Climate Related Trends in U.S. Hazardous Material Releases Caused by Natural Hazards

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Research Article

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Abstract

Natural hazards are the underlying cause of between 1 and 7 percent of federally reported hazmat releases in the US every year. During the period from 1990 through 2019 the fraction of releases caused by natural hazards has increased, in large part due to increased releases from hurricanes as well as floods, storms and wind. Many of these events are minor, but some have resulted in large and expensive releases as well as deaths, injuries, and evacuations. Inter annual variability of these releases are correlated with occurrence of extreme weather and associated climate indices. Given observed and future predicted increases in extreme weather events, it is likely many of these types of releases will continue to increase. Greater attention to management of natural hazard risk to industry, and in particularly to bulk storage facilities, is required to prevent further increase in the frequency and severity of these events.

Introduction

The presence of facilities handling hazmat in areas of high population density and natural hazard risk together present the potential for natural hazard triggered releases (natechs) with significant public health as well as environmental impacts (e.g. Nicole 2021). The potential for simultaneous releases along with loss of site access and lifeline resources typically available for response can make natural hazard related events particularly threatening (Steinberg and Cruz 2004). Such risks have been dramatically evidenced in the aftermath of Hurricane Katrina (Santella et al. 2010) as well as other recent US hurricanes such as Hurricane Harvey (Quin et al 2020) and the Tohoku earthquake (Krausmann & Cruz 2013). Changes in sea level, the frequency of extreme weather events and continued development of industry in low-lying vulnerable areas is expected to result in increased risk from extreme weather events, particularly for the oil and gas industries (Cruz & Karusmann 2013). To justify investment in managing these risks requires a better understanding of their spatial distribution, frequency, trends and consequences. A growing body of research has utilized a variety of approaches to evaluating these risks (Nascimento & Alencar 2016, Mesa-Gómez et al 2020). However, comprehensive and quantitative information describing these events, necessary to inform risk assessment and mitigation, is limited.

Efforts to better understand natech occurrence in academic studies and in public media often utilize records from existing spill databases. In a broad effort encompassing the entire US, Senegul et al (2012) quantified natech events from the period 1990 to 2008 by extracting a subset of the National Response Center (NRC) database of release reports. Luo et al. (2020 and 2021) used machine learning methods to identify natechs within the NRC record through 2017, and evaluated this record to assess the potential influence of climate parameters on tropical storm related natechs. Here the analysis of Senegul et al (2012) has been extended through 2019 and analyzed to evaluate in detail events associated with an array of natural hazards. Trends and interannual variability in the frequency of natech events are evaluated in relation to underlying climate trends. The retrospective analysis presented here provides a starting point that can help guide future policy, mitigation and response efforts to address natechs as a whole.

Methodology

The primary source used to identify natechs was the NRC's Incident Reporting Information System (IRIS) database. The nature and limitations of the NRC database were summarized in detail by Senegul et al. (2012). Briefly, limitations in data quality include inconsistencies with other databases, lack of identification of root causes, incomplete reports, inclusion of many records where casualties were not related to hazmat, duplicate reports, and the inclusion of many low severity releases. Despite these limitations the IRIS database is suited to the purposes of this study in that it is covers the entire US, has maintained fairly uniform data specifications since 1990, and records releases of both hazardous chemicals and petroleum. A majority of larger releases with potential for serious environmental or human impacts are captured in the database though small releases are under-recorded.

Methodology of data analysis followed that of Sengul et al. (2012). Releases from the IRIS and the predeceasing ERNS databases were filtered to remove events not involving a release, planned continuous releases, and reports describing drills. Events caused by various natural phenomena were then identified through use of the "incident cause" field and keyword searches of written descriptions. Event descriptions were reviewed manually to ensure a high degree of confidence in the natech records identified. A uniform descriptor of facility type was created merging the existing "incident type" field with information from the "fixed facility type" field and keyword searches of the event descriptions. Releases were also characterized by the type of material involved and the size of the release. Linear regression was utilized to evaluate magnitude of temporal trends in the data. A non-parametric (Mann-Kendal) test was utilized to evaluate the significance of temporal trends as annual occurrence of some natechs did not have a defined distribution.

To evaluate the relationship of the identified natech events to underlying weather and climate drivers, this record was compared to two data sources. The NOAA Storm Events Database (NOAA NCDC b 2020) was used as a measure of the annual occurrence of damaging or significant weather events. Only data from 1996 on was utilized as collection of information on a full range of 48 weather event types began at that time. Although limitations of this database for evaluating trends in occurrence over time are well known, data from recent decades is more consistent and provides insight into the occurrence of extreme weather (e.g., Kunkel et al. 2013). Database events were aggregated into cold, flood, hurricane (sum of hurricane, storm surge and tropical storm), rain, combined storm and weather, and wind. Counts of heat, lighting, tornado and wildfire events from the database were also utilized. Climate Extreme Index (CEI) values (NOAA NCDC a 2020) were used to place the natech record within the context of a longer climate record beginning in 1900. The natech record was compared to national and regional CEI values for precipitation (three values based on portion of precipitation derived from extreme precipitation events and fraction of days with and without precipitation), maximum and minimum temperature, and landfalling tropical storm and hurricane wind velocity. Correlation of annual data (Pearson R) was used to evaluate the relationship between natech occurrence and weather and climate measures.

Results

Number and Facility Type of Natech Events

Natech events identified with the NRC record totaled almost 10,000 between 2009 and 2019 giving a total of over 26,000 natech events between 1990 and 2019. Rain related events make up a quarter of events, followed in order by hurricanes, weather, wind and floods. These results differed somewhat from those by Luo et al. (2020) who identified a greater number of hurricane, storm and flood events. The discrepancy in hurricane events is in large part due to several thousand reports associated with ongoing releases from a single offshore platform destroyed during Hurricane Ivan in 2004 which were treated as duplicate reports and are not included in this assessment. Evaluation of the higher number of storm and flood related events reported by Luo et al. (2020) suggest that they are largely attributed to events incorrectly identified as natechs due to their description (e.g., a spill affecting a storm drain).

The largest number of natechs are associated with releases from fixed facilities many of which are caused by rain, followed by floods and hurricanes. Second most common are releases from transformers associated with wind, storms and lightening. Third most common are releases from storage tanks equally due to hurricanes, rain and floods. These findings are generally consistent with those of Sengul et al. 2012 with the exception that releases from platforms due to hurricanes were more prominent during the period from 1990 through 2008 (approximately 12% of the total), compared to 2009 to 2019 (only 3%). This is noteworthy given that subsequent to significant damage to offshore platforms during the 2004 and 2005 hurricane seasons the American Petroleum Institute issued updated guidance pertaining to hurricane risk to offshore platforms and significant investment in upgrades of offshore platforms has been reported (Cruz & Karausmann 2013).

Materials and Size of Releases During Natech Events

Petroleum releases are a majority (76%) of the total reports between 2009 and 2019 while chemical releases are only 11% of reports and wastewater releases were 5% of the total. This represents an increase in the fraction of petroleum events compared to Sengul et al. (2012) who reported petroleum releases as only 60% of the total. Given the wide variation in the size of releases, many of which are small, the quantity of material released due to natural hazards could give a better indication of risk than the number of releases alone. However, due to the limitations of the NRC database, quantities are not expected to be accurate, particularly for offshore events where estimation of the volume of a release is more difficult. For example, a total of about 90,000 gallons of petroleum is listed as being released from offshore platforms due to various hurricanes during 2009 to 2019. In contrast, recent estimates of crude oil released between 2009 and 2017 from a single platform destroyed during Hurricane Ivan in 2004 range from 0.7 to 3 million gallons (Skytruth 2017). When reported, spill quantities do provide a useful qualitative indicator of event severity.

Volume of petroleum released was reported in approximately two thirds of total records. Total petroleum released was approximately 3 million gallons during the period from 2009 to 2019. Gasoline, crude oil and diesel/#2 fuel oil were released in the largest volumes, about 650,000 gallons each. In contrast the record from 1990 to 2008 was dominated by several large crude oil releases primarily occurring during

Hurricanes Katrina and Ike. Although most petroleum releases are reported in gallons, a single large release of asphalt totaling 2 million pounds due to flooding was also reported. In the period from 2009 through 2019 storage tank releases of petroleum were the largest in volume averaging over 4,000 gallons in size followed by pipelines (2,000 gallons) and vessels at 1,000 gallons. Hurricanes, lightning and floods accounted for most of the larger events and the majority of petroleum releases as illustrated in Fig. 1. While the large volume of petroleum released during hurricane and lightning related events is consistent with observations by Sengul et al. (2012), the large volume of petroleum released due to flooding was not observed in the earlier record and is associated with a number of large releases between 2015 and 2017.

The amount of chemical released was reported for only one third of events. Chemical quantity was most often reported by weight and totaled 1,800,000 pounds between 2009 and 2019. These releases were predominantly from flaring (sulfur dioxide, carbon monoxide) or other air releases from fixed facilities due to hurricanes, lighting and other weather. This differed from observations from Sengul et al. (2012) who noted that several large flood related releases dominated the mass of chemicals. Anhydrous ammonia stands out as the material released most commonly (over 100 releases) and in the greatest amount with a source other than flares. These releases commonly represent damage to refrigeration systems at storage tanks and other fixed facilities. Chemical releases reported by volume made up one third of events and totaled approximately 650,000 gallons. The majority of the total was from a small number of large volume releases from storage tanks during hurricanes in 2012 and 2017. Sengul et al. (2012) also observed substantial volumes of chemicals released by hurricanes but in that time period cold, flood, rain and weather also resulted in sizable releases. Although reported less frequently, the NRC database also includes reports of releases of 14,000,000 pounds of solid bulk materials such as coal ash, largely due to storms and hurricanes, 154,000,000 gallons of wastewater, attributed primarily to rain and to a lesser extent hurricanes, and 52,000 million cubic feet of natural gas primarily attributed to the impact of storms on fixed facilities. In all cases the volumes of these materials were highly dependent on a small number of very large events.

Natech Events with Human Impacts

During the period from 2009–2019, 33 injuries were reported during 9 natech events and at least 2,600 people were evacuated in 85 events. Flooding was associated with two events with injuries with the rest due to lighting or other weather. Of evacuation events, 38% were associated with lightning, another 38% were associated with various weather, largely cold, wind and rain and 20% were associated with more severe natural hazard primarily floods (9%), tornadoes (6%) and hurricanes (4%). Releases at fixed facilities, storage tanks and pipelines accounted for the majority of evacuations.

These results are generally in accord with Sengul et al. (2012) who identified 2 deaths, 52 injuries, and the evacuation of at least 5,000 persons in 102 separate natech events. However, due to the nature of the

NRC record, these human impacts are expected to be underreported. As an illustration, while the NRC database contains multiple reports of releases at an Arkema facility triggered by flooding from Hurricane Harvey in 2017, these records do not report the numbers of injured (at least 21) or evacuated persons (which included more than 200 residents).

Trends in Natech Occurrence

The frequency of natechs caused by various natural phenomena from 1990 to 2008 as reported by Sengule et al. (2012) and from 2009–2019 are illustrated in Fig. 2. During the period from 1990 to 2003 natechs averaged 2.4% of all reports; while since they have increased, averaging 4.4% of the total. The number of all hazmat releases reported to the NRC, on average 29,000 per year, remained reasonably stable during this period. Hurricane related events increased sharply beginning in 2004 with Hurricane Ivan and have remained high during years with significant hurricane activity, accounting for much of the increase in natech occurrence.

Although the largest changes in natech occurrence are in hurricanes related events, events associated with other weather have also changed over time. The full natech time series from 1990 through 2019 was evaluated for trends. As they are not clearly distinguished in the NRC record, storm, weather and unknown cause events were evaluated as a combined total for each year. Trends were evaluated for both the US as a whole and for climate regions as defined by NOAA for tabulation of CEI data. Table 1 summarizes the average number of natech events per year, slope of linear regression of annual frequency and confidence level of a Mann-Kendall trend test. Nationally, increases (> 95% confidence level) were observed in total natechs and in subsets related to flood, hurricane, storm/weather, tornado, wildfire and wind. Decreasing trends were observed for cold, tide and lightning events in the US as a whole.

Significant trends in these types of events were observed in some but not all climate regions. The number of hurricane related events increased (95% confidence level) only in the south and southeast. Storm events increased more widely, in the Ohio valley, south and northeast (where the largest numbers of such events were observed). Tornado related events increased only in the south where over half of events were reported. Wind related events increased in the Ohio valley, northeast northwest southeast and west, but not in the south where a large number of events were reported. While flood related events increased in the US as a whole, no individual region evidenced an increase.

Overall, natechs from all causes have increased (> 95% confidence level) in the northeast, due to increased events from wind, storms and hurricanes. Increases are also observed in the northwest due to rain and wind. In contrast, in the south and southeast where large number of natechs are reported, trends are not significant at a high confidence interval. This is because increases in frequency of some types of events, most notable hurricane related, are partially offset by decreases from other causes such as rain and lightning. Similarly, in the Ohio valley region increasing trends in storm and wind events are offset by decreases in in rain and lightning related natechs.

Trends largely reflect the frequency of petroleum releases as they make up the majority of the records. Total chemical natechs in the US evidenced no significant trend. Chemical natechs associated with hurricanes varied from year to year with a pattern similar to petroleum natechs but did not evidence a significant trend. Chemical releases caused by lighting and rain decreased significantly but this results from a sharp decrease starting in 2006 associated with changes in reporting requirements for flaring releases (Sengul et al. 2012). Likewise, annual number of natech releases of natural gas had no significant trends. Trends in the quantity of various materials released over time were not evaluated quantitatively due to the incomplete and episodic nature of the data. However, in general, the quantity of material released in each year for the US as a whole had no obvious temporal trends.

Identified trends are potentially affected by sharp increases in oil and gas development in the US during recent decades. To evaluate this factor, state level petroleum production data from 1990 through 2019 (USEIA 2020) was compared to natech occurrence in each state both for the total record and record excluding hurricane related events (which were highly variable from year to year). Of 30 states with oil production data, no significant positive correlation was observed between annual natech occurrence and annual production volume, with two exceptions. For Oklahoma moderate and significant correlation ($R = 0.52$ $p < 0.05$) was observed between production and natechs. Both production and natechs had similar trends of a gradual decrease through 2010 followed by increases with a sharp peak in 2015. This results in an overall trend of approximately 0.5 additional natechs in Oklahoma per year. The same pattern was observed in total natechs and the subset of the record excluding hurricanes. For Louisiana a strong and significant correlation ($r = 0.7$ $p < 0.05$), was observed for the record excluding hurricanes with both production and natechs having a declining trend amounting to roughly a halving over the record (a decreasing trend of around three natech events per year). In both states, rain related natechs accounted for these temporal patterns suggesting that, in these two areas, changes in production affected the incidence of only smaller spills. A recent review of all petroleum spills in the US (CRS 2017), also suggests that increased production has not resulted in a greater frequency of releases nationally over the last two decades. Overall, this assessment indicates that changes in petroleum production have not been a major driver of the natech occurrence summarized in Table 1.

Correlation with Occurrence of Causative Hazards and Climate Index Values

To evaluate correlation between natech occurrence and that of the underlying natural hazards, the natech record was first compared with annual reports of damaging weather events from the NOAA Storm Database from period from 1996 through 2019. Observed Pearson correlation and significance level is provided in Table 2 nationally and for US climate regions. As expected, positive correlation was generally observed between frequency of weather events and associated natechs. Exceptions were lightning related events in the upper Midwest and wind related events outside the continental climate regions (Other) where a significant inverse correlation was observed. This reflected an increase in natechs, while reports of damaging lightning and wind decreased over the same period. The increased lightening related

natechs were largely strikes on residential gas meters in Minnesota while wind related events were largely vessels outside the continental US. The specific nature of these releases suggests this inverse correlation is an artifact of changes in reporting practices. On a national level, annual natech occurrence for flood, hurricane, lighting, tornado, wildfire and wind was weak to moderately correlated ($p < 0.05$) with the reported occurrence of these events in the Storm Database. Similar or higher levels of correlation were observed in many US regions. Notably flood, hurricane, tornado and wind related natechs, showed moderate to strong correlation in a number of regions. Overall, the level of correlation in Table 2 suggests that the interannual variability in many natechs is dependent, at least in large part, on the frequency of damaging weather. Although correlation is in most cases moderate, this is unsurprising given the variability in the population of facilities which may be exposed to any given weather event. Additionally, in the case of hurricanes, Storm Database events associated with named hurricanes are often recorded under proximal causes of damage such as wind reducing the calculated level of correlation. Where no correlation is observed across all regions (i.e., rain) this may reflect the fact that a majority of rain related events are minor in nature and may not be triggered by a damaging event.

To place the natech record in the context of a longer climate history, reported releases were also compared to individual CEI component values from 1990 through 2019 as summarized in Table 3. In addition to comparison of natechs to directly related weather indices, landslide, lightning, wind and tornado natechs were compared to extreme precipitation CEI as a general indicator of convective weather. On a national level, weak to moderate correlation ($p < 0.05$) are observed between flood, hurricane, tornado, wildfire and wind related natech occurrence and related CEI values. Despite discrete causative events with high interannual variability, hurricane natechs only weakly correlated with the tropical storm CEI. A similar weak correlation ($r = 0.38$, $p < 0.05$) is observed between annual hurricane natech frequency and annual Accumulated Cyclone Energy (ACE) commonly used as a measure of hurricane energy. This low correlation appears to reflect variation in the industry present in areas where hurricanes make landfall (e.g. low natech occurrence associated with Hurricane Andrew in 1992) as well as the fact that tropical storm CEI and ACE are based on winds speed while hurricane natech occurrence is heavily driven by storm surge (Santella et al 2010), the size of which are also dependent on other factors. These findings are consistent with those of Luo (2021) who observed low levels of correlation between hurricane natech occurrence and climate indices affecting tropical storm intensity and frequency. On a regional level it is notable that moderate and significant correlation is observed between flood natechs and extreme precipitation CEI in the northeast, northwest and southern regions but not in other regions. These three regions make up more than half of total flood natechs. In the northeast and south both CEI and natechs have similar increasing trends, about a 2% increase annually. In the northwest they are correlated with no overall trend. Correlation with rain related natechs in Table 3 is higher than in Table 2, similar or higher levels of correlation are observed with the CEI value measuring wet years compared to the extreme precipitation CEI. This may reflect the fact that a majority of rain related natech events are minor and more dependent on frequency of rain rather than severity. Correlation is also observed between CEI values for heat and dry years and the relatively small number of wildfire related natechs.

Discussion

This study presents a comprehensive assessment of the occurrence of natechs within the US from 1990 to 2019. Natechs occur frequently in the US and have increased from less than 3% to highs of up to 7% of all releases reported to the National Response Center during this period. This increase is largely driven by hurricane related events, but statistically significant and sizeable increases were also observed in natechs related to floods, storm/weather and wind. In contrast, significant and sizable decreases in cold weather and lightening related natechs are also observed. Hurricane, lighting and flood related releases make up a disproportionately large volume of materials released due to natural hazards. Although the largest numbers of natech petroleum releases occur at fixed facilities (excluding storage tanks), the greatest quantities of petroleum were released from storage tanks. While natech events make up a small fraction of human impacts in the IRIS database, these events still accounted for a significant number of injuries and evacuations as well as several deaths during the study period. Particularly when taking into account the incomplete nature of the NRC record, the number of injuries and evacuations due to natechs suggest that additional consideration of natech risk in industrial facility design and emergency planning may be warranted. Supporting this conclusion, a review of major natech event with sizeable evacuations and injuries which occurred during Hurricane Harvey concluded that lack of guidance on evaluating flood risk to industry contributed to the incident (CSB 2018).

Evaluation on a national and regional basis confirms that in many cases natech occurrence is correlated with the incidence of damaging weather. This suggests that increasing trends for some natechs reflect both the common location of oil and gas infrastructure in costal and other hazard prone areas (Cruz & Karusmann 2013) along with increasing frequency of the causative hazards. Flood, hurricane, storm/weather, tornado, wildfire and wind related natechs have increased as summarized in Table 1. Although not having received the same attention as hurricane related natechs, increasing trends in flood, storm/weather, and wind related natechs have a cumulative annual increase of 7.4 events/years, the same order as that of hurricane related natechs (9.1 events/year). Although also increasing, tornado and wildfire related natechs are relatively infrequent in comparison. The decreasing trend in lightning related natechs is notable as these events, along with natechs during floods and hurricanes, account for much of the material released. Additionally, along with earthquakes, floods and hurricanes natechs are perhaps the most likely to impact public safety on a large scale. Consequently, particular attention is warranted for hurricane, flood and lightning related natechs and their trends are further evaluated below.

Increasing trends in hurricane natech occurrence reflect the fact that the hurricane natech record commenced during a period of low hurricane activity in the US, while recent years have seen greater hurricane activity. Periods of damaging hurricane activity comparable to that during the last decade and a half are documented in the historic record (e.g., Pielke et al 2008) suggesting that periods of high hurricane natech occurrence are likely to continue to occur. There is limited consensus on changes in hurricane impacts to the continental US in the future, thought there may be potential for more frequent

and intense hurricanes (USGCRP, 2017). Increases in sea level will also result in increased storm surge height and shorter return periods for a given water level (Tebaldi et al 2012). These two factors are projected to have varying effects on US costal flooding (Marsooli et al 2020). Given that storm surge is the cause of many hurricane natechs (Santella et al. 2011), it follows that hurricane natechs are likely to increase with sea level rise. Santella et al. (2011) reported that per foot of additional storm surge inundation, an additional 2 to 3 reported releases are expected for every 100 onshore facilities exposed. While this increase may seem small, large hurricanes in industrialized areas may expose many facilities to storm surge flooding (e.g., Hurricane Ike with approximately 650 facilities exposed which resulted in 225 releases). This suggests that potential sea level rise of 1 to 4 feet by 2100 (NCA 2018), could result in a 5–33% increase in releases during a hurricane due solely to increased flood depth. Additional releases would also be expected due to sea level rise induced expansion of inundated areas. For these reasons, security of storage tanks against hurricane damage is still an important area for improvement, despite receiving significant attention subsequent to Hurricanes Katrina and Rita.

While flooding related natechs increased significantly in the US on the whole, trends in individual regions do not reach a confidence level greater than 95%. However, moderate to strong correlation with storm database reports and extreme precipitation CEI are observed in many regions suggesting that variation in precipitation is driving variability, if not strong trends, in flood related natechs. Increasing trends in occurrence of extreme rainfall have been reported in the northeast, southeast and midwest (which is a combination of the upper Midwest and Ohio Valley CEI regions) (e.g., Kunkel et al. 2013), and as summarized in USGCRP (2018) increases in extreme rainfall are documented for much of US. Flooding is more complex due to seasonal and geographic factors (e.g., Sharma et al 2018) but there is evidence for increased flooding in the midwest and to a lesser extent in the northeast, while flooding in the northwest is decreasing (USGCRP 2017). Although attempts at prediction of regional changes in extreme precipitation are complex, heavy precipitation events are generally projected to increase (USGCRP 2017). Findings suggests that without mitigation, observed increasing trends in flood natechs will continue in step with future increases in extreme precipitation. This is particularly true in the northeast and southern regions where larger numbers of flood related natechs occur and extreme precipitation CEI has increased markedly since the 1960s.

For lightening, stable to decreasing trends were observed for both natechs and storm database reports in all regions. For the US as a whole, and all regions with significant trends, damaging lightning activity is correlated with natech occurrence. Decreasing lighting related events in both records is consistent with literature which describes reduced lightning strikes and resulting wildfires in the US over the period from 2003 to 2012 (Koshak et al 2015). However, Villarini and Smith (2013) observed increased lightening activity in central portions of the US (and decreases in the Rockies) between 1996 and 2005 and predictions by Romps et al (2004) suggesting that increased lighting strike frequency will accompany increasing atmospheric temperatures. Although the overall natech record presented here suggests decreasing trends, there may be potential for increased lightning related natech risk in limited geographic areas.

Conclusion

This assessment adds evidential weight to the concern that increased natural hazard risk will drive a greater number of natechs in the future, with the potential for more severe human health, ecological and economic impacts. These findings demonstrate that without increased attention to mitigation, natechs have and will continue to become more frequent in some regions. Further research is warranted to evaluate the geographic, climate and regulatory factors that contribute to hurricane and flood related natech risk in particular. Nantech trends vary by geographic region and more work is necessary to understand the interaction of regional climatic trends and infrastructure vulnerability as they may develop over the next few decades. For example, recent experience during east coast hurricanes, while without catastrophically large releases, have resulted in a very large number of smaller releases. This experience raises questions regarding the roles of facility siting, hurricane preparedness planning and regulatory and insurance industry pressure on natech vulnerability on the east and gulf coasts. Similarly, additional evaluation of offshore natechs associated with oil and gas production would be helpful in determining if updated recommendations and resulting upgrades have reduced the frequency or severity of offshore releases during hurricanes, or if decreased offshore release reports since 2005 are due to spatial/temporal variation in hurricane hazards.

Declarations

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Compliance with Ethical Standards

This study was funded by Brownfield Science and Technology Inc. The author declares that he has no conflicts of interest. This article does not contain any studies with human participants or animals.

Statements & Declarations

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Tables

Tables 1 to 3 are only available as a download in the Supplemental Files section.

Figures

Figure 1

Volume of Petroleum Released by Natechs 2009-2019

Figure 2

Number of Releases Associated with Various Natural Phenomena

Supplementary Files

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- Tables.docx