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Global Occurrence of Large Tsunamis and Tsunami-like Waves Within the Last 120 years (1900–2019)

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Abstract—The run-up catalogs of two global tsunami databases maintained by the NCEI/WDC NOAA and NTL/ICMMG SD RAS are examined to compile the list of annual maximum runups observed or measured in the oceanic, marine and inland basins during the last 120 years (from 1900 to 2019). All the retrieved annual maximum runups were divided into four groups according to four main types of tsunami sources (seismogenic, landslide-generated, volcanic, and meteorological). Their distribution over the type of sources shows that of the 120 maximum runups only 78 (65%) resulted from seismogenic sources, while the remaining 42 runups were divided between landslide-generated (19%), volcanic (8%), and meteorological (7.5%) sources. The analysis of geographical distribution of source locations demonstrates that tsunamis are not exclusively a marine hazard—over 15% of all maximum runups were observed in coastal and inland water basins (narrow bays, fiords, lakes, and rivers). Temporal distribution of the collected runups shows that annual occurrence of large tsunamis was more or less stable throughout the twentieth century and only demonstrates some increase during the last 27 years (since 1992) when the practice of post-event surveys of all damaging tsunamis was implemented. This paper also outlines the existing problems with data compilation, cataloguing, and distribution, and discusses incompleteness of runup and wave-form data for a considerable number of non-damaging tsunamis, even those resulting from the strong (magnitude higher than 7.5) submarine earthquakes.

Keywords: *Tsunami*, tsunami sources, tsunami occurrence, historical catalogs, historical databases, data processing, tsunami hazard, early warning.

1. Introduction

The significance of catalogs and databases, especially those that cover not only the instrumental period but historical and pre-historical periods as well, becomes increasingly important both for tsunami hazard assessment and for early warning. In the problem of hazard assessment, historical data are needed for correct evaluation of recurrence rates of tsunamigenic earthquakes and for determination of a maximum possible event in a particular tsunamigenic zone. In the operational forecast they are needed for determining tsunamigenic zones threatening coastlines and for rational selection of magnitude thresholds for the issuing of tsunami warnings. Therefore, the completeness and quality of historical catalogs, the correctness of their parameterization, and the transfer of this information into the databases are of critical importance for many areas of tsunami research.

A comprehensive analysis of the problems associated with tsunami data compilation, cataloguing and parameterization was given in Gusiakov (2009). Currently, two global historical tsunami databases exist and are separately maintained by the NOAA National Centers for Environmental Information (NCEI) and the Novosibirsk Tsunami Laboratory (NTL) of the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Division of the Russian Academy of Sciences (ICMMG SD RAS). In this paper, these databases are referenced as NCEI database (NCEI/WDS 2020) and NTL database (NTL/ICMMG 2020), respectively. For the instrumental period (20th and 21th centuries), the two databases are similar in content in terms of the number of events and runup observations. The difference is mainly connected with event classification (e.g. type of sources, validity index). Another difference is that most of the events in the NTL database are provided with their intensity on the Soloviev-Imamura scale, enabling events to be compared by their intensity value, which is a good proxy for their energy scale (Gusiakov 2011). In this study, the

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NCEI database is used to determine general statistics on tsunami occurrences (temporal and spatial distribution of tsunamigenic events) and the statistics of run-up observations. The NTL database is used to retrieve the annual maximum runups during this period and determine statistics related to tsunami classification by the types of sources. In cases where minor differences between the NCEI and NTL databases are not important, they are both referenced as the Global Tsunami Database (GTDB).

Recently, several papers (Okal 2019; Gusiakov et al. 2019; Arcos et al. 2019) reviewing global occurrence of tsunamis in the last 25 years that mark the "high-instrumental" period of tsunami observations have been published. In this paper, a similar analysis is made for the last 120 years (1900–2019). The starting year of this period (1900) is pretty close to the median date (1902) that divides (by number of events) the global tsunami dataset into two equal parts. This 120-year period also roughly coincides with the "instrumental" period in seismological and tsunami measurements. The results of this analysis will provide users with a better understanding of the completeness of the global tsunami dataset and the level of uncertainty of the available data.

An important parameter of both databases is the validity index that varies from − 1 to 4 in the NCEI database and from 0 to 4 in the NTL database. The validity index relates not only the degree of confidence that a particular event was a tsunami or tsunami-like phenomenon, but also to its relationship to the indicated source location and indicated date. In this analysis we include tsunamis and tsunami-like events that resulted from of all types of tsunamigenic sources and that have positive validity indices, thus excluding only those events that are currently considered as erroneous entries.

2. *Data Selection and Description*

The Global Tsunami Database contains a total of 1270 tsunamigenic events that have been observed in oceanic, marine, and inland basins during the period from 1900 to 2019; this gives an average global tsunami occurrence of 10.6 events per year. The "size" (energy scale) of these events is very different and varies from very minor and local, hardly visible only on a single tide-gauge record, up to the catastrophic trans-oceanic mega-tsunamis affecting an entire oceanic basin that have thousand or more runup measurements. The vast majority of the registered tsunamis were weak events that are seen only on tide-gauge records. However, of the total 1,270 tsunamis there were 401 damaging or potentially damaging (with $H_{max} > 1$ m) events and among them there were 140 destructive tsunamis resulted in human fatalities.

Of these 1270 events, 412 do not have measured or estimated run-up or wave height measurements. The absence of quantitative data on a tsunami manifestation does not necessarily mean that they were all weak and had negligibly small runups or wave heights. Some of these events could have had a damaging impact (e.g. May 26, 1946 tsunami in Peru which resulted from a destructive M_w 8.2 earthquake) but historical catalogs (e.g. Soloviev and Go 1975) do not supply quantitative data on the tsunami effect. The remaining 858 events have at least one measurement or witness report on the runup height. These events were analyzed in order to obtain a set of annual maximum runups resulting from all types of tsunamigenic sources. Selection of annual maximum runups was done on the basis of a special computational procedure built-in in the PDM/TSU (Parametric Data Manager for Tsunami) graphic shell developed in the NTL/ICMMG for the database maintenance.

Results, presented in Fig. 1 show the temporal distribution of annual maximum tsunami runups observed or measured at oceanic and marine coasts, and in inland waters, during the last 120 years (1900–2019). For further analysis, all tsunamigenic sources were divided into four main groups: seismogenic, landslide-generated, volcanic, and meteorological. It is important to note that in Fig. 1 non-seismic events are indicated only when their runup heights are larger than those of seismogenic events for the same year.

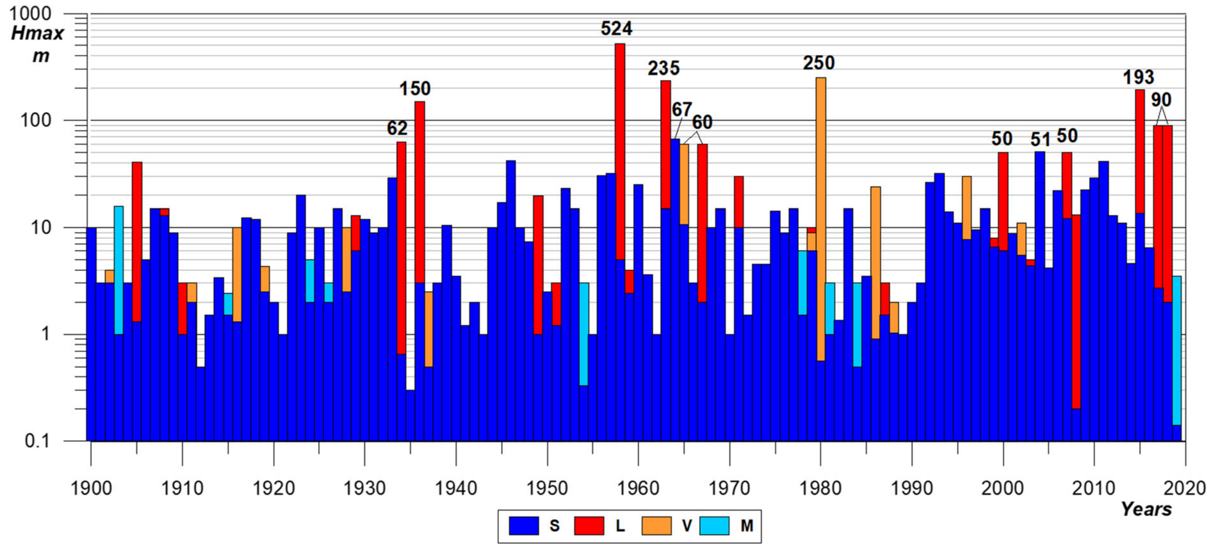

Figure 1
Maximum tsunami runup heights per years observed or measured globally during the last 120 years (from 1900 to 2019). Colors indicate the type of sources: *S* seismogenic, *L* landslide-generated, *V* volcanic, *M* meteorological. Non-seismic events are indicated only when their runup heights are larger than those of seismogenic events. For runups higher than 50 m their exact values are indicated

It should be further noted that due to the complex nature of tsunami generation mechanisms, the event classification by type of source can present a certain problem and in many cases requires expert judgment, so its result can be subjective. For example, the input of slide mechanism into the total tsunami energy can vary from very limited [as in the case of the 1964 Alaska tsunami where coastal and shallow-water landslides produced several of the highest (more than 25 m), but localized runups observed before the main tectonic tsunami arrived at the coast (Lander 1996)] to almost 100% [as in the case of the 1958 Lituya Bay tsunami where the large subaerial landslide was triggered by a strong (M_w 7.8) earthquake which itself did not contribute to the generation of the huge water wave in the bay that climbed up to a height of 524 m on a steep slope of its northern coast (Miller 1960)]. A similar situation exists for volcanic tsunamis—their generation mechanism almost always involves a slope failure or volcano flank collapse caused by the preceding volcanic activity.

The average annual maximum runup during this 120-year period is 25.4 m. In consideration of this value, one should take into account that this number is largely affected by a few years with the highest run-ups from several large landslide-generated tsunamis, e.g. July 10, 1958 Alaska 524 m, May 18, 1980 Spirit Lake, Washington 250 m, October 9, 1963 Vajont Dam, Italy 235 m. The average annual maximum runup for seismogenic tsunamis is just 9.2 m, for landslide tsunamis—65.4 m, for volcanic tsunamis—30.4 m, and for meteorological tsunamis—4.0 m.

Geographical distribution of the sources of these 120 tsunamigenic events with annual maximum runup heights is shown in Fig. 2. Historically, the Pacific remains the main tsunamigenic region of the World Ocean. Within its basin, 91 events with annual maximum runups occurred. The remaining events are divided between the Indian Ocean (6 events), the Atlantic Ocean (13 events), and the Mediterranean (10 events) regions.

Based on the data presented in Fig. 1 we can estimate that on the global level an average return period of the tsunamis and tsunami-like events with $H_{max} > 100$ m is 24 years, $H_{max} > 50$ m is 10 years, $H_{max} > 20$ m is 4 years, $H_{max} > 10$ m is 2.2 years, $H_{max} > 5$ m is 1.6 years, $H_{max} > 2$ m is 1.2 year, $H_{max} > 1$ m is 1.1 years.

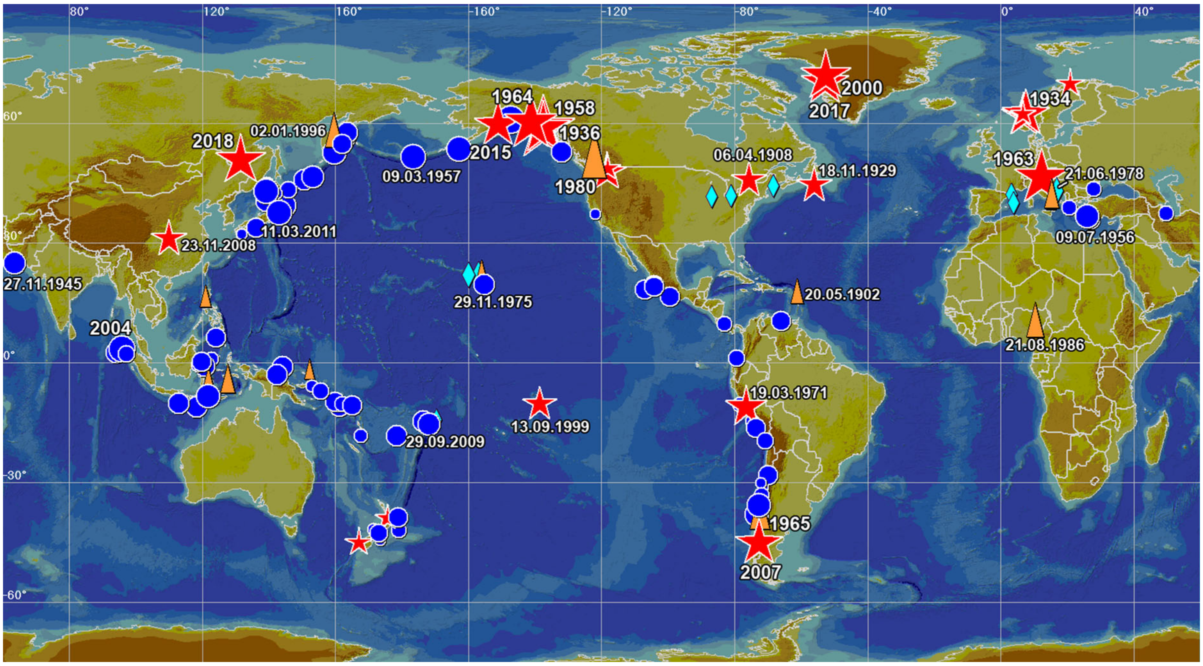

Figure 2

Map showing the locations of tsunamigenic events presented in Fig. 1. Symbols indicate the type of tsunami source: (circles) seismogenic, (stars) landslide-generated, (triangles) volcanic, and (diamonds) meteorological. The symbol size is proportional to the runup height of the corresponding tsunami. The sources of the events with runup values $H_{max} > 50$ m are marked by the year of the occurrence; some other selected events are marked by their full date (dd.mm.yyyy)

3. *Discussion and Conclusions*

The first and foremost conclusion that follows from the diagram in Fig. 1 is that among the 120 annual maximum runups, only 76 (63.3%) resulted from seismotectonic tsunamis generated by submarine earthquakes. The rest of the maximum runups are divided between 23 landslide-generated events (19.2%), 12 volcanic tsunamis (10%), and 9 meteorological events (7,5%). Taking into account that for the vast majority of volcanic events the actual generation mechanism of destructive water waves is a volcanic slope failure, the fraction of landslide-generated tsunamis in the oceanic and marine basins and tsunami-like waves in coastal and inland waters increases up to 29%.

Despite the fact that these numbers do not reflect the actual breakdown of tsunami occurrence by the type of source (in Fig. 1 we count only events that produced an annual maximum runup and ignore all other events with smaller runups), they are quite interesting because they clearly demonstrate the importance of non-seismic events in the assessment of overall tsunami hazard. In total they constitute 36.7% (that is more than one third) of annual maximum tsunami run-ups. However, with a few exceptions, the contribution of these events to tsunami hazard maps constructed according to the PTHA methodology, is not taken into account, and early warning of such events presents a problem for the existing Tsunami Warning Systems.

All seven trans-oceanic mega-tsunamis that occurred within the last 120-years (1946 Aleutians, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska, 2004 Indonesia and 2011 Japan) gave annual maxima in runup heights in their respective years. The average of their maximum run-ups is 40.2 m. Based on this and on a wide extent and a variety of types of coast affected by mega-tsunamis, we can consider this value as the upper limit of maximum runup possible for seismogenic tsunamis. Any substantial excess in a reported height of a seismogenic tsunami above this level at some stretched coastline (ignoring possible localized runups into small steep-sided valleys) must be considered as an indication to the involvement of the submarine or coastal slides in the tsunami generation (as was a case for the 1964 Alaska tsunami).

Another important conclusion that follows from the source location map presented in Fig. 2 is that tsunamis are not exclusively a marine hazard. Over 15% of all maximum runups were observed in coastal and inland water basins (narrow bays, fiords, lakes, water reservoirs and rivers). All ten extreme (higher than 60 m) runups shown in diagram in the Fig. 1 fall within this category.

Temporal distribution of the collected runups demonstrates that the annual occurrence of large tsunamis was more or less stable during the whole twentieth century with some increase during the last 27 years (since 1992), when the practice of post-tsunami surveys of all damaging tsunamis was implemented. The tsunami occurrence rate was on average 106 events per decade with only one notable exception for the decade of 1981–1990 when 77 tsunamigenic events globally occurred. An even more prominent decrease was observed in the number of strong tsunamis: just three events with runup heights exceeding 3 m. In fact, within this decade only one really damaging and fatal seismogenic event occurred—the Japan Sea tsunami of May 26, 1983 with maximum run-up height of 14.9 m (Shuto 1983). Another fatal event was a rather unique and rare volcanic tsunami with 24-m runup resulting from a "limnic eruption" (also referred to as a "lake overturn") that occurred on August 21, 1986 in Lake Nyos in Cameroon (Gusiakov 2014).

An essential increase in the annual maxima in the run-up heights of seismogenic tsunamis for the last three decades is clearly visible in Fig. 1. An average H_{max} for 1992–2019 is 14.2 m, while for the preceding years (1900–1991) an average H_{max} is only 7.2 m. This is obviously a result of the practice of Post-tsunami Surveys for all damaging tsunamis that was implemented in 1992 (Arcos et al. 2019), as well as a considerable improvement in the tsunami instrumentation that occurred in the same years (Rabinovich and Eblé 2015). Of the total 24,620 runups available in the Global Tsunami Database for the last 120 years, this period (1992–2019) contains 15,307 (62%).

The final comment concerns the year of 2019, the last year in the time period considered. This year looks like the most quiet year for more than a century, at least, as far as "geological" tsunamis are concerned (under this term, following Okal (2019), we understand the tsunamis triggered by earthquakes, landslides and volcanoes). Only six tsunamigenic events are available in the database for this year, all of them being very weak. The maximum reported runup height was only 0.3 m, and it was measured at the coast of Stromboli Island, Italy after a paroxysmal explosion on August 28, 2019. The largest instrumentally recorded height of a seismogenic tsunami was just 14 cm recorded in New Zealand after the M_w 7.2 submarine earthquake in the Kermadek region on June 15, 2019. However, the year of 2019 is marked by at least two considerable meteotsunamis that occurred on April 14, 2019 in Lake Erie (with an estimated height of about 3.5 m) and on June 21, 2019 at the northwestern coast of Mallorca Island, Spain (maximum wave height was 1.74 m) (Rabinovich 2020).

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