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ORIGINAL PAPER

Coasts: the high-risk areas of the world

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Abstract No other region is more threatened by natural perils than coasts. Fierce winds, storm surges, large waves and tsunamis expend their destructive energy when they reach the coastline. Constituting, in many cases, the boundary between continental plates, coasts experience earthquakes and volcanic eruptions more frequently. The changing climate poses the threat of sea level rise. Most global trade crosses the oceans; ports are the entry and exit points of a nation's trade. As a consequence, coasts attract people, businesses and industries. Some coastal regions rank among the top places in the world in terms of population and value accumulation. Enormous catastrophe loss potentials have been created and are increasing. Risk is the result of a natural hazard, the values at risk and their vulnerability. Living with and reducing the risk requires awareness at all levels of society and partnership between the public authorities, the people and enterprises concerned, and the financial sector. Great natural events are not avoidable, great disasters are. Catastrophes are not only products of chance but also the outcome of the interaction between political, financial, social, technical and natural circumstances. Effective safeguards are both achievable and indispensable, but they will never provide complete protection. In order to manage the risks faced by a society, we have to be aware of that.

Keywords Coasts · Disaster losses · Disaster risk · Climate change · Risk reduction · Insurance

1 Introduction: natural disasters on coasts

There are few natural catastrophes that are not somehow related to coasts. While not all of them occur right on the borderline between land and sea, their causes can be found either in meteorological events produced over the water or in geological events that happen at the crustal plate boundaries along the continents or mid-ocean ridges. "Coasts" stands in this paper for the potentially affected regions on both sides of the shoreline: the land side that

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may extend more than 100 km inland, but also the water above the continental shelf, where wind farms and offshore platforms are located. Wind forces and wave action from tropical and extra-tropical storms are normally at their most consequential at the point of landfall; on the open ocean, away from the continental shelf, there are—apart from vessels—no assets to be damaged and, over land, the wind gradually loses strength. The clouds of low-pressure systems derive their water content from the sea. Tsunamis triggered by—albeit distant—earthquakes exert their highest destructive potential when they reach the coast. Even earthquakes and volcanic eruptions happen much more frequently near the coast than further inland, their origin being closely related to the formation of the continents and, through this, related to plate tectonics (the best example being the Pacific "Ring of Fire").

It is also important, however, to recognise that not only are coasts subject to more intense and more frequent natural events, but they are also the places with the highest concentration of people and values. Disaster happens only if people are killed or injured and/or their possessions damaged or destroyed. Similarly, whether a location is risk-prone depends on (a) the likelihood that a natural event may occur and (b) the presence of vulnerable items. Rising sea levels, increased tropical cyclone frequencies and intensities (rain and wind), unprecedented flood experiences, on the one hand, and megacities with rapidly growing populations and industrial development, on the other, are making coastal regions ever riskier.

This paper is written from the perspective of a reinsurance company operating on a global scale. Loss events caused by natural disasters that hit coastal areas are among the critical loss scenarios for such companies as they are crucial in terms of their overall performance and even their survival. Therefore, such scenarios must be treated with high priority. The need to assess the risk properly requires the commitment of considerable effort and resources. Proper assessment of natural catastrophe risks is key to business operations. The outcome of that assessment need not necessarily, as is the case with scientific studies, meet sound statistical confidence criteria. The important criterion is for the company to be confident that the result is valid, that is, that it best represents the expectation value of the parameter/variable in that particular case. This by no means implies that a conservative figure, that is, one which is most advantageous for the reinsurer, is chosen, since the figure must be reasonable and acceptable to both parties to a reinsurance contract. If the rate (price of insurance cover) is too low, the business will not yield revenues for the reinsurer. If it is too high, the reinsurer's business partner (a primary insurer) may take the business to a company that offers the desired cover more cheaply.

Proper risk assessment must include each of the risk components, take into account a number of variables and quantities—physical and economic, social and political, even psychological and cultural—and consider a plethora of different aspects. This paper begins with a brief statistical review of recent natural catastrophes. It then defines and discusses the components that make up risk, hazard, values at risk and vulnerability, and one potential factor of changing risk: climate change. Risk reduction and the role of the different sectors involved, that is, public (authorities), private (people/companies) and insurance (primary insurance, reinsurance), are then described. Important aspects of natural perils insurance—in particular those with major, widespread consequences—are presented and conclusive statements drawn.

2 Loss statistics and trends

We need not go far back in history to find examples of extraordinary events in nature that produced extreme catastrophes—extreme in different respects: in terms of scale (regional intensity or large-scale impact), number of fatalities or financial losses.

The tsunami of 26 December 2004 killed more than 220,000 people in 13 countries around the Indian Ocean, and the 11 March 2011 tsunami devastated a whole region in Japan. In 2005, Hurricane Katrina left the United States with a bill of some US$ 125bn (Fig. 1). In Europe, Winter Storms Kyrill (January 2007) and Xynthia (February 2010) cost US$ 10bn and US$ 6.1bn, respectively, the latter claiming 41 lives due to storm surge, Europe's highest storm surge death toll since 1962, when more than 300 people were killed in Hamburg. Bangladesh (2007) and Myanmar (2008) were hit by tropical cyclones that left thousands dead and vast areas destroyed by wind and flooding. Australia's east coast was beleaguered by four consecutive storms, in June 2007, that brought wind, rain, snow and high waves, and drove one large vessel onshore. Only in the case of Africa does one have to go back a few more years to the last major coastal disaster, with the exception of the 2004 Indian Ocean tsunami mentioned above (which killed about 300 people in Somalia, Kenya, Tanzania, Seychelles and Madagascar): namely to 2000 and 2001, when large parts of countries in the south-east of the continent were hit by a number of cyclones.

Table 1 shows the 23 greatest natural disasters (exceeding US$ 10bn in terms of monetary losses and in original values) in the 12 years from 2000 to 2011. In all, 15 of these events occurred, at least in part, in coastal areas (as indicated in row 5 of the table). In the past 4 years, several strong earthquakes have assumed top ranks (1, 3, 6, 8) in this table, while, in the first 8 years, meteorological events clearly dominated.

Some events not included in Table 1 are nevertheless worth mentioning because they were extreme on a regional scale. One of these was Cyclone Gonu, which caused flood losses of US$ 3.9bn (US$ 650 m insured losses) in the Masqat area of Oman on the Arabian Peninsula in June 2007. Another was the Mumbai flood of June 2005. Almost

Fig. 1 Casino in Biloxi, Mississippi, USA after Hurricane Katrina in 2005 (© Munich Re)

Table 1 The 23 costliest natural catastrophes since 2000 (losses exceeding US$ 10bn in original values) (Source: Munich Re NatCatSERVICE)

Rank	(Month/ year)	Event	Country/region	Event related to a coast	Total losses US$ bn	Insured losses US$ bn
1	2011	Earthquake, tsunami	Honshu/Japan	x	210[a]	40[a]
2	2005	Hurricane Katrina	Gulf coast/USA	x	125	62.2
3	2008	Earthquake	Sichuan/China		85	0.3
4	2011	Floods	Thailand		43	10
5	2008	Hurricane Ike	Caribbean, USA	x	38	18.5
6	2010	Earthquake, tsunami	Chile	x	30	8.0
7	2004	Two earthquakes	Honshu/Japan	x	28	0.8
8	2010/2011	Three earthquakes	New Zealand	x	24	18.8
9	2004	Hurricane Ivan	Caribbean, USA	x	23	13.8
10	2005	Hurricane Wilma	Caribbean, Mexico, USA	x	22	12.5
11	2008	Winter damage	China		21	1.2
12	2004	Hurricane Charley	Florida/USA	x	18	8.0
13	2002	Floods	Central Europe		16	3.4
	2005	Hurricane Rita	Gulf Coast/USA	x	16	12.1
15	4/2011	Tornadoes	Midwest/USA		15	7.3
16	5/2011	Tornadoes	Midwest/USA		14	6.9
	2003	Heatwave, drought	Europe		14	1.1
18	2007	Earthquake	Niigata/Japan	x	13	0.3
19	2004	Hurricane Frances	Caribbean	x	12	5.5
20	2007	Winter storm Kyrill	Western, Central Europe	x	10	5.8
	2008	Hurricane Gustav	Caribbean	x	10	3.5
	2004	Earthquake, tsunami	Indian Ocean	x	10	1.0
	2008	Floods	Midwest/USA		10	0.5

[a] Preliminary estimate

1,000 mm of rainfall in just 1 day produced US$ 5bn (US$ 770 m insured) in flood losses in one of India's most industrialised and certainly most densely insured regions. And one should also mention the 2010 earthquake in Haiti, which claimed more than 220,000 lives and caused US$ 8bn in damage.

Munich Re's NatCatSERVICE, the world's largest natural catastrophe loss database, has collected data systematically since 1980. It holds more than 20,000 event descriptions from the past 32 years, between 700 and 1,000 being added each year. All loss figures presented in this paper are taken from the NatCatSERVICE database. The events are classified into four categories:

(a) Geophysical events (earthquakes, tsunamis, volcanic eruptions);
(b) Meteorological events (tropical storms, winter storms, convective storms);
(c) Hydrological events (floods, mass movements);
(d) Climatological events (temperature extremes, droughts, wildfires).

By far, the majority (86 %) are weather related (Fig. 2). Meteorological and hydrological catastrophes account for 38 and 35 %, respectively, and climatological catastrophes for 13 %. The picture is almost the opposite for fatalities. Here, geophysical events are responsible for 39 % and climatological events (mainly heatwaves and droughts) for 32 % of all deaths.

In terms of losses, storms are the prime cause. They make up 39 % of overall economic losses and 72 % of insured losses. The shares of geophysical events and hydrological events for overall losses (26 and 23 %) and insured losses (12 and 9 %) are similar. It should also be pointed out that fatalities and losses from storm surges are included under meteorological losses, and the corresponding tsunami data under geophysical losses.

There is no doubt that the number of natural catastrophes has been increasing in past decades. The main causes are rising global population and wealth, settlement in high-hazard regions and growing vulnerability in general. Two further factors may also contribute to the upward trend: reporting bias and climate change.

Reporting bias stems from developments in communication technology. While, in the 1950s and 1960s, news of local disasters from remote regions did not normally reach the global media, in the current Internet age, we quickly learn of local loss events, no matter where they occur. However, we can assume that the effect of this factor has been relatively small for the past 30 or so years as a whole.

It is interesting to note that the number of loss events per year has increased at different rates for the four natural hazard categories (Fig. 3). In particular, the geophysical-causes gradient is much less steep than that for weather-related events. If the socio-economic factors mentioned above were the only causes behind the disasters, the gradients ought to be similar. The fact that this is not so is most probably due to climate changes. Protection measures such as earthquake-resistant design and storm-proof construction can, at most, affect the losses incurred from a disaster, but not the number of events.

The sequence of annual losses (Fig. 4) shows an even more pronounced rise for overall and insured losses. Here, socio-economic factors are clearly the main drivers of the increase, but climate change is also thought to play a part, as noted in the case of certain regions and hazards (Neumayer and Barthel 2011).

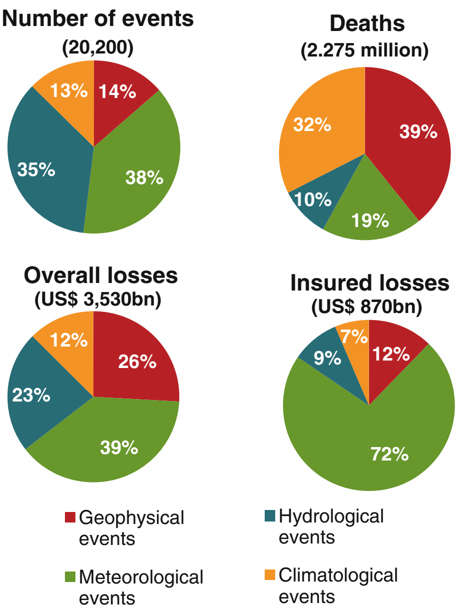

Fig. 2 Natural catastrophes 1980–2011: breakdown by event (% worldwide, losses in 2011 values; source: Munich Re NatCatSERVICE, January 2012)

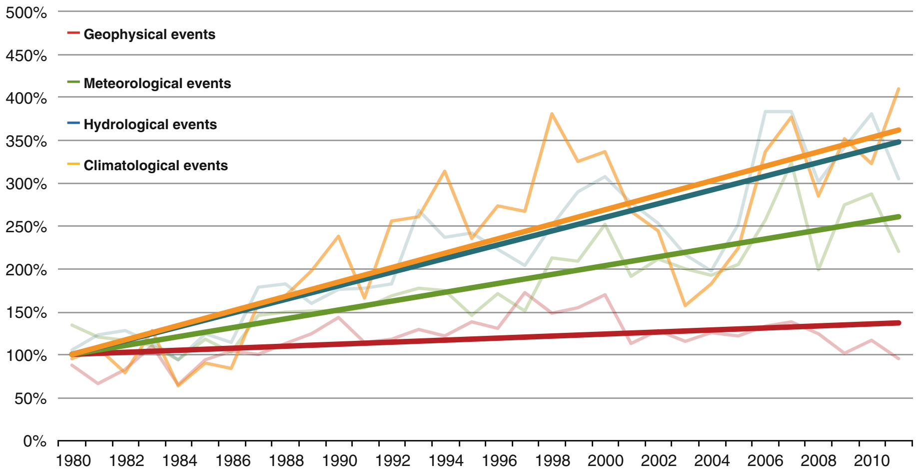

Fig. 3 Relative number of loss events from different causes 1980–2011, normalised to the number of events according to the value of the respective trend line in 1980: Geophysical events (earthquakes, tsunamis, volcanic eruptions): 100 % = 73. Meteorological events (storms): 100 % = 134, Hydrological events (floods, mass movements): 100 % = 100, Climatological events (extreme temperatures, droughts, wildfires): 100 % = 34 (Source: Munich Re NatCatSERVICE, January 2012)

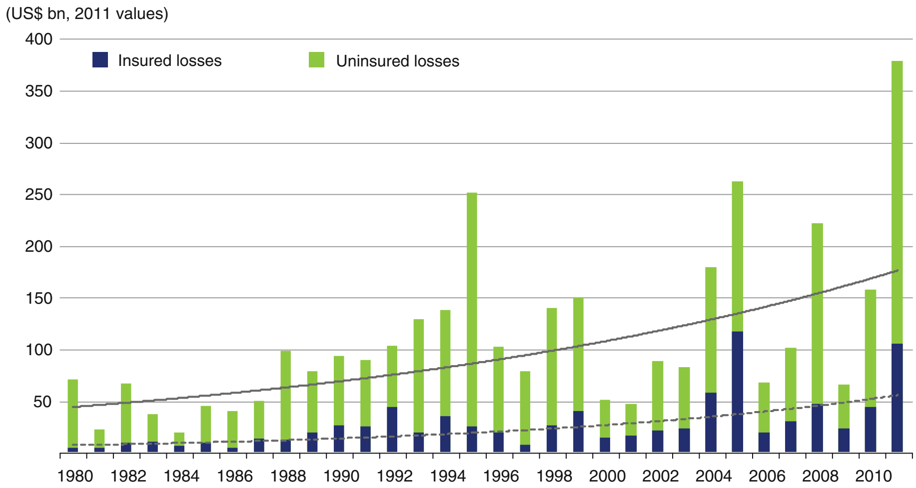

Fig. 4 Natural catastrophe losses 1980–2011: annual overall losses and insured portion with exponential trend curves (in 2011 values) (Source: Munich Re NatCatSERVICE, January 2012)

3 Changing risk

The increase in natural hazard losses is a direct function of the number of people who have to or wish to settle in risk-prone areas, the values they possess and the susceptibility of those values to the forces of nature. Hence, it is not the natural hazard as such that accounts for the consequences of an extreme event.

3.1 What is risk?

The term risk is used in different ways in different situations. For the purpose of scientific discussion, it should be defined in a consistent, unambiguous way. In this paper, risk is understood in qualitative terms—as the product of a hazard and its consequences. It is thus determined by three components (Kron 2005):

- Hazard H, that is, the probability of occurrence of the threatening natural event;
- Exposed values or values at risk E, that is, the objects situated at the location involved;
- Vulnerability V, that is, the lack of resistance to damaging/destructive forces.

In its most simple form, risk is calculated by multiplying the three components:

$$R = [H] \times [E] \times [V] \tag{1}$$

where there are no people or values to be affected by a natural phenomenon, there is no risk.

3.2 Coastal hazards

Coastal hazards are usually associated with weather hazards. The most common is storm surge. Water is driven towards the land by sustained, strong winds, and the water level rises along the coast, inundating coastal lowlands—sometimes up to several metres. Storm surges have been among the deadliest and costliest disasters in past decades. However, the other, much rarer but, therefore, often far more dramatic hazards (in particular tsunamis), also need to be considered. Even on a sunny day, coasts can be hit by flood events whose cause originated thousands of kilometres away.

Coastal hazards in the context of this paper, however, include not only those that just occur at the coast, such as storm surge, but all hazards that may hit a coastal region. Most of the hazards classified into the four categories described above may be present in coastal regions. A few tend to be less severe—such as heatwaves and droughts—but many are considerably more frequent and powerful than in regions far from the coast.

Hazard is the threat posed by natural processes that cannot be influenced. The strength of an earthquake, maximum wind speed, the height of a storm surge or a tsunami are more or less beyond mankind's control or even influence. Dykes do not affect the hazard, but should be considered part of the vulnerability factor, as they reduce the impact of a high water level. There is one way, however, in which we can influence hazard and this concerns human-induced climate change. While mankind has played its part in making climatic peculiarities more severe, it can also take action to render our global climate more favourable again. This will be possible only in the long run, however. To reduce current and near-term risk, we have to come up with other forms of response.

The implications of a changing climate are probably more important for coasts than anywhere else. Average global sea level is expected to rise some 20–60 cm by 2100, according to the 4th report of the Intergovernmental Panel on Climate Change (IPCC 2007). More recent findings, which consider increased melting of the polar ice shields as well, suggest that this rise could even double (e.g. Rahmstorf 2007). The global temperature increase will also mean greater probabilities of extremes such as higher rainfall intensities, prolonged heatwaves and droughts.

3.3 Values at risk

The dramatic increase in the world's population, in particular in certain regions, is the main reason why natural disaster losses have virtually skyrocketed in recent decades. No other locations are as attractive to people as coastal areas. Today, one-tenth of the world's population lives in low-lying areas along the coast, less than 10 m above mean sea level and therefore potentially threatened by storm surges and—in some cases—tsunamis (Lichter et al. 2010). One-third of mankind settles within 100 km of a coastline, and thus has to cope with higher wind speeds (Small and Nicholls 2003), and about half within 200 km (Creel 2003). In addition to permanent residents, millions choose coastal regions as a holiday destination. In Florida, for example, 18.8 million residents (2010 figure, compared with 100,000 in 1920) are joined by more than 80 million tourists every year (compared with zero in 1920; State of Florida 2011).

Cities develop best, given optimum access to mass transport. Ports are the entry and exit points of a nation's trade. Due to their often flat topography, coastal areas are also favourable sites for industrial facilities that need a lot of space, and they are easy to develop. A study sponsored by the OECD (Nicholls et al. 2008) looked at 136 port cities around the world that have more than one million inhabitants.

According to this study, around 38 % of the largest ports are in Asia, and 27 % are located in deltaic settings, again mainly in Asia. Cities located on deltas are at low altitudes and therefore tend to have a higher coastal flood hazard. The twenty cities projected to be most exposed to coastal flooding in the 2070s are compared with their present-day situation (Table 2). The comparison considers two aspects: exposed assets (that is, the value of buildings, infrastructure, etc.) and population. The 100-year flood zone was considered, that is, the exposed area with a 1 % probability of being flooded in any 1 year.

The list of cities with the highest exposed values in the 2070s is headed by Miami, which was already at the top in 2005. Six of the top twenty are located in the USA and Europe, six in China, seven in the remainder of Asia and one in Africa. In all twenty, assets of some US$ 2,204bn are currently exposed to flooding; in the 2070s, that figure will exceed US$ 26,000bn, a more than 12-fold increase. The growth rate of the American and European cities (mean increase factor less than seven) is far below the average. Each of the six Chinese cities listed is projected to grow more than 24-fold, and outright leader Qingdao, 201-fold.

All but two (Miami and New York/Newark) of the twenty most densely populated coastal cities (last column in Table 2) will be located in Asia (15) and Africa (3) in the 2070s. The total population of the twenty will be 113 million, that is, 470 % of the current 24 million. Some cities are expected to grow by a factor of more than ten (Dhaka and Chittagong in Bangladesh, Ningbo in China), whereas the population of those already highly developed (e.g., New York, Miami, Tokyo, Shanghai) will only double.

3.4 Vulnerabilities

Vulnerability can refer to human health (human vulnerability), structural integrity (physical vulnerability) or personal wealth (financial vulnerability). Residents of coastal settlements have always put a great deal of effort into protecting their properties against flooding and wave action. Building on artificially created mounds in the past and implementing giant projects such as the Netherlands Deltaworks have proved reasonably successful. Since the catastrophic storm surge in 1953, the Netherlands coast has not experienced any major storm surge damage. The measures taken provide good protection

Table 2 The twenty cities with the largest assets and the twenty cities with the highest population exposed to coastal flooding (after Nicholls et al. 2008)

Rank	City	Country	Current (2005) exposed assets US$ bn	Future (2070s) exposed assets US$ bn	Increase factor	Population in the 2070s ($\times 10^3$)
1	Miami	USA	416	3,513	8	4,795
2	Guangzhou	China	84	3,358	40	10,333
3	New York—Newark	USA	320	2,147	7	2,931
4	Kolkata	India	32	1,961	61	14,014
5	Shanghai	China	73	1,771	24	5,451
6	Mumbai	India	46	1,598	35	11,418
7	Tianjin	China	30	1,231	41	3,790
8	Tokyo	Japan	174	1,207	7	2,521
9	Hong Kong	China	36	1,164	32	
10	Bangkok	Thailand	39	1,118	29	5,138
11	Ningbo	China	9	1,074	119	3,305
12	New Orleans	USA	234	1,013	4	
13	Osaka	Japan	216	969	4	
14	Amsterdam	Netherlands	128	844	7	
15	Rotterdam	Netherlands	115	826	7	
16	Ho Chi Minh City	Vietnam	27	653	24	9,216
17	Nagoya	Japan	109	623	6	
18	Qingdao	China	3	602	201	
19	Virginia Beach	USA	85	582	7	
20	Alexandria	Egypt	28	563	20	4,375
	Dhaka	Bangladesh				11,135
	Rangoon	Myanmar				4,965
	Hai Phòng	Vietnam				4,711
	Khulna	Bangladesh				3,641
	Lagos	Nigeria				3,229
	Abidjan	Ivory Coast				3,110
	Chittagong	Bangladesh				2,866
	Jakarta	Indonesia				2,248
	Total		2,204	26,817	12	113,192

against moderately frequent natural events, to which Dutch cities and industrial facilities now have very low vulnerability. The protection system is designed to cope with water levels with return periods of several 1,000 years (Ministerie van Verkeer en Waterstaat 2005).

If we extend the scope to rare and very rare events, we note that vulnerability suddenly becomes extremely high—boosted by high concentrations of exposed values in certain locations. It is very difficult to evacuate several hundred thousand people in just 1 day if a hurricane is approaching, or move 50,000 new cars awaiting shipment from a port to higher ground in the few remaining hours before a storm surge hits the coast. On 22 June 2008, a hailstorm damaged 30,000 new cars in the port of Emden, Germany. It took just 15 min to produce a US$ 150 m loss. Given a complex infrastructure (e.g. traffic and power networks), a failure in one place may cause domino effects that bring the whole system to a standstill. After the March 2011 tsunami, manufacturers all over the world (electronics, automotive, etc.) were not able to assemble their end products because their Japanese suppliers were no longer able to deliver.

An important aspect in this context is the impression that dykes fully protect. The fact that people are living in areas endangered by floods and other natural perils is ignored, or eventually forgotten. Alternatively, they may be lulled into a false sense of security, totally relying on coastal protection and preventive measures. It is also likely that systems that "always work" may not do so in the event of disaster.

In general, modern equipment is highly susceptible. Almost everything contains electric or electronic components prone to damage when exposed to flood water or even humid, salty air. Drying them out and then using them again, as in the past, is no longer an option.

In many coastal areas, one fairly common consequence of urban growth is subsidence, caused, for instance, by groundwater extraction or simply by the weight of buildings on the underlying relatively soft and unconsolidated coastal soil. A few decimetres of subsidence can create huge problems in low-lying ports, some areas suddenly finding themselves below a given flood level or even below the average local sea level.

4 Climate change

The world is getting warmer. 2008 is the only year in the period from 2001 to 2010 that does not rank among the ten warmest recorded since 1852, based on global mean temperature (NOAA 2012). 2011 was the eleventh warmest year, but the warmest La Niña year ever. Usually years in which the Pacific La Niña phenomenon is present are considerably colder than neutral or El Niño years (NOAA 2012). Hence, there is no doubt that the average global sea level will rise. Whether the new level is 50 or 100 cm higher by the end of the century is a moot point, but problems will result. Small islands and large reaches of coast in a number of poor countries will be submerged. Other regions will avoid permanent flooding, but will either lose their protection standard against storm surges (which may, for instance, fall from a 1-in-500 to a 1-in-50-year chance of failing to protect) or will have to invest enormous sums to maintain their current standard. Among the regions most endangered are Florida, New York and Shanghai, which can be found in Table 2.

There is some evidence that the intensities of hurricanes in the Northern Atlantic and typhoons in the Western Pacific have increased (Webster et al. 2005). In 2005, all previous storm records were broken in the North Atlantic (Munich Re 2006): there were 27 named tropical storms (the average number is ten, the previous record 21), 14 of which developed into hurricanes (average six, previous record 12). The 14 included Wilma, at 882 mb, the most intense hurricane ever recorded in the North Atlantic, Rita (897 mb, ranking fourth) and Katrina (902 mb, ranking sixth). The latter became the most expensive natural disaster at that time, the loss figure only having been surpassed by that of the Tohoku earthquake and tsunami in March 2011 (cf. Table 1). Overall losses from the 2005 hurricane season totalled US$ 165bn (US$ 83bn insured losses). Hurricane Ike, in 2008, was the storm with the highest recorded integrated kinetic energy (IKE), a measure which combines the parameters wind speed and area in the storm's path (Powell and Reinhold 2007). Coincidentally, the hurricane's name reflects this parameter.

One further issue: Will Europe find itself in the path of hurricanes? Were storms Vince and Delta, which took an easterly course and hit Madeira and the Canary Islands, causing losses there at the end of the 2005 season, harbingers of changing hurricane tracks?

The North Atlantic hurricane seasons of 2010 and 2011 caused comparatively moderate losses. Both were very active, with 19 named storms each (12 and 7 of which, respectively, were hurricanes), but few of these made landfall and caused damage. Nevertheless, Hurricane Irene, which struck in August 2011 and was initially expected to become a "monster" storm, with catastrophic storm surge levels along the north-east US coast, triggered extensive evacuation activity and was a close call. The losses were significant (US$ 6.5bn in the USA), but much lower than had been feared before it made landfall. This very loss scenario—a hurricane and storm surge in the New York region—is among the costliest in the world.

Apart from catastrophes of sudden onset, climate change will involve a number of other potentially severe consequences for our seas and coastal regions. Melting polar ice will decrease the salt concentration in the water, affecting global heat transport and the composition of our ecosystems. Water exchange between ocean basins (e.g. between North Sea and Baltic Sea) may change. The intensification of tide dynamics will have consequences for tides and tidal currents and the transport of salt, sediment and ice, and interfere with certain morpho-dynamical processes, the probable result being increased coastal erosion. Seawater intrusion into estuaries and groundwater bodies will even affect onshore ecosystems and possibly lead to adverse economic consequences (BMVBS 2007).

The fishing industry will have to deal with the immigration of more southerly species and displacement of cold-water fish, for example, cod, to the north. The insurance sector will be involved, too, as fish farms are heavily insured—and very vulnerable—businesses. The consequences may even affect engineering structures: if the growth and distribution of toxic algae increases, they may settle on the surfaces of hydraulic structures and vessels, causing considerable damage in the form of what is termed bio-fouling. Last but not least, aesthetic aspects such as increased algae growth may considerably affect the attractiveness of the coast for tourists, also with implications for the insurance sector, as many hotels, resorts and travel companies are insured against business interruption.

Climate change will bring a few advantages for shipping, for example, more favourable ice conditions in the North-west and North-east Passages. But, compared with the adverse effects, this is likely to be "a mere drop in the ocean."

5 Risk reduction

During the industrialisation of the past two centuries, we believed we would be able react to natural threats by introducing better technical protection. Building codes were improved, dykes built, and measurement, observation and communication networks established, especially when satellites came on the scene. Our understanding of physical processes was increasing, resulting in enhanced early warning and alert potential. In the wake of and relying on such developments, millions moved to, for the most part, attractive locations, where immense values accumulated. As beautiful and economically advantageous as such areas often are, once in a while they turn into disaster areas.

The most efficient way of reducing the risk is to avoid settlement in hazardous locations. If a house is built not at the beach, but further inland, on higher ground, a storm surge cannot tear it from its foundations. However, preventing people from moving to areas where they expect better living conditions is all very well in theory, but does not work in practice. Convincing people that they should leave their homes and move elsewhere is an even more futile exercise.

Cities must, therefore, be protected against storm surges and other sea-bound hazards. The same is true of engineering structures which, by their very nature, cannot avoid exposure to marine hazards, namely harbours, offshore platforms and offshore wind farms. The only way to reduce the risks they face is to lower their vulnerability or increase their resistance and resilience using technical means.

Much has been achieved in the past decades in this regard. After the 1953 flood, the Netherlands spent billions of dollars on strengthening and raising their sea defence system; in the United Kingdom, London is now protected by the Thames barrier. Generally, the design of sea dykes in European countries aims at a failure probability with respect to overtopping in the order of less than 0.5–1 % (once in 200–100 years). In Germany, a 1 % overtopping probability is officially assumed, but safety margins have been added to computed dyke heights, and the actual overtopping probability is lower. In the Netherlands, the design criterion for the central part of the coast is as little as 0.01 % (1 in 10,000 years), but no safety margin is included.

The Dutch authorities have recognised, however, that the height of a dyke—assuming maximum water level to be the only load factor and overtopping the only design failure mechanism—is too short-sighted because it excludes other types of failure such as piping, erosion, sliding, gate failures, etc. The latter may have probabilities that are one order of magnitude greater than the design specification; at the very least, the existence of a number of possible failure modes lowers the nominal probability of failure. The government has therefore set up the Flood Risk and Safety in the Netherlands (FLORIS) project (Ministerie van Verkeer en Waterstaat 2005). Postulating that absolute safety from flooding does not exist and recognising that flooding does not depend only on the probability a certain water level will be exceeded, and the conclusion drawn is that the probability of flooding is not the factor of greatest concern, but that decisions should be based on the probable consequences of flooding. The project calculates the flood risk for all 53 of the country's dyke rings, taking into account not only the hazard involved but also the respective values at risk and vulnerabilities. The goal is ultimately to define the specific risk posed by the sea and large rivers in different regions of the country. In 2008, the Delta Committee made twelve recommendations for a future strategy to deal with the threat from water bodies. These recommendations included increased flood protection levels, plans for new urban development, political/administrative, legal and financial measures, and specific recommendations concerning various regions in the Netherlands (Deltacommission 2008).

In the United Kingdom, too, extensive adaptation efforts are being undertaken to address the growing flood risk. The Thames Estuary 2100 (TE2100) project, established in 2002, aims to develop a tidal flood risk plan for London and the Thames Estuary (DEFRA 2009). A strategy is being worked out to manage the flood risk up to the end of the century, taking account of the existing, ageing flood defence system, rapid development of the flood plain and climatic changes. Spatial planning and emergency preparedness will play a major—and increasingly prominent—role in reducing the risk along the estuary.

In Bangladesh, where storm surges claimed 300,000 lives in 1970 and 139,000 in 1991, more than 5,000 flood shelters (elevated structures to which people can flee if a storm surge inundates the land) have been built in the past two decades (UNICEF 2004). Far fewer people were killed in more recent surge events on a scale comparable to the two referred to above: 111 died in May 1997 and 3,295 in November 2007 (Cyclone Sidr). By contrast, 70,000 died when Cyclone Nargis struck Myanmar's unprepared Irrawaddy delta in May 2008.

Although technical flood protection is certainly the most important factor in preventing large disasters, we need to be aware that even the strongest, best-designed systems have a limited effect. The 2004 and 2011 tsunamis and Hurricane Katrina showed that 100 % safety is not possible. Therefore, it is crucial not to rely on a purely structural approach to the problem but to include “soft” factors.

Risk (and loss) minimisation calls for integrated action. The flood risk must be borne on several shoulders: the state, the populations and companies affected, and the financial sector, particularly the insurance industry. Only if they all cooperate in a finely balanced relationship and in a spirit of risk partnership can disaster prevention be truly effective. In this context, maintaining a high-risk awareness at all levels of society plays an important role.

5.1 Public authorities

The primary task of the state or the government is to reduce the underlying risk for society as a whole. The government provides access to observation and early warning systems, builds dykes, enacts laws that determine the framework for use of exposed areas and prepares emergency plans, including programmes alleviating recovery (temporary housing, financial assistance, tax relief, etc.). In some countries, insurance programmes are state-run. Much of the responsibility for flood protection lies with the public authorities. By contrast, homeowners themselves are responsible for ensuring their houses are properly protected against the earthquake and windstorm perils.

5.2 People and companies

Those immediately affected (individuals, companies, communities) have great potential for loss reduction. The crucial point is whether their risk awareness is maintained. Even those who are conscious of the danger of flood may, in time, forget about it, especially if nothing happens over considerable periods. People rely on coastal protection systems, at the same time making their property more and more valuable by adding extra features that are often susceptible to water damage. Anyone proposing to erect residential or commercial properties must be informed and educated to ensure they are constructed in the appropriate manner. They need to check the level of exposed values and be ready to take action in an emergency. That action includes financial precautions for dealing with catastrophic losses, for example, purchasing insurance cover.

5.3 Insurance industry

The true task of insurance companies is to compensate financial losses that would have a substantial impact on insureds or even constitute their ruin. Insurers carry the financial risk of events with such a low probability that they cannot be considered foreseeable. Insurance redistributes the burden borne by individuals among the entire community of insureds. Ideally, that community is composed in such a way that all its members have some chance of being affected—even though the degrees of probability differ. Furthermore, insurers perform educational and public relations services, such as publishing brochures that draw attention to the hazards and explaining how to deal with them (e.g., ABI 2006; Munich Re 2011, see Fig. 5).

5.4 Reinsurance sector

Insurance companies, like private individuals, try to avoid volatility in their payments. Natural perils insurance is highly volatile. Large single losses (from one event) can be reduced if part of the risk is transferred to the reinsurance sector, where business is often transacted worldwide. Catastrophic losses that occur in one country are distributed all over the world, thus relieving the burden on the local insurance market and possibly even preventing its collapse.

Insurance, and especially reinsurance, companies have to be ready to pay large amounts of money after major events. For example, Munich Re faced claims in the order of US$ 2bn both in 2001, following the World Trade Center attack, and in 2005, as a result of Hurricane Katrina. Despite the enormous amounts involved, the company's existence is not under threat. However, volatility is expensive. Money for loss payments must be made available very quickly and cannot be placed in long-term, and thus profitable, investments. With single-loss amounts increasing, the whole financial market—including banks, lending institutions, and investors—is becoming more and more involved in the coverage of risk (Kron 2009).

6 Insurance aspects

Insurance against storm surge flooding is not widespread or even available in many countries. Among the problems encountered are adverse selection and lack of the loss data needed as a basis for calculating adequate premiums. Also, the extremely high loss potential (→ ∞) from a single event coupled with very low occurrence probability (→ 0) makes it difficult to calculate the risk and thus the premium; the result of such calculations is subject to considerable uncertainty. The required premiums would certainly be very high—and practically unaffordable. All these factors prevent storm surge cover from being

Fig. 5 World Map of Natural Hazards (© Munich Re 2011); coloured regions indicate high storm (*green*) and earthquake (*yellow–red*) hazards

a popular product, from the perspective of the insurance companies and from that of their potential customers.

6.1 Adverse selection and multi-risk policies

In most countries, only a small proportion of buildings are exposed to storm surge flooding. People in the areas concerned usually know that they are not living on safe ground and would like to obtain insurance cover. Those who live at some distance from the coast are not interested in such cover. Hence, if an insurance company were planning to sell individual policies as part of a voluntary insurance scheme, the premiums would be so high that prospective policyholders would normally find them prohibitive. This phenomenon is called adverse selection or anti-selection.

Flooding typically has a higher frequency in some parts of the country than in others. While the flood risk at a particular site has to be identified, insurance packages, risk-adequate premiums and deductibles, and—to some extent—cross-subsidisation, are necessary to achieve a viable portfolio. In practice, only obligatory insurance schemes seem capable of establishing a fully functioning community of insureds with the necessary critical mass and an adequate geographical spread of risks. However, there is no single best or ideal flood-insurance solution. Instead, each solution has to be tailored to the specific hazard situation of the country concerned and is to a large extent dependent on the long-term situation there. Although attempts have been made at political level to introduce obligatory flood insurance in a number of countries, voluntary covers are still widespread. In some countries, forcing people to insure against their will also involves legal problems.

Adverse selection can be avoided if multi-risk insurance packages are offered. The portfolio is then composed of different categories of client: those who live close to a river or the sea (flood risk), those in a geologically active region (earthquake risk) or those on a mountain slope (landslide and avalanche risk), etc.

6.2 Hazard zoning and premium calculation

Premiums for the various hazards should reflect individual exposure. For the bulk of business—that is, for private homes and small businesses and their contents—the effort required to assess the exposure of a particular building has to be seen in the context of the annual premium income for one such property, which may be in the order of US$ 100 in low-risk areas. Since individual assessment of the risk and calculation of an individual premium for such properties are impossible, the premium has to be fixed on the basis of a blanket assumption. For this purpose, zones that have a similar level of flood (earthquake, landslide) hazard have to be identified and/or defined, premiums being constant within a given zone. In most developed countries, hazard-zone data of this kind are available.

On a global scale, Munich Re produced its first World Map of Natural Hazards in 1978. The 4th edition is now available, together with a “Globe of Natural Hazards” DVD (Munich Re, 2011), which shows the worldwide distribution of all the major natural perils (Fig. 5) and provides a wealth of information on natural hazards and natural catastrophes. For the first time, several topics relating to climate change have now been included.

The annual net premium for insurance cover is the same as the expected average loss per year over a long period. Mathematically, it is determined in the same way as the risk (cf. Eq. 1). Insurance contracts are based on the status quo. If the hazard is substantial and the precautions taken minimal, the premium will be high (if the property is insurable in the first place); if the hazard is low or protection standards high, low premiums can be charged.

In practice, insurers often recommend (or require) that precautionary measures (structural, emergency plans, etc.) be taken to reduce the risk and render it more calculable.

Pricing also has to take into consideration the cost of maintaining reserves for large losses. The probability of a single home, for example, in the Netherlands, just behind a sea dyke, being flooded is very small ($<10^{-3}$) and would result in an annual premium of around 0.1 % of the insured value. However, if such a loss did occur, thousands of other houses would be damaged at the same time, and the overall loss would be enormous. Maintaining reserves against such contingencies costs a multiple of the amount that reflects the individual risk, and thus constitutes another component of the premium. The annual premium required may therefore be as much as 1 % of the insured value, which would make insurance cover practically unaffordable.

6.3 Modelling probable expected loss

Modelling for insurance purposes in the natural perils context is mainly aimed at estimating probable maximum (accumulation) loss (PML). Correctly assessing PMLs and holding adequate reserves are factors crucial to an insurer's economic survival. Flood losses are much more difficult to model than windstorm and earthquake losses. This is true not only of riverine but also of coastal flooding. Relatively small features can have major consequences: whether or not a dyke is overtopped (or breached) and the protected area flooded may be governed by a few centimetres' difference in water levels or a local weak spot in the protection system. Alternatively, a road or wall that is not even intended to prevent water entering a site may in fact do so, and stop damage. Modelling flood losses, therefore, requires detailed data. It is not helpful to "lump together" large areas on the basis of average impact intensities, not least because the areas prone to flooding are much smaller and more contained than those affected by the windstorm and earthquake hazards.

PML models are based on Eq. 1. The values at risk are represented by the portfolio under consideration, that is, the distribution of (insured) values in a country. Typical (average) loss rates for different types of building and given loads (wind speed, water level, earthquake intensity) are applied and account for vulnerability. The hazard is introduced by simulating a storm/earthquake/flood event in the area represented by the portfolio (Fig. 6). Simulating a large number of—stochastically generated—events yields the same number of event losses. The losses are arranged by order of magnitude to form an (empirical) PML curve, from which the expected loss for a given return period can be read off, or the return period of a historical event with a known loss determined (Fig. 7).

7 Facts—expectations—solutions

7.1 Facts

No other region is more threatened by natural perils than coasts. Coastlines are boundaries. The most obvious boundary is the one between water and land. Over land, the strongest winds usually occur at the point where a storm makes landfall. If the wind drives the water towards the land, extreme storm surge levels may occur. Large waves and tsunamis travel hundreds or even thousands of kilometres before expending their energy on reaching the coast. Furthermore, a coast often forms the boundary between continental plates, so that earthquakes and volcanic eruptions are more likely to occur there.

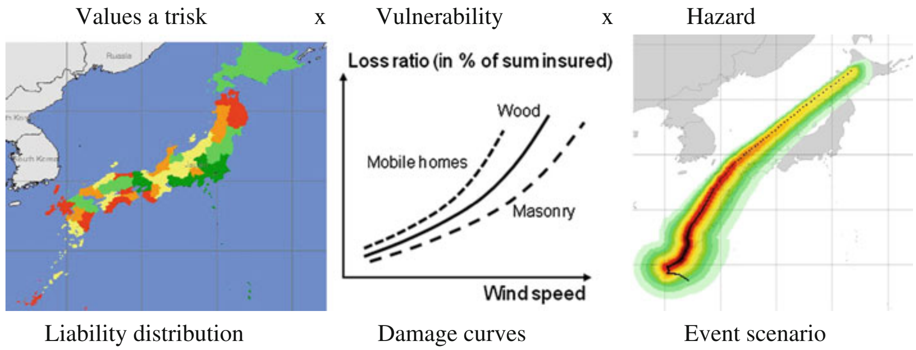

Fig. 6 Principle of probable maximum loss (PML) modelling (© Munich Re 2012)

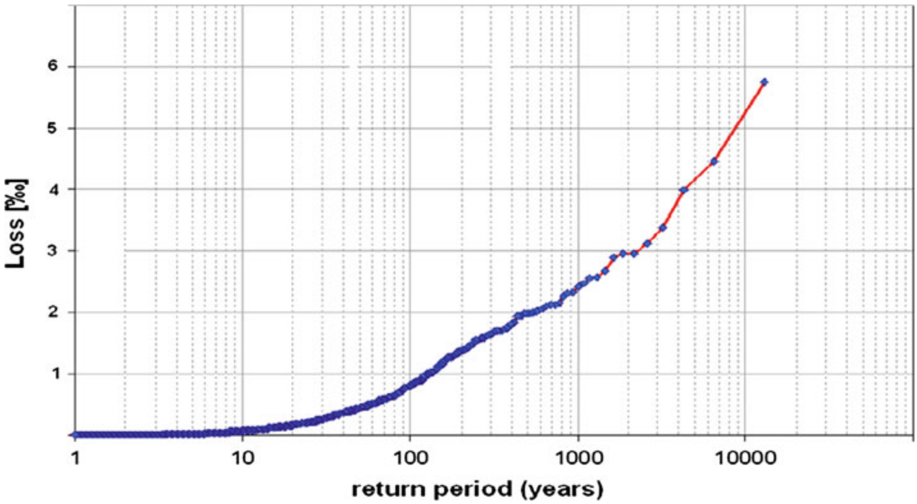

Fig. 7 Empirical PML curve: losses from a large number of simulated events arranged in order (© Munich Re 2012)

Despite these hazards, people are attracted to the coast, where economic conditions are better and many other quality-of-life aspects more favourable than elsewhere. Besides residents, tourists make up a large proportion of the population in many coastal areas. Being unfamiliar with the hazards, they may be even more vulnerable than the local residents and likely to react in the wrong way. Most global trade crosses the oceans. Industrial and commercial companies prefer to be close to ports and transport their raw materials and goods over shorter distances. Some coastal regions rank among the top places in the world in terms of value accumulation, this aspect being the main risk driver.

Virtually no other type of natural hazard protection is as high as that against storm surges, in developed countries at least. However, vulnerability has been reduced only where relatively frequent events are concerned, and it is not possible to ensure absolute security. Extreme events can produce unbelievable losses.

Natural disaster losses along coastal strips and in cities have already reached new dimensions. The top five losses of the last 20 years were as follows: the Tohoku earthquake and tsunami (2011, Honshu, US$ 210bn), Hurricane Katrina (2005, US Gulf Coast, US$ 125bn), the Great Hanshin earthquake (1995, Kobe, US$ 100bn), the Sichuan earthquake (2008, China, US$ 85bn) and the Northridge earthquake (1994, Los Angeles, US$ 44bn). The natural disasters of the past 20 years that produced the most fatalities were the Haiti earthquake (2010, 223,000 deaths), the 2004 Indian Ocean tsunami (220,000), Tropical Cyclone Nargis in Myanmar (2008, 140,000), the storm surge in Bangladesh (1991, 139,000) and the earthquake in Kashmir (2004, 88,000). Eight of those ten events occurred near a coast.

7.2 Expectations

The only way to contain the mounting risk along the world's coasts is to control settlement in high-hazard areas. This, however, is by and large a theoretical possibility only in most regions. Development policy and land-use regulations simply do not work, even when governments endeavour to impose them. We have to admit that we cannot really stop the concentration process in the short term.

In the same way, we have to accept that climate change is a fact and will increasingly make the situation worse. It is not something we can halt, let alone reverse, within the space of a few decades, even with a zero emissions policy. Today's CO_2 and temperature changes are caused by the emissions mankind introduced into the atmosphere in the 1970s and 1980s. The most we can do is to slow the rate of climate change.

Consequently, coastal risk reduction will have to rely on adaptation measures. Where possible, coastal defence systems will have to be upgraded and strengthened. In this context, new engineering techniques and more rigorous emergency procedures will assume an increasingly important role.

We must expect rising sea levels to drive people out of the areas they currently occupy, especially in poorer countries such as small island states, and in delta regions, where the potential scale of the defence works is enormous, due to the area involved and the number of river outlets.

7.3 Solutions

Forced abandoning of coastal areas due to flooding as a result of sea level rise is one, albeit non-voluntary, solution.

There is no substitute for structural engineering measures, and there are many new methods available on the market for improving the stability of newly constructed and existing dykes. The accuracy of forecasting and quality of warning, alert and evacuation procedures are now adequate, but can (and will) be improved. Refining and developing existing techniques and introducing new techniques will also help reduce loss of life and property.

There will always be a residual risk. This must be shared between government, the people concerned and the insurance industry. Although it may not seem obvious, there is huge potential in this respect for reducing the overall risk posed to society by natural hazards. Thus far, determining protection levels and designing corresponding structures have been factors often based on the "principle of equal hazard" (i.e. every area should be safe from, say, a 100-year flood). While this may be equitable, it ignores the fact that locations with high value concentrations are far more risk prone than, for instance, agricultural areas with scattered dwellings. An approach that bases decisions on risk (not hazard) should be the role model.

8 Conclusion

Great natural events are not avoidable, great disasters are. Disasters are inevitably the net result of the largely negative effects of extreme natural events and the largely positive response to those events (including prepared response in the form of precautions). Catastrophes are not only products of chance but also the outcome of an interplay between political, financial, social, technical and natural circumstances. Effective safeguards are both achievable and indispensable, but they will never provide complete protection. The determining factor is the awareness that nature can always come up with events against which no human means can prevail. As Aristotle (384–322 B.C.) said, “It is probable that the improbable will happen.” We have to establish a culture that copes with all the components of risk. Scientists, engineers and decision makers need to support this culture by being aware, open and honest. Pretending and announcing that we can make everything 100 % safe is not only reckless but contrary to our task of helping to achieve minimum risk.

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