TSUNAMI HISTORY - RECORDED

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Introduction

Historical data on tsunami occurrence and coastal run-up are important for basic understanding of the tsunami phenomenon, its generation, propagation and run-up processes, its damaging effects. Such data are widely used for evaluating tsunami potential of coastal areas and for determining of the degree of tsunami hazard and risk for use in coastal-zone management and disaster preparedness. Also, historical data are of a critical importance for real-time evaluation of underwater earthquakes by the operational Tsunami Warning Centers, for the establishment of thresholds for issuing tsunami warnings and for design criteria for any tsunami-protective engineering construction.

In terms of documented total damage and loss of human lives, tsunamis do not come first among other natural hazards. With an estimated 700,000 fatalities, resulted from tsunamis for all historical times (Gusiakov et al., 2007), they rank fifth after earthquakes, floods, typhoons and volcanic eruptions. However, because they can affect densely populated and usually well-developed coastal areas, tsunamis can have an extremely adverse impact on the socioeconomic infrastructure of society, which is strengthened by their full suddenness, terrifying rapidity, and their potential for heavy destruction of property and high percentage of fatalities among the population exposed to their action.

There is evidence that tsunami as a catastrophic natural phenomenon has been known by humankind since antiquenty. Many languages have of a special word for this type of disaster coming from the sea - *tidal waves, seismic sea waves* (English), *raz de maree, vagues sismiques* (French), *flutwellen* (German), *maremoto* (Spanish), *vlogengolden* (Holland), *tsunami* (Japanese), *hai-i* Chinese, *loka* (Fijian). The earliest tsunami event, recorded in historical chronicles, occurred in the eastern Mediteranean off the coast of Syria in 2000 B.C (Ambraseys, 1962). The second historically known case is a destructive tsunami in the Aegean Sea generated by the catastrophic eruption of the Santorini volcano on the Thera Island dated to 1628 B.C. (Marinatos, 1939). For the whole BC period, 23 historical events are presently known. Most of them occurred in the eastern Mediterranean whose coastline was densely populated since the ancient times and was repeatedly damaged by tsunami waves. Despite so long and close relationship of humans and tsunamis, until recently they were not considered worth of independent historical compilation, and the data on tsunamis were typically included in catalogs of other natural hazards such as earthquakes, volcanoes, hurricanes and other dangerous natural phenomena.

Historical Tsunami Catalogs

To the best of the author's knowledge, the first historical tsunami catalog was compiled by N.H.Heck, former Director of the US Coast and Geodetic Survey and Chairman of the American Committee of the International Commission of Raz de Maree, IUGG, who summarized the tsunami data from previous earthquake catalogs. Initially, this catalogue was published in French (Heck, 1934), the English, slightly updated version of the catalog appeared in 1947 as a journal article published in BSSA (Heck, 1947). Undoubtedly, this latter publication was inspired by the April 1, 1946 Aleutian tsunami that caused damage and losses of life on Hilo, Hawaii and further damage on certain islands in the Pacific.

The revised tsunami catalog (Heck, 1947) had a global coverage and contained 270 events spanning from 479 BC till AD 1946. The format of this catalog was just a list of tsunami observations with date, descriptive location, short account on the tsunami effect and bibliographical references. There is no specific information related to tsunami source or to coastal impact. Also, there is no quantification of tsunami intensity, only reference to the degree of associated earthquake destruction (I – moderate, II – strong, III – widespread destruction). The author notes, however, that "for older sources, the existence of record, no matter how bare or brief, indicates that the wave must have been large". Since Heck's compilation was mainly based on the available earthquake catalogs, most tsunamigenic events in his catalog are of seismic origin with few exceptions for well-known volcanic events such as the 1792 Unzen and 1883 Krakatau tsunamis.

N.H.Heck was well aware of incompleteness of his tsunami catalog and its dependence on such factors as the density and cultural level of population on the coast. He wrote, for example, that "many waves have undoubtedly occurred to the eastward of New Guinea, but the record for that region is very scant" (Heck, 1947, p.269). He made also an important observation that "with respect to well populated shores, absence of records may be accepted as meaning no occurrences; this conclusion may or may not be valid, however, with respect to sparsely settled coast". In a brief introduction to his catalog, he wrote that "in spite of the paucity of data for many regions and the certainty that many tidal waves are missing, there is little doubt that the list gives a good idea of the distribution of such waves and indicates where they are likely to occur" (Heck, 1947, p.270). Finally, he indicated the immediate practical application for the catalog compiling noting that "appraisal of probability of occurrence and of the type of such waves can be made only from the historical records. The advisability of appraisal is evident from the needs of mariners and from the possible hazards of military and naval bases so placed as to be in jeopardy" (Heck, 1947, p.270).

Heck's catalog is the only global tsunami catalog published to date. All subsequent catalogs have been compiled on the regional or national basis. Despite the briefness and incompleteness of Heck's catalog, for number of years it was the only source of information for experts studying the tsunami problem until other historical compilations began to appear in Japan, Russia, USA and other countries.

All the historical tsunami catalogs (there are more than 100 of them, published so far, a comprehensive list can be found at http://tsun.sscc.ru/tsulab/tsu_catalogs.htm) can be divided into two large groups: **descriptive** and **parametric**. Descriptive catalogs are a compilation of original descriptions of tsunami coastal effect and resulted destructions retrieved from the primary reports, scattered in different publications sometimes with a very difficult access (Heck, 1934, 1947; Imamura, 1949; Takahashi, 1951; Agostinho, 1953; Iida, 1956; Berninghausen, 1962, 1964, 1966, 1968, 1969; deLange, Healy, 1986; Zayakin, Luchinina, 1987; Murty, Rafiq, 1991; Lander et al., 2002). Quite often the compilers just repeat the original description of unusual water behavior using different styles, formats and approaches for data selection. In these catalogs, further interpretation of a described phenomenon (for example, classification, localization and quantification of its source) is left for their readers. The quantitative data in the descriptive catalogs are scattered through the text and are not easy to be retrieve and process. These limitations restricts to some extent further application of these catalogs in the tsunami research. However, they are still of great value as indicators to the degree of tsunamigenic activity and a resulting hazard for a particular region.

The second type of the tsunami catalog is parametric, where gathered information is presented in table form, listing tsunami events in chronological order and providing some set of the basic source parameters on each event (Soloviev, 1978; Iida, 1984; Papadopoulos, Chalkis, 1984; Hamzan et al., 2000). These parameters varies from simple locality and magnitude of a tsunami source to very detailed sets of source parameters provided in the recent tsunami databases such as supported by NOAA's National Geophysical Data Center in Boulder, USA (http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml), Tsunami Laboratory in Novosibirsk, Russia (http://tsun.sscc.ru/htdbwld) or University of Bologna, Italy (Tinti, Maramai and Graziani, 2001). A major problem with parametric catalogs is that they usually include very little original descriptive information on tsunami manifestation and thus force a reader to rely upon the interpretation made by a catalog compiler. Another problem is that there are differences in scales used for quantification of tsunamis. It was quite typical that compilers of earlier catalogs proposed their own scales for measuring tsunami intensity, as an example we can indicate to Sieberg's (Sieberg, 1927), Iida-Imamura's (Imamura, 1942; Iida, 1958), Soloviev-Imamura's scales (Soloviev, 1972). Another problem is the reporting of maxima which might not be representative, the reporting of tsunami inundation depth instead of run-up height, or maximum amplitude instead of maximum wave height measured on mareograph records, and the potential lack of means to differentiate these values.

Some of the published catalogs have both descriptive and parametric parts, the latter presented as the tables with basic source parameters of tsunamigenic events retrieved from or estimated on the basis of historical descriptions collected in the descriptive part. As the examples of these catalogs we can indicate to Soloviev, Go, 1974, 1975; Soloviev et al., 1992; Soloviev et al., 2000; Lander et al. 1993; Lander, 1996; Watanabe, 1989; Everingham, 1977, 1987; Papadopoulos, 2000; Fernandez et al., 2000; Lockridge, 2002; O'Loughlin, Lander, 2003; Fokaefs, Papadopoulos, 2006; Papadopoulos et al., 2007.

Tsunami Databases

Even the most complete historical tsunami catalogs, having both descriptive and parametric parts, such as Soloviev and Go (1974, 1975) or Lander (1996) catalogs have somewhat limited application in the tsunami research, because the data and information from these catalogs cannot be easily retrieved and handled. Present-day information technology demands the organization of data in the form of computerized databases, where data can be kept in a constantly updated and active form and are easily accessible. The information from a database can be quickly retrieved in many different ways and formats, and can be transferred to other relational databases and to data processing and visualization programs.

Conversion of descriptive catalogs into parametric databases is not a trivial task and quite often presents a number of specific problems to be solved. One of the problems results from a fundamental feature of tsunami waves, namely, their ability to propagate over great distances from the source area. As distinct from earthquake cataloguing, an observation of unusual wave activity near a particular coast may relate to a source in quite a remote part of the same oceanic basin (or even another basin). In the database creation, this problem is usually resolved by dividing all the data into two parts – the tsunami event catalog and the tsunami run-up catalog. The event catalog contains the list of tsunamigenic sources, usually arranged in chronological order. The run-up catalog contains the list of observed and measured tsunami wave heights provided with location names or even exact geographical coordinates of observational sites. The relation between these two tables is provided through a special event identification number or, quite often, through the full date of the event (that includes also the source time) and is considered to be a unique characteristic of any record in the tsunami event table.

Initial work on the development of a computerized tsunami database was started at the International Tsunami Information Center (ITIC) in Honolulu, Hawaii (USA) in the mid-1970s. Following this initial work and in response to the recommendation of the ITSU-XI (Summary Report…, 1987), a standardized database format was developed, and the first tsunami database was compiled from many available sources and distributed through the ITSU National Contacts (Pararas-Caraynnis, 1991). However, at that time, the ITIC efforts were not sufficiently supported both financially and conceptually. Also, few tsunami data were available in the computer readable form. Therefore, the progress in further data collection was slow, and the proposed format did not become mandatory for data compilers and database developers.

In the middle of 1980s, the NOAA's National Geophysical Data Center (NGDC/NOAA) in Boulder, Colorado (USA) began compilation of quantitative tsunami data from all available catalogs and many special studies of tsunamis, and initiated their conversion into a computer-readable form. For a number of years, the NGDC/NOAA World-Wide Tsunami Database (Lockridge, Dunbar, 1995) remained the only source of tsunami information available in computerized form and was used to create tsunami databases in several research institutions and operational centers. Unfortunately, their large data set, initially compiled in the 1980s, has never been subject to careful refining, checking for errors and matching to later catalogs and research publications. These limitations affect to some extent the value of a large amount of gathered and digitized information and its application in the tsunami research. However, until now the NGDC/NOAA World-Wide Tsunami Database remains the most frequently cited source of historical tsunami information.

The next step in the tsunami database development was undertaken in the beginning of the 1990s within GITEC (Genesis and Impact of Tsunamis on the European Coast) Project initiated in 1992 by the University of Bologna, Italy (GITEC, 1992). One of main outputs of this project was the development of the comprehensive historical tsunami database for the Mediterranean and other European surrounding seas which summarized data of numerous published historical catalogs for this region (Tinti et al., 2001, 2004). The present version of the European Tsunami Catalog (ETC) is being developed and maintained within the Workpackage 1 (Tsunami Catalogue) of the TRANSFER *(*Tsunami Risk ANd Strategies For the European Region) Project launched in 2005 by the European Community (TRANSFER, 2005).

Another initiative in tsunami database development was undertaken in the middle of 1990s by the Novosibirsk Tsunami Laboratory (NTL) of the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Division of Russian Academy of Sciences (ICM&MG SD RAS) made under the Expert Tsunami Database (ETDB) Project (Gusiakov, Marchuk, Osipova, 1997). The concept of this project is based on integration of observational data, some numerical models and analytical and processing tools with the visualization and mapping tools within a single software package. Therefore, from the beginning attention was paid to development of a geographical mapping subsystem intended for easy data retrieval and visualization. Another important feature of this project is that the ETDB is intended to be a multi-entry database, which means that a particular tsunamigenic event is provided with the full set of original data and information retrieved from different sources, thus giving the user a possibility to make his/her own interpretation and judgment.

The Historical Tsunami Database for the Pacific (HTDB/PAC) Project was initiated by the IUGG Tsunami Commission (IUGG/TC) in 1995 under the leadership of the NTL/ICMMG. By that time, the NTL/ICMMG had the basic parametric tsunami catalog for the whole Pacific compiled from a variety of sources that was provided with the specialized graphic shell written in Turbo-Pascal.

At present, there are two global historical tsunami databases maintained separately by the NGDC/NOAA in Boulder , USA and the NTL/ICMMG in Novosibirsk, Russia. The NGDC/NOAA database is maintained in the Oracle RDBMS from where the data can be accessed via Web-based HTML forms and ArcIMS interactive maps (http://www.ngdc.noaa.gov/seg/hazard/tsunami) as well as exported in several different formats. The NTL/ICMMG database is maintained in the MS SQL Server and is provided with a specially developed GIS-type graphic shell (WinITDB) allowing the fast and efficient manipulation of maps, models and data. The web-version of this database is accessible at http://tsun.sscc.ru/htdbwld.

The content of these two databases is fairly close in terms of total number of historical events, temporal and spatial coverage and basic source parameters. However, for many historical events they differ in types of origin, number of available run-up observations, resulting fatalities and degree of validity for some older historical events. At the ITSU-XIX (Wellington, 2003) the International Tsunami Information Center (ITIC), WDC/NOAA, and NTL/ICMMG were tasked to implement a Global Tsunami Database (GTDB) by merging the content of these two existing databases into a single unified data set. This work, being implemented under the GTDB (Global Tsunami DataBase) Project (Gusiakov, 2003), is still in progress, since it requires application to the primary sources of historical information to resolve the existing uncertainties in the parameters of many old historical events. Further analysis of historical data, given in this Chapter, is based on the content of both databases, generally referred to as the GTDB catalog, and making reference to a specific database if needed.

Problems with Historical Data

Anyone dealing with historical tsunami data should bear in mind several intrinsic problems closely associated with this type of information. These problems result from inaccuracy and from the fragmentary nature of available information about old or geographically remote events. Quite frequently, the information on an older event is so incomplete that it is difficult to make a reliable judgment on the nature of reported phenomenon and/or to evaluate its actual scale. Basically, there are two types of errors in tsunami catalogs. The first is confusion of tsunamis with other hazardous natural phenomena (e.g., storm surge, high tide, river flood, rogue waves). The second is errors in interpretation of available descriptions in order to retrieve the basic parameters of an event (date and time, location, intensity, type of a source).

The main reason for confusion with other phenomena is the scarcity of information and the lack of details in description of a reported events. Regarding this type of errors, the catalog compilers can do almost nothing but assign a low validity index 1 (very doubtful) or 2 (doubtful) to events with doubtful nature, thus alerting users to practice caution in treating (this particular piece of) said data. Sometimes it happens that additional data are found later thus allowing one to resolve the uncertainty and to increase its validity index up to 3 (probable) or 4 (definite) or alternatively to exclude the event from the list. In practice, in modern catalogs and databases the latter events are not excluded at all, but are kept on the list with validity 0 (false entry) to prevent re-entry because information about these events exists in archives and literature. Both NGDC/NOAA and NTL/ICMMG databases currently have about 5-6% of all entries with validity 0.

The validity index relates not only to the degree of confidence that a particular event is a tsunami but also to its relationship to the indicated source on the date given. Indeed, the correct date is one of the main problems for older historical events. The reasons include the poor event dating in the primary reports and using different calendar systems. For example, the Gregorian calendar was proclaimed in 1582, and then gradually adopted by most but not all Christiandominated countries over the next 200 years. Another good example is the dating of the Aegean Sea tsunami resulted from the catastrophic Santorini eruption. Historical catalogs indicate very different dates for this event spanning over 270 years from 1380 BC (Soloviev et al., 2000) to 1650 BC (NGDC/NOAA database). In the NTL/ICMMG database, we have adopted 1628 BC for this event, based on (Papadopoulos, 2001) and tree-ring dating for Santorini (Baillie and Munro, 1988).

The location of a source for historical tsunamis is commonly a problem because tsunami waves can propagate over a great distance. Historical documents usually report on tsunami manifestation at some *coastal* location, but association of these reports with some earthquake, volcanic eruption or landslide that may have occurred a hundred or a thousand miles away is a complicated task. For this reason even in recently published catalogs so many old events have not been assigned the source coordinates and contain only indication to the general area of tsunami manifestation (like SW Portugal, Azores, Baleares, etc.). Such an approach, however, is unacceptable for a database compiler, because most data retrievals start from selection of a geographical area for the data search. Therefore, in the NTL/ICMMG database, for example, we try to assign source coordinates to as many events as possible, based on all sorts of available information even if the accuracy of such an assignment is poor (order of ±2º). However, in this catalogue up to 135 events still lack any source coordinates.

Another problem concerns an important group of parameters describing the "size" of a tsunami. Many of old reports do not contain any quantitative indications to run-up height, inundation depth, or a measure of in-land flooding. Quite often, available documents mention only the damage to vessels and buildings, sometimes they tell something about human fatalities. If any height estimates in old reports are given, they should be treated with care, because eyewitnesses are typically not trained observers and their reports can be greatly exaggerated or simply erroneous.

A potential problem also results from conversion of old measuring systems to the modern metric system. For instance, the old Russian fathom had several metric equivalents (from 1.62 to 2.16 m), and sometimes it is not clear which unit was used by an eyewitness. Eyen in contemporary reports, feet are occasionally mixed with meters and inches with centimeters. Another problem is the implied accuracy of the estimates given. For example, the report given by S.Krasheninnikov for a maximum run-up height of 30 fathoms for the 1737 Kamchatka tsunami (Krasheninnikov, 1755) can be an approximation meaning something between 25 and 35 fathoms, and its conversion to the metric system (63 m) should not be considered to have 1 meter accuracy. Besides, a single report, even given by a scientist (S.Krasheninnikov was a staff naturalist of the Second Russian Research Expedition sent to Kamchatka in 1737-1741) should be treated with care, especially when the data are not confirmed by a contemporary study of their physical or geological traces.

Another important issue in cataloguing historical tsunamis is the nature of data on human fatalities and on damage. Usually, these data the very numbers that mass media and general public are most interested in, but at the same time they are the most difficult parameters to resolve. First of all, old historical reports rarely give exact numbers of fatalities. Typical wording is "many people washed away" or "all villagers drown". When digits are available, quite often they relate to the total number of victims of both the source event (such as an earthquake) and the tsunami. For example, the widely cited 60,000 fatalities for the 1755 Lisbon tsunami will probably be never be resolved in terms of the death toll from the parent event (earthquake) and from the resulting tsunami. (In Table 1 we adopt 30,000 as very rough approximation of tsunami-related fatalities from the Lisbon event). The same is true for the 1815 Tambora tsunami caused by the most catastrophic volcanic eruption of the last millennium.

Death toll from this event is poorly constrained and sometime include even those who died from starvation resulted from the ash fall that killed vegetation over the large area (NGDC/NOAA Historical Tsunami Database). Death tolls for a number of most destructive ancient tsunamis like 1628 BC Santorini, AD 416 Java, AD 1452 Kuwae is not known at all. Even for the recent events, collection of reliable data on human fatalities presents difficulties for catalog compilers. Usually, these data are taken from mass media reports and newspaper articles that rarely make reference to their information sources. Being uncritically adopted and cited in the field reports and even per-reviewed articles, these numbers obtain the status of "scientific data", but they are not. As the most recent example of, we can refer to the 2004 Indian Ocean tsunami. The estimates of the number of fatalities circulating in mass media, reported in scientific publications and accessible through the Internet, vary from 180,000 to 300,000 (including missing people). Since in many affected countries (except Thailand), burial of victims took place without any body identification and sometimes even without body counting, and because many people were washed to sea, the actual numbers of fatalities will never be known. At present, the most realistic estimates of the human toll for the 2004 Indian Ocean tsunami are available from UN Office of the Special Envoy for Tsunami Recovery (http://www.tsunamispecialenvoy.org/country/humantoll.asp). Their site lists 186,983 persons as killed and 42,883 as missing that giving a total of 229,866 victims. The site does not give any supporting data for these digits (such as breakdown of losses by coastal communities), but at least this number conforms to the published statistics of human losses in the most affected countries (Indonesia 167,736, Sri Lanka 35,322, India 18,045, Thailand 8,212).

Tsunami Quantification

As noted above, one of the main problems in cataloguing historical tsunamis is the measure of the overall "size" or "force" of an event. To compare different tsunamigenic events, we need some scale by which to measure them. The best parameter for estimating the size of different tsunamis would be their total energy. However, this value is not easy to calculate because it requires knowledge of tsunami waveforms at different locations, covering all possible propagation directions, and that is not always the case even for most recent tsunamis.

There are two types of scales for measuring the "size" of a hazardous natural phenomenon – the magnitude scales and the intensity scales. Magnitude scales relate to the source area of an event, while the intensity scales describe the resulting effects at different locations. So, one event can have a single value of its magnitude and many values of its intensity. Both scale types can be descriptive (e.g., the Mercalli scale for intensity of seismic shaking), or quantitative, based on measuring some physical parameter characterizing the source of an event (e.g., the Richter scale for the magnitude of earthquakes, the VEI scale for quantification of explosive volcanic eruptions) or combined, containing both a descriptive part and quantitative values for some measured parameter (e.g., the Saffir-Simpson hurricane scale, the Beaufort wind scale).

Historically, the first scale proposed for measuring a tsunami was the Sieberg scale (Sieberg, 1927). It was a descriptive intensity scale, based on the destructive effect of a tsunami, consisting of only four grades and not including any quantitative measures of tsunami wave height. Ambraseys (1962) slightly modified this scale, making it 6-grade, by dividing the upper grade into three additional grades. This 6-grade scale was mainly used for quantification of the Mediterranean tsunamis, most of them being old historical events with limited descriptions that often did not contain any quantitative values. Although both of these scales are typical intensity scales, based only on local tsunami effects at the coast, from the very beginning they were used for characterization of overall tsunami size (i.e., as magnitude scales) by assigning to a tsunamigenic event its maximum observed intensity at the coast. This practice is in fact still used by cataloguers of pre-instrumental historical earthquakes.

Another scale for the tsunami quantification was introduced in 1942 in Japan (Imamura, 1942). This scale was also descriptive, consisting of five grades (0 to 4), but the description of each grade contained some quantitative parameters – run-up heights and extension of the coast flooded by the waves. A.Imamura called it a *tsunami magnitude* scale, but it is a typical example of *intensity* scale, since it is based on coastal tsunami effects and does not contain any correction for distance from source.

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

$$m = \log_2 H_{max} \tag{1}$$

This so-called Imamura-Iida intensity scale was widely used in cataloguing historical Pacific tsunamis and, as a magnitude scale, for overall quantification of tsunamigenic events in the catalogs (the latter, possibly, because a large tsunami has many reported coastal run-up observations, but only one *maximum* run-up value). H.Watanabe (Wanatabe, 1963) was the first to point out this contradiction and proposed to use the term *tsunami magnitude* for a value defined as

$$m = \lg H_0, \tag{2}$$

where H_0 is the wave height in the open sea at the edge (boundary) of a tsunami source. This proposal, of course, was not implemented, because there was no practical way to measure such a parameter in the open sea.

Noting this difficulty (mixing of intensity and magnitude scales, based on the same parameter), Shuto (1993) proposed to use the formula

$$i = \log_2 H, \tag{3}$$

where H is the local tsunami height in meters, for defining the *tsunami intensity scale i*, that would be used for quantification of tsunami damage at the coast. His 6-grade (from 0 to 5) scale contains description of expected damage for boats and different type of constructions tabulated on the basis of the local H value.

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

$$I = ½ + \log_2 H_{av}, \tag{4}$$

where H_{av} is the *average* wave height along the nearest coast. Soloviev argued that this value is a more steady characteristic of a tsunami and closer relates to the total tsunami energy radiated from a source. With this scale, Soloviev evaluated the intensity for a large number of Pacific tsunamis during compilation of his catalogs (Soloviev, Go, 1974, 1975; Soloviev, 1978). The I scale is also used in the NGDC/NOAA and NTL/ICMMG global tsunami databases as the main parameter characterizing tsunami size.

T.Hatori (1986) attempted to formalize calculation of tsunami magnitude m on the Imamura-Iida scale by taking into account the propagation distance, that is, to convert it from the an intensity scale to a fully magnitude scale. He proposed to calculate m value by the following formula:

$$m = 2.7 \lg H + 2.7 \lg R - 4.3, \tag{5}$$

where H is a tsunami wave height at a coastal observation point, and R is the distance from this point to the tsunami source along the wave propagation path. Hatori's proposal was quite reasonable but did not get adopted by practitioners due to unevenness of wave heights along the coast and to uncertainty involved in determination of the propagating distance. A typical dimension of a tsunami source is about 100 km which is comparable to or even greater than a distance to the nearby coast, so that the uncertainty in the travel path length can be on the order of 100%.

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

$$M_t = \mathrm{a} \lg H + \mathrm{b} \lg R + \mathrm{D}, \tag{6}$$

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 the M_t scale closely related to the earthquake M_w (moment-magnitude) scale. The M_t scale is a real magnitude scale because it is based on quantitative parameters (instrumental wave height) and includes correction for propagation distance. K.Abe determined and published the M_t value for almost 200 large tsunamis occurred in the Pacific since tide gauges came into use. However, old historical events and most of weak contemporary tsunamis do not have M_t values thus limiting to some extent usage of the M_t scale for overall size comparison of tsunamigenic events.

Another magnitude-type scale, based on the total tsunami energy and providing a wide, actually unlimited range for tsunami quantification, was proposed by T.Murty and H.Loomis (Murty, Loomis, 1980). Their ML value is defined as

$$ML = 2 (\log E - 19), \tag{7}$$

where E is tsunami energy in ergs. In their initial publication (Murty, Loomis, 1980), ML values were determined for about 25 of the largest Pacific tsunamis, and since that time almost no new determinations of ML have been made. The reason is difficulties involved in tsunami energy calculation. In the future, however, this scale can become more applicable for quantification of contemporary tsunamis, based, for instance, on knowledge of detailed distribution of initial displacement in a tsunami source.

A new 12-grade *intensity scale* for quantification of coastal tsunami effect was proposed by Papadopoulos and Imamura (2001). A detailed description of each grade, based on (a) effects on humans, (b) effects on vessels and nature, and (c) damage to buildings, was elaborated on the basis of well-documented damaging effects of recent destructive tsunamis in the Pacific. The new scale was made consistent with several 12-grade seismic intensity scales used in seismology for quantification of seismic shaking effects (Papadopoulos, 2001). Despite no quantitative parameter is used in definition of each grade, in their original publication Papadopoulos and Imamura provided a table of possible correlation of grade number I_{PI} on their scale with grade number i (and, therefore, with local run-up height H) on the Shuto scale as defined by (3). This correlation can be quite helpful in quantification of old historical events whose description often lacks any quantitative elements.

In the following analysis of historical data I use mainly the tsunami intensity I on the Soloviev-Imamura scale, considering it, among other existing scales, to be most closely related to the overall size of a tsunami. This scale is incorporated in two most complete historical tsunami databases (maintained by the NGDC/NOAA and NTL/ICMMG SD RAS), and, what is most important, the intensity *I* is now determined for more than 2/3 of all historical tsunamis worldwide thus allowing me to rank the different tsunamigenic events by their overall size.

Geographical and temporal distribution of tsunamis in the historical records

The present version of the GTDB catalog on tsunamis and tsunami-like events covers the period from 2000 BC till present and currently contains nearly 2100 historical events, having the validity index equal to or more than one. Of these events, 1206 occurred in the Pacific, 263 in the Atlantic, 125 in the Indian ocean and 545 in the Mediterranean region. The geographical distribution of sources of historical tsunamis is shown in Fig.1. When analyzing this map, one should take into account that it reflects not only the level of tsunami activity, but also the regional historical and cultural conditions that strongly influence the availability of the historical data. From geographical distribution of tsunamigenic sources, we can see that most known tsunamis have been generated along subduction zones and major plate boundaries in the Pacific, Atlantic and Mediterranean regions. Very few historical events occurred in the deep ocean and central parts of marginal seas, except several cases of small tsunamis originating along middle-ocean ridges and some major transform faults.

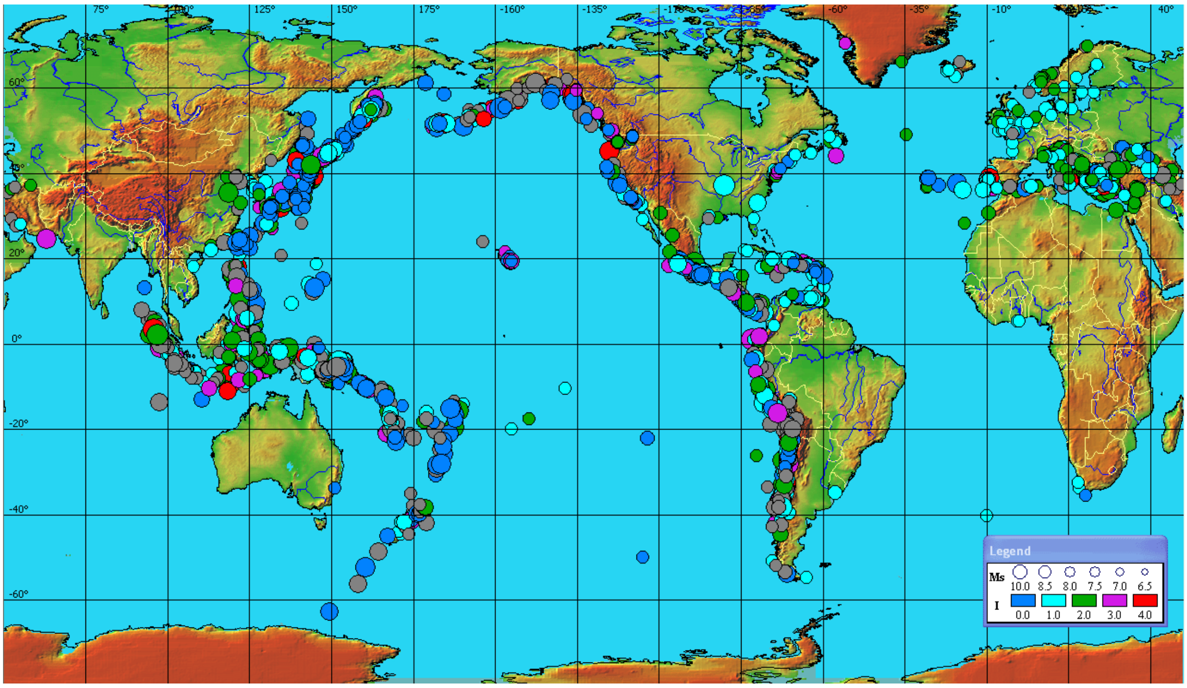

Fig.1. Visualization of the NTL/ICMMG global historical tsunami catalog. 1965 tsunamigenic events with identified sources are shown for the period from 2000 BC to present time. Size of circles is proportional to event magnitude (for seismically induced tsunamis), color represents tsunami intensity on the Soloviev-Imamura scale.

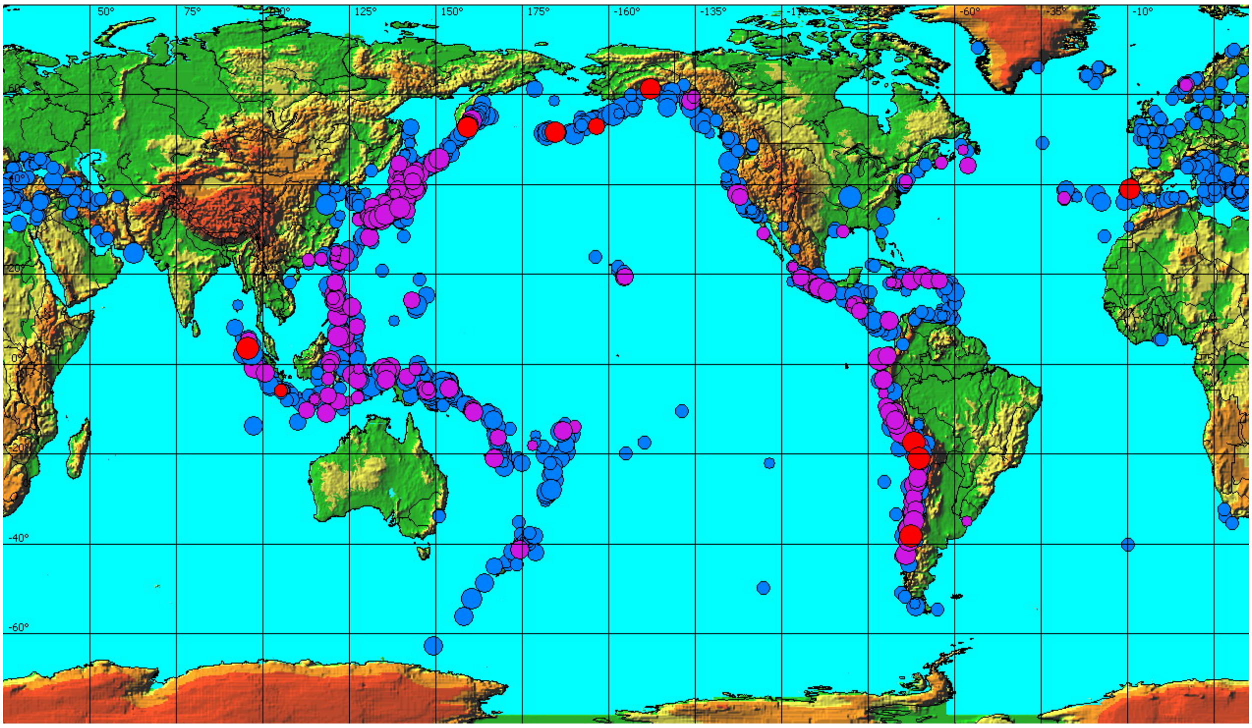

Fig.2. The same data as in Fig.1. but presented with 1965 historical tsunamigenic events having identified sources divided into three groups: 1 - transoceanic tsunami (red) (see text for definition), 2 - regional tsunami resulting in human fatalities (magenta), 3 - all other tsunamis (blue).

In Fig.2 the same data are shown in slightly different way. All the tsunamis are divided into three groups – 1) trans-oceanic, 2) resulting in human fatalities, and 3) non-fatal tsunamis. Trans-oceanic events are defined according to a formal criterion – those events whose reported run-up reaches 5 m or so at a distance exceeding 5000 km from the source, thus able to produce considerable damage on the opposite side of an oceanic basin. From the 2100 tsunamigenic events only 11 met this criterion, and all of them occurred during the last 250 years. They are shown in Fig.2 in red color and listed in Table 1 with their basic source parameters. All these events were highly destructive and fatal - altogether they are responsible for 274,000 (39% of the total) fatalities. The remainder of documented fatalities (426,000) occurred in 213 regional and local tsunamis. Thus, in all, tsunamis are responsible for about 700,000 human fatalities during all the historical time. With this number, tsunamis rank fifth among other natural catastrophes, after earthquakes, floods, hurricanes and volcanic eruptions. However, in the third millennium, after the 26 December 2004 Indian Ocean tsunami, tsunami fatalities rank first, and probably will, until the next big earthquake in a large metropolitan area or a catastrophic monsoon flood in the overpopulated Bangladesh coast.

Table 1. List of historical trans-oceanic tsunamis (see text for definition). $\boldsymbol{M}$ – magnitude (macroseismic, $\boldsymbol{M_S}$ or $\boldsymbol{M_W}$), $\boldsymbol{I}$ – tsunami intensity on the Soloviev-Imamura scale, $\boldsymbol{H_{maxNF}}$ – maximum reported run-up in the near field in m, $\boldsymbol{H_{maxFF}}$ – maximum reported run-up in the far field (more than 5000 km) in m, **FAT** – number of reported fatalities due to tsunami.

Date and place	M_S	I	H_{maxNF}, m	H_{maxFF}, m	**FAT**
1 November 1755, Lisbon	8.5	4.0	30.0	7.0	30,000
7 November 1837, Chile	8.5	3.0	8.0	6.0	many
13 August 1868, Chile	9.1	3.5	15.0	5.5	612
15 June 1896, Sanriku	7.4	3.8	38.2	5.5	27122
3 February 1923, Kamchatka	8.3	3.5	8.0	6.1	3
1 April 1946, Aleutians	7.9	4.0	42.2	20.0	165
4 November 1952, Kamchatka	9.0	4.0	18.0	9.1	>10,000
9 March 1957, Aleutians	9.1	3.5	22.8	16.1	none
22 May 1960, Chile	9.5	4.0	15.2	10.7	1,260
28 March 28 1964, Alaska	9.2	4.5	68.0	4.9	221
26 December 2004, Sumatra	9.3	4.5	50.9	9.6	229,866

The temporal distribution of historical tsunamis is shown in Fig.3 for the last 1000 years. The chart clearly demonstrates that historical data have highly non-uniform distribution over time with three quarters of all the events reported within the last two hundred years. In all the regions (except, possibly, Japan) there are obvious gaps in reporting even large destructive events for the period preceding the XIXth century. Although the total duration of the global historical catalog exceeds 4000 years, its median date, dividing the data into two equal parts, lies around 1885.

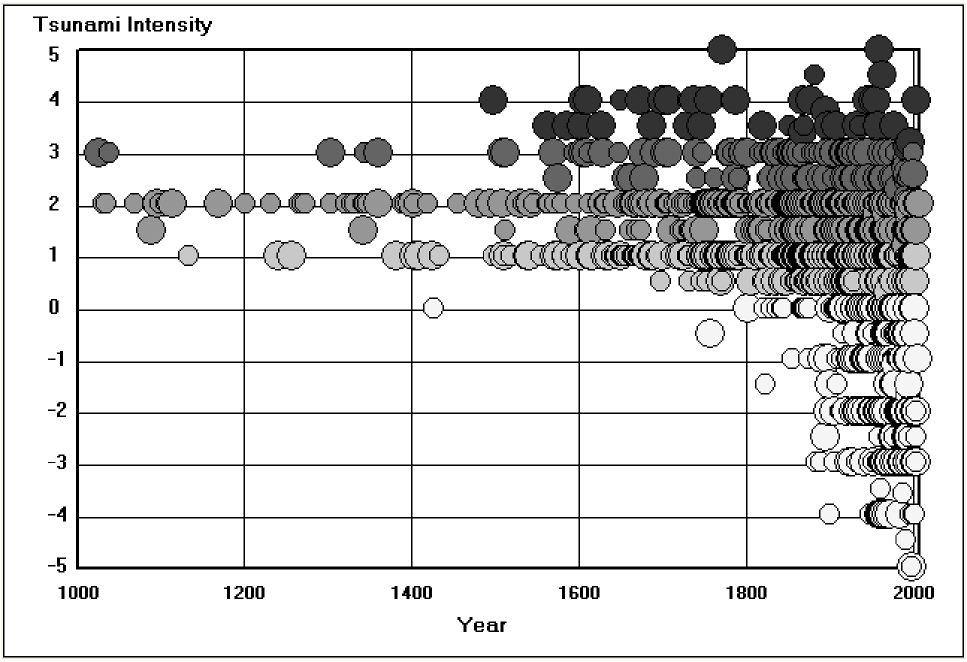

Fig.3. Recorded tsunami occurrence in the World Ocean vs time since AD 1000. Events are shown as circles with the density of gray tone depending on tsunami intensity (on Soloviev-Imamura scale) and size proportional to the earthquake magnitude. Systematic data on weak tsunamis appear in the catalog only from the end of XIX century when the tide gauge network was put in operation. For the period earlier than the XV century the data are fragmentary even for the large events.

Length and to some extend completeness of historical catalogs for different tsunamigenic regions can be seen in Fig.4. Patterns reflect, first of all, availability of historical data which, in turn, strongly depends on population density and cultural features of a region. The longest catalog exists for the Mediterranean (4000 years, the first 2000 years not illustrated in Fig.4). The second longest catalog, exceeding 1500 years, exists for Japan and neighboring seas. For many areas, like Kuril-Kamchatka, Aleutians, Central and South America, New Zealand, Philippines and Indonesia, the catalog starts with the arrival of the first arrival of European travelers in the area. The temporal distribution of events in the regional catalogs is very uneven, typically with a large gap (up to several centuries) between the first event in the catalog and the beginning of more or less constant coverage, at least in terms of destructive events.

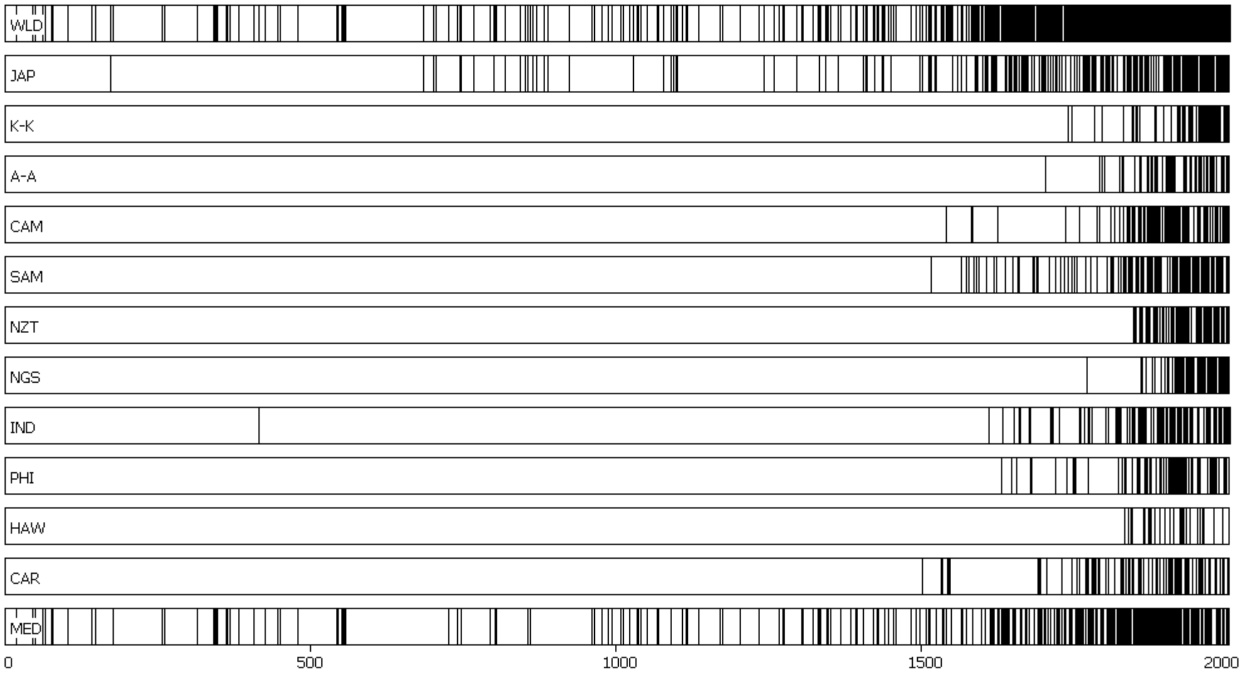

Fig.4. Comparative length and completeness of regional tsunami catalogs and entire global catalogue for the last 2000 years. Each tsunamigenic event is represented by a vertical line on the horizontal time axis.

For all the tsunamigenic regions, the most complete data exist for the last 100 years, when the instrumental measurements of weak tsunamis became available and the reports on all or almost all of damaging tsunamis were carefully collected. Completeness of the catalog for the XXth century can be confirmed statistically because the position of its median date that lies around 1951. In 1901-2000, a total of 990 tsunamis were historically recorded in the World Ocean, an average rate of about ten tsunamigenic events per year. Most of these tsunamis were weak, observable only on mareograph records. About 260 tsunamis were “perceptible”, defined as having a run-up height exceeding one meter. Among them, in 33 cases run-up greater than one meter was observed and recorded at a distance exceeding 1000 km from the source. During the previous century, five trans-oceanic tsunamis, all in the Pacific, occurred and all these events fall in an 18-year time interval (1946 Aleutians, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska).

The histogram of tsunami occurrence in the World Ocean during the XXth century is shown in Fig.5. The rate of tsunamigenesis over that century is more or less constant with only one distinct minimum of damaging events that had place in the 1980s. This minimum is the lowest in more than two last hundred years. Possibly, the low tsunami rate in this decade led to many comments on "the increased level of tsunami activity" in the 1990s. However, in the longer historical perspective, the 1990th were just a return to the normal, long-term average in tsunami occurrence.

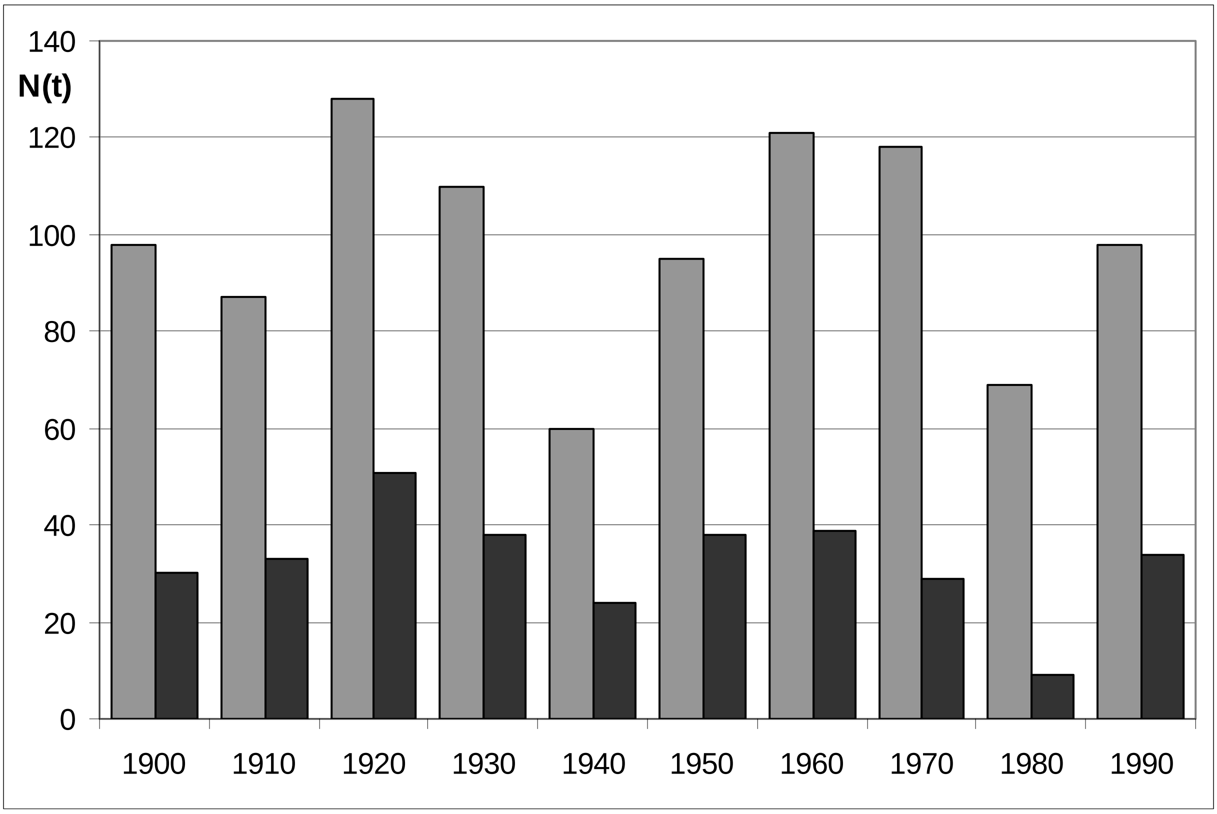

Fig.5. Histogram of global tsunami occurrence (in 10-year intervals) for the period from 1901 to 2000. Grey tone shows all tsunami, black tone – damaging tsunami with intensity *I* > 1.0.

Basic types of tsunami sources as historically recorded

Analysis of distribution of historical tsunamigenic events over the types of sources is based on the content of the NTL/ICMMG database, since the NGDC/NOAA database uses slightly different classification of tsunamigenic sources. A pie-type diagram of tsunami occurrence depending on the type of sources is shown in Fig. 6. Most of known tsunamis (up to 75% of all historical cases) are generated by shallow-focus earthquakes capable of transferring sufficient energy to the overlying water column. Remaining cases where source is apparently known are divided between the landslide (10%), volcanic (4%) and meteorological (3%) tsunamis. Up to 8% of all the reported historical run-ups still have unidentified sources. In this cases, some unusual wave activity near the coast was observed, but it was not possible to associate it with any of known potential sources (earthquake, volcano, landslide, or atmospheric event). Even for the XXth century, the NTL/ICMMG catalog contains 51 events with unidentified sources. Most of them were weak, non-damaging events, found only in tide-gauge records, however, among them there are six cases when the reported run-up was more than five meters (04.01.1923 San

Felix Is., 09.08.1929 Northern Chile, 19.08.1929 Atlantic City, 14.09.1944 US East coast, October of 1954 SE Greenland, 12.09.1999 Guerrero, Mexico).

From the events with unidentified sources, one of the most interesting cases is 30 January 1607 when the large destructive waves hit the lowland coast of the Bristol Channel, UK, resulting in more than 2000 fatalities, possibly, the largest fatality rate from this type of a hazard in all UK history (Bryant and Haslett, 2007**)**. The waves occurred on a fine day and surprised inhabitants. The source and nature of these waves is highly debated, with most of experts interpreting this event as an extreme high storm surge. However, a line of strong evidences, retrieved from the analysis of erosional and depositional features left by these waves along more than 570 km of coastline, may favor a long-wave such as tsunami (Bryant, Haslett, 2003**)**. This event is not included in the NGDC and GITEC catalogs, in the NTL/ICMMG catalog it has a validity index 4 (definite), but the cause attribute is still kept as U (unknown) pending further evidence of its origin.

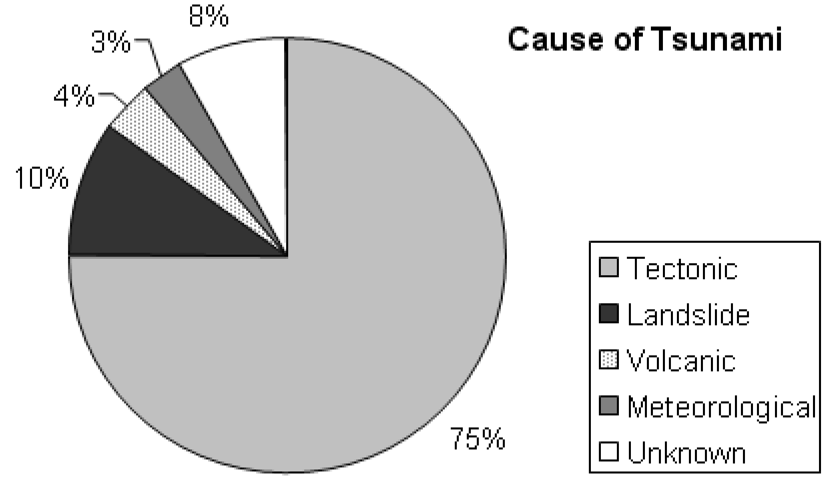

Fig.6. Pie-type diagram of historical tsunami occurrence depending on the type of tsunami source as it is classified in the NTL/ICMMG database. The NGDC/NOAA database has slightly different classification, but ratio between events of different origin is generally the same.

Seismogenic tsunamis. Seismogenic tsunamis are generated by submarine earthquakes due to the large-scale co-seismic deformation of the ocean bottom and the dynamic impulse transformed to a water column by compression waves. The size of tsunami generated by an earthquake relates to the energy release (earthquake magnitude), source mechanism, hypocentral depth, fault rupture velocity and water depth over the source region, but even in the most favorable cases, the energy transferred into tsunami waves is an order of 1% of the total energy released by an earthquake (see Chapter 5 in this volume). A list of some largest regional seismogenic tsunamis with their basic source parameters is shown in Table 2.

Table 2. List of some largest regional seismogenic tsunamis in the historical catalogs. M_S – surface wave magnitude, M_W – moment-magnitude, I – tsunami intensity on the Soloviev-Imamura scale, H_{max} – maximum reported run-up in m, **CAU** - cause of tsunami (T- tectonic, L – landslide), **FAT** – number of reported fatalities due to tsunami

Date and Place	M_S	M_W	I	H_{max}, m	**CAU**	**FAT**
9 July 1586, Lima, Peru	8.5	-	3.5	26.0	T	many
31 January 1605, Shikoku, Japan	8.0	-	3.5	30.0	T	many
2 December 1611, Sanriku, Japan	8.1	-	4.0	25.0	T	4,783
28 October 1707, Nankaido, Japan	8.1	-	4.0	25.7	T	30,000
23 December 1854, Nankaido, Japan	8.3	-	3.0	28.0	T	5,000
15 June 1896, Sanriku, Japan	7.4	8.5	3.8	38.5	T	27,122
2 March 1933, Sanriku, Japan	8.3	8.6	3.5	29.3	T	3,064
9 July 1956, Aegean Sea	7.5	7.7	3.0	30.0	TL	none
12 December 1992, Flores Sea	7.6	7.7	2.7	26.2	TL	2,200
July 12, 1993, Okushiri, Japan	7.6	7.7	3.1	31.7	T	198

One of the most important questions about seismogenic tsunamis is their possible maximum run-up value in the near-field. Reliable historical data, summarized in Tables 1 and 2, suggest that this value can hardly exceed a 35-50 meter even for the largest possible submarine earthquakes. Maximum run-up values of 60-70 m run-up reported for 1771 Ishigaki, 1788 Sanah-Kodyak, and 1737 Kamchatka tsunamis are not very reliable. They are based on single anecdotal reports, which are not always confirmed by the recent geological investigation (see, for instance, Pinegina, Bourgeois, 2001), and can relate to run-up from a locally landslide–generated tsunami that could accompany the main tectonic tsunami. As it was demonstrated for the 1964 Alaska tsunami, all the major run-ups exceeding 25-30 meters were generated by slides from the fronts of the numerous deltas on the affected Alaska coast. These waves arrived at the coast almost immediately after the earthquake and were followed by the main seismically-induced tsunami that typically had a height of 12-18 meters (Lander, 1996).

Another important question about seismogenic tsunamis is the dependence of the resulted run-up height on the source magnitude of the parent event. In this analysis, I use the average run-up values at the nearest coast for calculation of the tsunami intensity *I* on the Soloviev-Imamura scale because average values are clearly less dependent on a particular coastal topography and thus give more stable estimates for overall tsunami intensity. The dependence tsunami intensity on earthquake magnitude is shown in Fig.7 for surface-wave magnitude Ms and moment-magnitude Mw. In this analysis, I used only the historical data for the instrumental period of seismic observation (since the beginning of the XXth century). Both diagrams clearly demonstrate that there is little to no dependence of tsunami intensity on source earthquake magnitude, there is only a general tendency of increase in tsunami intensity with increase in source magnitude. This absence of direct correlation of tsunami intensity with earthquake magnitude makes operational tsunami warning, based solely on the seismic data, a difficult task. Moreover, the data scatter is considerable and exceeds six grades on the tsunami intensity scale. The reasons for this scattering are multi-fold. First, it is a difference in the focus depth and the source mechanism Second, there are differences in the source location (marginal seas, subduction zones, deep-water oceanic plate, etc.). Third, and possibly the most important, is the degree of involvement of secondary mechanisms (foremost being submarine slides and slumps) in the tsunami generation process (see next section).

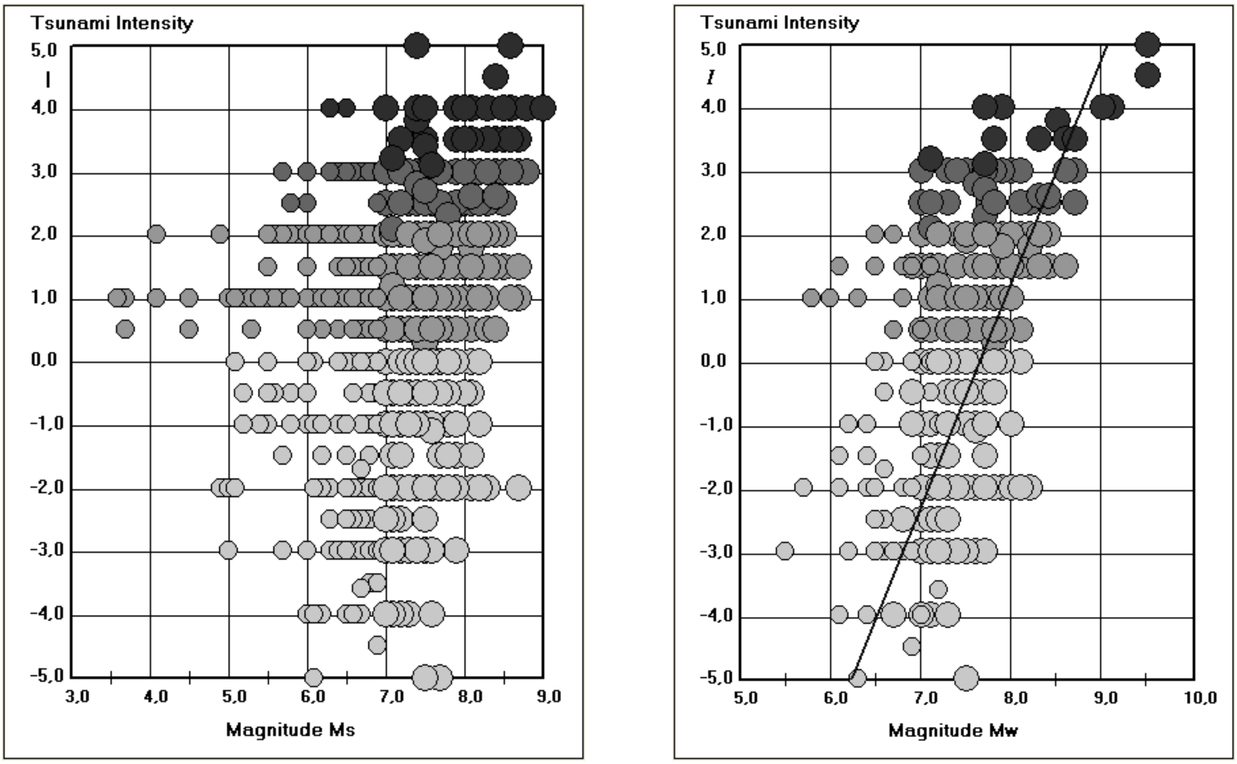

Fig.7. Tsunami intensity *I* on the Soloviev-Imamura scale versus magnitude M_S (on the left) and M_W (on the right) for tsunamigenic earthquakes occurring in the World Ocean from 1901 to 2005. The predicted intensity *I* calculated by the formula $I = 3.55\ M_W - 27.1$ (Chubarov, Gusiakov, 1985) is shown as a solid line on the right diagram.

Slide-generated tsunamis. Not as frequent as seismogenic tsunamis, but still very common world-wide, the slide-generated tsunamis result from rock and ice falling into the water, and sudden submarine landslides or slumps (see Chapter 6 in this volume). They can produce an extremely high water splash (up to 50-70 m, with the highest historical record of 525 m in Lituya Bay, Alaska in 1958) but not widely extended along the coast. In general, the energy of a landslide-generated tsunami rapidly dissipates as tsunami waves travel away from the source, but in some cases (e.g., if the landslide covers a large depth range), a long duration of slide movement can focus the tsunami energy along a narrower beam than the equivalent seismic source (Iwasaki, 1997). One of the most recent cases where the involvement of slide mechanism in tsunami generation has been confirmed is the 1998 Papua New Guinea tsunami when 15-m waves were observed after a M_W 7.0 earthquake (Synolakis et al., 2002; Tappin et al., 2002). Slide-generated water waves occur not only in the oceans and seas, but also pose a clearly recognized hazard to reservoirs, harbors, lakes and even large rivers where they may endanger lives, overtop dams, or destroy the waterside property.

In the case of large earthquakes, the accompanying landslides, locally triggered by strong shaking, can produce local waves greatly exceeding the height of the main tectonic tsunami. They are particularly dangerous as they arrive within a few minutes after the earthquake, leaving no time for a evacuation. One of the primary causes of death in the 1964 Alaska earthquake was the secondary tsunamis generated by slides from the fronts of the numerous deltas at the Alaska (Lander, 1996).

The global tsunami catalog gives many examples of historical events where involvement of subaerial and submarine landslides in tsunami generation was clearly observed and well documented. Some of these waves were destructive and resulted in considerable economic damage and loss of numerous lives. Among the best-known examples of the extreme water splash in the recent history is a well-documented 525-meter run-up in the Lituya Bay, southeastern Alaska, caused by a massive landslide occurred after the magnitude 7.8 earthquake of July 10, 1958 in the south-eastern Alaska (Miller, 1960). Lesser known cases of the extreme run-up heights in the same bay are the 1936 and 1853 events with the maximum run-up heights of 150 and 120 meters, respectively (Lander, 1996).

The first indication of involvement of the slide mechanism into tsunami generation comes from the absence of any associated seismic activity mentioned in the historical description. The global catalogs contain on average 10-15% such events. The percentage strongly varies regionally, exceeding 50% for the waters around England, the North Sea, the Norwegian Sea and the Baltic Sea. Obviously, a considerable proportion of these events could result from the meteorological and oceanographic phenomena (e.g., storm surges, rogue or freak waves). However, there are many cases where the catalog compilers specifically emphasized that an event occurred under “clear sky” and in a “calm sea”.

A second indicator of slide generation is the value of the maximum run-up height for the particular event. The results of numerical modeling show that for a typical tsunamigenic earthquake in the magnitude range from 7.0 to 7.5, the coseismic bottom displacement alone can hardly be responsible for the coastal run-ups exceeding 2-3 meters (Chubarov, Gusiakov, 1985). In fact, the instrumental data for the last decade give several examples of the shallow-depth earthquakes with magnitudes even above 7.5 when tsunami heights did not exceed several tens of centimeters (e.g., M_W7.7 Santa Cruz earthquake of April 21, 1997; M_W 8.1 Balleny Islands earthquake of 25 March 1998, M_W.7.8 Rat Island earthquake of November 17, 2003; M_W.8.1 Macquare Island earthquake of December 23, 2004). Therefore, each case of a seismogenic tsunami with run-up heights exceeding 4-5 meters, resulted from an earthquake with magnitude below 7.5, can be considered as “suspicious” in terms of the involvement of a slide mechanism.

Table 3 lists the historical tsunamis with run-up values more than 50 meters. Five of these 13 events are known to have been generated by landslides, and in three cases the involvement of slide mechanism was confirmed by later studies. Only for four cases (1674 Indonesia,1737 Kamchatka, 1788 Aleutians and 2004 Sumatra) the involvement of a slide mechanism has not been documented. Three of four are the old historical events with very limited data available.

Table 3. List of the historical tsunamis with run-up greater than 50 m, sorted in order of their H_{max} value. M_S – surface wave magnitude, I – tsunami intensity on the Soloviev-Imamura scale, m – tsunami magnitude on the Iida scale, H_{max} – maximum reported run-up in m, **CAU** - cause of tsunami (T- tectonic, L – landslide, V- volcanic), FAT – number of reported fatalities due to tsunami.

Date and Place	M_S	I	m	H_{max}, m	**CAU**	**FAT**
July 10, 1958 Lituya Bay, Alaska	7.9	2.5	9.1	525	TL	5
October 27, 1936 Lituya Bay, Alaska	-	2.0	7.2	150	L	unknown
1853-1854 Lituya Bay, Alaska	-	2.0	6.9	120	L	unknown
August 6, 1788 Sanak Is., Aleutians	8.0	4.0	6.5	88*)	T	unknown
April 24, 1771 Ishigaki Is, Ryukuy	7.4	3.5	6.4	85	TL	13,486
February 17, 1674 Oma, Indonesia	8.0	4.0	6.3	80*)	T	unknown
September 13, 1936 Loen, Norway	-	2.0	6.1	70	L	4
March 28, 1964 Alaska	8.5	4.5	6.1	68	TL	115
October 17, 1737 Kamchatka	8.5	4.0	6.0	63*)	T	unknown
April 7, 1934 Tafjord, Norway	-	2.0	5.9	62	L	40
September 10, 1899 Yakutat Bay, Alaska	8.6	3.5	5.9	60	TL	unknown
May 21, 1792 Unzen volcano, Japan	-	2.0	5.8	55	VL	4,300
December 26, 2004, Sumatra, Indonesia	8.8	4.5	5.7	51	T	229,866

*) Run-up value is based on a single witness report and, therefore, is not very reliable.

The hazards of the underwater slumping range from just technical problems and economic loss due to submarine cables breaks resulted from turbidity currents (which were first documented for the 1929 Grand Bank earthquake) to the destructive effects of huge waves devastating the nearby coast and resulting in large death toll (e.g., 1998 Aitape tsunami). Mitigation and countermeasures against this hazard are quite difficult because very often the destructive water waves come without any seismic or meteorological precursors. The only way to mitigate this hazard is careful investigation of historical and pre-historical cases of waves caused by underwater slumping, identification of slump-prone zones and the evaluation of the long-term risk imposed upon the nearest populated areas by mass failures.

Volcanic tsunamis. Though relatively infrequent, volcanically-generated tsunamis can be extremely destructive and devastating in the immediate source area and can result in numerous fatalities. Until the 2004 Indian Ocean tsunami, the 1883 Krakatau tsunami was on the top of the list of deadliest tsunamis historically known. The explosive caldera-forming eruption with 18-20 km^3 estimated volume of the eruptive material resulted in 35-40-meter tsunami waves that flooded the coast of the Sunda Strait and killed 36,416 people. Another great volcanic tsunami, devastating the northern coast of the Crete Island, was generated by a caldera-forming eruption of Santorini volcano in 1628 B.C. with the estimated volume of erupted material in 50-60 km^3 (Beget, 2000). The number of fatalities of this tsunami will possibly never be known, but undoubtedly it seriously affected the northern coast of the Crete Island, destroying most of the Minoan fleet. These effects, along with a general environmental downturn resulting from the giant eruption, could have led to the demise of the Minoan civilization (Baillie, 1999).

Both the 1628 BC Santorini and 1883 Krakatau eruptions were highly explosive where the following caldera collapse could have been the leading mechanism of tsunami generation. Smaller eruptions of island and coastal volcanoes can generate a significant tsunami if they are accompanied by volcano's slope failure. Active volcanoes are dynamically unstable structures, whose growth and development typically include episodes of the edifice instability and structural failure (McGuire, 2006). Part of their cones may collapse from time to time, generating giant rock slides and avalanches that can travel downslope at a speed exceeding 100 km/hour. When these mass movements enter the water, they can produce destructive tsunami waves. The latest event of this type occurred on 30 December 2002 at the Eolian Islands in the Tyrrhenian Sea, when two large slides, separated by about 7 minutes, with an estimated total volume of about 17 million cubic meters, entered the water at the NW flank of the Stromboli volcano and generated 7-meter waves that severely attacked the NW part of the island (Tinti et al., 2004).

Growing volcanoes may become unstable and experience a collapse at any scale and by different reason, some of them (heavy rainfall, erosion of the base of the volcano, deformation and tilting of volcano basement, earthquake shaking) do not include any eruption of volcano itself. A destructive collapse of the Ritter volcano (Papua New Guinea) in 1888 occurred without any sign of volcanic eruption and led to generation of 15-meter tsunami waves that killed hundred of villagers along the West New Britain coastline (Johnson, 1987). In May of 1792, the southern part of the cone of the Unzen volcano in Kyushu, Japan with an estimated volume of only 0.33 km^3 collapsed, and a debris avalanche entered Ariake Bay forming a devastating tsunami with a maximum height of 55 meters that killed more than 4,300 people (Katayama, 1974). The slope failure of the Unzen volcano occurred suddenly and was not accompanied by any major eruption which actually ended three months before.

Volcanogenic tsunamis also can be produced in lakes. On 2 January 1996, an explosive eruption of nearby Karymsky volcano (Kamchatka, Russia) generated large water waves in the 4-km diameter Karymskoye (Belousov et al., 2000). The highest run-up (up to 27-29 m) occurred on the shore immediately adjacent to a tuff ring, 700 m from the center of crater. On the opposite eastern shore the run-up height was within 5-7 m. Runup heights in this case are based on physical evidence of soil erosion that was still clearly visible on the lake shore in the summer of 1996. In another case, a series of five tsunamis were generated on 28-30 September of 1965 in the Taal crater lake in the Luzon Island, Philippines. These waves were large enough to cause fatalities and to destroy several nearby villages (Hedervari, 1986).

Submarine eruptions can also generate tsunami if they occur in the water of 500-1000 m depth. The largest known event of this type occurred during the 11 April 1781 eruption near Sakura-jima, Kuyushu Island, Japan. Three boats overturned and 15 people were lost (Iida, 1984).

The list of top-ten volcanic tsunamis in the historical records is shown in Table 4. Altogether, the global catalog contains about 100 cases of volcanic tsunamis, that is about 4% of all historical tsunamigenic events. But their fatality rate is almost twice as high as seismically-induced tsunamis (almost 67,000 deaths that is about 9% of the total). However, most of them (at least, those resulting from explosive eruptions) cannot transport significant energy over long distances because even giant Santorini-class volcanic eruptions are essentially point sources and initially large waves lose their energy rapidly with distance. For example, all the fatalities of the 1883 Krakatau tsunami occurred within 1-hour propagation time. According to the NDGC/NOAA database, the largest far-field amplitude was observed in Geraldtone, western Australia and was only 1.8 m.

Table 4. List of largest historical volcanic tsunamis. **VEI** – volcanic explosion index, **VOL** – total volume of eruptive material in km^3, $\boldsymbol{H_{max}}$ – maximum reported run-up, ***I*** – tsunami intensity on the Soloviev-Imamura scale, **FAT_EVE** – total number of fatalities, **FAT_TSU** – fatalities from tsunami

Date and place	**VEI**	**VOL, km^3**	***H$_{max}$*, m**	***I***	**FAT_EVE**	**FAT_TSU**
1628 BC Santorini, Aegean Sea	6	60-70	40-90	4.0	unknown	unknown
1452 Kuwae, Vanuatu	6	32-39	10-15	3.0	unknown	unknown
31 July 1640 Komagatake, Japan	5		10	2.0	unknown	700
29 September 1650, Santorini	4		30	3.0	unknown	unknown
29 August 1741 Oshima, Japan	4		15	2.5	15,000	1,475
21 May 1792 Unzen, Japan	2		35-55	2.5	9,745	4,300
10 April 1815 Tambora, Indonesia	7	80-100	5-10	1.5	117,000	unknown
27 August 1883 Krakatau, Indonesia	6	18-20	36-41	4.0	37,000	36,416
13 March 1888 Ritter, Bismark Sea	3	1-2	12-15	3.0	3,000	500
4 August 1928, Paluweh, Flores Sea	3		5-10	2.0	226	160

Meteorological tsunamis. All historical tsunami catalogs contain reports on unusual tsunami-like changes in water level and currents that are not directly associated with typical tsunami sources like earthquakes, volcanoes or submarine landslides. The global tsunami catalog contains about 3% of such events. These seiche-type oscillations are generated by some large-scale atmospheric disturbances like a rapidly moving atmospheric pressure front moving over a shallow sea at about the same speed as tsunami allowing the air and water to couple. They have different names in different countries or even in particular bays (“rissaga” in Spain, “abiki” and “yota” in Japan, “marrubio” in Sicily, “milghuba” in Malta). Their period varies from 2-3 min to 2-3 hours, and amplitudes can be from tens of centimeters to several meters. In the latter case, they can be destructive and sometimes result in serious damage. Typically, they occur within straits and in particular bays and harbors; however, sometimes they can happen along a straight coast. The term “meteorological tsunami” or “meteo-tsunami” has been proposed as a general name for this type of phenomena (Rabinovich, Monserrat, 1996). In some publications, another term, “atmospheric tsunami” is used, but it should not be considered as appropriate name, since this term is more applicable to infra-sonic gravitational waves in the stratified atmosphere. These waves are generated by some large volcanic explosions and can propagate far away from their source, even round the globe, like the widely known infra-sonic waves generated by the 1883 Krakatau explosion.

It is important to stress that meteorological tsunamis should be distinguished from a more common phenomenon, storm surges, which occur in many coastal areas vulnerable to hurricane and typhoon impact. A storm surge results from the hydrostatic water rise due to the a low pressure zone in the cyclone center that is amplified by the dynamic surge caused by a strong wind pressure. The main difference between these phenomena is in their periods and duration. The waves observed during a storm surge have a shorter wave length but the coastal flooding can last from several hours up to several days and usually accompanied by a strong wind and a heavy rain, while meteorological tsunami lasts from 15-20 min to several hours, and quite often occurs in calm weather. However, distinguishing these two types of phenomena quite often creates a problem for catalog compilers, mainly, due to the lack of details in description of old historical events. For instance, for the Yellow Sea, Soloviev and Go (1974) catalog lists a total of nine destructive tsunamis between 1076 and 1636. Of these nine events five tsunamis were not associated with earthquakes and they are listed with remark “probably, of meteorological origin” (but no additional details on weather conditions are provided). As it is indicated in (Gusiakov, 2001), some of these cases possibly could be slide-generated tsunamis, because they occurred in the area with very high sedimentary loading, resulting from nearby mouth of the largest China's river (Huang He or Yellow River).

A typical example of meteorological tsunami, that hit Daytona Beach, Florida on July 3, 1992 (Sallenger et al., 1995). The anomalously large wave, reportedly 5-6 m high, struck at least 20 km of shoreline on a clear, calm evening when the ambient waves were small. Eyewitnesses described the large wave, rapidly approaching the coast as "a wall of white water with the roar of a breaking wave". Approximately 20 vehicles, parked on the road near the beach, were lifted by incoming water and there were about 20 minor injuries, but no fatalities. The initial explanation for the cause (offshore landslide creating a tsunami) was soon replaced by a "squall-line surge" hypothesis that explained the effect as a resonant coupling with a meteorological disturbance moving along the coast with the speed of a long wave at this depth.

Among other cases of tsunami-like waves, when resonant conditions with a moving atmospheric front were observed, one occurred in the Lake Michigan at Chicago lakeshore on June 25, 1954. The case caused seven fatalities as a result of the first unexpected increase of water level, which reached 2.4 m at Mountrose Harbor, and 3.3 m at North Avenue (Ewing et al., 1954).

Unusual cases of tsunami-like water disturbance

Tsunamis and tsunami-like water wave disturbances can occur not only in oceans and seas, but also in any water reservoir provided that its surface or bottom experiences some large-scale disturbance. This section describes several unusual historical cases of generation of tsunami-like waves in rivers, lakes, bays and harbors as well as long-period water waves resulted from explosions.

A rare case of tsunami-like wave in the large, ice-covered bay is described V.Semyonov (1985). In April of 1939 Semyonov was skiing across Avacha Bay, Kamchatka, covered with thick ice at that time. Being on ice, approximately 1.5 km from the coast, he saw a two-meter ice swell moving from the south-west. For several minutes the swell crossed the bay leaving behind a ridge of broken ice. A depression of up to 1.5 – 2.0 m preceded the swell, and then Semyonov could not see the coast; he estimated the total height of "ice wave" to be up to 3.5-4 m. Since no felt earthquake or volcanic eruption was reported for that day in Kamchatka, the only possible explanation for this large-scale disturbance was an underwater slide or a slump on the bottom of the bay, possibly from Avacha River delta or from other deltas in Avacha Bay.

Another interesting case of landslide-generated tsunami is the two-meter waves generated in Lake Coatepeque, El Salvador, soon after a 7.6 magnitude earthquake occurred on 13 January 2001 in the Pacific, 50 km off the coast. Five deaths were reported as a result of run-up of these waves at the coast of the lake (J.Borrero, 2001). It is worth to note that this earthquake did not generate any significant tsunami at the Pacific coast near the earthquake area.

Huge and destructive water waves were generated in Lake Nyos, Cameroon, on 21 August 1986, when a giant "bubble" of about 3 million cubic meters of CO_2 came from depths of the lake to the surface and generated destructive water waves that killed many people. "A wave of water was sent crashing across the lake reaching on average a height of about 25 m along the southern shore and overtopping a 75-m-high promontory" (French, 1988).

One of the most appalling phenomena accompanying the $M_S8.6$ New Madrid earthquake of 16 December 1811 was agitation of water in the Mississippi River that began almost simultaneously with seismic shaking. In a detailed report on this earthquake, Fuller (1912) cites several eyewitness accounts on this phenomenon: “The waters of the Mississippi were seen to rise up like a wall in the middle of the stream and suddenly rolling back would beat against either bank with terrible force... The water moved inward with a front wall 15 to 20 feet high and tore boats from their mooring and carried them up a creek … for a quarter of a mile... Just below New Madrid, a flatboat was swamped and six men drowned… The river was laterally covered with the wrecks of boats”. The generation mechanism of these water waves in the river is not known – it could be strong seismic shaking or river bottom disturbance. Fuller says “There is no reason to doubt that fissures opened and closed beneath the water as they did on the land, giving rise to large waves by the ejection of water. These waves of great size moved upward against the current”.

A similar case of large water waves in the Volga River is described by Didenkulova and Pelinovsky (2002). The 5-6 meter waves were generated by a sudden slope failure with an estimated volume of about 150,000 m^3 which occurred on a steep bank slope of the river near Nizhniy Novgorod on 18 June 1597. Waves damaged numerous vessels anchored along the river, some of them were thrown aground and left on the dry bank 40-50 m beyond the bank.

The global catalog also contains several cases of tsunamis generated by large explosions. In December of 1917, large waves were generated by the greatest man-made explosion before the nuclear era. This explosion happened in the Halifax Harbor (Nova Scotia, Canada) after collision of the munitions ship *Mont Blanc*, having 3,000 tons of TNT on board, with the relief ship *Imo*. At the coast near to the explosion site, the waves were over 10 m high, but their amplitude diminished greatly further away (Murty, 2003). Some nuclear tests, made in the 1950s and 1960s at small Pacific atolls resulted in generation of tsunami-like waves with up to 10-m height near the source area. An extensive study of water waves generated by nuclear explosions, both on and under the sea surface and up to 10 Mt yield, and also of a series of smaller-scale tests carried out in Mono Lake (California) was made Van Dorn et all (1968) for the US Navy. The main conclusions from their study were that tsunamis from explosions have a shorter wavelength as compared to the size of the resulted cavity (a few km in diameter), in near-field their height can be very large, but rapidly decays as the waves travel outside the source area. They also noted to the effect of breaking short-length waves as they crossed the continental shelf, generating a large-scale turbulence, but leaving the coast without damaging run-up. The discovery that explosion waves or large impact-generated waves will break on the outer shelf and produce a little damage on the coast has since been known as the “Van Dorn effect”, that, however, has not been confirmed by actual observations

Conclusions

1. The present version of the GTDB catalog on tsunami and tsunami-like events covers the period from 2000 BC till present and currently contains nearly 2100 historical events with 1206 of them occurring in the Pacific, 263 in the Atlantic, 125 in the Indian Ocean and 545 in the Mediterranean region. All together, these events are responsible for nearly 700,000 lives lost in tsunami waves during the whole historical period of available observations.
2. Of all 2100 tsunamigenic events, only 223 (10%) tsunamis resulted in any fatalities, all others were weak local events observable only in several particular areas of the nearest coast. From these 223 deadly tsunamis, 213 (95%) fall into the category of local and regional events with most damage and all fatalities limited to one-hour propagation time. In total, they are responsible for 426,000 (61%) fatalities.

3. Ten trans-oceanic tsunamis that occurred in the World Ocean during the last 250 years are responsible for 274,000 (39%) fatalities. Among them, nearly 230,000 people were killed during just one event – the December 26, 2004 Indian Ocean tsunami. All other trans-oceanic tsunamis are responsible for 34,000 deaths or 5% of all tsunami-related fatalities.
4. The study (Gusiakov et al., 2007) of the death toll for 10 most destructive trans-oceanic tsunamis occurred in the World Ocean during the last 250 years shows that although the damaging impact of large tsunamis can last up to 23-24 hours, over 84% of their fatalities occurring within the first hour of propagation time. Another 12% of fatalities occur within the second hour, with the rest of 4% occurring at the remaining time (exceeding two hours).
5. The intensity of seismically induced tsunamis is mainly controlled by an earthquake magnitude and, in general, is directly proportional to it. Detailed study of historical data for the instrumental period of available observations (since 1900) shows, however, that the actual scattering of tsunami intensity for earthquakes with the same magnitude exceeds six grades on the Soloviev-Imamura scale. That means than tsunami amplitudes can differ by a factor of 60 for earthquakes of the same magnitude, that makes unreasonable an operational prediction of expected tsunami height at the coast, based solely on earthquake magnitude.
6. Both distantly and locally generated tsunamis are a typical example of “low probability – high consequence” hazard. Having long recurrence intervals (typically from 10s to 100s of years) for a particular coastal location, they can have very adverse impact on the coastal communities resulting in heavy property damage, many fatalities, and major disruption of commerce and community life.
7. There is a persistent need for any information that predates or augments historically reported and instrumentally measured past occurrence of tsunamis. Geological data on paleotsunamis therefore should be included in tsunami catalogs. Only on the basis of integrity of all data (instrumental, historical and geological) can we study the time-space patterns of large tsunamis and evaluate their long-term occurrence rates.

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