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Analysis of NaTech Accidents Triggered by Extreme Temperatures in the Chemical and Process Industry

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The increase both in frequency and magnitude of natural events makes the study of the interaction between natural events and industrial facilities of paramount importance. Natural events may affect facilities leading to major accidents (e.g. explosion, fire, …) and these events are called NaTech (natural hazards triggering technological disasters). Extreme temperatures are one of the causes of NaTechs and the first step in studying their interaction with industrial facilities is given by the historical analysis of past accidents, being essentially the only source of information. To do this, a dataset of 305 past events was collected and analysed in order to highlight the main features of these accidents, such as the trend over the years, the geographical location, the final scenarios and the type of industrial sectors involved.

1. Introduction

Industrial accidents can be triggered by a multitude of causes that could be internal or external to the plant. Among the external initiating factors there are also the natural events and this particular type of accidents are called NaTech (natural hazards triggering technological disasters). According to many studies, the occurrence of natural phenomena is increasing over the last decades, both at global and regional level (Catholic University of Louvain (UCL), 2019). The increase of the recurrence of the triggering factors make NaTechs of crucial importance for the Chemical and Process Industry (Salzano et al., 2013). In addition, the occurrence of NaTechs with severe consequences, like those related to the impacts of the Great East Japan earthquake and tsunami (Krausmann and Cruz, 2013) and of the hurricane Harvey (Misuri et al., 2019), increases even more the interest on the topic. Moreover, the consequences of major accidents caused by natural events can be exacerbated by the occurrence of multiple simultaneous failures, cascading events (domino effect) and the disruption of utilities, safety systems, and lifelines (Cozzani et al., 2014).
Recent literature has shown that the NaTechs that lead to the release of dangerous substances can be caused, in principle, by any kind of natural event, such as flooding and lightning, and not necessarily by major ones, such as earthquakes and hurricanes (Krausmann et al., 2011). Nevertheless, almost all the studies carried out so far were focused on severe natural events and much less attention has been given to others (Suarez-Paba et al., 2019), such as extreme temperatures.
Among others, one of the most evident climate change effects are variation of average temperatures (NASA, 2020). In fact, climate change can lead to a change in the mean temperature, in the variance of temperature probability distributions and in their shape. These variations, individually or combined, can lead to changes in frequency, intensity, duration and spatial extent of extreme weather and climate events, among which also extreme temperatures (IPCC, 2012). The latter, despite not being considered major natural events, can interact with industrial sites and cause NaTech events, as pointed out by recent literature (Casson Moreno et al., 2019a). Clearly enough, the term “extreme temperatures” does not refer to absolute values but rather to the ones that deviate significantly from the mean in a given area and therefore depend on the place being considered. For this reason, extreme temperatures are a phenomenon that occur worldwide, and they do not affect a limited number of states, as shown in Figure 1.

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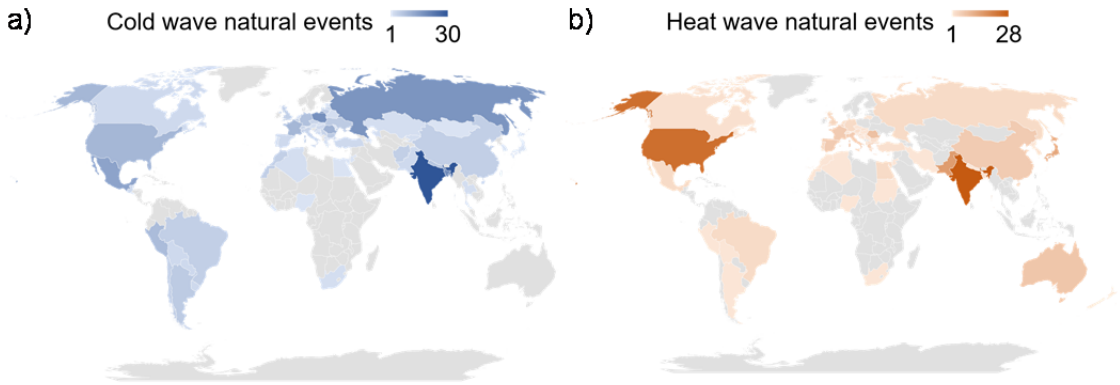

Figure 1: Maps of the states affected by: (a) cold wave natural events and (b) heat wave natural events. Data provided by (Catholic University of Louvain (UCL), 2019).

From a risk management point of view, understanding the dynamics that lead to an accident is of crucial importance. Therefore, it is very important to analyze past accidents as they are almost the only source of information for NaTechs. It is in fact possible through them to obtain information on the scenarios that can affect the chemical and process industry in case of natural hazards.
In the present study, NaTechs triggered by extreme temperatures, such as cold wave and heat wave, will be considered and a database of past accidents occurred in chemical and process industry is created and analysed. The analysis focuses on the trend of natural accidents over time in relation to natural hazards, the geographical location of accidents, the accidental dynamic, the final scenarios (such as fires or explosions) and the types of industries involved. In the analysis of the cause-consequence chains, attention is paid to understand the equipment most involved in these types of accidents.

2. Data retrieval and database structure

The records were collected starting from four existing database specialized on industrial accidents: the ARIA database (The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI), 2019), the MHIDAS database (Health and Safety Executive (HSE) of United Kingdom, 2019), the FACTS database (Unified Industrial & Harbour Fire Department in Rotterdam-Rozenburg, 2019) and the eMARS database (European Major Accident Hazards Bureau (MAHB), 2019).
In order to collect records, a list of keywords was defined to query the sources which are: “low temperature”, “cold wave”, “cold weather”, “freeze”, “ice”, “snow”, “high temperature”, “hot wave”, “heat wave” and “hot weather”. Furthermore, keywords used for the French database ARIA were also translated in the original language.
Inclusion criteria were therefore defined. The records were retrained in the dataset if they meet the following characteristics:

1. Events had to be accidents, incidents and near misses (i.e. event that does not result in an actual loss but that has the potential to do so) as defined by (Rathnayaka et al., 2011) caused by extreme temperature.
2. Events that occurred in the chemical and process industry, such as chemical industry, petrochemical industry, manufacture of plastic and metals, etc.
3. Events that occurred in the transportation of hazardous materials including the transport via pipeline, road, rail and water.
4. Events that occurred in the power production except for the nuclear power plant that was disregarded.
5. Events that occurred in the waste and water treatment plants.

Clearly enough, records found in more than one existing database were considered only once counting them in the first database in which was found and completing the information with the one provided by the other database.

3. Results and discussion

The resulting database collects 305 records occurred worldwide between the 1948 and the 2018. The source from which more data were obtained is ARIA with 236 records (78% of the total) followed by FACTS with 31 records (10%), MHIDAS (28 records, 9%) and eMARS (10 records, 3%).

Considering the geographical location, 84% of the accidents occurred in Europe (257 records) followed by America (37 records, 12% of the total) and only 11 records (4%) occurred in other part of the world. Going more in detailed, 68% of the records occurred in France, 10% in the United Sates, 5% in the United Kingdom, 3% in Germany and 2% both in Netherlands and Canada. The remaining 10% is occurred in other country. The unbalanced distribution of the geographical location just described is due to the use of the ARIA database, whose records mainly concern France.

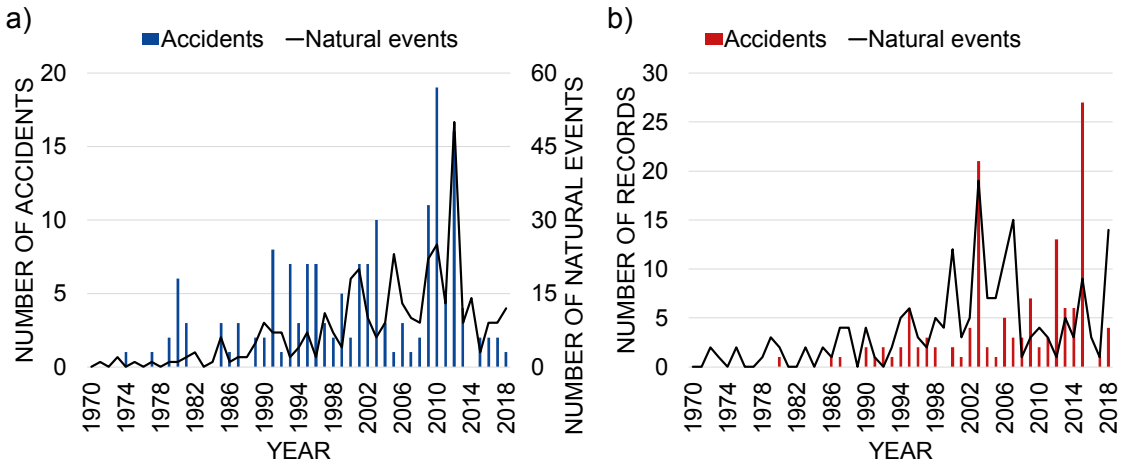

Figure 2: Trends over the years of: (a) cold wave-related accidents (blue bars) and natural events (black line), (b) heat wave-related accidents (red bars) and natural events (black line). Number of natural events provided by (Catholic University of Louvain (UCL), 2019).

Among the records collected, 166 events are caused by cold wave including freeze, snow and ice (54% of the total), 137 records are caused by heat wave (45%) and the last 2 records are caused by the thermal excursion between day and night. Due to the scarce number of records collected, the thermal excursion as cause of accidents is disregarded in the further analysis. Moreover, because of the intrinsic differences between cold wave and heat wave, the analyses are made separately.
The trends over the year are shown in Figure 2 respectively for cold wave-related events (panel a) and heat wave-related events (panel b). In the figures, the trends are compared to the one of natural events as reported by the International Disaster Database (EM-DAT) of the Centre of Research on the Epidemiology and Disasters (Catholic University of Louvain (UCL), 2019). It can be seen that the trends of accidents both for cold wave and heat wave is increasing over the years and that somehow reflect the ones of natural events.

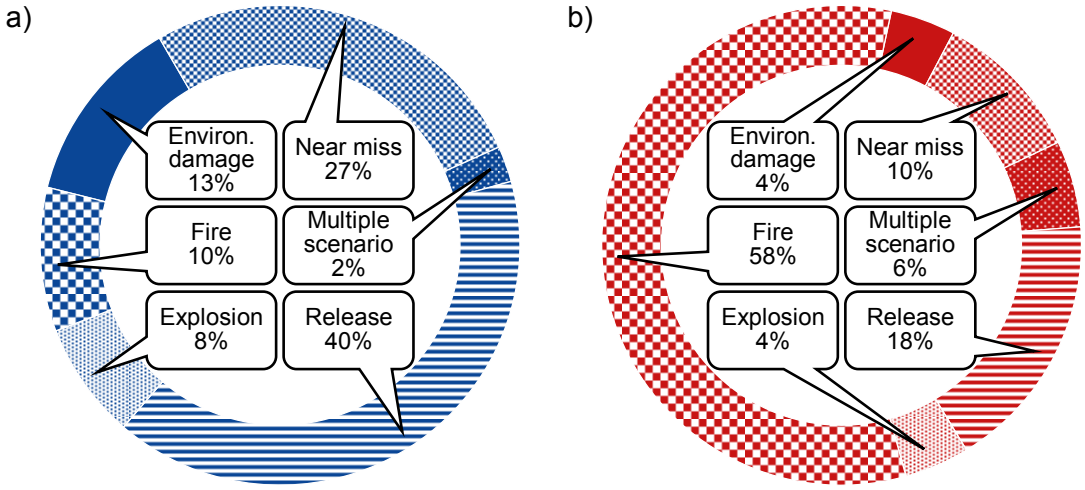

Figure 3: Share between the final scenarios recorded for accidents triggered by cold wave (panel a) and heat wave (panel b).

Figure 3 shows the share between the final scenarios recorded. The final scenarios considered in the present work are fire, explosion, toxic cloud, release (i.e. the loss of containment of substances without any other consequences among the ones listed), environmental damage, near miss and the combination of more scenarios simultaneously. Only in 1 record the outcoming final scenario was toxic cloud and the triggering natural event was a cold wave. Due to the resulting low percentage, this record is not represented in Figure 3. Considering the accidents triggered by cold wave (Figure 3a) the most probable final scenario is the release with 67 records (40%) followed by near miss with 44 cases (27%) and environmental damage with 21 cases (13%). Only in the 20% of the cases the loss of containments found an ignition source leading to fire (16 records, 10%), explosion (13 records, 8%) and multiple scenarios (4 records, 2%) which were “fire & explosion” (3 records) and “fire & environmental damage”. Substantially different is the case of accidents triggered by heat wave (Figure 3b) for which the ignition source is found in the 68% of the records. In fact, fire occurred in 58% of the cases (79 records), whereas multiple scenario and explosion occurred respectively in the 6% and 4% of the cases (8 and 6 records). For completeness, multiple scenarios caused by heat waves were “explosion & toxic cloud” and “fire & explosion” both in 4 cases.
The share among the industrial sectors affected by cold and heat wave is shown in Table 1. Accidents occurred in the Chemical & Petrochemical sector in the 25% of the cases (76 records), in the Transportation sector in the 24% (72 records), in the Waste treatment sector in the 13% (38 records), in the Manufacturing sector in the 12% (36 records) and in Storage site in the 11% of the cases (32 records). Other industrial sectors are affected in a lower number of cases and they are: power production (15 records, 5%), transport via pipeline (14 records, 5%), Food & Beverage (10 records, 3%) and water treatment (10 records, 3%).
Looking at Table 1, some industrial sectors are indiscriminately affected by cold wave and heat wave, such as Chemical & Petrochemical, Manufacturing, Storage site, Power production and Water treatment. On the other, it is also pointed out that some industrial sectors are more exposed to cold wave rather than heat wave or vice versa. For instance, the Transportation sector and the Transport via pipeline are mainly affected by cold wave whereas the Waste treatment and Food & Beverage are chiefly affected by heat wave.

Table 1: Share between the industrial sectors affected in the records collected in the present work.

Industrial sector	Records for cold wave	Records for heat wave	Total number of records	Percentage
Chemical & Petrochemical	35	41	76	25 %
Transportation	63	9	72	24 %
Waste treatment	0	38	38	13 %
Manufacturing	18	18	36	12 %
Storage site	19	13	32	11 %
Power production	9	6	15	5 %
Pipeline	14	0	14	5 %
Food & Beverage	3	7	10	3 %
Water treatment	5	5	10	3 %

4. Type of item involved

A very important aspect in the analysis of accidents is the evaluation of the equipment most affected in the plant. In the present work, attention is given to the Chemical & Petrochemical sector, which is the most vulnerable to both cold and heat wave, to the pipeline sector regarding cold wave and to the waste treatment sector for heat wave.
Starting form cold wave, the most affected component in the Chemical & Petrochemical sectors are the pipelines (12 records, 34% of the records) followed by valves (7 records, 20% of the records). Although the remaining percentage of records is high (46%), it is not possible to recognize other relevant equipment, as each one is involved only in 1 or 2 cases. Clearly enough, considering the transport via pipeline the most affected components are the pipeline itself (8 records, 57%). Nevertheless, also in this case valves represent another vulnerable element to cold wave (6 records, 43%). From the collected records, two failure modes are recognizable both for pipelines and valves. The valves can fail both for problems related to the cooling of the valve itself (for example the stiffening of the spring for low temperatures does not allow correct regulation) and because the internal fluid freezes, obstructing the passage. The second failure mode described above is also typical of pipelines while the other mode is due to the brittle fracture at low temperatures. The final scenarios resulting from the damage of pipelines and valves do not show a different trend from that shown in Figure 3 as regards cold wave accidents. A summary of the accidental patterns in case of cold wave-related is provided in Figure 4.

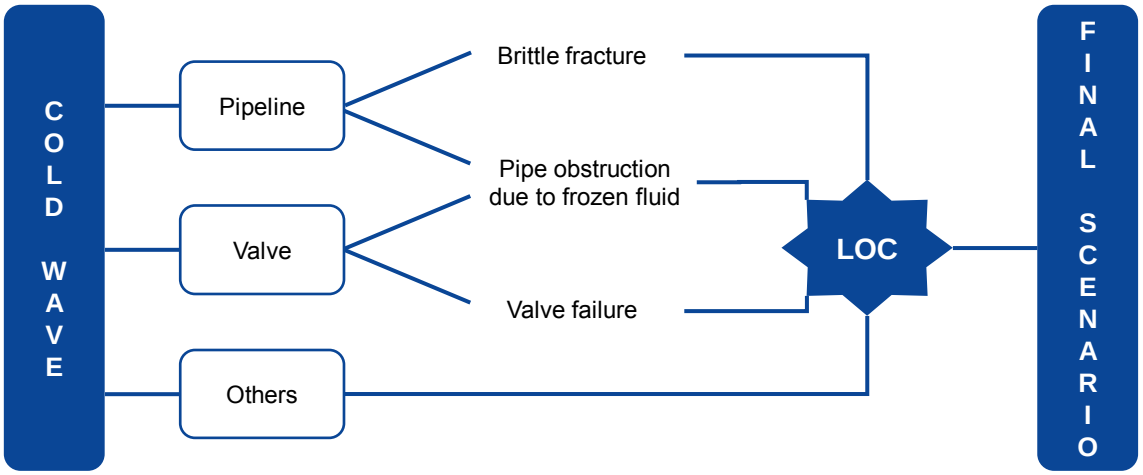

Figure 4: Schematic of the accidental patterns in case of cold wave as observed in the present study.

Considering heat wave, the final scenario of accidents occurred in the waste treatment sector was fire in the 97% of the cases (37 records). These accidents mainly involved piles of material (i.e. the unconfined storage of wastes to be treated) and landfill cells, respectively in the 45% (17 records) and 39% (15 records) of the cases. Obviously, the piles of materials are not an equipment, but they are a widely used storage method in waste treatment sector and therefore they are included in the analysis. The accidental dynamics that led to the fire in both types of storage is the self-combustion of waste, which is triggered by two factors. On the one hand, solar radiation heats the waste and causes exothermic decomposition or undesired reactions leading to self-combustion. On the other hand, heat waves can lead the waste to reach the self-ignition temperature. Regarding the Chemical & Petrochemical sector, the heat wave once again led to the combustion of the substances following self-ignition, involved in the equipment in the 46% of the cases (19 records). Another accidental dynamic in this sector is the pressure increase in the equipment due to the heat provided, occurred in the 15% of the cases (6 records). Nevertheless, it is not possible to recognize particularly vulnerable equipment to heat wave in the Chemical & Petrochemical sector as each one is involved in a limited number of records. Accidental patterns in case of heat wave are summed up in Figure 5.

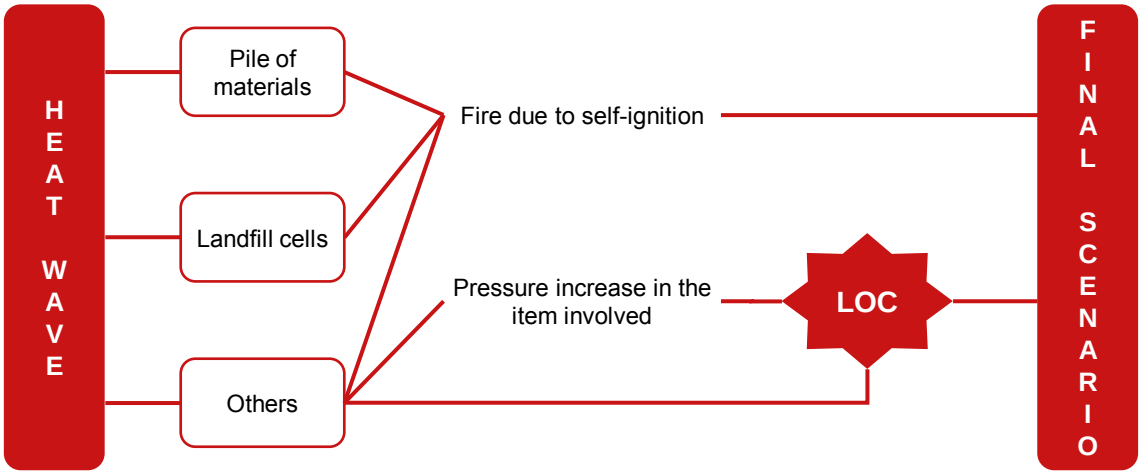

Figure 5: Schematic of the accidental patterns in case of heat wave as observed in the present work.

As a matter of facts, ambient temperature is one of the factors to consider when designing equipment (American Petroleum Institute, 2012). The variation in the mean temperature due to climate change requires a continuous updating of the estimates of the minimum and maximum ambient temperature of the industrial plant location. In this way it is possible to proceed to a correct and more effective design of industrial site equipment and allows to evaluate safety barriers needed to protect the existing one. Furthermore, accidents

occurred in the waste treatment sector demonstrate that the storage methods used so far may no longer be effective, unless implementations of safety barriers to protect the plant.

5. Conclusions

Extreme temperatures as cause of accidents in the Chemical and Process Industry have been analyzed by collecting a dataset of 305 records. The increasing occurrence of extreme temperature events worldwide has aroused interest in studying their possible interaction with industrial site. The importance of the study is demonstrated by the increasing number over the year of extreme temperature-related accidents, which trend reflects somehow the one of natural events. What emerge in the present work is that cold wave and heat wave cannot be ignored as the cause of an accident because the consequences that derive from them are not negligible. The analysis performed in the present work provide a wide source of information about the topic. Moreover, the analysis of industrial sectors and items more easily affected by cold wave and heat wave have pointed out a starting point for risk assessment and the emergency response planning.

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