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Global mortality from storm surges is decreasing

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Abstract

Changes in society's vulnerability to natural hazards are important to understand, as they determine current and future risks, and the need to improve protection. Very large impacts including high numbers of fatalities occur due to single storm surge flood events. Here, we report on impacts of global coastal storm surge events since the year 1900, based on a compilation of events and data on loss of life. We find that over the past, more than eight thousand people are killed and 1.5 million people are affected annually by storm surges. The occurrence of very substantial loss of life (>10 000 persons) from single events has however decreased over time. Moreover, there is a consistent decrease in event mortality, measured by the fraction of exposed people that are killed, for all global regions, except South East Asia. Average mortality for storm surges is slightly higher than for river floods, but lower than for flash floods. We also find that for the same coastal surge water level, mortality has decreased over time. This indicates that risk reduction efforts have been successful, but need to be continued with projected climate change, increased rates of sea-level rise and urbanisation in coastal zones.

Introduction

Storm surge events are projected to become more severe under climate change due to sea-level rise (Lin *et al* 2012), and impacts can increase due to population growth in coastal zones. However, compared to fatalities from riverine and rainfall-related flooding (Jonkman 2005), fatality numbers for storm surges are not consistently recorded in national and global databases (Jonkman and Vrijling 2008), and are often neglected in scientific assessments. Reducing loss of life from natural hazards has been set as a priority outcome in the 2015−2030 Sendai Framework for Disaster Risk Reduction (UNISDR 2015). Some countries including the Netherlands (Jonkman *et al* 2011) are also adopting criteria for risk to human life for determining flood protection levels and coastal adaptation. Storm surge events, after earthquakes, have the highest death tolls per event from all natural disasters (Pears-Piggot and Muir-Wood 2016). Regional analyses of fatalities from tropical cyclones and related surge events are available (Rappaport 2014, Alam and Dominey-Howes 2015), but the lack

of consistent recording and reporting at the global level of storm surge events, coastal flooding, and their impacts hinders the understanding of the frequency and impacts of these phenomena. In the much used EM-DAT database (EM-DAT) on global disaster impacts, storm surge events are listed under both the flood and storm (cyclone) categories. The analysis of large scale impacts of storm surges, and long term trends in occurrence and impacts is valuable for planning of risk reduction and adaptation efforts.

Other analyses have highlighted the projected increase in the storm surge hazard caused by future increased cyclone intensities (Hoffman *et al* 2010, Vousdoukas *et al* 2016), as well as increased fatality numbers driven by increasing exposure as a result of demographic pressure (Maaskant *et al* 2009, Peduzzi *et al* 2012). While increasing exposure is indeed the key driver for increased property losses from weather-related natural hazards in recent decades (Handmer *et al* 2012), other lines of research indicate possible declines in vulnerability (that is sensitivity of impacts to a given flood hazard) over time, shown for both property losses and especially fatality risk

(Mechler and Bouwer 2015, Jongman *et al* 2015). Specifically for flood risk, urban coastal development has been identified as driver for current and future risks (Bouwer 2013), but much less is known about changes in vulnerability of exposed people and assets (Handmer *et al* 2012). There are reasons to expect that changes in fatality losses are different compared to property losses. For instance, in the country of Bangladesh, risk reduction efforts over the last decades have led to major declines for storm surge fatalities, attributed to improved forecasting, early warning and cyclone shelters, but also improved coastal protection (Chowdhury *et al* 1993, Paul 2009, Lumbroso *et al* 2017). Capturing such changes in vulnerability are essential for making reliable projections of disaster risk into the future, and in turn to provide a basis for appropriate decisions on levels of protection and risk management strategies.

Here, we focus on storm surges caused by windstorms or cyclones. High wind speeds in windstorms (both at tropical and extra-tropical latitudes) in combination with low atmospheric pressure cause set-up of water levels at the coast. Especially when this situation coincides with an astronomical high tide at the coast, this can lead to exceptionally high water levels and flooding of coastal areas. A compiled record of major global storm surges caused by windstorms was built on events for the period 1900–2015. This list of 121 events can be considered to be the first compilation of global historic storm surge events with high numbers of fatalities.

Methods

Data on storm surge events, and related number of fatalities and people affected, were principally derived from the EM-DAT database (EM-DAT) collected by CRED in Belgium, which holds information for several natural and man-made disaster events. An obstacle for identifying fatalities from storm surges is the fact that storm surge events, depending on their main characteristics and impacts, have been classified in EM-DAT as either a flood event (typically windstorms with large numbers of casualties and damage, where the main impact consists of coastal inundation), or storm event that has both wind and inundation related impacts, which are often smaller events in terms of fatalities. Events were collected from both classes of event types, and combined into one database. All events listed under storm surge/coastal flood were included. Storm surge events from the category of storm events in EM-DAT would ideally be selected based on event descriptions. But good descriptions on causes of fatalities for events before 1980 are typically scarce, and therefore a threshold had to be introduced. The selection for storm/cyclone events was based on events with at least 2000 fatalities until the year 1980, and at least 500 fatalities after 1980. This selection criterion was included, as only events with high numbers of fatalities

are likely caused by coastal flooding (see discussion below), and events with small numbers related to wind impacts or torrential rains and landslides should be excluded. Only 36 of the total 121 events included in our database were taken from the storm/cyclone category, and therefore the bias introduced by the selection threshold of 2000 casualties before 1980, and 500 casualties thereafter, is expected to be limited. The possible bias is also statistically tested in the results section.

Next, impacts were identified and additional sources of information from literature and internet sources were used to establish in which events storm surge and coastal flooding actually occurred. In a final step, it was determined whether fatalities could be attributed to the coastal flood event from the recorded data, as in windstorm events there are often also fatalities resulting from high wind speeds, rainfall-related (flash) flooding, and landslides. From previous assessments (Rappaport 2014) it can be concluded that storm surge is the cause of a major part of the fatalities in cyclones that have high fatality numbers. For example, hurricane Betsy (in 1965), hurricane Frederic (in 1979) and hurricane Katrina (in 2005) occurred in Louisiana (USA) near New Orleans and were of similar strength (category 3). Frederic did not lead to surge flooding and caused 5 fatalities. Betsy lead to flooding in the eastern parts of New Orleans and caused 76 fatalities. The flooding during Katrina was much more substantial and this led to hundreds of fatalities in New Orleans (Jonkman *et al* 2009).

For this analysis, we collected data on storm surge events and several characteristics, including: continent; country; date; type of event; cyclone name; total fatalities; and total affected population. Important additional sources for verification consisted of records of surge events in the Bay of Bengal (Alam and Dominey-Howes 2015), the United States (Rappaport 2014), as well as various other literature and anecdotal sources, mostly found through Internet. Similar to previous studies (Jonkman 2005) it was assumed that an event did not result in fatalities if EM-DAT did not report a value for the number of fatalities. Fatality numbers, especially for events in the more distant past, are associated with considerable uncertainty. For instance the estimated number of casualties in the 1970 Bhola cyclone in Bangladesh ranges from 200 000−500 000 (Alam and Dominey-Howes 2015). In addition, loss of life directly related to the event represents only a small part of total loss of life and health impacts, as shown by high infant mortality rates after natural hazard events (Anttila-Hughes and Hsiang 2013).

Although likely many smaller events are not included in our database, it does include events with major loss of life. The data is expected to be reasonably complete since the 1960s for events that have led to 1000 casualties or more. Since the 1980s also events with smaller fatality numbers are included. As the EM-DAT database was originally set up to record events in developing countries in low latitudes, surge events

Table 1. Distribution of storm surge events and fatalities between world regions (1900–2015).

World region	Events	Total fatalities	Percentage fatalities	People affected	Average event mortality [—]
Africa	5	102	0.01	684 329	0.0001
East Asia	15	118 546	12.3	14 442 267	0.005
Europe	11	2588	0.3	1 170 410	0.01
Latin America	9	2566	0.3	341 085	0.001
North America	13	10 713	1.1	9 548 533	0.02
Pacific	15	34	0.004	110 459	0.002
South Asia	27	684 783	71	120 806 828	0.007
South East Asia	26	148 284	15.3	25 398 458	0.004
Total	**121**	**967 616**	**100**	**172 502 369**	**0.006**

from extra-tropical cyclones in high latitudes are possibly underrepresented.

Mortality (F_D) in flood events is calculated as the ratio between the number of people killed and the number of people exposed to the flood (Jonkman 2005):

$$F_D = N / N_{\text{EXP}}$$

where N is the total number of fatalities, and N_{EXP} is the exposed population.

The number of people exposed consists of the local population, minus the number of people that have been evacuated. Data on the exact number of people exposed to the actual flood event is often not recorded in existing databases, and is difficult to reconstruct for events in the more distant past. Therefore the number of people affected is commonly used as a proxy (Jonkman 2005). The reported event mortality values are average values: due to the spatial variation of the surge, population density and protection, different mortality values will generally be found for locations affected by a single event. For example, estimated average mortality for hurricane Katrina in New Orleans was 0.004, while mortality fractions in the most severely affected neighbourhoods (such as the Lower Ninth Ward) were higher than 0.05 (Jonkman *et al* 2009).

Storm surge level data was taken from the SURGEDAT database (Needham *et al* 2015, SURGEDAT), complemented with information for surge events in the Bay of Bengal (Alam and Dominey-Howes 2015) and other recorded sources. Here, the peak surge levels, i.e. maximum water level during an event are reported. It is noted that coastal surges generally affect large areas and the water levels could differ between locations affected in the same event. Where possible the total water level is used. However, the water levels contain considerable uncertainty, as different elements are reported, some including the tidal component as well as waves, but at least the surge component.
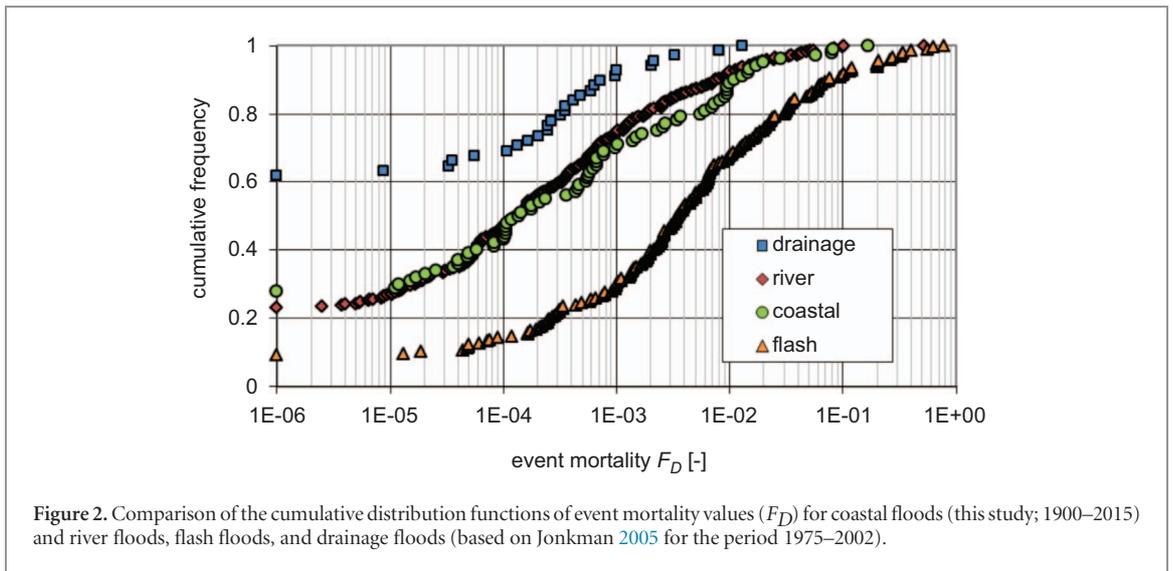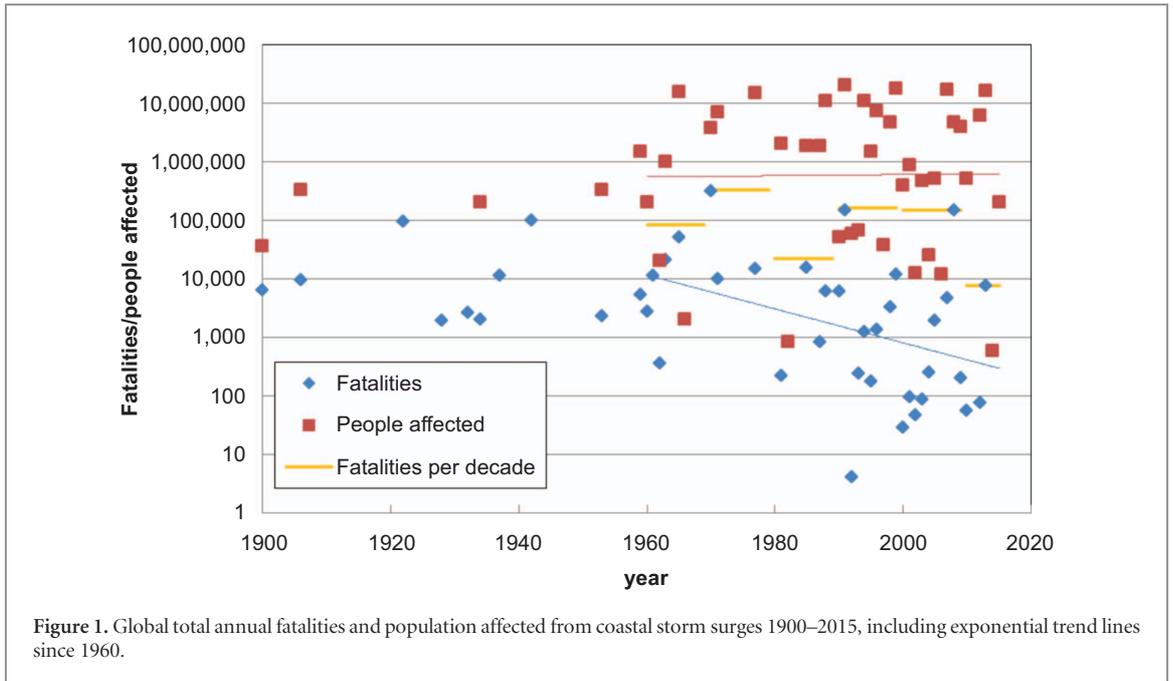
Results and discussion

The estimated total number of people killed over the period 1900–2015 according to this database amounts to 967 616, while the total number of people affected is 172 million (table 1). This is on average 8342 fatalities and 1.5 million people affected per year, and 7996

fatalities and 1.4 million people affected per event. The largest share of fatalities has occurred in South Asia, with a total of 684 783 fatalities (71%) over the period 1900–2015. This is caused by a dense coastal population, frequent cyclones, and in some places low protection levels and lack of warning.

We find that total annual fatalities from major storm surges have declined since the 1960s (figure 1). Large events with over 100 000 fatalities still do occur, such as during Cyclone Nargis in Myanmar in 2008, but the trend is downward. This is impressive, given that world population has approximately doubled since the 1960s, and increased six-fold since 1900 (Maddison database), with much of this increase occurring in the coastal regions (Hallegatte *et al* 2013). This downward trend is probably related to improvements in the prediction of storms and typhoons, and warning and evacuation of the population have a discernible effect on loss of life (Schultz *et al* 2005). At the same time, the number of affected people has remained quite stable since the 1960s, and perhaps even increased since the end of 20th century. This is clear from the fact that 8 of the 12 events with more than 5 million affected people in the database have all occurred since 1991.

Event mortality (F_D) is the estimated fraction of fatalities within the exposed population, thus indicating how lethal a certain event or type of event is. We find an average event mortality of 0.006 for all events with sufficient information to estimate event mortality, including events with zero or more fatalities (100 out of the total of 121 events), and 0.009 for events with fatalities (72 events). A previous study (Jonkman 2005) developed mortality distributions for drainage floods, river floods, and flash floods, and these are reproduced here for comparison. Compared to other types of floods (figure 2), the event mortality distribution found here for storm surges is slightly higher than what is found previously for river floods, but lower than for flash floods that generally affect fewer people. Other coastal hazards can have even higher mortalities: event mortality for the most affected region by the 2011 Tohoku tsunami in Japan ranged between 0.1 on average and up to 0.8 in the most severely affected communities (Nateghi *et al* 2016).

The decline in fatalities from storm surges over time is also reflected by a decline in event mortality F_D. Previous research (Jonkman and Vrijling 2008) placed

Figure 1. Global total annual fatalities and population affected from coastal storm surges 1900–2015, including exponential trend lines since 1960.

Figure 2. Comparison of the cumulative distribution functions of event mortality values (F_D) for coastal floods (this study; 1900–2015) and river floods, flash floods, and drainage floods (based on Jonkman 2005 for the period 1975–2002).

the average mortality from storm surges at approximately 0.01, but here we show this value has not been constant over time. Broken down by regions, it becomes clear that within consecutive historic events, mortality has consistently declined for most world regions (figure 3). This is especially clear for South Asia and East Asia, where events with mortality values between 0.01 and 0.1 were frequent during the 20th century, but have decreased to less than 0.01 since the beginning of the 1990s. For South East Asia, no clear decline in mortality can be found. The possible selection bias due to the inclusion of only large storm/cyclone events before 1980 does not affect the conclusion with respect to a declining trend in mortality, as the event mortality for all events with more than 2000 fatalities ($n = 17$) also shows a significant decline after 1980, indicated by the dotted line in figure 3.

Two tests were performed in order to check the significance of these results. First, the significance of the least-squares regression lines was tested. As the mortality data is highly skewed, a log-transformation was applied. The regression line for all mortality data is significant (F-test, $p < 0.001$, $n = 72$), and the regression line for the data including only events with more than 2000 fatalities is also significant ($p = 0.01$, $n = 17$). The difference between these two regression lines was tested in a multiple regression by adding a categorical variable that discriminates the events with fatalities of more than 2000. This variable has a significant contribution to the multiple regression ($p = 0.016$, $n = 72$). Although the two regression lines in figure 3 are different, both demonstrate a significant decline.

Second, in order to exclude the possibility of a selection bias, we tested the difference between the mortality before and after 1980 for events with at least 2000
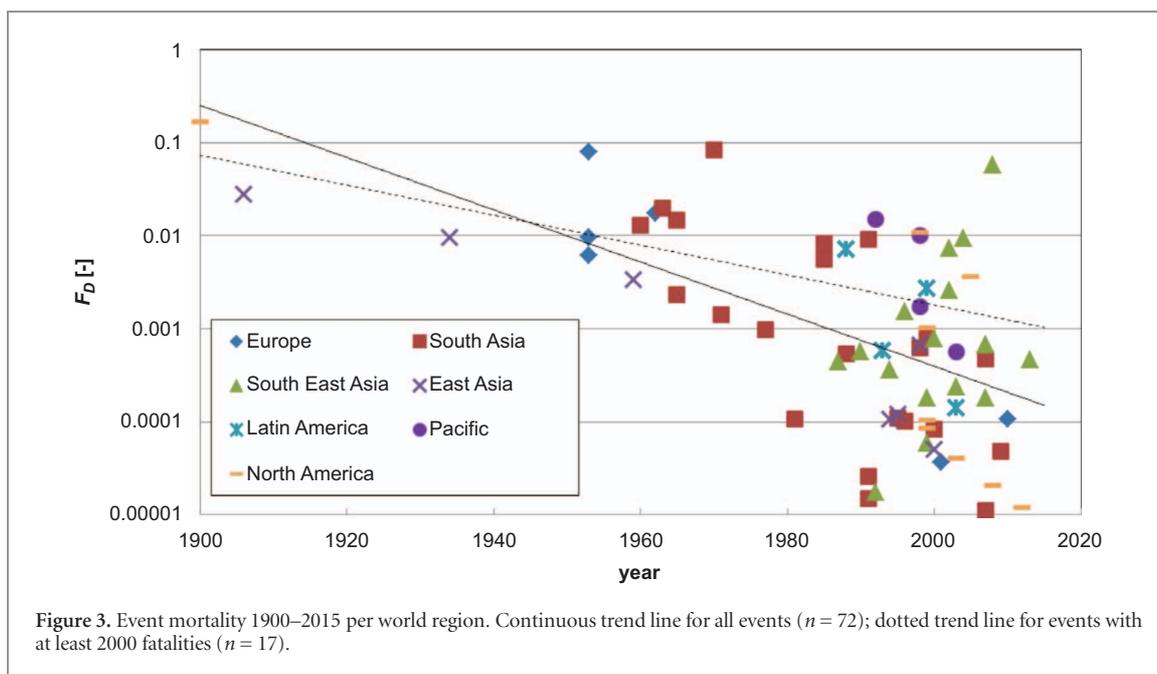
Figure 3. Event mortality 1900–2015 per world region. Continuous trend line for all events ($n = 72$); dotted trend line for events with at least 2000 fatalities ($n = 17$).
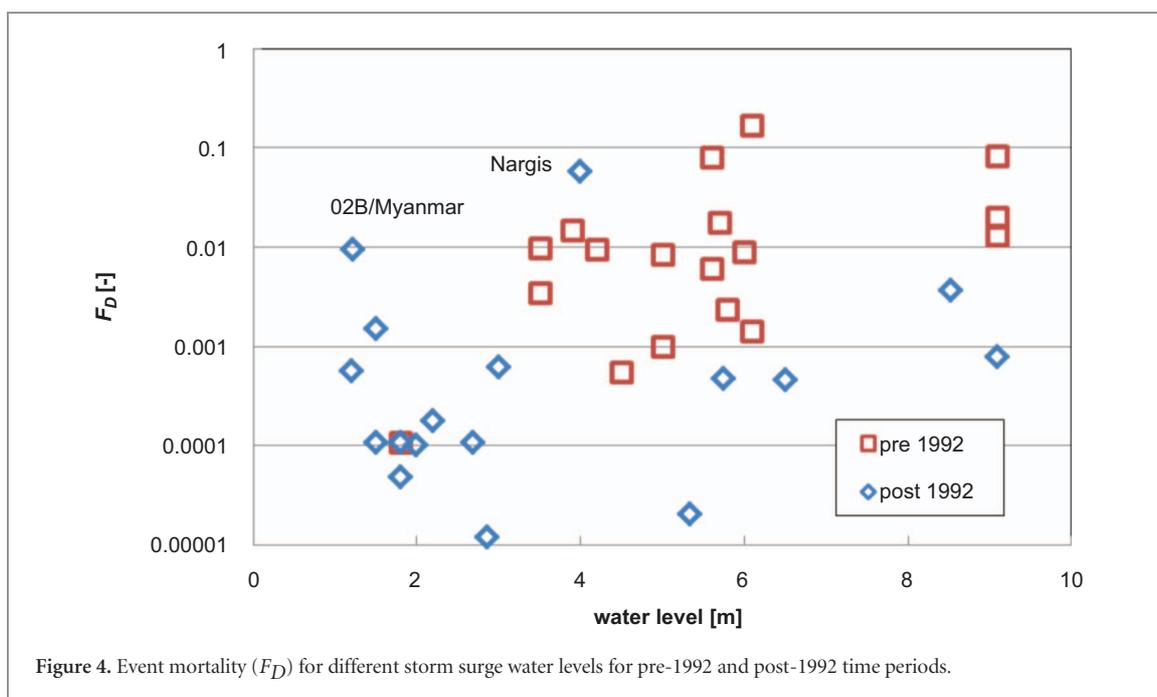

Figure 4. Event mortality (F_D) for different storm surge water levels for pre-1992 and post-1992 time periods.

fatalities ($n = 17$; 9 events before 1980, and 8 events after 1980). A one-tailed *t*-test on the log-transformed data shows that the average mortality before 1980 is significantly higher than after 1980, also for events with more than 2000 fatalities ($t = 1.82$, $t_{crit} = 1.75$, $p = 0.04$).

In order to understand the role of surge severity in event mortality, the relation between mortality and storm water levels is displayed in figure 4. Surge height clearly can only partially explain the level of event mortality. Factors such as coastal topography and flood protection measures will determine the depth and area of the flood, as well as early warning and evacuation that determine the number of exposed people. However, by splitting the data into two periods, it is revealed that the relation between surge severity

and mortality may have changed over time. The period before 1992 has a significantly higher average mortality than the period after 1992 (see supplement available at stacks.iop.org/ERL/13/014008/mmedia), possibly related to more early-warning and evacuation schemes becoming effective. This, in combination with the decreasing trends in fatality numbers (figure 1) and mortality (figure 3) indicates that coastal communities on average have become less vulnerable to coastal surges.

Over the last decades, flood protection and forecasting, quality of residential buildings, early warning and evacuation, have improved considerably in most parts of the world. This has led to a steady decline in mortality from storm surges. The exceptions are the

coastal floods in Mexico (hurricane Frances in 1998; not displayed in figure 4), and Myanmar (Cyclone 02 B in 2004; and Cyclone Nargis in 2008 with over 138 408 fatalities). These are the only events since 1992 with mortality equalling or exceeding 0.01 (F_D= 0.01, 0.009, and 0.057, respectively). The high mortality in Myanmar can be explained by the absence of sufficient protection, forecasting and early warning systems in this country (Fritz *et al* 2009). Other recent events with very high surge levels and high numbers of fatalities had much lower mortalities, such as Cyclone Sidr (Bangladesh) in 2007 (F_D= 0.0005, maximum surge level 5.75 m) and Cyclone Haiyan (Philippines) in 2013 (F_D= 0.0005, maximum surge level 6.5 m). This illustrates that predicting mortality based on historic events may lead to too high estimates of current and future impacts for most coastal countries, and for locations where adequate warning, evacuation and protection are in place.

Conclusions

These findings have important implications. They show that the fatality risk from storm surge hazards is considerable, with high numbers of casualties per event and per year. As a hydrological hazard it is only exceeded in terms of mortality by flash floods, but storm surges affect more people. Also, benefits of efforts put in forecasting, early warning, evacuation, as well as coastal protection, risk-zoning and land-use planning, and shelters are reflected in the declining number of fatalities and declining mortality. It remains to be evaluated whether measures that have been successful so far are also effective for projected increased rates of sea-level rise. Sea-level rise could contribute to more frequent events, higher flood depths and thus less effective protection. Other factors such as subsidence and population growth can affect potential loss of life (Maaskant *et al* 2009). This could imply that the current decrease fatalities and event mortality could slow down or even reverse. Therefore, continued investments in the reduction of the vulnerability of coastal regions will remain important, through forecasting, emergency and land use planning as well as physical protection, especially under changing environmental and socio-economic conditions.

We found that fatalities for storm surge events are not systematically collected, and from EM-DAT events had to be selected from two events types: storm surge/coastal flood and storm/cyclone. In general, there is a reporting bias towards more recent events, which is also a well-known reality for other natural hazard event types. Better systematic collection, classification and reporting of loss of life due to coastal storm surges is recommended, to supplement current practices for other hazard types. This will enable continued monitoring and reporting on storm surge impacts, and support decisions on risk reduction efforts around the world.

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