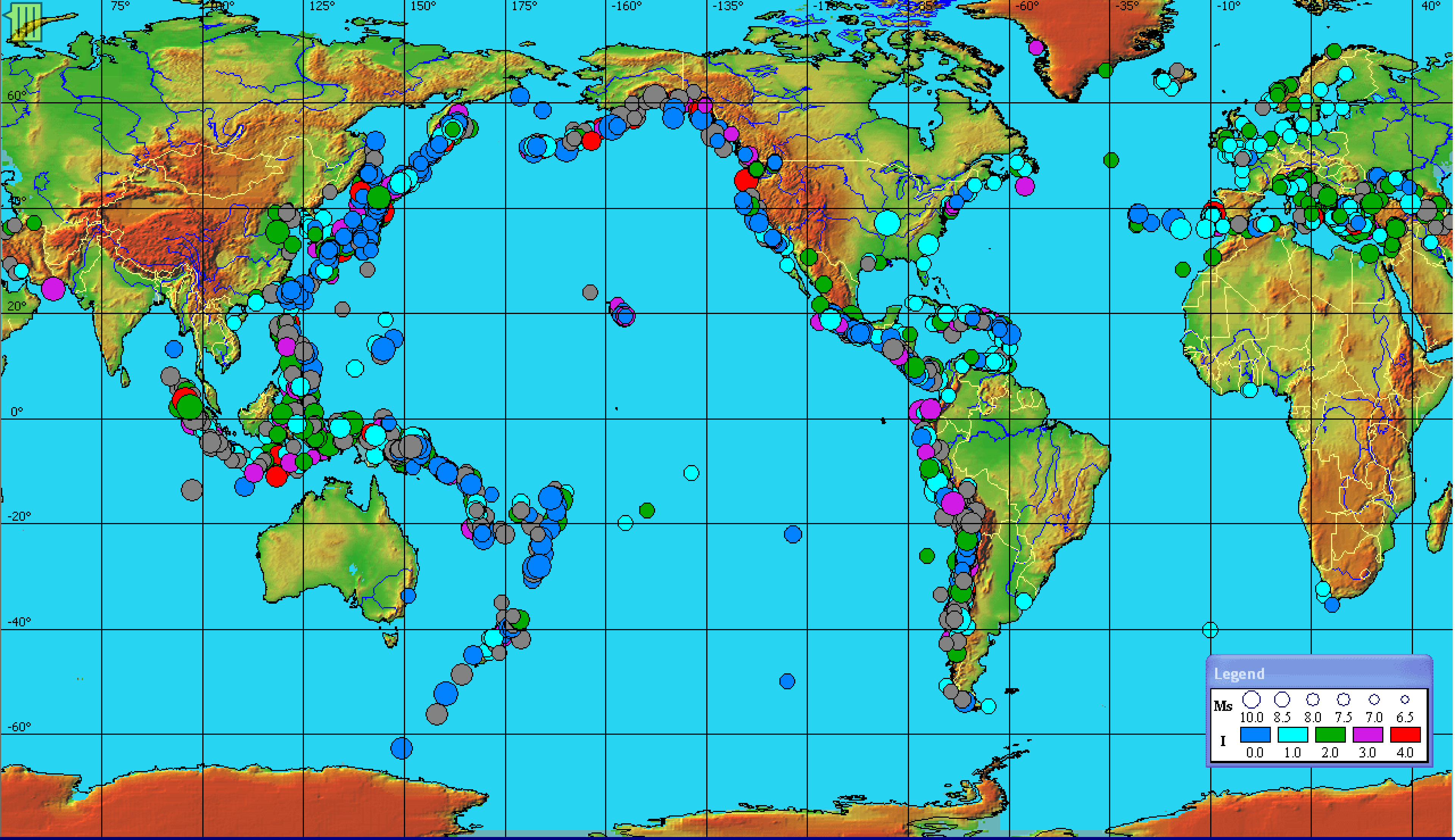
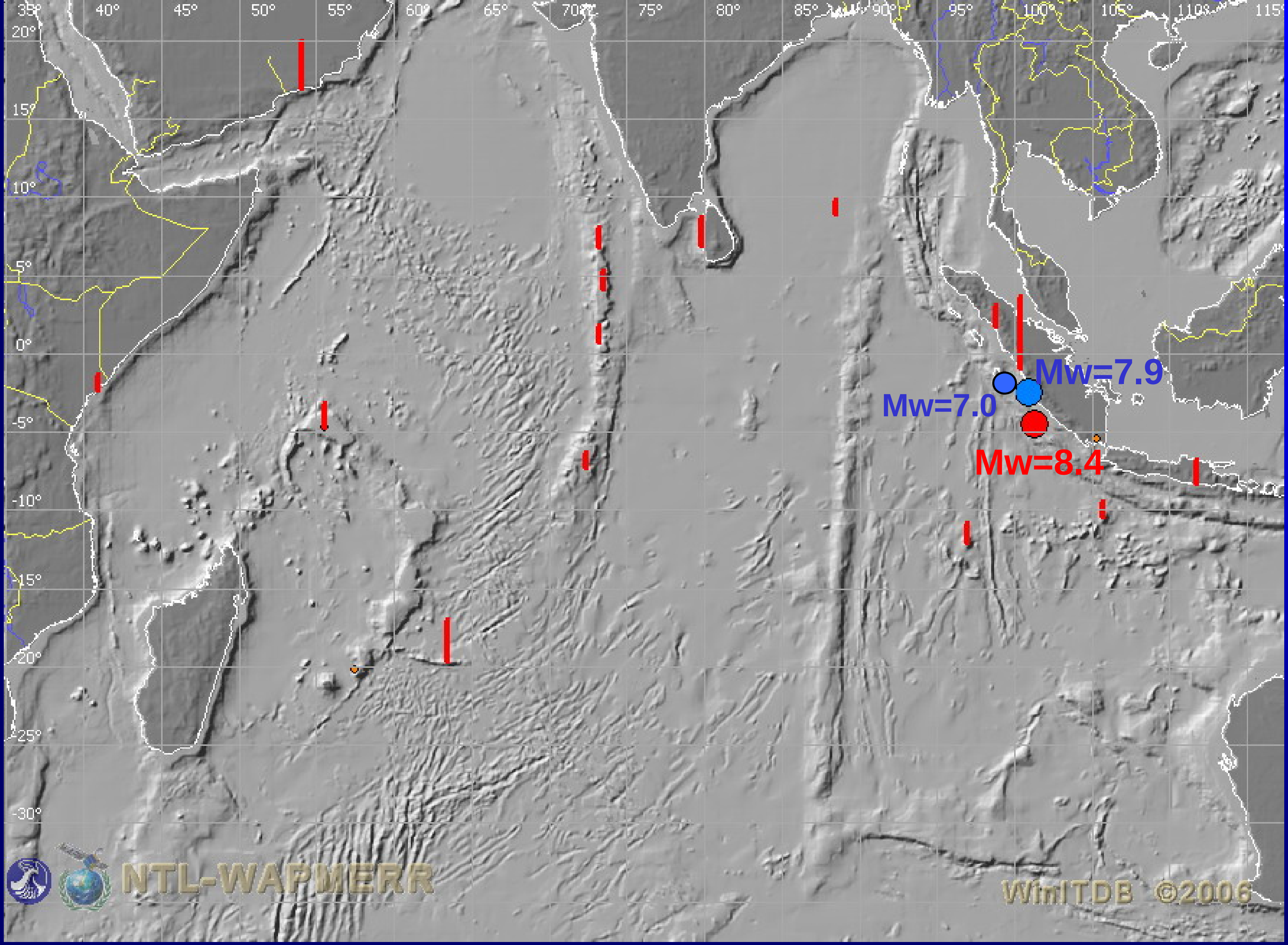
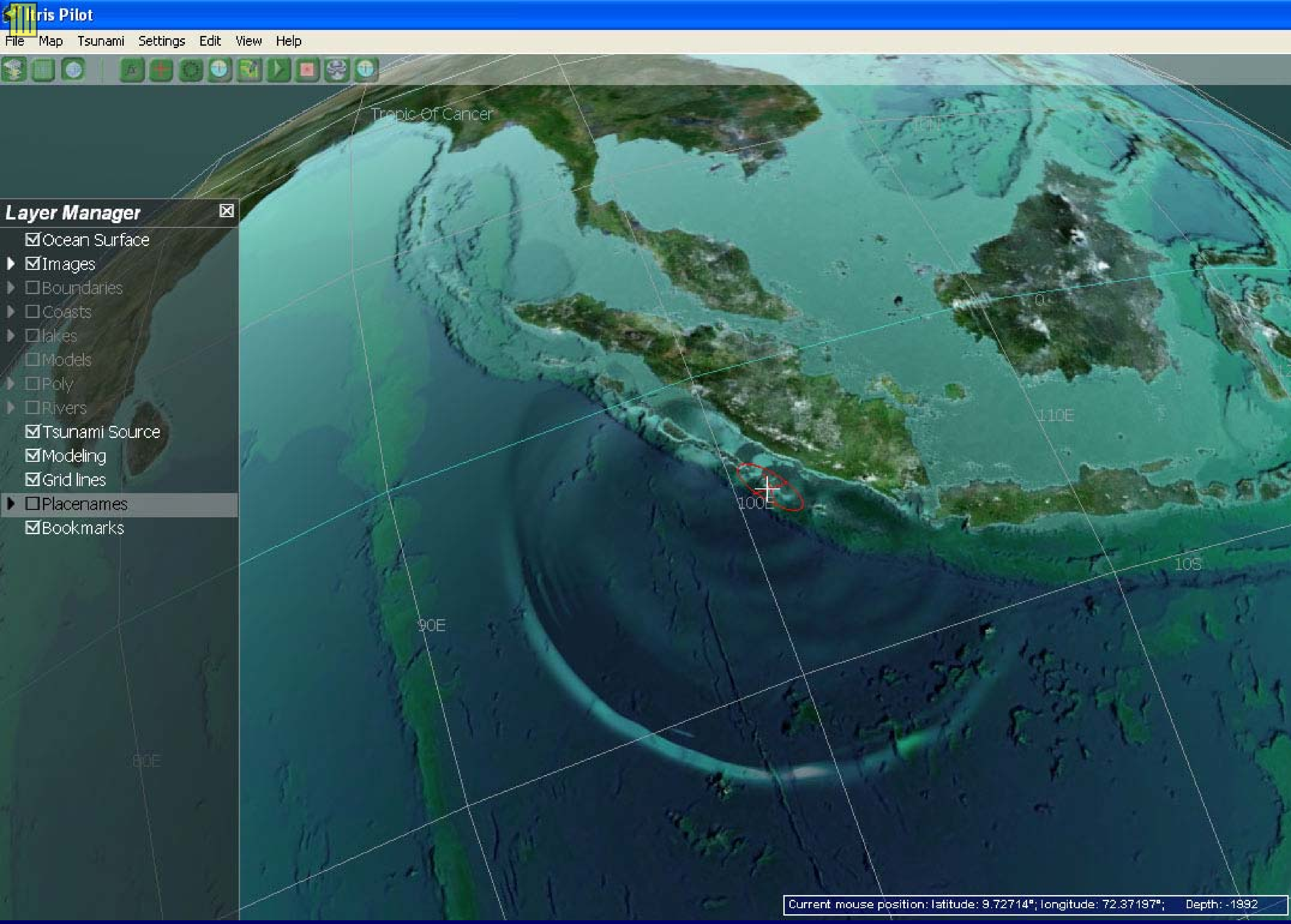


Global historical tsunami database covers the period from 2000BC to 2007, contains **2275 records in total, 2120 events with V=1-4)**



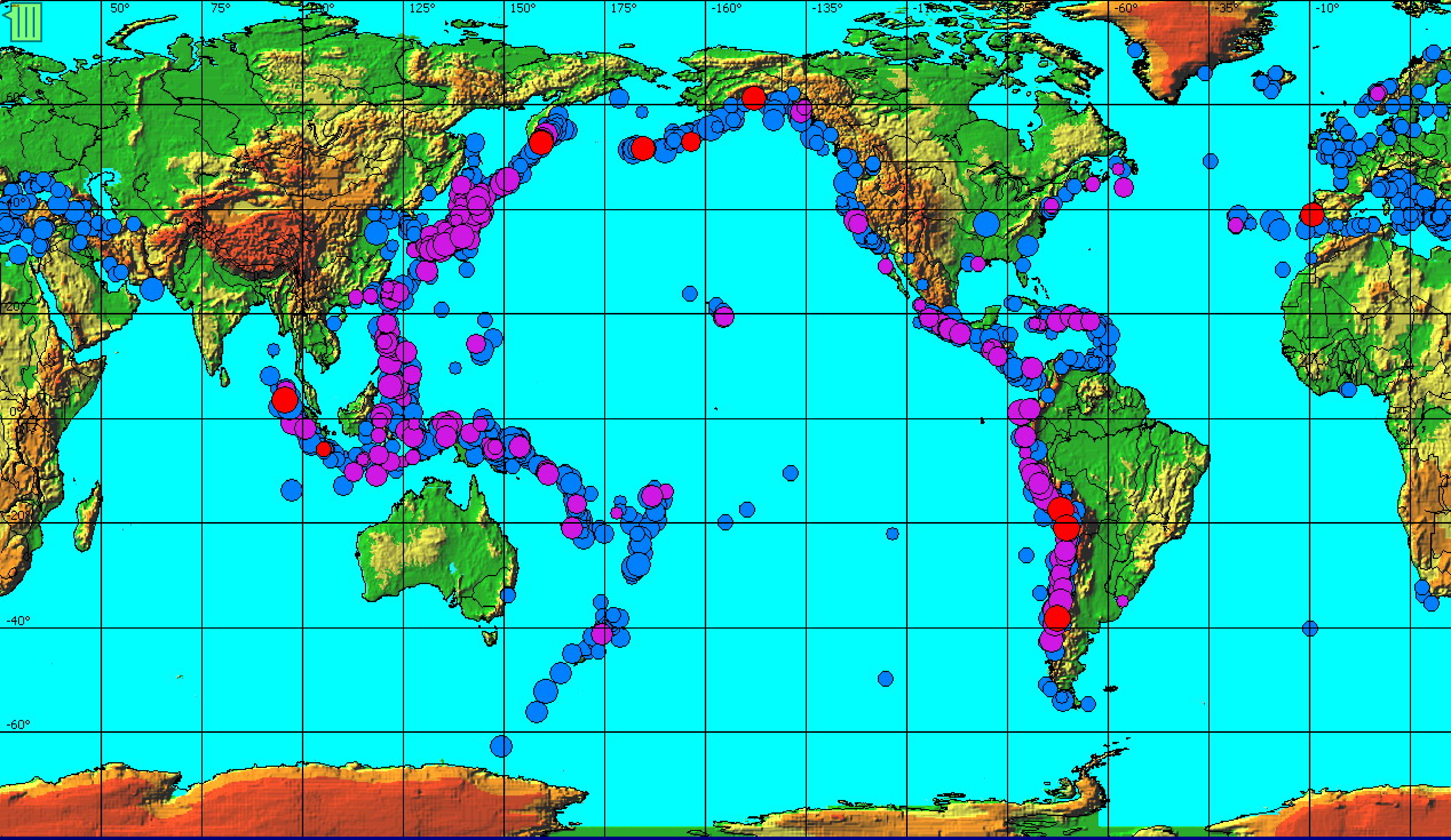
Source position and tide-gauge records of September 12, 2007 earthquakes



Numerical modeling of the September 12, 2007 Sumatra Tsunami

Three groups of top-ten largest tsunamis as compared by different parameters

Ten trans-oceanic tsunamis (H>5m at D>5,000km), sorted by N_{RN}	Top-ten tsunamis with highest run-up, sorted by H_{max}	Top-ten tsunamis with largest fatalities, sorted by N_{FAT}
630 1960 Chile	525m 1958 Lituya Bay	229,866 2004 Sumatra
577 2004 Sumatra	150m 1936 Lituya Bay	36,417 1883 Krakatau
478 1946 Aleutians	120m 1854 Lituya Bay	30,000 1755 Lisbon
392 1964 Alaska	88m 1788 Aleutians	30,000 1707 Nankaido
340 1952 Kamchatka	85m 1771 Ishigaki Is.	27,122 1896 Sanriku
322 1957 Aleutians	80m 1674 Indonesia	26,000 1498 Enshunada
115 1868 Chile	70m 1936 Norway	15,000 1741 Osima
49 1755 Lisbon	68m 1964 Alaska	13.486 1771 Ishigaky Is.,
39 1923 Kamchatka	63m 1737 Kamchatka	12,000 1952 Kamchatka
23 1837 Chile	62m 1934 Norway	10,000 1765 Guanzhou



Map of known historical tsunami sources. All the events are divided into three groups: red - transoceanic tsunami (10), magenta –regional tsunamis resulted in human fatalities (230), blue - non-fatal tsunamis (1880).

One of the main problems in catalogization of historical tsunamis is the measure of the overall "size" or "force" of an event. To compare different tsunamigenic events, we need some scale to measure them.

In general, there are two types of scales for measuring the "size" of a hazardous natural phenomenon – the magnitude scale and the intensity scale. The magnitude scale relates to the source of an event, while the intensity scale describes the resulted effect at impact locations.

Examples of magnitude scales

Richter scale for earthquakes (0 – 10)
VEI scale for volcanic eruptions (1 -9)
Saffir-Sympson hurricane scale (1 – 5)

Examples of intensity scales

Mercally scale for seismic shaking (I –XII)
Beaufort wind scale (0 – 10)

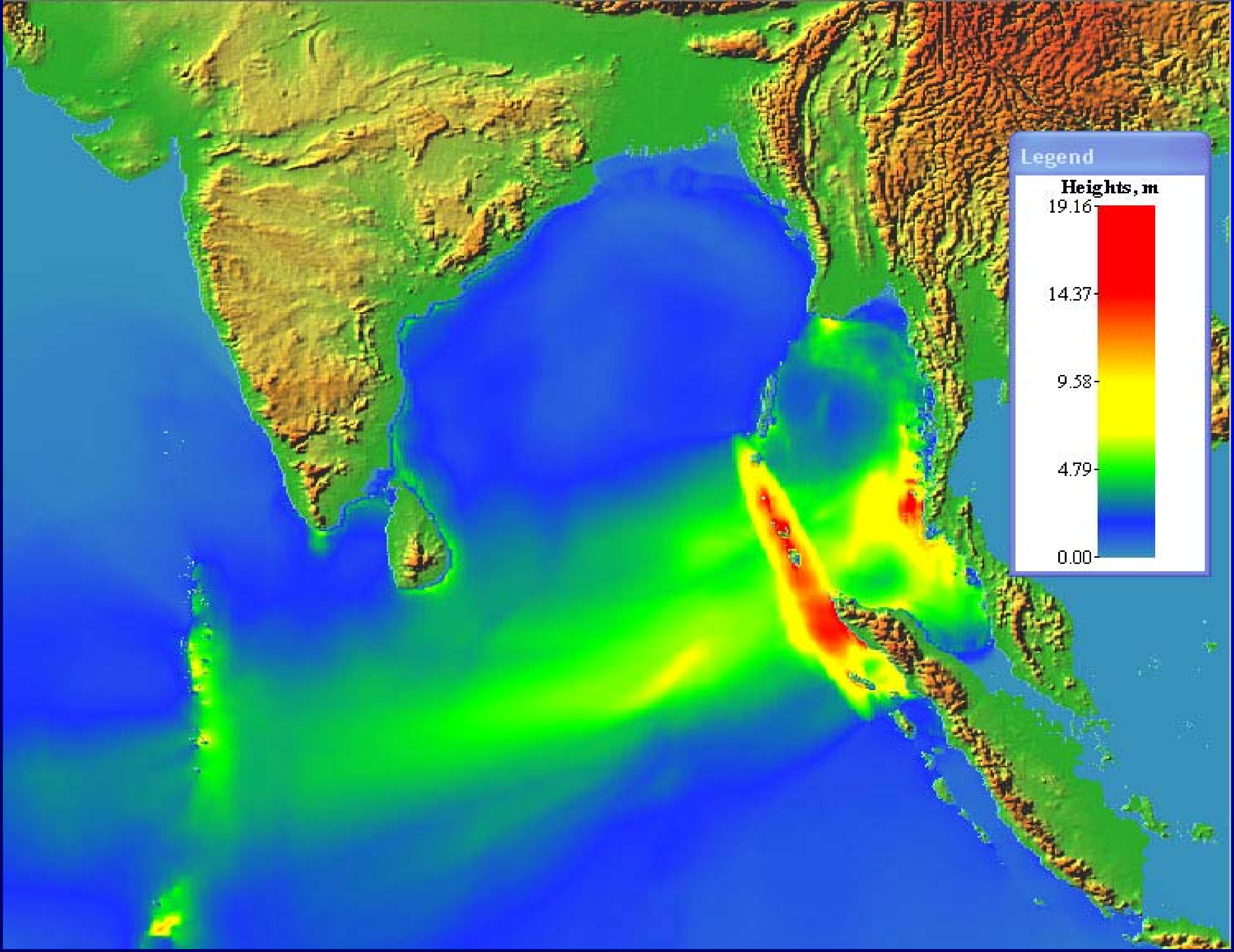
Both scales can be descriptive, based on descriptive characteristic of some "grades", or quantitative, based on the value of some measurable physical parameter.

The best parameter to estimate the size of different tsunamis would be their total energy. This true magnitude-type scale was proposed by T.Murty and H.Loomis (Murty, Loomis, 1980). Their *ML* value is defined as

$$ML = 2\,(\log E - 19),$$

where *E* is the tsunami energy (in ergs).

n the original publication (Murty, Loomis, 1980), *ML* values were determined for about 25 largest Pacific tsunamis, since that time almost no new calculations of *ML* were made. The reason is that the *ML* value is not easy to calculate since it requires knowledge of initial displacement in a tsunami source or tsunami waveforms at different locations and azimuths, that is not always possible for real tsunamis.



Maximum wave height distribution for the 2004 Indian Ocean tsunami

Historically, the first scale proposed for measuring a tsunami was the Sieberg scale (Sieberg, 1927). It was a descriptive 4-grade scale, based on the destructive effect of a tsunami, and it did not include any quantitative measures of tsunami wave height. N.Ambraseys (Ambraseys, 1962) slightly modified this scale, making it 6-grade, by dividing the upper grade into three additional steps.

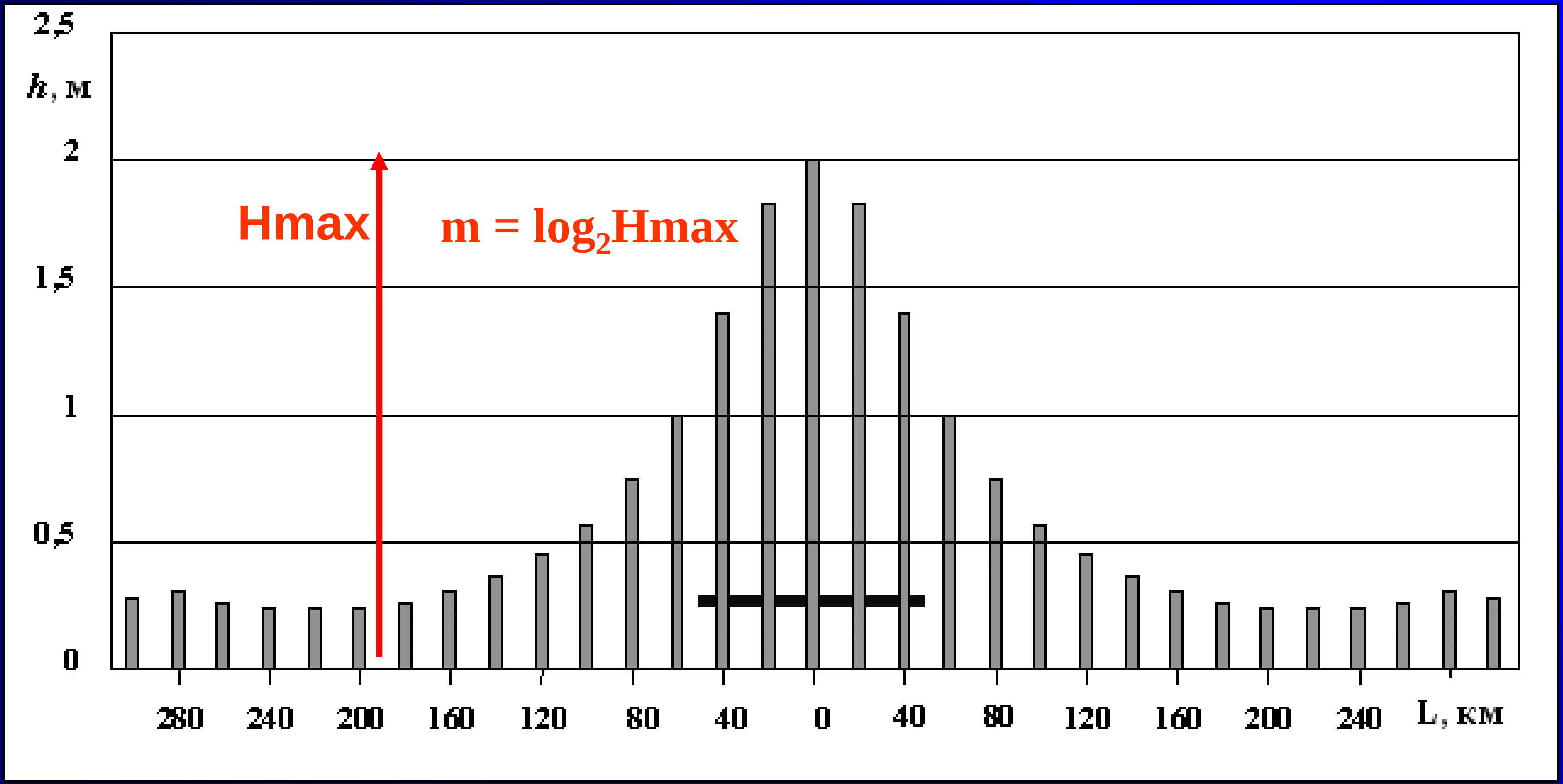
Sieber-Ambraseys scale is a typical examples of the intensity scale, because is based exceptionally on the effects of tsunami manifestation at the coast. However, from the very beginning it was used for characterization of overall size of a tsunami (i.e. as magnitude scale) by assigning to a tsunamigenic event its maximum observed intensity at the coast. In p**ractice, it was mainly applied for quantifications of the Mediterranean tsunamis.**

In the Pacific, A.Imamura (Imamura, 1942) was the first who proposed a 5-grade descriptive scale, but the description of each grade contained some quantitative parameters – run-up height and extension of the coast flooded by tsunami. A.Imamura called it *tsunami magnitude* scale, although this was a typical *intensity* scale, since it was based on the effects of tsunami manifestation at the coast and did not contain any correction for a source distance.

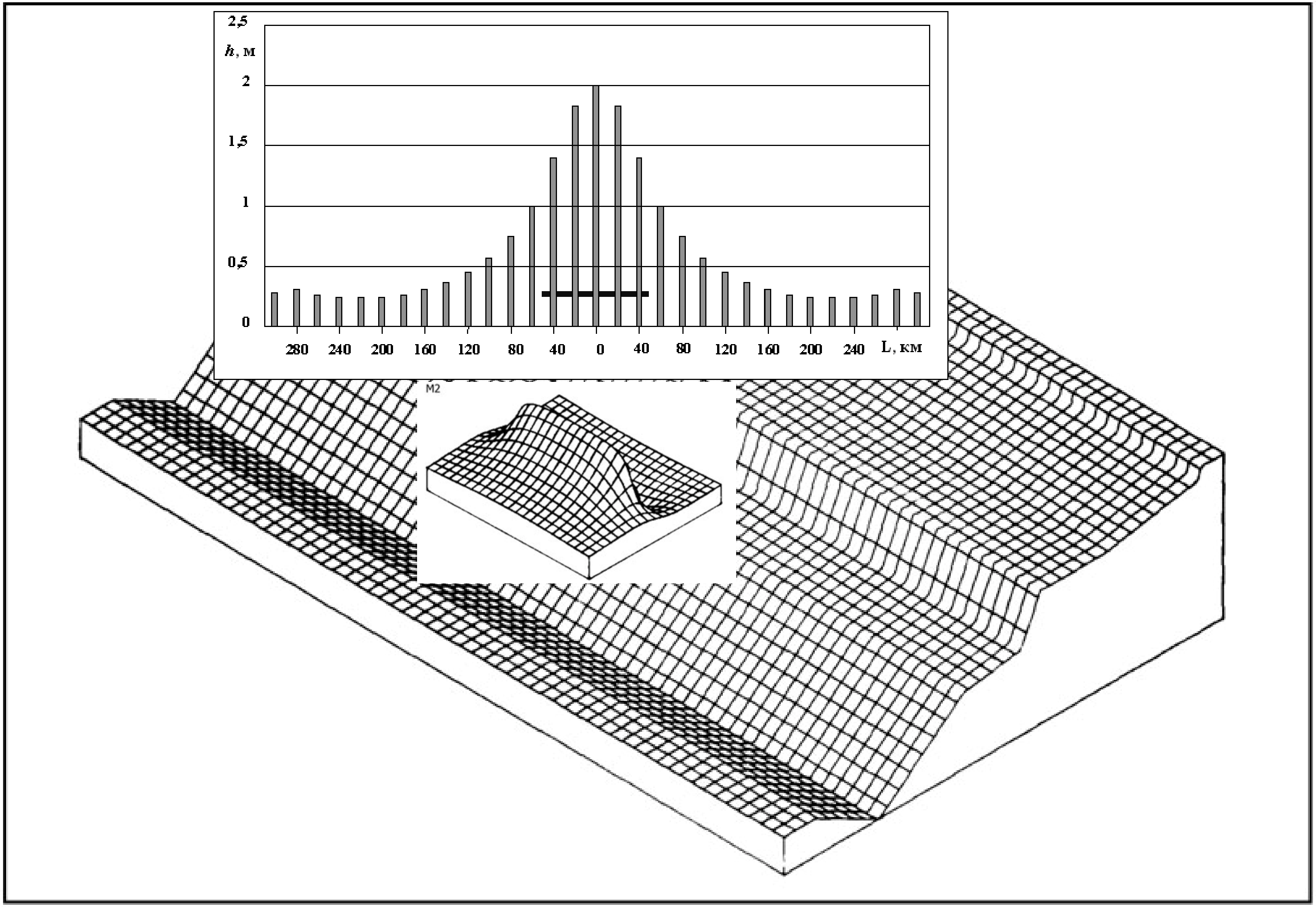
Later K.Iida (Iida, 1963) modified this scale by adding one additional grade (m=-1) for characterization of weak tsunamis. He also directly connected the grade number *m* with a maximum observed run-up value at the coast *Hmax* by the formula

$$m = \log_2 H_{max}$$

This so-called Imamura-Iida intensity scale was widely used in catalogization of historical Pacific tsunamis.



Typical distribution of tsunami run-up heights along the coast calculated for seismic source equivalent to a magnitude 7.5 submarine earthquake for a model bottom relief typical for Island arc regions

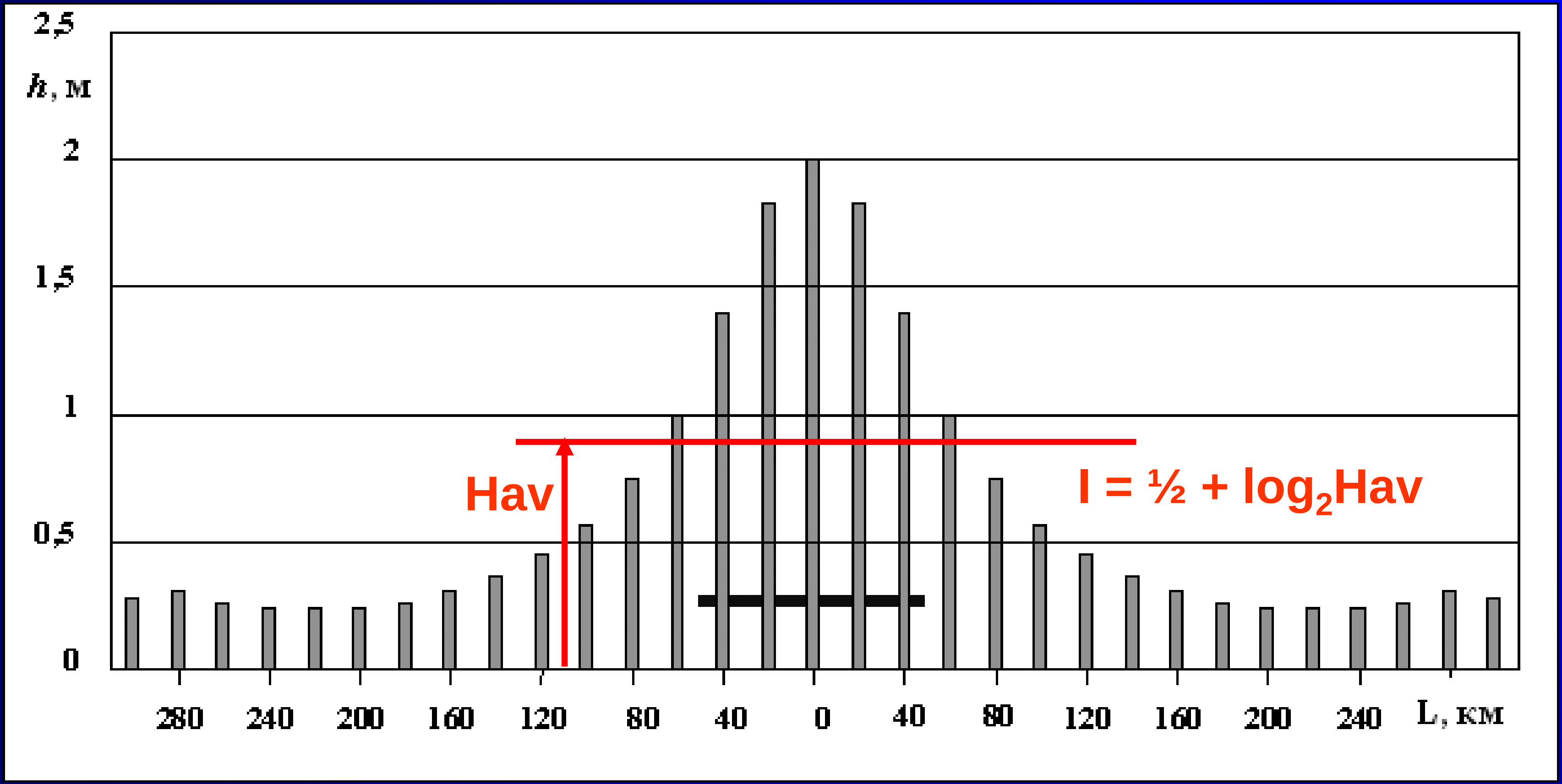


Model bottom relief for a typical subduction area

Important modification of this scale was made by S.Soloviev (Soloviev, 1972), who proposed to calculate the tsunami intensity *I* according to the formula

$$I = \tfrac{1}{2} + \log_2 Hav,$$

where *Hav* is the *average* wave height along the nearest coast, arguing that this value is a more steady characteristic of a tsunami and closer relates to the total tsunami energy radiated from a source. In this scale, S.Soloviev evaluated the intensity for a large number of Pacific tsunamis during the compilation of his catalogs. The *I* scale is also used in the NGDC/NOAA and NTL/ICMMG global tsunami databases as the main parameter characterizing the tsunami size.



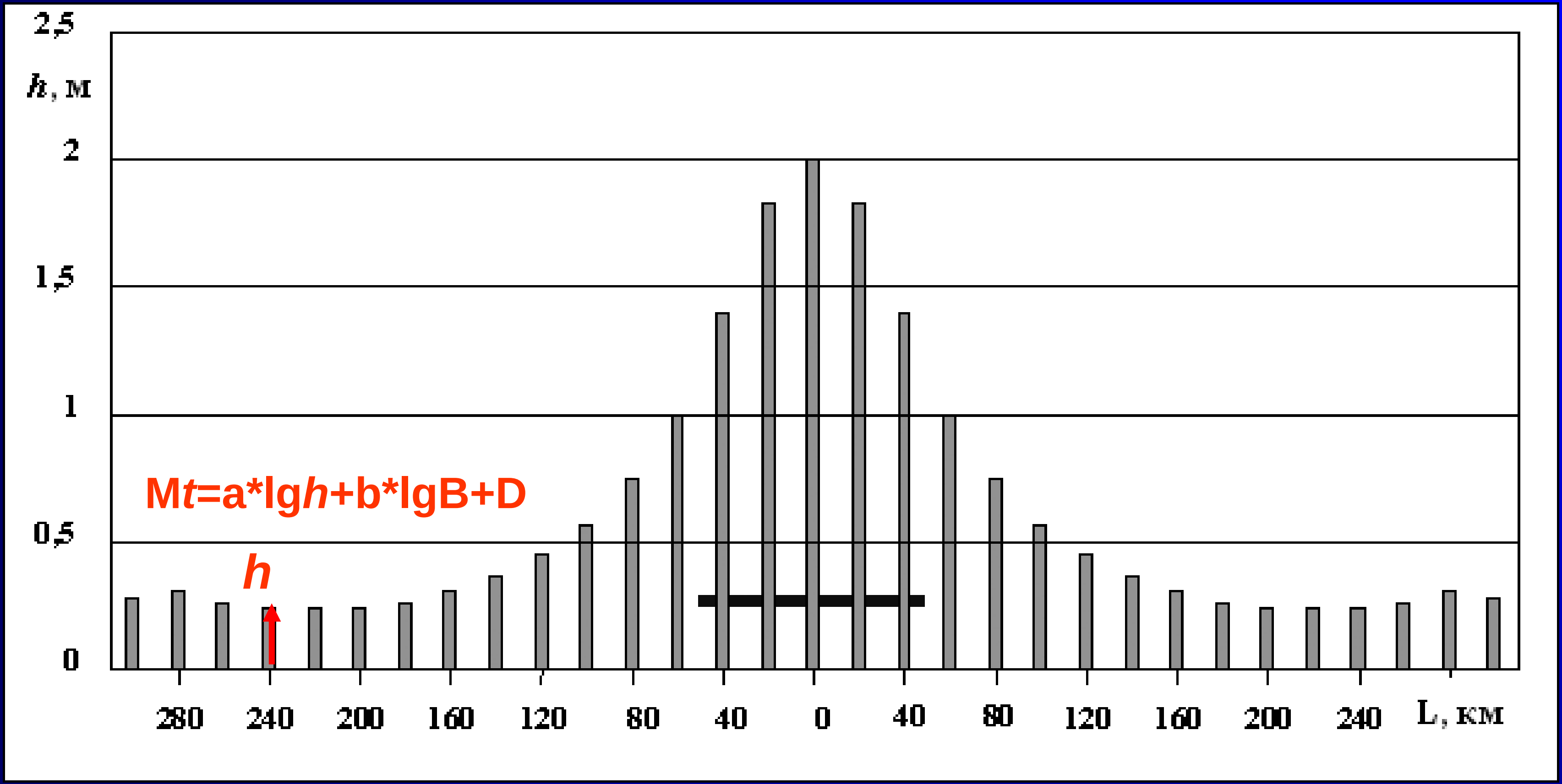
Typical distribution of tsunami run-up heights along the coast calculated for seismic source equivalent to a magnitude 7.5 submarine earthquake for a model bottom relief typical for Island arc regions

A new, tsunami magnitude scale *Mt*, based on instrumental measurement of tsunami height, was introduced in 1979 by K.Abe (Abe, 1979, 1981) who proposed calculate it based on a maximum amplitude of tsunami waves that were recorded by tide-gauges according to the formula

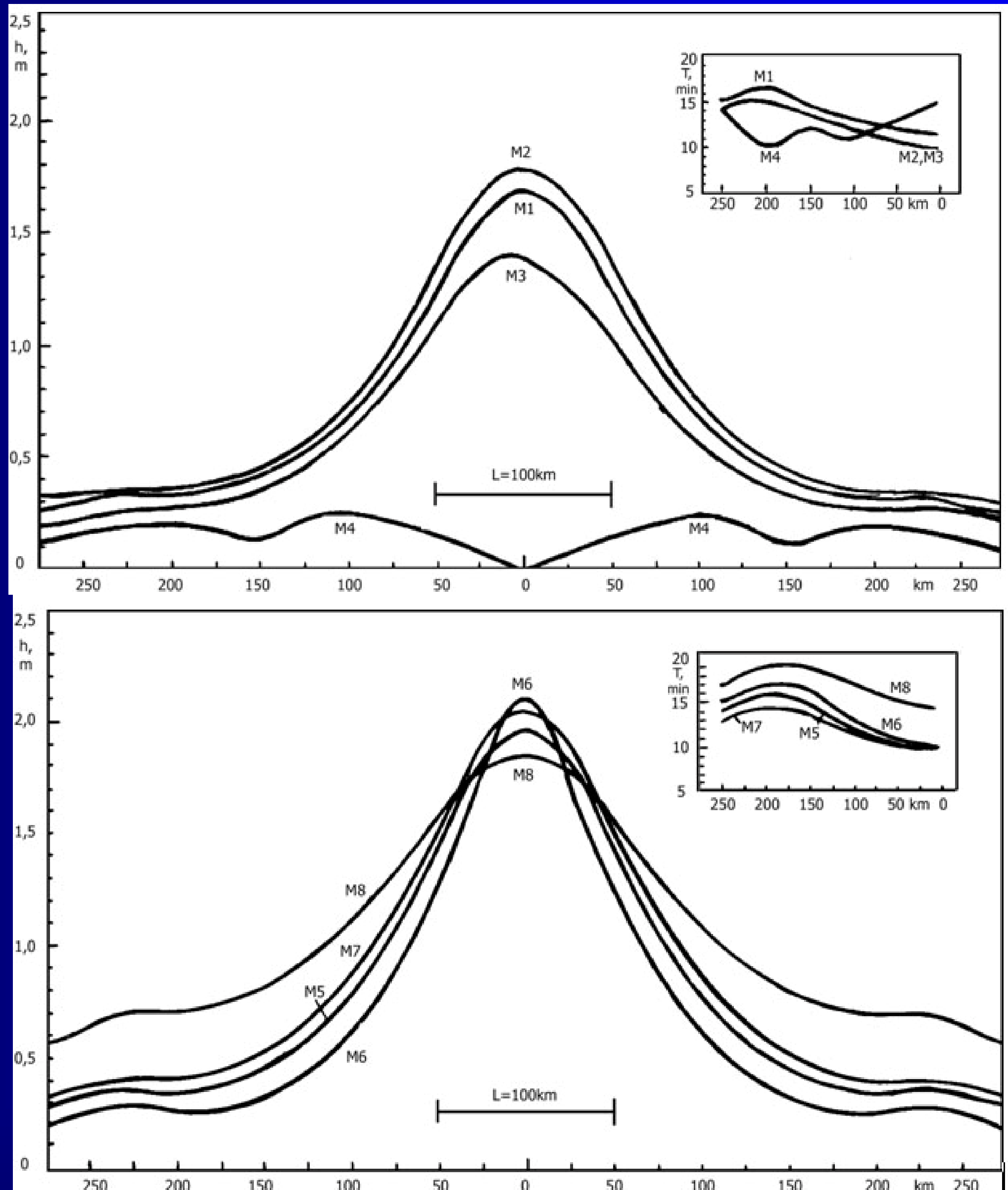
$$Mt = a \lg h + b \lg R + D,$$

where *h* is a maximum tsunami-wave amplitude (in m) measured by tide gauge, *R* is the epicentral distance (in km) and a, b and D are constants that are determined to make *Mt* scale closely related to *Mw* (moment-magnitude) scale. This is a real magnitude scale since it is based on the quantitative parameters (instrumental wave height) and includes the correction for a propagation distance.

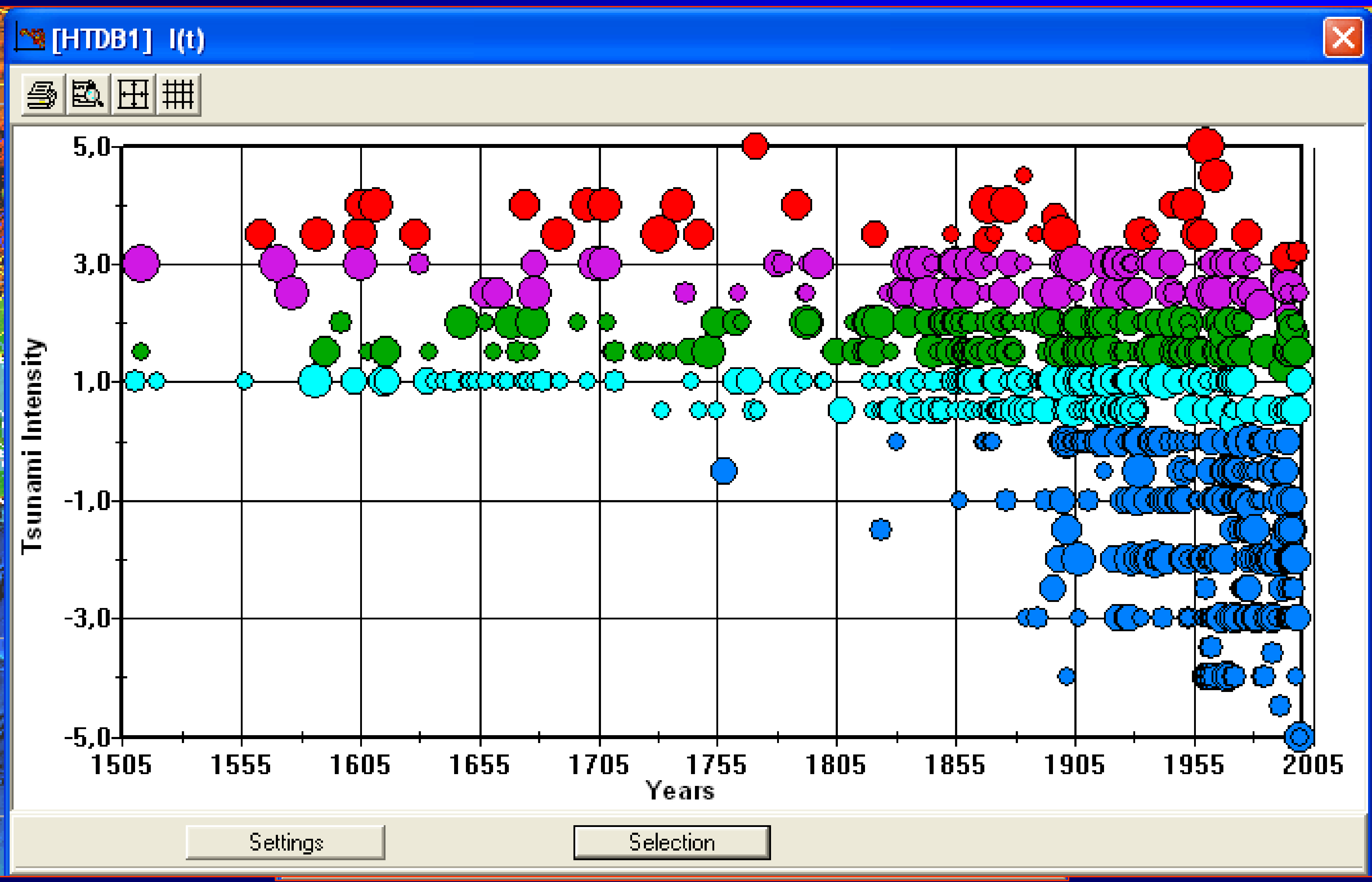
Important: *R* should be more than 100 km from a source



Typical distribution of tsunami run-up heights along the coast calculated for seismic source equivalent to a magnitude 7.5 submarine earthquake for a model bottom relief typical for Island arc regions



Run-up height distribution along the coast for different type of the tsunamigenic earthquake sources


[HTDB1] I(t)
Tsunami Intensity
5,0
3,0
1,0
-1,0
-3,0
-5,0
1505
1555
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1955
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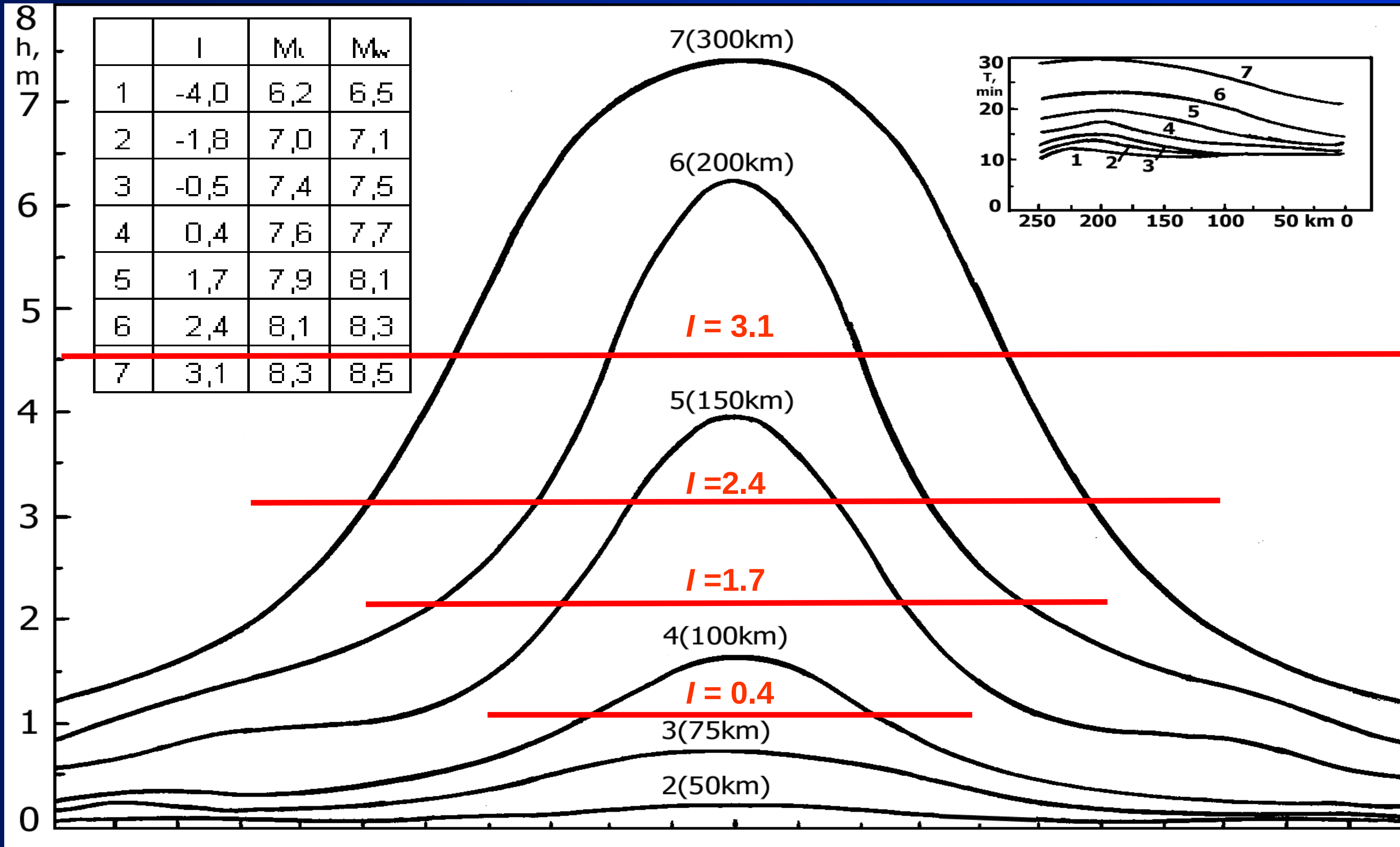
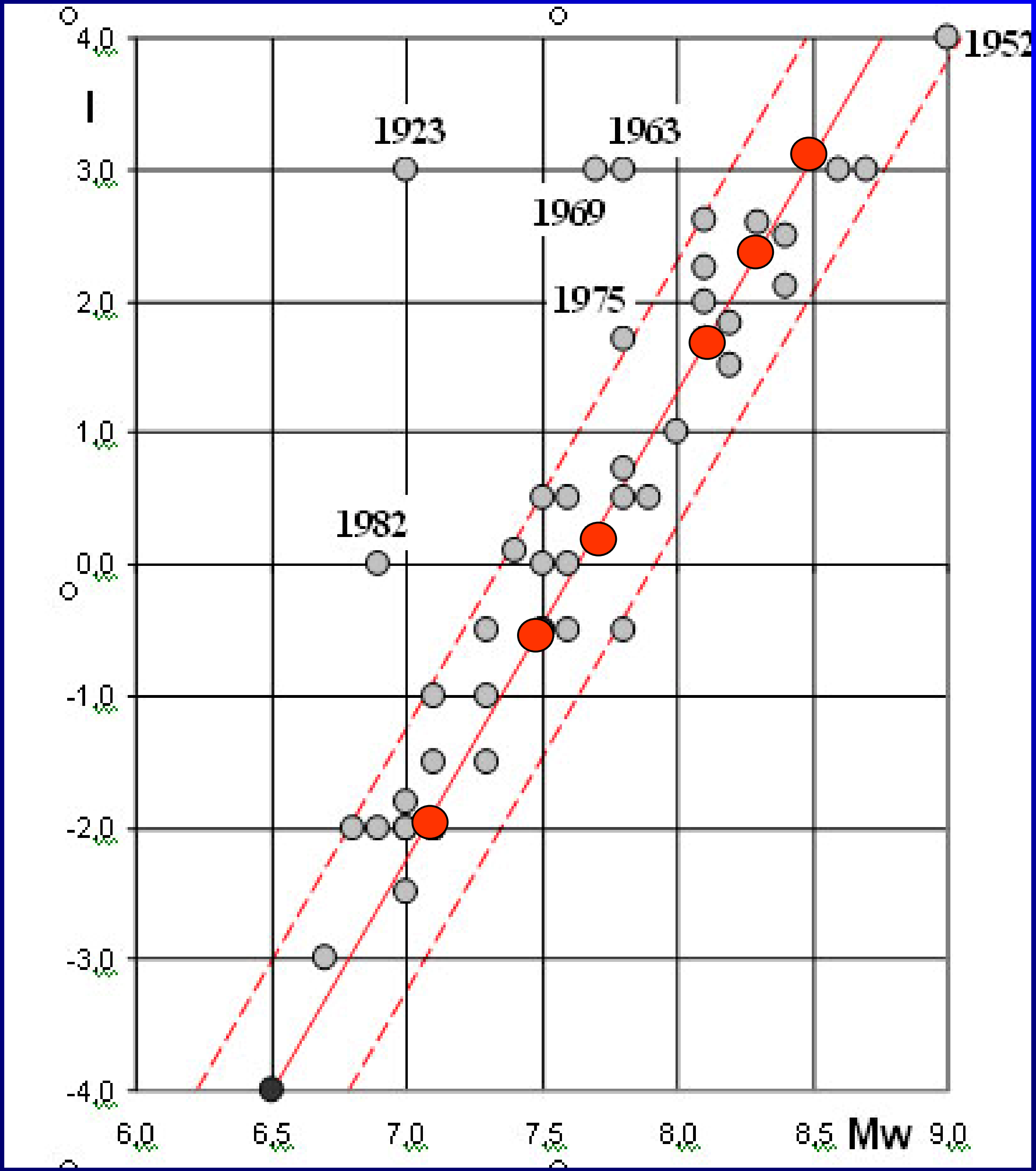
Years
Settings
Selection

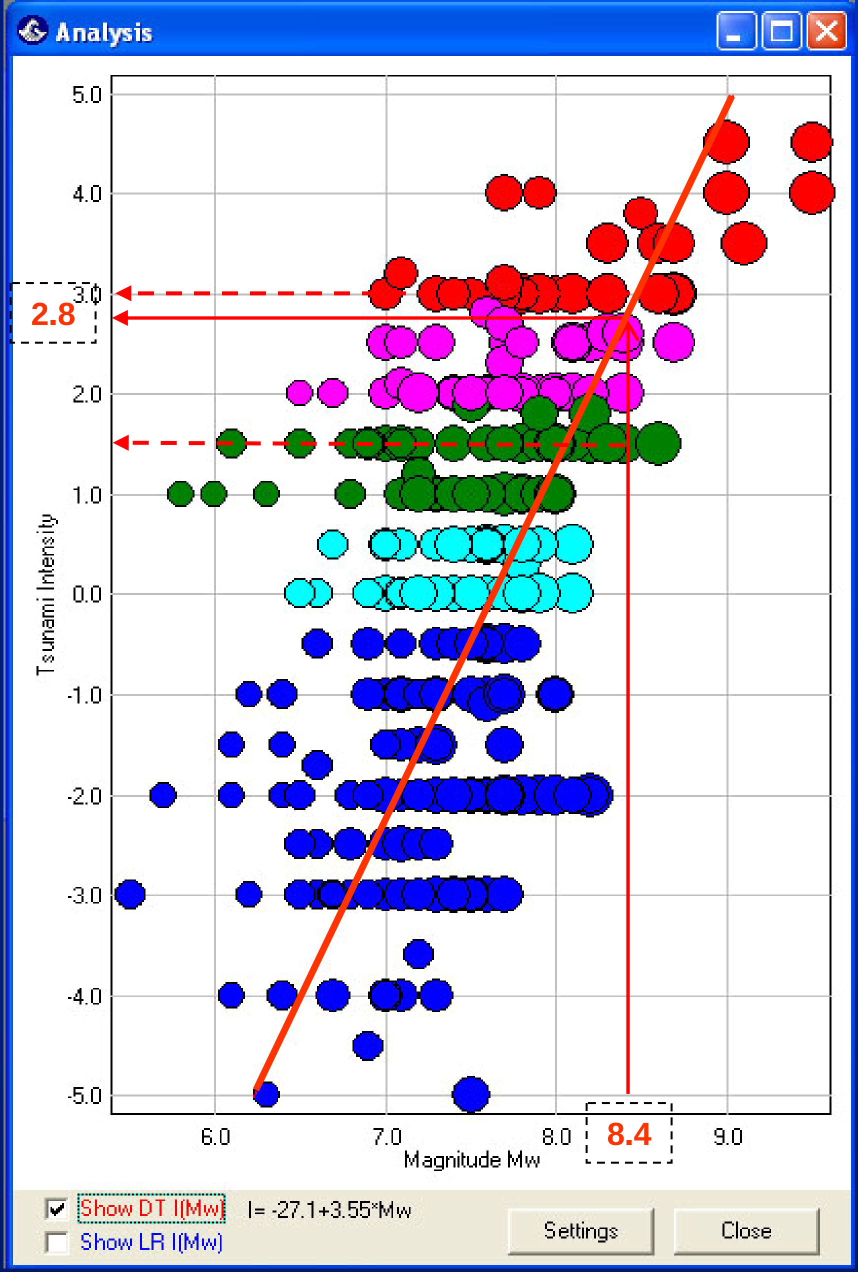


	I	Mt	Mw
1	-4,0	6,2	6,5
2	-1,8	7,0	7,1
3	-0,5	7,4	7,5
4	0,4	7,6	7,7
5	1,7	7,9	8,1
6	2,4	8,1	8,3
7	3,1	8,3	8,5

Distribution of tsunami run-up heights along the coast calculated for seismic sources with different magnitudes Mw

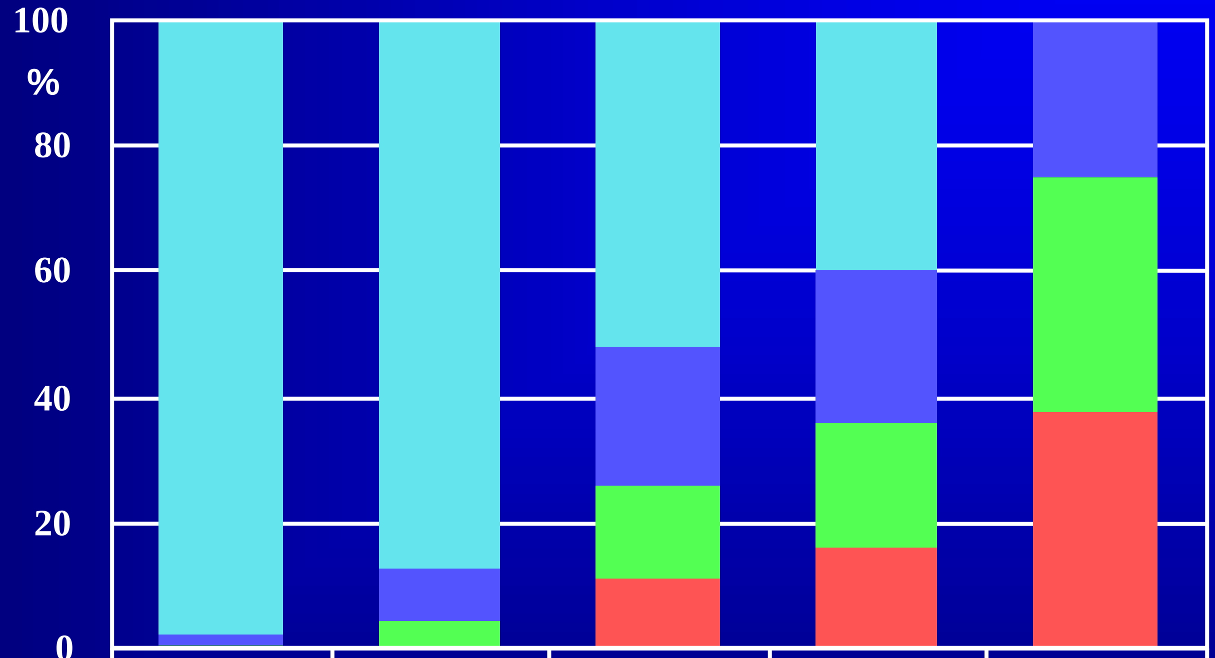


I(Mw) diagram from (Chubarov, Gusiakov, 1985) with the data for Kurile-Kamchatka region overlaid



Dependence of tsunami intensity *I* on magnitude M_w for the tsunamigenic earthquakes occurred in the World Ocean in 1900-2007

Fraction of tsunamigenic events occurred in the Pacific in 1990-2000 in the different magnitude intervals



	6.0-6.4	6.5-6.9	7.0-7.4	7.5-7.9	8.0-9.5
no tsunami.	233	76	24	10	0
I<-0.5	4	7	10	6	2
-0.5<=I<=1.5	1	4	7	5	3
I>1.5	0	0	5	4	3

Conclusions

- **Among all the existing tsunami magnitude and intensity scales, the Soloviev-Imamura scale *I* is the most appropriate scale allowing to compare different tsunamis by their “size” or “force”**

- **For the “typical” subduction zone tsunamigenic earthquakes, it rather closely correlates to the moment-magnitude of an earthquake**

- **Calculation of the *I* value cannot be formally defined and always involves some “expert knowledge”**

- **Large difference (more than 2) between tsunami magnitude *m* and tsunami intensity *I* may be an indicator of involvment of secondary mechanism (slides or slumping) in the tsunami generation process**