Abstract

Over 30,000 hazardous material pipeline failures in the United States have been documented by the Pipeline and Hazardous Material Safety Administration (PHMSA) since 1970. Hazardous pipeline failures, particularly failures associated with synoptic-scale extreme weather events like tropical cyclones, cause massive damage to the social, environmental, and economic landscapes. Yet even though tropical storms are broadly recognized as important drivers of pipeline failures, limited research has been conducted associating tropical storm characteristics with the likelihood of pipeline failure. This is largely due to limitations in historical records of pipeline failures, which are based on operator-generated incidence reports. As a substantial fraction of the hazardous material pipeline infrastructure is located in tropical storm/hurricane-prone regions, understanding how tropical cyclone (TC) characteristics impact pipelines is of critical importance, both now and as the intensity and frequency of tropical storms/hurricanes increase due to climate change. This analysis focuses on quantifying the relationship between tropical storm/hurricane characteristics and pipeline failure frequency. To accomplish this, PHMSA Failure Dataset and NOAA HURDAT2 Dataset are associated based on spatiotemporal concomitance to estimate the frequency of failure of pipelines in the aftermath of a tropical storm/hurricane. Over 70% of reported pipeline failures in TC active regions occur within the first year of TC exposure, and 17% occur within two months (60 days) of TC exposure. Since 1975, the annual frequency of pipeline failures within 60 days of TC exposure has more than doubled. The frequency of hazardous pipeline failures directly relates to the intensity (minimum pressure/maximum windspeed) of the tropical cyclone. Tropical storm/hurricane intensity explains 33% of inter-system variability in pipeline failure. Assuming linear continuations of strong increasing trends in mean tropical cyclone intensity, associations between storm strength and tropical cyclone intensity suggest that we may see an 5% increase in the frequency of annual hazardous pipeline failures in TC track regions per year by 2050. The results of this study can guide inspection and monitoring practices and create more responsive emergency response plans to reduce the potential contamination after a failure occurs. Limitations to the current PHMSA failure reporting data collection practices for pipeline failure cause attribution are discussed.

PREDICTING THE RISK OF PIPELINE FAILURES AFTER HURRICANES

by

Marilyn Smith

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1. Introduction

1.1 Scope of hazardous material failure impacts

The onshore pipeline network in the United States totals 3.3 million miles and serves as an essential part of the nation's transportation system that delivers energy services across the country. Petroleum products delivered by the United States through hazardous material pipeline networks or HMPs, including commodities such as crude oil, natural gas, and other refined products, are responsible for a variety of functions from fuel for transportation to generating electricity. Petroleum products transported through this pipeline network represent the biggest source of energy in the United States. As the energy demands of the United States population continue to grow, so does the dependence on HMPs. This can be seen in the expansion of nearly 14% of the onshore pipeline network in the past eight years (Parfomak 2015, 2023). As well as the predicted an increase of about 30 million barrels per day from 2012 to 2040 from a report published by the International Energy Agency (IEA) (International Energy Agency 2016). The projected expansion of the infrastructure size and demand would benefit from regulations reflective of the network capacity and associated hazards. As beneficial as hazardous material pipeline infrastructure is, the economic, environmental, and social costs of pipeline failures range from substantial to catastrophic (PHMSA 2023).

Over 30,000 pipeline failures have been reported in the United States since 1970 by the Pipeline and Hazardous Material Safety Administration (PHMSA). Between 2005-2023, reported hazardous pipeline failures were associated with 274 fatalities, 1,120 injuries, and nearly $11 billion in damages (PHMSA 2023). Previous studies indicate between 28-95% of the total costs of pipeline failures are associated with environmental damage and remediation

(Restrepo, Simonoff, and Zimmerman 2009; Belvederesi, Thompson, and Komers 2018). Even with the large price tag associated with remediation, about 85% of products released remain unrecovered after the accident (Belvederesi, Thompson, and Komers 2018). This unrecovered product is then an environmental contamination event for air, water, and soil of the affected communities. The economic detriment after a pipeline failure can vary for these reasons. Restrepo, Simonoff, and Zimmerman (2009) conducted a study aimed to develop a holistic picture of how to predict the economic fallout of pipeline failures referencing the 1582 accidents documented by the POT Pipeline safety office from 2002-2005. The highest cost category in the failures, again, was clean-up and recovery. The data highlighted that cleanup and recovery costs associated with nonzero cleanup and recovery accounted for at least 95% of the total costs of the failures (Restrepo, Simonoff, and Zimmerman 2009).

The potential for pipeline failures to be catastrophic causes these events to be a top public health risk as well. In an analysis of the 10 most fatal pipeline failure incidents around the world, there were reported to be over 4,000 deaths, implicating lack of maintenance, monitoring, and reporting as primary culprits in the high mortality rates (Biezma et al. 2020). The catastrophic consequence of the mismanagement of these causes can be seen through various pathways. One of those pathways is associated with an increased risk of fires and gas clouds affecting the surrounding community (Bonvicini, Antonioni, and Cozzani 2018). The most pervasive intersections between pipeline failures and public health is by way of water supply contamination. It was determined that, on average, 0.8% of failures annually occur on HMPs that run across water sources such as rivers and lakes, also referred to as water-crossing HMPs (Belvederesi, Thompson, and Komers 2018). In addition to these on-shore water crossing HMPs, there are also off-shore HMPs that are located directly under a natural seabed. The intersection of this infrastructure with our water sources creates a risk for water contamination. Exploring the cause and effect of these failures with a public health perspective can guide inspection and monitoring practices and create more effective emergency response plans that reduce the extent of contamination after a failure occurs (Belvederesi, Thompson, and Komers 2018). There are various factors that are considered when making efforts to mitigate impacts such as the average amount of released product, time elapsed between accidents, emergency response times, and costs of damages. The impacts of these factors have been shown to be less severe with shorter response times, enabled by rapid reporting, resulting in a reduction of potentially released product (Belvederesi, Thompson, and Komers 2018; Shahriar, Sadiq, and Tesfamariam 2012; Biezma et al. 2020)

Among the causes of failure, natural disasters cause an estimated 36% of pipeline failures and are the causal mechanism associated with the highest release of hazardous materials (Serkan Girgin and Krausmann 2014). Though the attribution can vary widely based on incidence reporting, meteorological events, specifically tropical storms and hurricanes (tropical cyclones, TCs), account for at least half the total damages associated with natural-hazard triggered pipeline accidents in the United States (S. Girgin and Krausmann 2016), and have been estimated to be the cause of up to 86% of all natural-hazard mediated pipeline failures worldwide (Ricci, Casson Moreno, and Cozzani 2021). While the true magnitude of natural-hazard associated pipeline failures is likely underestimated due to reporting bias (Serkan Girgin and Krausmann 2015), TCs are broadly recognized to be an important, and under-characterized, driver of pipeline failures (Ricci, Casson Moreno, and Cozzani 2021; Serkan Girgin and Krausmann 2015).

During a TC, there can be heavy winds and precipitation that cause landslides, tornados, inland flooding, and coastal storm surges; all of which create complex stress on pipeline infrastructure (Czajkowski, Simmons, and Sutter 2011; Czajkowski et al. 2017; Burow, Ellis, and Tran 2021). The most notable instances of the impacts on pipeline infrastructure occurred during hurricane Harvey in 2017 with over 300,000 kg of released product from the affected facilities of TC forcings (R. Qin, Khakzad, and Zhu 2020).

As average ocean temperatures across the Atlantic Basin continue to increase, TCs, which are fueled by warm ocean temperatures, have shown a commensurate increase in intensity and frequency, with about a 7% increase in TC precipitation rate documented for every 1° increase in global surface temperature (Knutson et al. 2020), or an increase of about 1.3% per year (Guzman et al., 2021). The increase in total precipitation associated with global warming is more extreme for more intense TCs. During the historic 2020 hurricane season, a 0.4-0.9°C sea surface anthropogenic sea surface temperature anomaly in the Atlantic Basin was directly associated with a 10% increase in 3-hourly rainfall intensity during TCs (Reed, Wehner, and Zarzycki 2022).

When it comes to TC impacts on HMP failures, TC intensity matters. Previous studies show that category four and greater TCs are associated with about 80% of total damages associated with TCs, though they make up fewer than half the total TCs. Category four or greater TCs can be particularly difficult to characterize in gridded climate models (Mallard et al. 2013). While results from numerical studies are inconclusive as to how anthropogenic climate change impacts the frequency and severity of the most intense TCs, historical analysis of data shows a marked increase in the frequency of category four or higher TCs which is consistent with trends expected from global warming (Vecchi et al. 2021, Ricci, Casson Moreno, and Cozzani 2021).

1.2 Operator-submitted data and causal attribution

The Iowa Law Review (Klass and Meinhardt 2014) details the complex history of oil and gas pipelines in the United States and the reasoning behind the current state of the legislation on a state and federal level. In 1542 that Spanish explorers discovered oil in the water of present-day Port Arthur, Texas. It was initially utilized to caulk boats. It wasn't until the 1700s, in response to the discovery of oil springs in now western New York, that oil began being traded for monetary gain. The discovery of the usefulness of this commodity and the transition to monetizing undoubtedly changed the trajectory of our economy. Edward Drake has been documented to be the first person to construct a reliable petroleum pipeline in northwestern Pennsylvania in 1859 (Klass and Meinhardt 2014). Since then, more than 2.6 million miles of HMPs that carry hundreds of billions of tons of liquid petroleum every year have been constructed in the United States. There are currently plans to expand this network due to increased production rates and the prediction of increased energy usage. In response to the frequency of failures and subsequent consequences, the Natural Gas Pipeline Safety Act of 1968 (Armstrong 1969) and the Hazardous Liquid Pipeline Act of 1979 (De Leon 1992) work to set regulations for design, construction, operation and maintenance, and failure response planning (Parfomak 2004). It is outlined in the Pipeline Safety: Request for Revision of a Previously Approved Information Collection - National Pipeline Mapping System Program in 2014 that the operators should be required to report the predominant year of installation for the HMPs as it specifies which regulations apply to which sections of the pipeline infrastructure (PHMSA Request for Revision). These efforts along with the ones of the Federal Government to place more HMPs under federal oversight are working to improve the data available and the practices that are employed to sustain this infrastructure (Eaton 2010).

Title 49 of the Code of Federal Regulations (49 CFR §Parts 191, 195) outlines the requirements for incident reporting for pipeline operators (Office 2019). This regulation requires pipeline operators to report the incident to PHMSA within 30 days of occurrence with accident-specific details providing information about location, facilities involved, operations, drugs and alcohol, and the cause of the incident (PHMSA). This information is collected and then stored in a public database. The Pipeline and Hazardous Material Safety Administration (PHMSA) is an agency within the DOT created in 2004 with the primary responsibility to "protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives" (PHMSA Mission). Although PHMSA was initiated in 2004, they maintain public databases of operator-reported pipeline failures reported from 1970 to the present for gas distribution, gas transmission, and hazardous liquid pipelines. These reports provide extensive information about various variables quantified from each failure compiled from incidence reports. These different types of HMPs consist of flow lines, feeder lines, transmission lines, product lines, and distribution lines. Distribution lines allow local low-pressure transport while transmission lines are larger in diameter and length and are responsible for a large portion of oil and gas transportation (Piccinelli and Krausmann 2013). Overall, PHMSA documents that the HMPs range from 2 inches to 42 inches in diameter.

Extensive work has been done on the causes and consequences of unplanned releases of hazardous liquids into the environment utilizing the PHMSA dataset. After a pipeline failure is identified, a consequence assessment is performed by the operators to detail the necessary information outlined in the reporting guidelines (Sergi and Davis 2022). These risk assessments are important to ensure adequate protection of human health and the environment, as well as to ensure that programmatic activities and policy decisions around protecting pipeline infrastructure are based on comprehensive data (Parfomak 2004). The data used by the PHMSA to generate life and property-saving regulations and programs are extremely important because of the hazardous materials that are being transported through remote and densely populated regions.

After a failure occurs, the polluter is expected to pay the cost of reconnaissance and recovery (NOAA ORR, Zardasti et al. 2017). Accurate causal attribution is therefore of critical importance in pipeline failure modeling (Awuku, Huang, and Yodo 2023). Substantial research has been devoted to quantifying the risk of system-side drivers of pipeline failure, including the probability of failure, consequences of failure, failure rate, and other predictions directly related to the potential outcome and trigger of an event (Zakikhani et al. 2020). A wide variety of empirical models have been applied to quantify the risk of pipeline failure, including the fuzzy technique (Guo et al. 2016; Shahriar, Sadiq, and Tesfamariam 2012), bow tie analysis (Dziubiński, Frątczak, and Markowski 2006; Shahriar, Sadiq, and Tesfamariam 2012; Lu et al. 2015), fault trees (Badida, Balasubramaniam, and Jayaprakash 2019; Lu et al. 2015), event trees (Cozzani et al. 2010), neural networks (Kakoudakis, Farmani, and Butler 2018), Monte Carlo simulations (Soomro et al. 2022; Li et al. 2019; Yu et al. 2018), regression analysis (Restrepo, Simonoff, and Zimmerman 2009), Bayesian networks (Lu et al. 2015), integrated matrix-based risk assessment (Kamsu-Foguem 2016; Henselwood and Phillips 2006), and self-organizing maps (Liang 2012). Each of these methods has its own advantages and disadvantages, depending on the context of the analysis.

One overarching limitation in empirical risk assessment that is consistently discussed in the literature is associated with the data themselves (Zakikhani et al., 2020). Most, if not all, empirical risk assessments of hazardous pipeline networks utilize data on both failure frequency and cause from various public databases, like the PHMSA failure dataset (Ricci, Casson Moreno, and Cozzani 2021). Records in these databases are self-reported by operators, and the "causal categories" available on incident reporting forms reflect what is useful for operational response, which may or may not be useful for research on comprehensive system risk. For example, of the various and potentially overlapping causes of pipeline failure, operators filling out a PHMSA incident report may select corrosion, excavation damage, natural force damage, other outside force damage, material/weld failures, equipment failure, and incorrect operation as the cause, as these are the causes specifically documented by PHMSA as criteria in their documenting report (PHMSA). Causal attribution in pipeline failure is rarely straightforward. Often, multiple overlapping potential causes coalesce in a failure event, undermining the validity of single-cause attribution. The attribution that is limited to a single selection within a PHMSA category, makes it difficult for just one model to be effective in quantifying risk associated with a myriad of drivers (Lam and Zhou 2016).

When natural force events, including earthquakes, heavy rains, high winds, and extreme temperatures trigger a pipeline failure (or other technologically related disaster), it is called a NaTech event (Awuku, Huang, and Yodo 2023). NaTech events are considered low-probability scenarios with high impacts on public health, economics, and the environment (G. Qin et al. 2020). NaTech pipeline failure studies are limited when compared to the literature on human and mechanical failure risk in pipeline systems (Ricci, Casson Moreno, and Cozzani 2021), but the available data underscores the importance of NaTechs estimating the total impacts of pipeline failures (G. Qin et al. 2020).

Analysis has been conducted for industrial accidents triggered by flood events (Cozzani et al. 2010) that details the importance of information about these events as a result of the substances interacting with the environment and water sources. Based on the data collected from this study, comprehensive event trees were developed to visually represent the various post-release scenarios that are possible from industrial accidents caused by floods. Girgin (2016) determined that natural disasters make up about 36% of pipeline failures, and result in the highest amount of release of hazardous materials. Of all natural hazards, meteorological events, specifically TCs account for over half of the damages associated with pipeline failure (Girgin and Krausmann 2016). From the data evaluated in (Ricci, Casson Moreno, and Cozzani 2021), it was found that about 44% of the Natech events resulted in environmental contamination. Ricci's study worked to analyze which natural events most commonly trigger Natech events to understand the trends of these events, where they are most commonly happening, and the social and environmental impacts of these events. The data used for this study outlined the date, location, casualty information, social and economic damage parameters, and substances involved. From the data, there was an obvious correlation in the US between natural disasters and Natech events that outline North America as the most affected geographical area (Ricci, Casson Moreno, and Cozzani 2021).

Not only are the complicated dynamics of cause to be considered, but pipeline characteristics are also used in modeling risk prediction. HMPs are an aging infrastructure. Many of the HMPs that are currently in operation have been functioning for at least 45 years (Lam and Zhou 2016). It has been determined that age and previous failures are the two factors that play a major role in the failure characteristics of pipeline failures (Awuku, Huang, and Yodo 2023). HMPs are deteriorating, not only due to age but also environmental factors, poor planning and design, and inefficient inspection and maintenance (Parfomak 2004). Failures are unavoidable but proper practice ensures that the most avoidable risks are mitigated (Shahriar, Sadiq, and Tesfamariam 2012).

Awuku conducted a study on pipeline failures due to natural forces considering climate change factors through artificial intelligence algorithms. This study utilized the PHMSA data and climate change data and was able to achieve 92.3% accuracy for the formulated model. The output of this model identifies high-risk HMPs for subsequent maintenance and safety measures to be made to mitigate potential failures. Along with the PHMSA pipeline failure data, the incorporation of climate change is considered a significant advancement in predicting pipeline failures. This study is important because, even though corrosion has been reported to be the largest cause of pipeline failure, there are other factors that can also exacerbate the intensity of failures such as location and weather conditions. Other factors that have been identified as predictors of pipeline failure include the diameter of the pipeline, temperature, and material. With more information for predictive modeling, there is increased probability for more effective solutions.

A recent report by the European Commission demonstrates that natural hazards are underreported as causes of pipeline failure incidents, suggesting that the definition of a natural-hazard cause is lacking in nuance, as natural hazards can accelerate other causes, facilitate the transport of spilled substances, or aggravate impacts of pipeline failures by delaying response and recovery operations (Serkan Girgin and Krausmann 2015). Because of this, it is important to characterize how TCs and pipeline failures intersect in space and time.

1.3 Quantifying risk of tropical cyclone associated NaTechs

Regulatory bodies across the world often only focus their NaTech efforts on certain types of natural disasters, such as earthquakes in California (Nair, Dash, and Mondal 2018) and tsunamis in Japan (Murphy and Conner 2012). This makes sense since these events are common in these places. TCs occur frequently along the Gulf Coast and the eastern United States, causing loss of life and billions of dollars of damage annually (Eaton 2010). The goal of this study is to quantify the additional risk of pipeline failure associated with TCs to inform dialogue on engineering standards and regulations in hurricane-prone regions.

Identifying a causal relationship between a TC and pipeline failure is complicated for several reasons. First, as TC-related damage is not a defined category on the PHMSA database, hurricane-mediated pipeline failures have been attributed to several other categories (See section 2.1). Second, TCs and hurricanes can stress pipeline systems through a variety of mechanisms, including but not limited to high windspeeds; atmospheric pressure variability; intense precipitation and related impacts including flooding, erosion, accretion, and landslides; storm surges and related impacts (coasts); and intensified tornado activity (inland). Some of these stresses are acute and can logically be associated with pipeline failure at low latency to the forcing. For example, tornado damage to an above-ground transmission pipeline is easily attributable. Many of these stresses are cumulative and can result in a decreased overall lifetime of the pipe system. For example, a pipeline network subject to frequent bouts of wetting and drying due to TC-related precipitation inland, or storm surges coastally, would experience more rapid rates of corrosion over time. Because of this, quantifying hurricane-mediated pipeline failures requires both identifying pipeline failures reported immediately after TCs, as well as cumulative exposure of the pipeline fail point to TC-related forcings over time.

Knowing the date and location of pipeline failures allows us the unique opportunity of examining regional hurricane activity occurring prior to the failure. Specifically, it is possible to examine features of hurricanes that coincide spatiotemporally with pipeline failures.

2. Methodology

2.1 Data sources

This analysis utilizes two data sets; the first being the PHMSA Distribution, Transmission & Gathering, LNG, and Liquid Accident and Incident Data for pipeline failures since 1970 (PHMSA Failure Dataset) and the National Hurricane Center and Central Pacific Hurricane Center Best Track Data from the Atlantic Hurricane Database since 1851 (NHC Data Archive).

The PHMSA Failure Dataset compiles all operator-generated incidence reports for gas distribution, gas transmission, and hazardous liquid pipelines starting in 1970 (gas distribution, gas transmission) pipelines and 1986 for hazardous liquid pipelines, to present. The PHMSA pipeline failure reporting consists of four different reports for each pipeline transmission type, reflective of the evolving reporting criteria since the implementation of the reporting regulation. The original regulation (Pipeline Facility Incident Report Criteria History) for incident report criteria in 1970 outlined the criteria for an “incident” as 1) any leak that caused death or personal injury, 2) a leak from a pipeline that required the segment to be taken out of service, 3) a gas ignition incident, 4) an incident that caused damage of $50,000 or more, or 5) an incident that was a significant occurrence through the judgment of the operator. Since the original regulation criteria were set 50 years ago, there have been seven amendments to these criteria. Each change was made to outline more clearly what is considered a reportable incident. The current definition of a reportable incident is 1) an event that leads to death or personal injury, 2) an event that causes property damage of $122,000 or more, 3) an unintentional loss of 3 million cubic feet or more of gas, 4) an event that results in an emergency shutdown on a Liquified Natural Gas facility, or 5) an event that is significant in the judgment of the operator. The evolving nature of the definition of an event underscores the complexity of working with PHMSA data in quantifying temporal trends in pipeline failures. The changes in frequency of reporting by change in reporting criteria can be observed in Figure 8.

The NOAA HURDAT2 Dataset, compiled by the National Hurricane Center (NHC), evaluates all available observations (real time and post-hoc) to generate an official assessment of the history of all tropical cyclones originating in the Atlantic Ocean following recommendations of the Best Track Change Committee (Landsea et al., 2012). For each unique tropical and subtropical cyclone recorded since 1949, the NOAA HURDAT2 dataset details six hourly increments, latitude, longitude, category, maximum wind, and central pressure. From 2004 to present, the NOAA HURDAT2 additionally details the TC force diameter (Landsea et al., 2012)for each TC.

2.2 Data processing

Due to changing reporting criteria in the PHMSA dataset, there are inconsistencies of and within the variables reported. Only pipeline characteristics that remain consistent over the 50 years of the PHMSA failure reports are considered for this analysis. These include the failure date, location, and cause of failure. All PHMSA records include county and state of incident, most provide the municipality, and many include a precise longitude and latitude of failure point. For records without a latitude and longitude of failure point, the provided address was used to geolocate the associated latitude and longitude coordinates using a google maps key. (Google Maps)

Operators filing PHMSA incident reports can select a number of pre-prescribed causes of failure. As cause of failure categories on incident reports have changed over time, and as many pipeline failures may have one or more overlapping causes (i.e., corrosion and natural force damage), PHMSA failure cause categories are aggregated into three types that are of interest to this analysis. The first category is meant to capture failures associated with *human error*, including construction/operator errors, excavation damage, and other operator errors. Human errors are expected to occur independently of TC forcings. The second category captures a wide array of *mechanical failures* associated with some outside forcing, including malfunction of equipment, material/weld failures, and outside force damage. Mechanical failures may or may not be associated with TC forcings. The third category is *natural force damages*, a category that is adopted in the PHMSA Failure Dataset starting in 2002. In theory, natural force damages ostensibly include damages directly associated with TCs after 2002. Trends in the frequency of human errors, mechanical failures, and natural forcing failure frequencies over time are evaluated using simple linear regression.

The data obtained from the NOAA HURDAT2 Dataset is originally formatted in a comma-delimited text format and was processed into an effective format using the Best Track Data code through GitHub from Metemaad (Metemaad, 2019).

2.2.1 TC-associated NaTech analysis

The goal of this analysis is to identify TC-associated pipeline failures. Since the literature strongly suggests negative reporting bias post-2002 in TC-associated pipeline failures (Restrepo, Simonoff, and Zimmerman 2009), and since there are no TC-associated pipeline failures prior to 2002 as it was not a causal category, we must instead examine the intersections between PHMSA Failure Data and 6 hourly points in the NOAA HURDAT2 Dataset and infer causality from TCs with an above-average number of failure intersections.

In the context of this analysis, an "intersecting" pipeline failure point is defined by the following criteria: 1) Occurs within the radius of TC force diameter (when available) OR within 300 miles (the HURDAT2 mean TC diameter) of the TC center and 2) Occurs within 60 days of TC intersection. The reporting criteria for pipeline operators is to report the pipeline failure within 30 days of occurrence, however during a TC there could be a delay in the detection of a specific failure. Therefore, the 60-day condition that was set with intention to capture the detection and reporting delays during hurricanes.

Utilizing the latitude and longitude location each hurricane is assigned a unique name that consists of the name of the TC and the year in which the TC occurred to account for TC names that have been used multiple times over the course of the NOAA HURDAT2 history. Pipeline failures that do not intersect with NOAA HURDAT2 point are retained with a TC name of "No Storm." Likewise, NOAA HURDAT2 hurricane track points that are not temporally associated with PHMSA pipeline failure points but are within 300 miles of any historical failure point (to establish spatial concomitance with pipeline infrastructure), are retained with no affiliated failure points. Using the latitude and longitude of failure point, or NOAA HURDAT2 point in the absence of a concurrent pipeline failure, are spatially classified using k-means clustering (Pedregosa et al. 2011). A total of twelve clusters were utilized, each roughly spanning a 300 square mile radius, which is the average TC force diameter determined from the NOAA HURDAT2 Dataset.

We hope to capture the annual, local frequency of three classifications of the TC-associated pipeline failure:

1)TC-associated failure: a failure that has likely occurred due to TC forcings (f_s).

2) TC-non-associated failure: a failure has occurred unrelated to TC forcings (f_o).

3) TC forcings unassociated with pipeline failure: a TC forcing has occurred, with no associated anomalies in pipeline failures ($f_s - f_o <= 0$).

For TC-associated pipeline failures class 1 and 2, we have a positive value (1) of TC failures associated with each TC name, year, and location category. For TC-associated pipeline failures class 3, we have a null value (0) of TC failures associated with the TC name, year, and location. Aggregating by sum on TC failure association yields the frequency (f) of TC failure associated with each of the three classes.

In order to account for the potential frequency bias from the causal attributions of failures from the merge of hurricane and pipeline data, we utilized the intersections between pipeline failures and TCs, and normalized them to the local 60-day average failure rate outside of hurricane season. To control for regional variability in the density of pipeline networks, we then define spatial sub-regions within the study area, such that each j = 1, …, 12 sub-regions is approximately equal to the reach of an individual HURDAT2 point, using a simple k-means cluster of the combined datasets latitude and longitude. To control for trends in hurricane failure reporting not associated with hurricane characteristics, we then calculate the 60-day average October-June failure frequency for each spatial sub-region for each five-year period between 1972-2022 (i.e., 1972-1976, 1977-1981, …, 2017-2022) (f_o). This regional non-TC associated 60-day failure rate (f_o) is then subtracted from each TC-associated failure frequency (fs) to derive an estimate of the potentially TC-related failure frequency as (fs’):

$$fs \quad = fs' \quad - fo' \qquad \text{Eq. 1}$$

Where fs is the estimated TC-associated failure frequency, fs’ is TC-intersecting failure frequency, and fo' is the regional non-TC associated 60-day failure rate, and are unique locations determined through k-means cluster, j are 5 year intervals from 1970-2022, and q are unique TC names. Any fs with negative values are assigned a value of zero.

2.3 Data analysis description and model selection

Three semi-independent analyses are conducted on the merged PHMSA Failure Dataset, NOAA HURDAT2 Dataset, and the Failure Dataset. The analysis of the PHMSA Failure Dataset aims to highlight the trends of all pipeline failures over time and identify if there is evidence of negative reporting bias in hurricane-related pipeline failures through associating failures with TCs. The NOAA HURDAT2 Dataset highlights trends estimated the change in TC intensity (specifically pressure and windspeed) and trajectory (min latitude, max longitude) of TCs associated with climate change (Section 2.3.1). The Failure Dataset serves to quantify the relationship between TC intensity and frequency of pipeline failures through mixed-effect modeling (Section 2.3.2). The optimal model will also allow for estimates of past and future change in TC failure frequency associated with climate change (Section 2.3.3).

2.3.1 Quantifying climate change associated impacts on TC parameters

Global climate models show substantial negative bias in the prediction of historic hurricane intensity and frequency, due in part to theoretical weaknesses in deterministic characterizations of hurricane-forming processes, and in part to the fact that hurricane-forming processes, and associated phenomena such as TC-associated hurricanes and convective TCs, occur below the spatial resolution of many numerical climate models. (Zhang et al. 2011) Historical negative bias in extreme TC prediction translates to high uncertainty in future numerical predictions of hurricane dynamics associated with global warming (Knutson et al. 2020). Alternatively, numerous empirical studies have documented strong trends in historical hurricane data parameters that are consistent with expectations for observed global warming in the late 20th and early 21st centuries (Knutson et al. 2019; Vecchi et al. 2021). As a result, we infer global-warming associated trends directly from NOAA HURDAT2 Dataset.

OLS linear regression is used to quantify historical trends on HURDAT2 annual TC minimum pressure and annual TC maximum wind speed, as well as trajectory for annual minimum TC latitude and annual maximum TC longitude from 1970-2022. For future predictions, we assume that coefficients will remain constant until the middle of the 21st century (2050) (Elsner 2006).

2.3.2 Quantifying the relationship between TC intensity and frequency of TC-associated pipeline failures

The relationship between TC intensity and frequency of pipeline failures is evaluated using a generalized mixed effects regression model (Bates et al. 2015). Taking into consideration the multilevel structure of the data, and the high number of zero failure records (Supplemental Figure 3) which represent class 3 associated failures, a zero-inflated Poisson mixed-effects model was fit utilizing hurricane characteristics (windspeed, pressure) as fixed effects, and location and year as random intercepts. This model is useful to reduce negative variance bias associated with non-independence in individual failure records associated with location and reporting year, while providing the opportunity to examine how much temporal and spatial variance in the PHMSA failure dataset is explained by hurricane characteristics. We accomplish this by comparing variance partitioning between all random effects in a null model (random effects only) and the trained model (with fixed effects of windspeed and pressure). The fixed effect parameters allow for the estimation of the relationship between hurricane characteristics and pipeline failure frequency. These parameters are also used to estimate how pipeline failure rates may be modified by TC intensification under climate change (Section 2.3.4).

2.3.3 Past and future changes in climate-change mediated TC-associated pipeline failures

For simplicity, we assume that significant linear trends in TC intensity observed between 1970-2022 are primarily attributable to global warming, and that global-warming associated TC intensity trends will remain constant into the near future (Section 2.3.2). Likewise, we assume that the coefficients from section 2.3.3, describing the relationship between TC intensity and pipeline failure frequency, will remain constant in the near future (section 2.3.3). Limitations to this approach are discussed in the conclusion. Mean annual maximum TC windspeed and minimum hurricane pressure predicted from the models in 2.3.2 predicted to 1970, 2020, and 2050 baselines are used to predict pipeline failure frequencies using the model trained in section 2.3.3. In this way, we aim to quantify current and future impacts of global warming on TC-associated pipeline failure.

3. Results

3.1 Pipeline characteristics and the failures associated with TC

The PHMSA Failure Dataset provides information about various variables, the key variables for this analysis being location given in coordinates, date, and cause of the failure (Supplemental Figure 1), and in this study, we examine failure points which are geographically exposed to Atlantic TC tracts (Supplemental Figure 2, Figure 1).

Substantial inconsistencies in failure reporting prior to 1986 are associated with changes in dollar-value of property damage threshold representing a pipeline failure incident (Supplemental Figure 4). Figure 1 shows the location and frequency of human-driven, mechanical, and natural forcing failures occurring since 1986. The largest clusters are to be found in Texas, Oklahoma, Louisiana, Illinois, Pennsylvania, and New York.

According to the causal attribution categories in the PHMSA dataset, between 1986-2022, 2.7% of reported pipeline failures were attributed to natural forces (347 total), 11.3% were attributed to human error (1,468 total), and 61% were associated with outside forcing (7,927 total) (Figure 1). The earliest attribution to "natural forces" in the PHMSA database was made in 2002, during which time no significant positive or negative trends can be observed in the frequency of its attribution (Figure 1, right). A significant, increasing trend in the annual frequency of human error attribution (2.5 failures/year annual increase between 1986-2022, $p = 1.29$ E-10) and in outside error attribution (6 failures/year increase between 1986-2022, $p = 2.81$ E-10) is observed

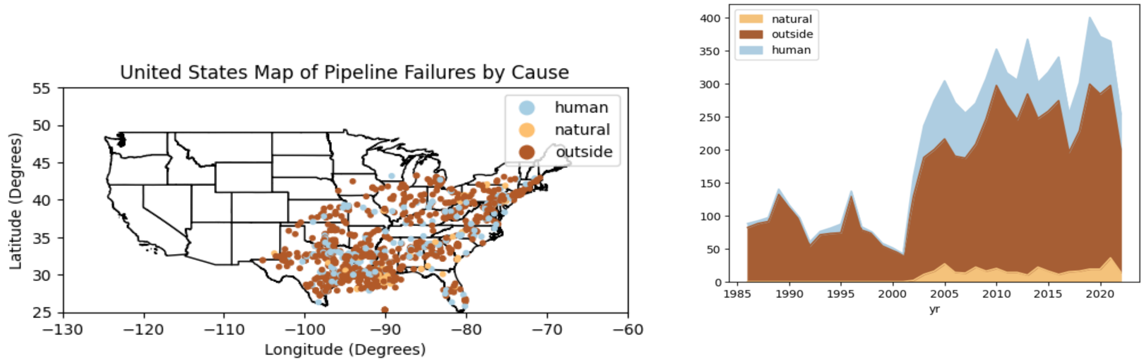

Figure 1: (Left) Pipeline failures since 1985 within 300 miles of a TC track, categorized by cause of failure. (Right) Frequency of pipeline failures since 1985 categorized by cause of failure.

It was found that 70% of pipeline failures occurred within one year of a spatial overlap with a HURDAT2 point. Of all the failures with a previous TC spatial overlap, 17% occurred within 60 days of the exposure. Over our study period, we observed a positive, significant linear trend in the annual TC-intersecting failure frequency (defined as occurring within 60 days of a TC exposure) as seen in Figure 1. In 1975, there was an annual mean of four failures less than 60 days from TC intersection. In 2020, there was an annual mean of 50 failures per year less than 60 days from a TC intersection.

3.2 Hurricane characteristics and trends estimating changing intensity of TCs associated with climate change

In total, 220 TCs have been reported in the NOAA HURDAT database since 1970. In order to make a naive, but useful, quantification of changing TC dynamics associated with climate change, linear trends are calculated on four annual indices: annual minimum TC latitude (Figure 2a), which is indicative of the origination point of the TC; annual maximum TC longitude (Figure 2b), which is indicative of the westward reach of the TC track; annual minimum TC pressure (Figure 2c), which is a metric for total TC intensity; and annual maximum TC wind speed (Figure 2d), which is also indicative of TC intensity (Figure 2).

Since 1975, we see a southward migration of hurricane origin of 0.14 degrees/year; an eastward migration of the westernmost point of the TC track of 0.41 degrees/year, an increase in maximum annual hurricane windspeed of 0.59 ms^{-1} and a decrease of minimum pressure (an increase of maximum annual intensity) of -0.65 mBar/year (Figure 2). The trends that are observed from this data are consistent with the predictions outlined in previous studies that highlight the predicted increase in hurricane TC intensity due to climate change (Elsner 2006). From this data the hurricane indices showed strong significant trends between 1970-2023 at alpha = 0.05. This approximate linearity is assumed for the near future, and as such we use 1970-2020 coefficients on TC parameters to estimate 2050 TC parameters (Section 2.3.4).

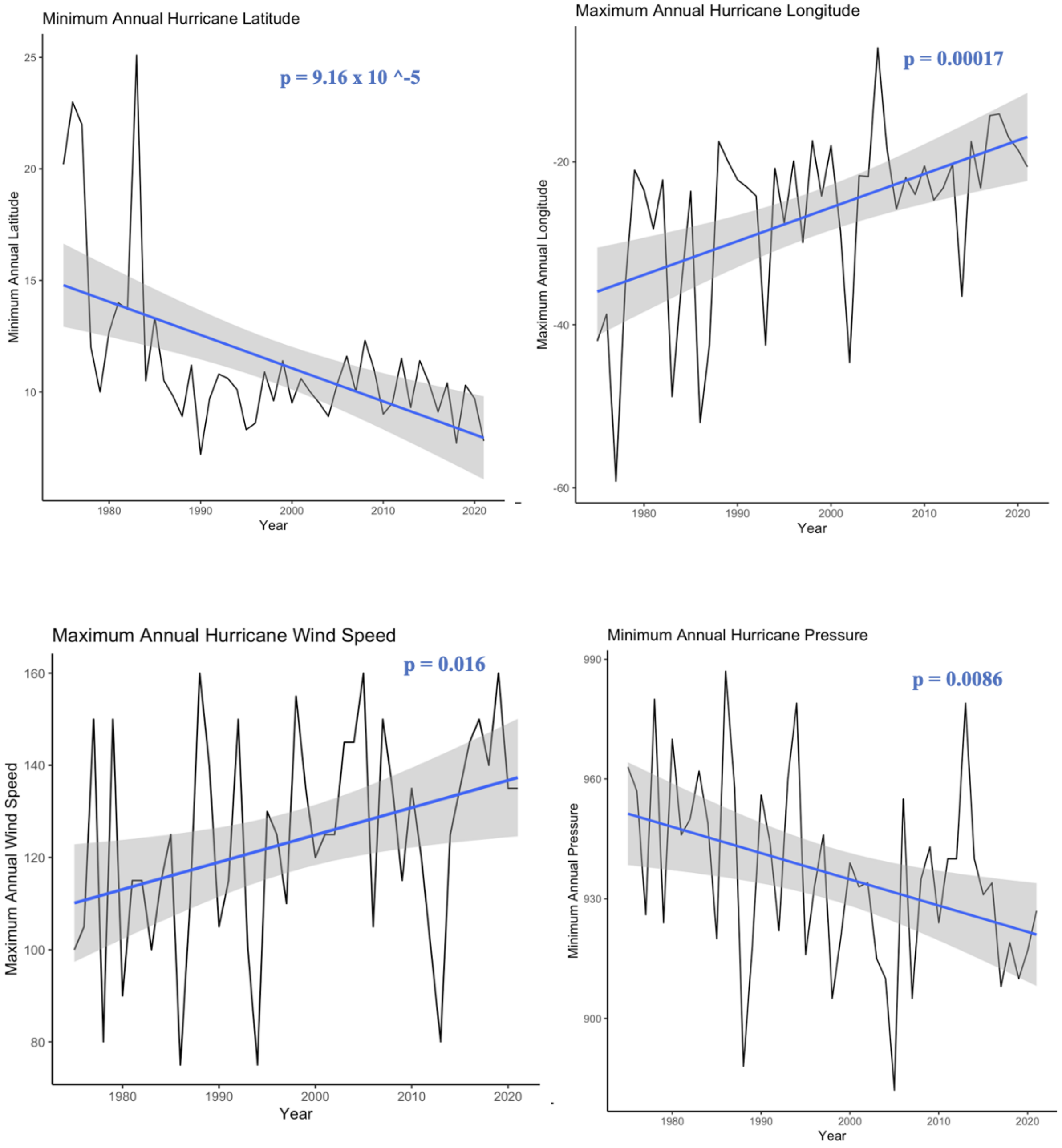

Figure 2: Annual average trends from NOAA HURDAT2 Dataset documented hurricanes. a) Minimum Annual Hurricane Latitude b) Maximum Annual Hurricane Longitude c) Maximum Annual Hurricane Wind Speed d) Minimum Annual Hurricane Pressure

3.3 Failure data analysis to quantify relationship between storm intensity and frequency of HMP failures

Utilizing the Failure Dataset to better understand the relationship between TC forcings and pipeline failures allowed for a model in which conclusions about the potential variability of the induvial TC parameters can be further evaluated. The outputs of the null and full mixed effect model show the change in the fixed and random effects. In determining the best model utilized for the TC-associated failures models utilizing one wind and pressure were also ran and compared for further validation that the combination of wind and pressure as random effects yields the most accurate predictions.

	Null Model	**Full Model**
Fixed effects	*Coefficients*	
intercept	-1.0033	-0.93926
wind	-	0.48066
pressure	-	-0.20286
Random effects	*Variance*	
yr	0.6615	0.5700
location	0.4330	0.3464
LogLik	-660.8	-638.6
AIC	1327.6	1287.2
BIC	1340.4	1308.5

Table 1: Null and full model of zero-inflated mixed-effects Poisson regression.

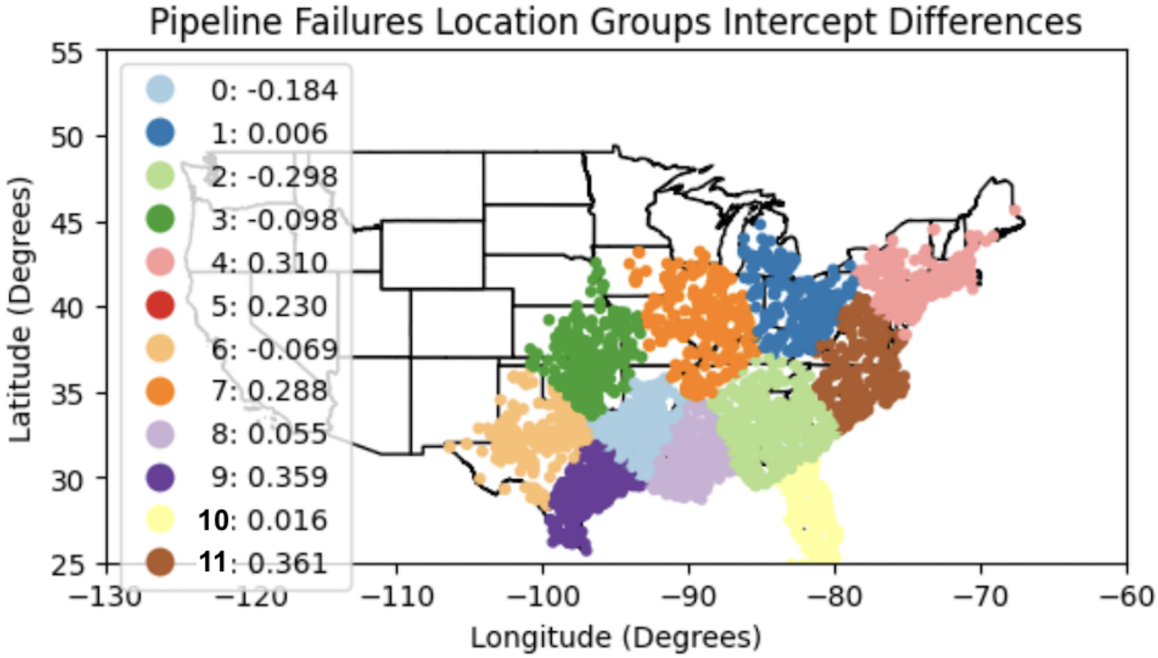

Figure 3: Difference in intercept of random effect of location of null and full model

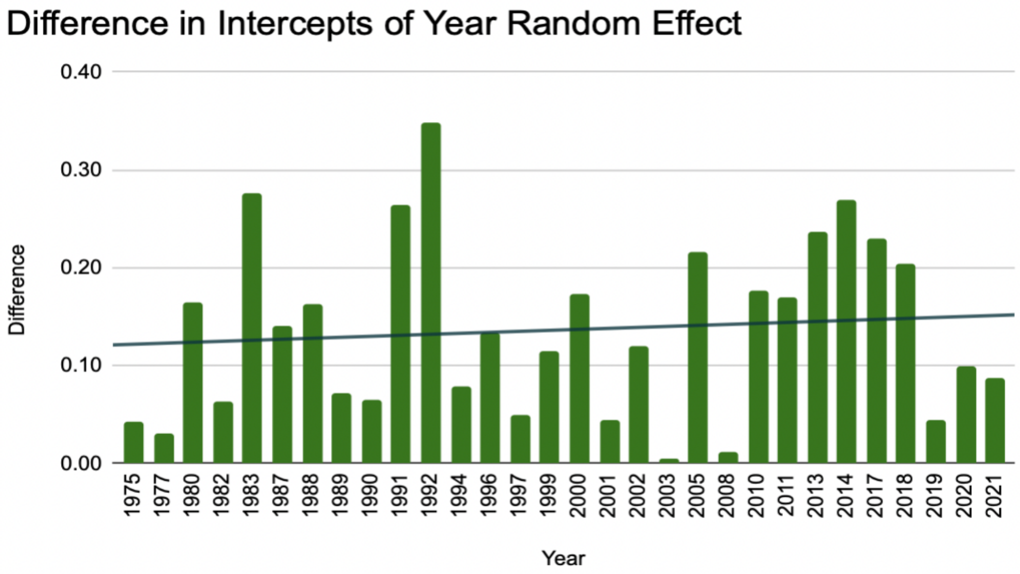

Figure 4: Years with positive difference in intercept of random effect of year of null and full model

Both windspeed and pressure were strong predictors of TC-associated failure frequency, yielding statistically significant coefficients in the zero-inflated Poisson regression (Table 1). According to the model, an increase in TC windspeed of 5 ms^{-1} associated with an 2.51 increase in fs , and a decrease in pressure of 10mBar is associated with an 2.13 increase fs . These results strongly suggest that an increase in TC intensity increases the likelihood of damage to pipeline infrastructure.

To evaluate spatiotemporal variance in the relationship between hurricane intensity and TC-associated frequency of pipeline failures (fs), two models were evaluated. In the null model, we see that 43% of total variance in TC-associated failure frequency (fs) is associated with the location group, and 66% is associated with year. In physical terms, that means that the difference in average fs per location group explains the majority of the variance in the dataset: some locations have more failures than others. Local variability in fs would be based on a number of factors, including age of pipeline, maintenance and operation, exposure to outside forcings including (but not limited to) TCs, and (perhaps most importantly) the total length of pipeline within the geographic region. A positive difference in intercepts from the null and full models indicate the factors that are better explained by the addition of hurricane parameters. For the random effect of location, difference in intercepts of the null and full model indicate the areas that were determined to be the most susceptible to TC induced failures, as seen in Figure 5. The highest positive intercepts were observed in locations eleven, nine, four, and seven. This demonstrates that fs were on average higher along the Gulf Coast, coastal Florida, and the Mid-Atlantic than in other locations. For the random effect of year, difference in intercepts of the null and full model indicate the years that were determined to be associated with the most TC induced failures, as seen in Figure 3. Variance in fs associated with year encapsulates all the interannual variability in fs, associated with changing reporting practices, policies, aging pipeline, and any source of non-stationarity in the frequency and intensity of outside forcings such as natural disasters. The top five highest fs year intercepts were 1977, 2017, 2005, 1983, and 1979 (Figure 4). The years with the highest positive intercepts occurred later in the study period reinforcing the observed trends of increasing failure frequency over time.

The outputs of these models provide detailed information for analyzing the spatiotemporal variability in fs response to hurricane parameters. The first model is the null model that only identifies the impact that the random effects have on predicting the frequency of failure. The second model utilizes both fixed and random effects. Through comparing how the random intercepts have shifted between the null and full model, there is evidence that indicates the local influence that hurricane parameters have on predicting the frequency of pipeline failures. Adding hurricane parameters as a fixed effect explains 33% of the total variance in fs, including 57% of the interannual variance, 35% of the local variance, and 2% of the random variance.

The summary outputs of the null and the trained model provided the AIC values of 1327.6 and 1287.2, respectively resulting in a delta AIC of 40.4. This is a strong indicator that the trained model evaluating the effect of hurricane parameters on fs, provides more understanding for how pipeline failures sensitivity to TCs are changing spatiotemporally.

3.4 Estimate past and future change in TC failure frequency associated with climate change

The trends identified in the NOAA HURDAT2 Dataset analysis highlight the change in TC intensity with respect to climate change. These trends can then be quantified and applied to the trained model to estimate the past and future trends in failure frequency observed in the

Failure Dataset. The trends of minimum annual hurricane wind speed, and pressure highlighted that in 1975 the annual averages were 110.12 ms^{-1} and 951.31 mBar, and assuming future linear increases are predicted to be 154.48 ms^{-1}, 901.95 mBar in 2050, respectively. These values were standardized and used to obtain estimates of failure frequency for 1975 and 2050. Through the predict function with the trained model, the expected average failure count per region per-TC in 1975 is 0.12 failures. The present failure prediction is 1.8 failures per region per-TC, with a projected failure average increase of 2.31 failure per region per-TC in 2050.

4. Discussion

4.1 Pipeline characteristics and the failures associated with TCs

The PHMSA failure reporting is extensive in documenting the thousands of failures that have occurred since 1970. There is an observed increasing frequency of failures across all cause categories since then showing the growing vulnerability of this infrastructure system. These failures have been increasing in frequency with no indication of a significant decrease anytime soon. The PHMSA Failure Dataset highlights an increase of failure reporting in 2002, which is when reporting criteria changed to include “natural disasters” as a causal category. This change in criteria was made in hope to positively impact the accuracy of failure reporting and collect sufficient data for this infrastructure when the failure occurs. It is clear that HMPs can fail for various reasons, but the presence of TCs intersecting with large portions of the pipeline network infrastructure shows a significant increase in failure frequency (Serkan Girgin and Krausmann 2015; S. Girgin and Krausmann 2016). TCs introduce complex forcings on pipeline infrastructure, including storm surges, inland flooding, landslides, high winds, and inland tornados and convective cells (Ricci, Casson Moreno, and Cozzani 2021). This is an increased area of concern. The analysis of the pipeline failures that have been attributed to TC forcings demonstrates the importance of consideration for this threat to the hazardous liquid pipeline infrastructure and the protection of the environment, both now and in the future.

Previous analyses of pipeline failure have focused on the “cause of failure” variable in the PHMSA Dataset. The cause category of natural force damage failures described as naturally occurring events such as earthquakes, flooding, extreme temperatures, lightning, and hurricanes, was not implemented until 2002. From the PHMSA Failure Dataset, 6% of failures are attributed to natural force damage, while our analysis identifies 32.47% of failures intersecting with TC forcings. The distribution of natural force damage failures is not as large as other cause categories; however, the low-probability high-impact nature of these occurrences motivates the need for more analysis. Not all TC-associated failures have the cause category of natural force damage associated with them. The difference in the percentage of failures TC-associated failures as being associated with TC forcings raises the question of the potential for underreporting of pipeline failures that are caused by TCs. One of those reasons is that there can be multiple causes of pipeline failures and the current reporting only allows for the identification of one. Failures are multidimensional and should be treated as such. Another avenue to explore to explain the underreporting of these failures is the potential for biased reporting of pipeline failures by operators leading to the misrepresentation of the primary cause of failure. This presents an opportunity for discussion about a better way of documenting and determining the primary cause of a pipeline failure. Also considering the vulnerability of the infrastructure that is weakened by consistent interaction with TC tracks, there is an obvious need to better understand in the long-term how TC forcings are contributing to pipeline failures, among other causes.

Taking into consideration the spatial distribution of the reported failures, there are geographical areas along the Gulf Coast and the Eastern Coast where the probability of TC-associated failures is much higher, likely due to the density of the pipeline network and the exposure to coastal storm surges and high-intensity TCs. These failures are occurring near large bodies of water, highly populated regions, and vital water sources. Uncontrolled releases of hazardous materials can be detrimental to the environment and public health, and these impacts are compounded when releases occur into surface water or aquifers. Contaminated water sources can also lead to an increased need for recovery and disinfection practices that can be even more difficult to circumvent when the frequency of failure is increasing and the prediction of these failures is still developing (Restrepo, Simonoff, and Zimmerman 2009; Serkan Girgin and Krausmann 2015).

4.2 Hurricane characteristics and trends estimating changing intensity of TCs associated with climate change

TCs are expected to increase in intensity in the near future for various reasons, the primary cause being climate change (Knutson et al. 2019). These predictions were validated through the analysis of the hurricanes documented in the NOAA HURDAT2 Dataset. Historic trends in the annual average of minimum latitude, maximum longitude, maximum windspeed, and minimum pressure provide some insight into how future trends. For this analysis, they provided the basis for a more detailed analysis of the impact of hurricane intensity on the frequency of pipeline failures. Identifying the relationship between hurricane intensity and pipeline failures leads to the prediction that with future hurricane predictions, there is subsequently expected to be an increase in pipeline failures. Though a necessary simplification in the absence of better predictions, assuming stable linear trends in intensification of hurricane parameters into the 21st century is highly problematic, as anthropogenic global warming is associated with complex changes in hurricane formation processes which imply non-linearity in system response (Wang and Lee 2007; Vecchi et al. 2021).

4.3 Failure data analysis to quantify relationship between storm intensity and frequency of HMP failures

We identified a significant number of recorded failures that are associated with TCs. Hurricane intensity (windspeed and pressure) show a significant association with increased local TC-level failure frequency (fs). Close analysis of random effects for location and year elucidates locations with increased failure vulnerability (higher intercepts on fs, which decreased with inclusion of hurricane parameters), as well as generally increasing trends in annual fs over time. There are some years that are associated with a higher frequency of failures that can be referenced to significantly higher TC forcings at that time.

The TCs that were reported to be the most catastrophic to the pipeline infrastructure were found to be hurricane Claudette in 1979, Harvey in 2017, Rita in 2005, Bob in 1979 and Frederic in 1979. These TCs intersected with locations four, nine, and five, where the the majority of failures and subsequent impacts were observed, both in the PMHSA failure database and in news media. During these years there have been heavily documented reports noting that these particular TC forcings have been detrimental to the pipeline infrastructure and the surrounding environment (G. Qin et al. 2020).

Random intercepts on location also indicate regions where HMPs appear more sensitive to TC forcings, specifically the Gulf Coast and Eastern Coast. As TC intensity increases, areas along the Gulf Coast that are intersecting with large portions of the pipeline infrastructure will continue to be more vulnerable. These findings are consistent with current literature that highlights the increasing vulnerability of pipeline failures as the infrastructure continues to age (Lam and Zhou 2016).

4.4 Estimate past and future change in TC failure frequency associated with climate change

Based on the predictions, pipeline failure frequency per TC is expected to increase significantly. This is reflective of the current prediction for increasing hurricane intensity affecting an aging infrastructure. The increase in failures that are expected by 2050 provide basis for a continuing discussion of improving monitoring and maintenance practices for pipeline infrastructure to mitigate the potential negative environmental impacts.

The present limitations of this study involved specific information about the pipeline infrastructure in the United States. The data available on public databases provide limited information about the location and age of the pipeline infrastructure. Quantifying the length of HMPs for each of the locations identified in this study would provide more information about the areas that are most susceptible to failures due to TC forcings. Future directions of this study would involve including the installation year variable of the HMPs as a random effect of the model for additional information about how the HMPs are becoming more vulnerable as they age.

5. Conclusion

Pipeline failures are growing more frequent for various reasons. One of these reasons is tropical cyclones, and the increasing intensity of these tropical cyclones due to climate change. Using the NOAA HURDAT2 Dataset to identify tropical cyclone associated pipeline failures, we see that recent exposure to TCs increases the likelihood of pipeline failure. This is particularly true for pipeline infrastructure located along the Gulf Coast region and in the Mid-Atlantic United States. Through utilizing the data directly related to pipeline failures and hurricanes, the results of this study echo previous conclusions that the true magnitude of TC-mediated pipeline failures are underreported. In addition to observing increased likelihood of failure in the aftermath of TC, we identify a strong, significant relationship between TC intensity and local TC-level failure frequency. We observe significant historical trends in hurricane intensity parameters included in the HURDAT2 database, which are associated with a marked increase in the local TC-level failure frequency. The results of this study confirm that increasing tropical cyclone intensity are associated with an increased pipeline failure frequency, creating an avenue for future predictions and research. This analysis suggests that 1) hurricane failures are likely underreported; 2) hurricane intensity is increasing over time; and 3) local TC-level pipeline failure frequency is related to hurricane intensity and increasing over time. Previous work to predict pipeline failures, and specifically NaTech events, have been limited by course causal attribution in the PHMSA dataset. Understanding the vulnerability of existing pipeline infrastructure is critical to improve the regulation, inspection, maintenance, and design standards in regions of the United States that are frequently exposed to tropical cyclones, where some of the densest pipeline infrastructure occurs. This analysis leverages spatiotemporal association between tropical cyclones and hurricane failures, due to data limitations, not empirically validated causal association. The primary findings of this study underscore the need for better failure-reporting criteria for natural hazard associated events, which is reflective of the reports from the current research that suggest that tropical cyclone associated pipeline failures are underreported. This analysis focuses on utilizing non-stationary TC characteristics to predict the frequency of pipeline failures due to hurricanes providing the basis to estimate how pipeline failures can potentially change as climate change progresses, allowing for quantitative exploration of more about the relationship between pipeline failures and hurricanes, including a preliminary identification of the most TC sensitive pipeline regions. The utilization of these characteristics were verified through the analysis of various mixed effect models and the results used to better understand the resilience of this infrastructure and enact better plans for future inspection and monitoring.

The results of this analysis suggest that TC associated pipeline failures will continue to become more prevalent in the future. Hazardous material pipeline failures are dangerous, damaging, and expensive events, associated with a myriad of complex forcings. However, with more precise prediction and modeling of these failures and the subsequent improved maintenance and monitoring practices, there is confidence that the potential impact of these failures can be mitigated and the negative impacts on the environment reduced.

6. Supplemental

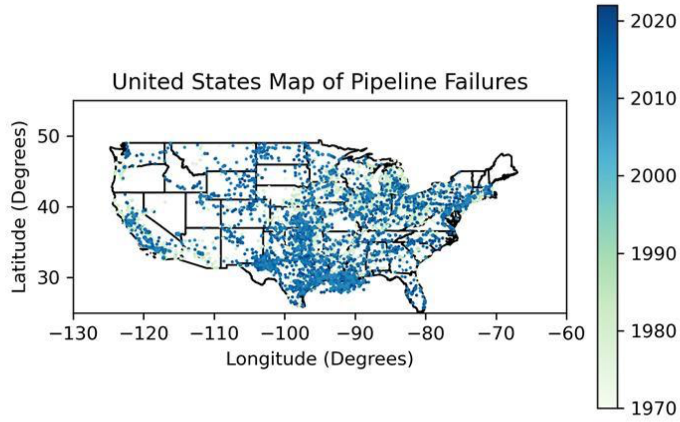

Figure 1: PHMSA Failure Dataset map of all pipeline failures delineated by year

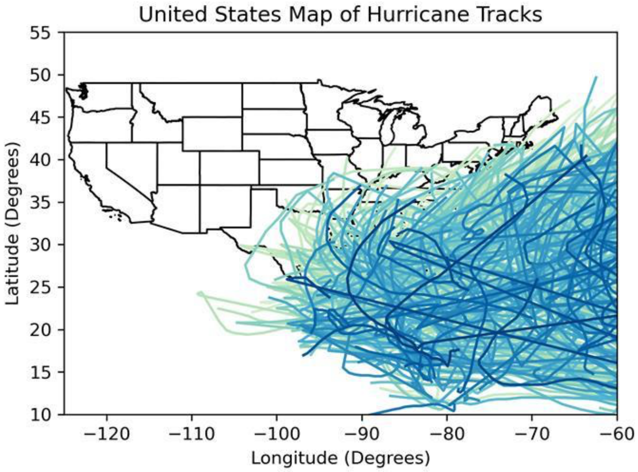

Figure 2: Map of NOAA HURDAT Dataset hurricane tracks

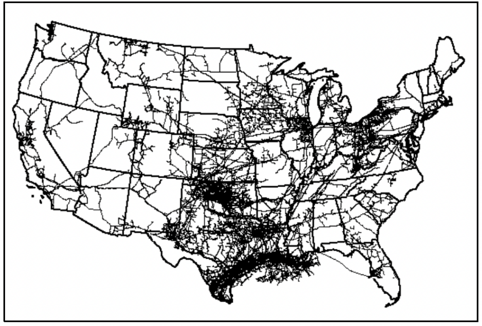

Figure 1: Major Pipelines in the Continental United States

Source: Energy Information Administration

Figure 3: Map of major pipelines in the continental United States

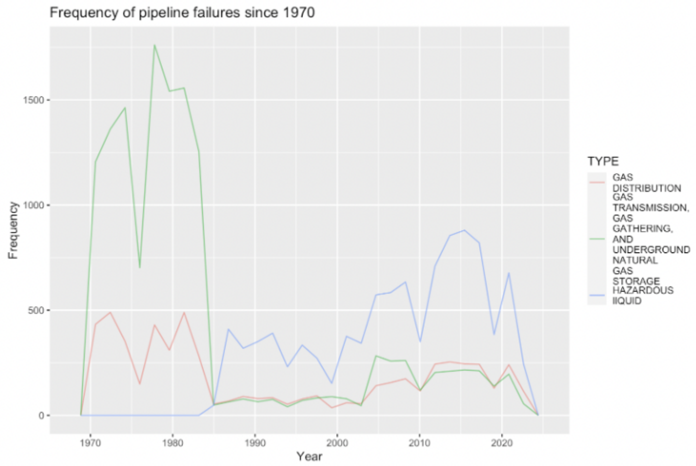

Figure 4: Frequency of pipeline failures since 1970

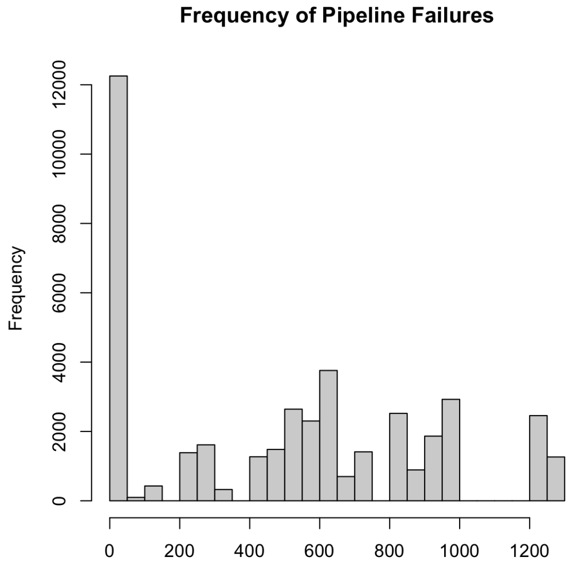

Figure 5: Histogram of frequency of pipeline failures grouped by year and name of the storm when associated

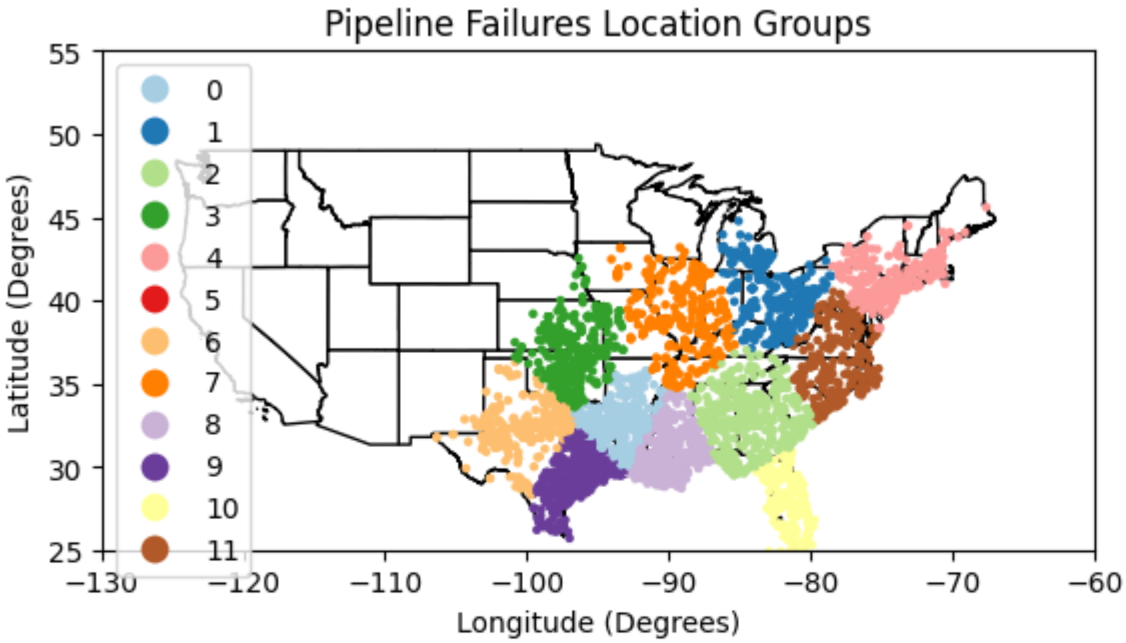

Figure 6: Map of location factor groupings used in analysis

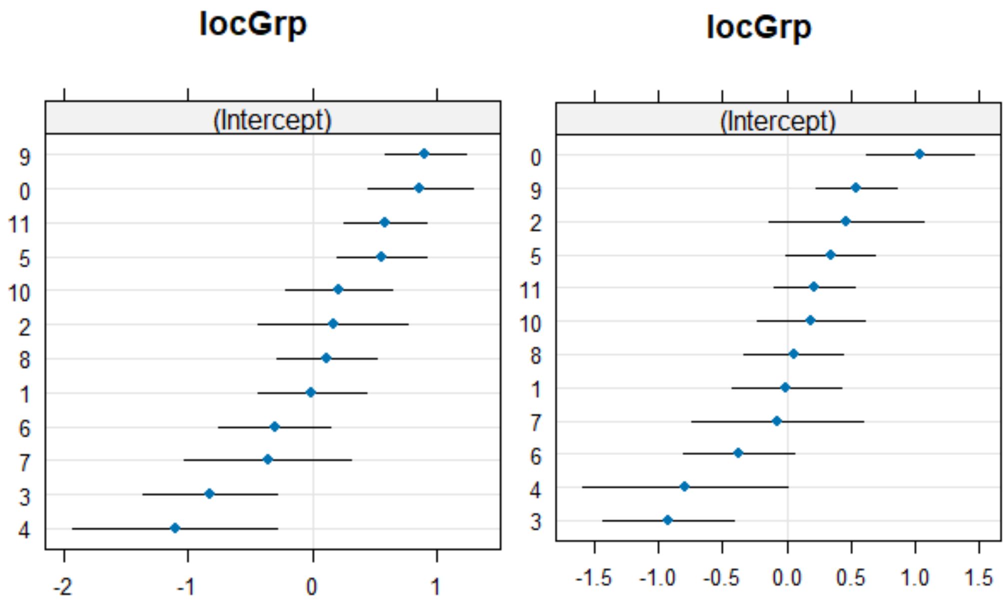

Figure 7: Random intercept from null model (left) and full model (right) on location.

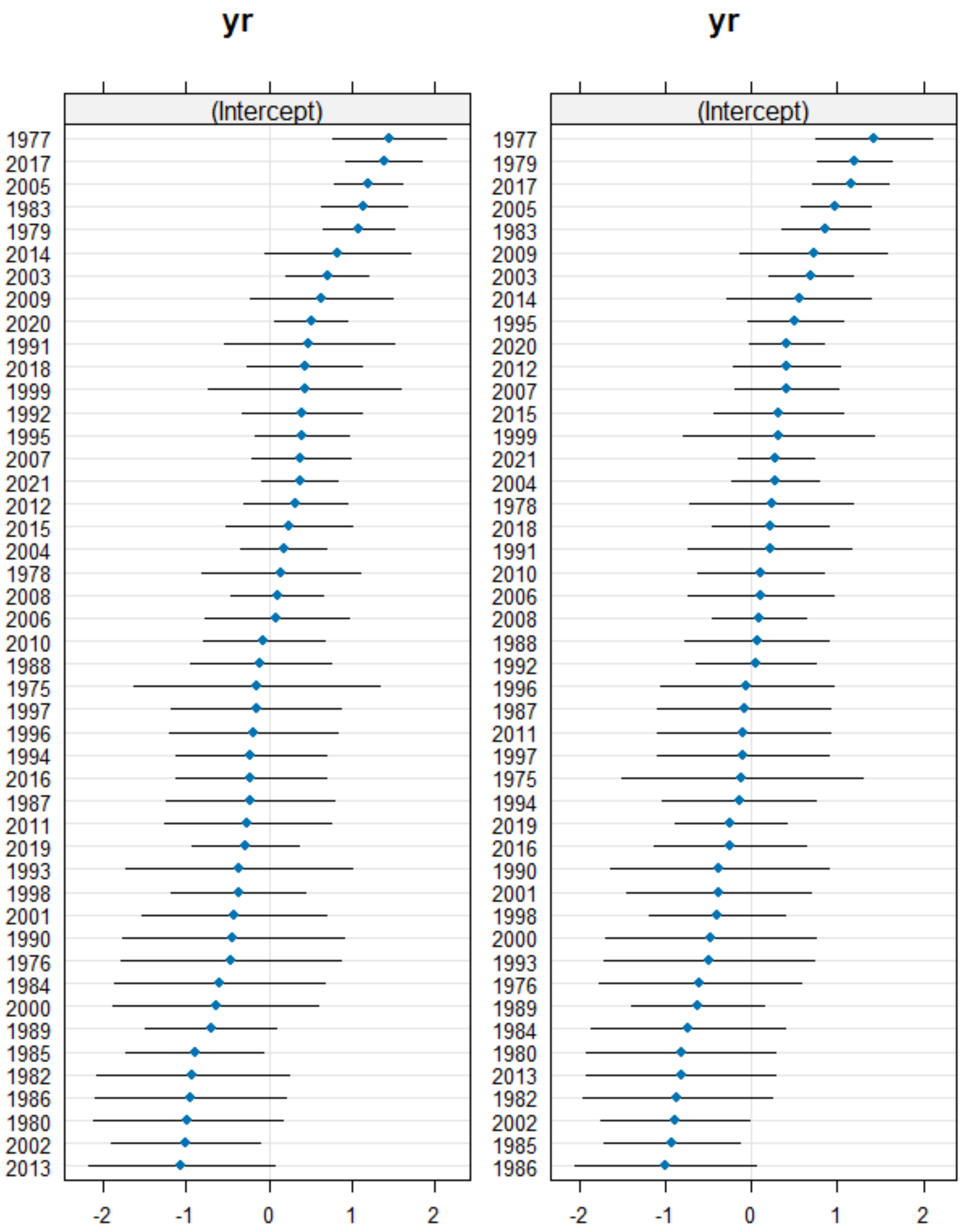

Figure 8: Random intercept from null model (left) and full model (right) on year.

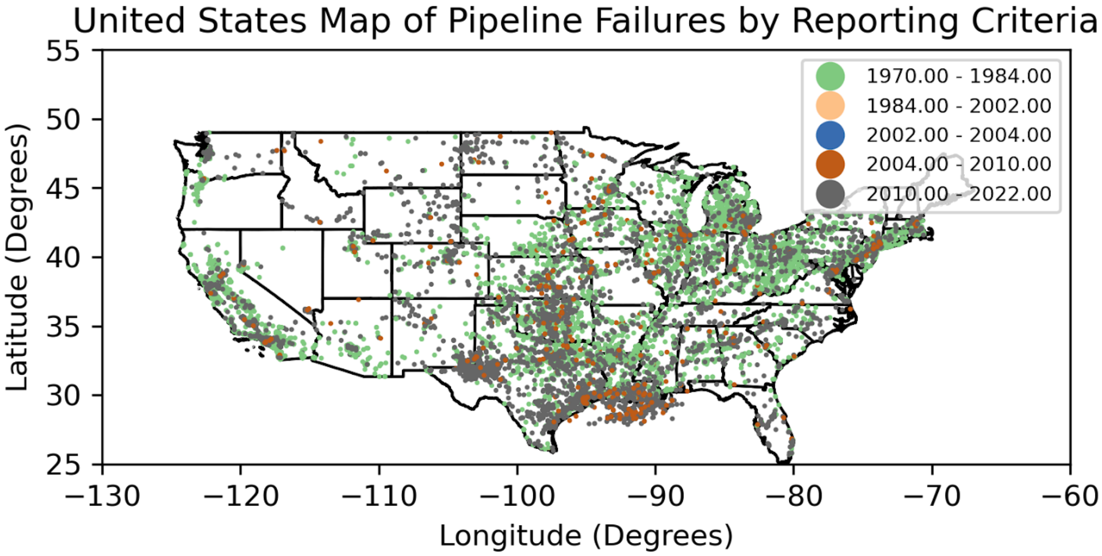

Figure 9: United States map of pipeline failures by reporting criteria

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Hurricane Database (HURDAT2) 1851-2018 (5.9MB Download) This Dataset Was Provided on 10 May 2019 to Include the 2018 Update to the Best Tracks. This Dataset (known as Atlantic HURDAT2) Has a Comma-Delimited, Text Format with Six-Hourly Information on the Location, Maximum Winds, Central Pressure, and (beginning in 2004) Size of All Known Tropical Cyclones and Subtropical Cyclones. The Original HURDAT Database Has Been Retired. Detailed Information Regarding the Atlantic Hurricane Database Re-Analysis Project Is Available from the Hurricane Research Division. Ref //www.nhc.noaa.gov/data/ #https://www.nhc.noaa.gov/data/hurdat/hurdat2-Format-Atlantic.pdf # HURDAT2 Processor This Is a Python Script That Convert Your HURDAT to a Dataframe and Generate a CSV File for You to Eaily Process This Data. This Work Is Part of Trajectory Segmentation research[1]. We Use This Dataset for Evaluation Purposes. If You Are Going to Apply This Script Please Cite to Our Work. Thanks. [1]: Etemad, Mohammad, et Al. "A Trajectory Segmentation Algorithm Based on Interpolation-Based Change Detection Strategies." EDBT/ICDT Workshops. 2019. Github. Accessed May 8, 2023. https://github.com/metemaad/HURDAT2_processor.

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MARILYN R. SMITH

(832) 317-1412 * ms3654@cornell.edu

EDUCATION

CORNELL UNIVERSITY, Ithaca, NY
Doctor of Philosophy in Environmental Engineering, May 2028 [anticipated]

SYRACUSE UNIVERSITY, Syracuse, NY
Master of Science in Environmental Engineering, May 2023

UNIVERSITY OF OKLAHOMA, Norman, OK
Bachelor of Science in Chemical Engineering, May 2021

- STUDY ABROAD, Arezzo, Italy, *June 2017*
- STUDY ABROAD, Puebla, Mexico, *June 2018*

FELLOWSHIPS AND AWARDS

- Cornell University Colman Fellow
- GEM Fellowship PhD – Cornell University
- GEM Fellowship Masters – Syracuse University
- Global Sustainability Scholar Fellowship
- Phillips 66 Research Fellowship
- Presidents Community Scholars Award
- Girl Scout Gold Award
- Most Involved Freshmen Engineer
- Dr. Wayne Jones Fulfilling Legacy Award

RESEARCH EXPERIENCE

ARGONNE NATIONAL LABORATOY – DECISION AND INFRASTRUCTURE SCIENCES, Lemont, IL
Graduate Research Fellow, May 2023 – August 2023

- Conducted a study to assess the performance of the SensiFlood environmental monitoring system by Envigia in indoor and outdoor conditions, under simulated and actual operational environments.
- Independently conducted planning, testing, performance demonstration, and documentation of the SensiFlood performance assessment research project.
- Participated in various meetings and thinking sessions about current research projects at Argonne.

GLOBAL SUSTAINABILITY SCHOLAR – Helmholtz Institute for Functional and Marine Biodiversity HIFMB, Oldenburg, Germany
Research Fellow, May 2022 – August 2022

- Selected to participate in the NSF funded Global Sustainability Scholar program through the University of Colorado – Boulder, through this program I engaged in work with the Belmont funded MARISCO project.
- Developed a Qualtrics survey to build knowledge of Natures Contributions to People (NCPs) derived from the Wadden Sea, in Germany with goals to link social science knowledge of values derived from the environment with ecological data of biodiversity and climate change.
- Delivered presentations detailing the impacts of climate change on biodiversity and the goals of the survey results to PIs at HIFMB and program funders.

SYRACUSE UNIVERSITY, Syracuse, NY

Graduate Student Researcher, August 2021 – Present

- Working under the advisement of Dr. Carter to develop a probabilistic hazard map to be used to calculate the failure rate of pipelines due to natural disasters and improve reconnaissance efforts.
- Utilize available data from PHMSA and NOAAHURDAT to perform data analysis using various programming techniques

UNIVERSITY OF OKLAHOMA, Norman, OK

Research Assistant, August 2020 – May 2021

- Assisted Dr. Bui in the lab to innovate new technologies for sustainable separations with systems-level assessments with hopes to transform the future water, energy, and environmental landscapes
- Conducted literature research to understand pyrolysis and how it is used in synthesizing carbon materials
- Designed tube furnace pyrolysis system detailing materials needed and performed necessary steps to submit items to be purchased

INTERNSHIP EXPERIENCE

SYRACUSE UNIVERSITY – Office of Diversity of Inclusion, Syracuse, NY

Office Coordinator, October 2021 – May 2022

- Demonstrated an appreciation and sensitivity to the needs of Black and/or within the African Diaspora students and the full spectrum of equity, diversity, accessibility, and inclusion elements
- Identified opportunities for community collaboration that can be presented to students for implementation
- Assisted in providing support services/resources for undergraduate and graduate students who frequent 119 Euclid Ave while also serving as a brand steward for the office's work and initiatives

UPSTATE FRESHWATER INSTITUTE, Syracuse, NY

Laboratory Analyst, June 2021 – October 2021

- Participated in receiving, processing, and running analyst for the New York State CSLAP program
- Expanded knowledge of Standard Methods, EPA methods, ASTM methods, and various other published methods necessary for in lab analysis using this knowledge to prepare and maintain an SOP for each analysis and analyze samples in conformance with the specific analytical SOP and any supporting SOPs for each test
- Efficiently improved various office systems with the goal to foster a more efficient work environment

CVR ENERGY INC., Wynnewood, OK

Process Engineering Intern, June 2020 – August 2020

- Preformed extensive evaluation on the Alky cooling tower to make recommendations to improve operating efficiency
- Constructed VBA code to automatically update large excel documents to be implemented throughout the office
- Designed PRO II simulation to model possible operating conditions of the BenFree splitter tower

HALLIBURTON, Houston, TX

Sperry Drilling Engineering Intern, May 2019 – August 2019

- Obtained hands-on field experience assembling tools, performing drilling surveys, and assisting field engineers on various jobs
- Granted opportunities to become well versed in drilling, company, and industry policies and procedures
- Engaged in the office learning about various department goals and performing reports based on my learned knowledge

HALLIBURTON, El Reno, OK

Production Enhancement/ Cement Engineering Intern, May 2018 – August 2018

- Innovatively developed various methods for continuous improvement for each product service line based on field observations
- Worked in the lab with scientists to assist in performing testing on performance gels and cement samples

LEADERSHIP

LOUIS STOKES ALLIANCE FOR MINORITY PARTICIPATION

Graduate Student Coordinator, September 2022 – Present

- Responsible for coordinating all aspects of the academic year Undergraduate Research Program such as recruiting and selecting participants, and planning workshops, program materials, and community-building activities
- Counsel and mentor undergraduate students in their undergraduate research, graduate school aspirations, and life
- Plan annual LSAMP research symposium and manage the LSAMP research program database

SYRACUSE UNIVERSITY – Center for Learning and Student Success, Syracuse, NY

Academic Coach, October 2021 – Present

- Provides and facilitates academic support through academic coaching to help students become expert learners
- Meets one-on-one with students to help them understand effective study strategies for their courses.
- Continuously developing skills of ethics, integrity, commitment to diversity and inclusion, critical and creative thinking, scientific inquiry and research skills, and communication skills

SYRACUSE UNIVERSITY – Office of Diversity of Inclusion, Syracuse, NY

Office Coordinator, October 2021 – May 2022

- Demonstrates an appreciation and sensitivity to the needs of Black and/or within the African Diaspora students and the full spectrum of equity, diversity, accessibility, and inclusion elements.
- Identify opportunities for community collaboration that can be presented to students for implementation.
- Assist in providing support services/resources for undergraduate and graduate students who frequent 119 Euclid Ave while also serving as a brand steward for the office's work and initiatives

GALLOGLY COLLEGE OF ENGINEERING

Teaching Assistant, July 2020 – May 2021

- Assisted Dr. Walden in developing and distributing course materials and ensuring timely grading and reviewing
- Served as a resource to students providing insight on improving their writing assignments and engineering goals

NATIONAL SOCIETY OF BLACK ENGINEERS

OU NSBE Secretary, July 2020 – May 2021

- OU NSBE Secretary (July 2020 – May 2021): Collated reports, managed correspondents and progress for the chapter while exuding excellent communication and organization skills
- Region V Regional Parliamentarian (March 2019 – June 2020): Provided guidance to chapter parliamentarians and enforced Roberts Rules of Order during meetings and voting; Implemented initiative that was able to increase senator voting participation at Regional and National Conferences
- Region V Regional Leadership Chair (March 2018 – June 2019): Planned and executed the Regional Leadership Conference with a goal set and exceeded to increase attendance; Organized the Fellowship Initiative Mentor Program geared to increase member interest in higher leadership
- OU NSBE Conference Planning Chair (May 2018 – May 2019): Capably coordinated chapter logistics to attend Regional and National conferences whilst remaining under budget
- OU NSBE Public Relation Chair (May 2017 – May 2018): Innovatively rebranded the chapter's public outlook and increased site interaction and overall membership by 25%

ALPHA KAPPA ALPHA SORORITY, INC., KAPPA PSI CHAPTER

Member, April 2019 – Present

- Organize community service events geared towards the national targets on and off campus
- Served on the global impact committee with the purpose to enhance the international footprint of the sorority through community service initiatives and partnerships

SOONER ENGINEERING EDUCATION AMBASSADOR

Team Leader, August 2019 – May 2021

- Developed and presented programming materials to encourage kids K-12 to become interested and educated on pursuing a career in engineering
- Assisted in giving tours of the College of Engineering to prospective students

TECHNICAL/ NON-TECHNICAL SKILLS

- Proficient in Microsoft Office
- ASPEN Plus Process Simulation Software
- Python, R, Html, Java, VBA
- Conversational in Spanish
- Risk Assessment and Toxicology Reporting
- ARC GIS Pro