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Review

Climate Change Impacts on Coastal and Offshore Petroleum Infrastructure and the Associated Oil Spill Risk: A Review

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Abstract: Climate change has been observed worldwide in recent decades, posing challenges to the coastal and offshore oil and gas infrastructure. It is crucial to identify how climate change affects these infrastructures and the associated oil spill risk. This paper provides an analysis of the vulnerability of coastal and offshore oil and gas infrastructure in response to climate change. The paper examines oil spill incidents worldwide and addresses climate change's possible influences on oil spill risk. Moreover, available oil spill modeling and decision support tools for oil spill response are reviewed considering climate change. The paper signals the need for emerging decision and modeling tools considering climate change effects, which can help decision-makers to evaluate the risk on time and provide early warnings to adapt or prevent the unforeseen impacts on the oil industry partially resulting from global warming, including oil spill accidents.

Keywords: climate change; coastal and offshore region; oil and gas infrastructure; oil spill

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1. Introduction

The industrial revolution and anthropogenic activities are the significant drivers of many changes in the atmosphere, ocean, and biosphere, leading to climate change [1]. In 2020, the oil sector contributed approximately 12.23 billion tons of CO_2 emissions worldwide [2,3]. However, a few studies highlight that the oil and gas sector is vulnerable to climate change, especially near coastal and offshore regions [4–8]. One of the significant impacts is damage to these infrastructures that can cause the spillage and release of oil and other hazardous contaminants, thus causing health and environmental risks [4].

Most of the extensive oil and gas facilities globally (e.g., Saudi Arabia, Jamnagar, Ras Tanura, and the Niger Delta) are in coastal areas [5]. Globally, approximately 30% of oil production and 27% of gas production have been offshore since the 2000s [6]. These facilities are exposed to climate changes such as extreme weather events, sea-level rise, and increasing storm activities [5]. Changing temperature may lead to water scarcity issues in the region and disturb industrial activities such as water-cooling requirements for refineries and energy production [7]. Extreme weather can directly cause unprecedented damage to the infrastructure and could increase the costs of construction, maintenance, and operation [8].

This paper explores the trends of the main climate changes that affect the coastal and offshore petroleum infrastructures and their influences on these infrastructures. It critically examines the major climate change drivers and their potential impacts on oil spill risks by investigating these occurrences. The article also discusses the options for oil spill decision support tools and risk assessment modeling when confronting the climate change impacts.

2. Climate Change Tendency

Climate change is demonstrated to increase infrastructure vulnerability in coastal and offshore infrastructure [5,7]. The key climate change drivers in coastal and offshore regions

can be characterized as air and water temperature, precipitation patterns, extreme storm events, and sea-level rise [7]. This section summarizes the global and regional tendency of these key climate change variables that are likely to affect the oil and gas infrastructure and associated oil spill risk.

2.1. Temperature

The average surface temperature in 2020 (combined land and ocean temperature anomaly) globally was 0.98 °C [1]. Compared to 1850–1900, the average global surface temperature increased by 0.85 °C and 1.09 °C in 1995–2014 and 2011–2020, respectively [1]. The global surface temperature trend from 1850 to 2015 shows that although there was a "slowdown" from 1998 to 2013, the global surface temperature is consistently increasing [9]. Human activities are regarded as the primary driver of global warming. The human-induced warming in 2010–2019 was 1.07 °C, while the change caused by natural forcing was only ±0.1 °C [1]. Lots of evidence reveals both the hottest and coldest extreme temperatures have changed in most land areas [10–13]. For instance, in Europe, the number of days with extreme heat increased over three times from 1950 to 2018, and severe cold has decreased by 2–3 days [12]. In Asia, the intensity and frequency of hot extremes have significantly increased, while those of cold extremes have decreased [13]. In North America, the recorded temperature in 2020 was 0.90 °C above the 1910–2000 average (NOAA, 2021).

The changes in land-surface air temperature (LSAT) show a similar tendency. There was spatially coherent warming on a global scale from 1901 to 2014 [10]. Moreover, the linear trends of annual LSAT for the northern hemisphere (0.115 °C/decade) are higher than that for the southern hemisphere (0.088 °C/decade) and the globe (0.104 °C/decade) [10]. Fifteen of the warmest twenty individual years occurred in the 21st century [11]. From 1979 to 2014, the temperature change trends in the high latitudes of the northern hemisphere are significantly higher than in other areas [11]. It was observed that the average global sea surface temperature (SST) rose during the 20th century and continues to increase [12]. From 1901 through 2020, the temperature increased at an average rate of 0.084 °C/decade [13]. As the oceans absorb more heat, SST increases and it influences the ocean circulation patterns, which are responsible for transporting cold and warm water around the globe [13]. The temperature in the polar regions, e.g., the Arctic, has increased at twice the global warming rate, and 2020 was the second warmest year after 2016 [12]. The warming temperature in the polar region impacts the melting of sea ice and thawing of the frozen grounds [12].

2.2. Precipitation and Flood

A consistent interest of the climate community is to explore the variance of global precipitation under climate warming due to its significance and significant social and environmental implications [14]. Adler et al. [15] analyzed trends of global precipitation from 1979 to 2014. The mean ocean and land total precipitations were 2.89 and 2.24 mm/day, respectively. Although the worldwide precipitation value did not show a significant increasing trend during this period, the regional precipitation trends are concluded and show spatial heterogeneousness. From 1950 to 2018, precipitation increased over most of North America, mid-high latitude Eurasia, southeast South America, and northwest Australia. A decrease in precipitation was observed over eastern Australia, most of Africa, the Middle East, the Mediterranean region, and parts of east Asia, central South America, and the Pacific coasts of Canada [16]. Furthermore, the trends of heavy precipitation events also show wide regional and seasonal variations. Since the mid-20th century, the average annual maximum precipitation amount in a day, daily mean precipitation intensities, and the probability of precipitation (>50 mm/day) have increased over the global land region [17,18]. Overland areas have increased the average global precipitation rate by 2.54 mm per decade [14].

The regional observed flood changes are heterogeneous, making it challenging to analyze the global trends. Based on the Global Runoff Data Centre database holding records of 9213 stations, peak flow trends are found consistent at the continental scale, with

increasing trends in parts of Europe and South America, eastern USA, and southern Africa, and decreasing trends in the western USA and Australia [19]. Furthermore, a marked increase in very severe floods since the late 1990s is found in the Amazon [20]. There is no monotonic pattern in Africa for the annual maximum peak discharge. An overall decrease exists before 1980, and an increasing trend appears afterward [21]. In Europe, although existing research cannot provide consistent continental-scale trends in flood discharge, the regional patterns conclude that floods have increased in northwestern Europe and decreased in southern and eastern Europe in the past five decades [22].

2.3. Extreme Storm Events

Extreme storms, including tropical cyclones (TCs), extratropical cyclones (ETCs), and severe convective storms, often have numerous influences on coastal regions [23]. For tropical cyclones, positive tendencies in intensity-related metrics are found on regional scales [24,25]. The increasing tendency of hurricane damage and a decreasing trend in TC translation speed in the United States have been identified, while there has been no trend in the TC frequency since the 1900s [13]. A decreasing tendency of TC landfall frequency has been observed in Australia since the 1970s [26]. In the North Indian Ocean, a similar trend has been identified that the overall TC frequency decreases while the intensity of TCs was enhanced during 1947–2015 [27].

More than 80% of annual precipitation is associated with ETCs in storm track regions in the mid latitude and high latitude [28]. Wang et al. [29] inter-compared ETC activity in nine global reanalysis datasets and concluded that all of them show an increase in the number of deep cyclones (core pressure < 980 hPa) in both hemispheres over the past five decades. On the other hand, trends of severe convective storms, associated with extreme phenomena such as tornadoes, hail, and strong winds, are highly regionally variable. In China, severe weather days (e.g., thunderstorms and hail) decreased by about 50% from 1961 to 2010 [30]. Prein and Holland [31] concluded that the hail hazard showed increasing trends in Australia, Europe, and United States. Additionally, the intensity of short-duration convective events increases over many regions, except in eastern China [13]. Trend analysis of thunderstorms in Europe reveals an increase over the Alps and central, southeastern, and eastern Europe and a slight decrease over parts of southwestern, south-central, and far southeastern Europe since 1979 [32].

2.4. Sea Level Rise

The global mean sea level (GMSL) has risen 7 inches since 1880 because of glaciers melting and thermal expansion by increasing ocean heat content, and in 2020, GMSL was 3.6 inches above the 1993 average [33]. The rising water level rate has accelerated since the 1960s, primarily associated with sea-level changes in the South Atlantic and Indo-Pacific [34]. The rise of global mean sea level increased from 2.2 mm/year in 1993 to 3.3 mm/year in 2014 [35]. Anthropogenic activities accelerate climate change and extreme events such as flooding [33]. Moreover, greenhouse gas emissions may lead to long-term committed sea-level rise by trapping the heat from the sun that is absorbed by oceans, resulting in warming sea surface temperature.

Sea level has been spatially quite variable at regional scales due to additional processes coming into play [36]. For example, variation in sea-level rise has been observed across the Pacific Basin in the last decade as high sea level has been observed in the western Pacific compared to the eastern Pacific. Additionally, sea level trends in the northeast coast of North America are higher than the global rate over the last decades, capped by an extreme and unprecedented sea-level rise event in 2009–2010 [37].

The ice in the polar regions reflects most of the incoming solar radiation to the atmosphere because of the light color of the ice and high albedo [13]. However, due to global warming, the rate of glaciers melting increases, thus aggravating the rise of sea level [35]. On the other hand, the ice and snow melting in the polar regions also decreases the amount of reflected solar radiation while increasing the amount of heat absorbed by oceans and the

land's surface [37]. The added heat further warms the polar regions and accelerates the rate of glaciers melting. Climate change's impact on oil and gas infrastructure situated on coastal and offshores is discussed in the next section.

3. Climate Change Impacts on Coastal and Offshore Petroleum Infrastructures

The impact of climate changes on oil and gas infrastructure in coastal and offshore regions is likely to manifest with an increase in global warming [5,7]. As discussed above, climate changes have intensified during the last decades. Previous studies show that climate changes significantly impact petroleum infrastructures [4,7]. This section summarizes the main climate change factors that affect the coastal and offshore infrastructure, and a summary of their impacts on oil and gas infrastructure is provided in Table 1.

The warmer temperature significantly impacts the integrity of oil and gas extraction and its infrastructures. The thawing of permafrost may decrease the availability of ice-based transportation, the stability of buildings laid upon permafrost, and the load capacity of these structures [38]. Hjort et al. [39] predicted the infrastructure hazard areas in the Northern Hemisphere permafrost regions under projected climate changes by 2050. The results show that around 70% of infrastructure in the permafrost region is located in the area with high risks because of the thaw-related ground instability that may cause severe damage to these buildings. Rapid warming also causes the land-fast ice to form later, break up earlier, and decrease sea ice thickness [40]. In the Arctic region (Beaufort Sea), due to the lack of sea ice, a US oil firm was unable to build the transportation and extraction infrastructure in this area, thereby hindering its plan to establish the first oil drilling operation in the Arctic waters. In Russia, approximately 23% of technical failures because of melting permafrost in 2021 caused hindrance to oil and gas production. Many production activities in oil refineries in Texas, USA, declined by 2.4 million barrels per day due to extreme cold weather observed in 2021 [40]. Furthermore, temperature extremes may contribute to maintenance problems, including roads, rail tracks, and facility buildings, since the extreme temperature may increase the degradation of construction materials [41].

The changes in precipitation patterns and runoff may potentially impact oil refining/processing, oil storage, buildings, and oil transportation. Drought may cause soil shrinkage and the reduction of water availability, which may significantly influence oil and gas pipelines and the drilling, production, and refining processes [42]. On the other hand, the heavy rain and high humidity may cause an unforeseen shutdown of the oil refinery process and the overload of air filters, further damaging downstream equipment. They can also contribute to the weakening of structures and increase the risk of mold presence [8]. The risk of structural damage to pipelines and electrical damage to equipment might also increase [43]. Flooding caused by heavy rain and extreme storm also damages oil refineries and storage tanks and then constitutes a potential trigger for oil and other hazardous contaminant releases [44]. In the Gulf of Mexico, such offshore operations and platforms are vulnerable to tropical cyclones and extreme wave heights [42]. In the Nigeria delta, more than 72% of the hydrocarbon production and such reserves are prone to changing rainfall patterns, flooding, and droughts [43]. The flooding in August 2021 because of Hurricane Ida disrupted Louisiana refineries and oil and gas offshore infrastructure [44].

Sea level rise can significantly impact coastal and offshore oil and gas infrastructure and pipelines through flooding and coastal erosion [8]. At high sea levels, oil and gas platforms are exposed to the risk of damage and disruption, and coastal oil refineries and gas processing plants are vulnerable to shoreline erosion and seawater inundation [45]. According to the data from NOAA tide gauges, the highest sea-level rise trends are found in the region of Louisiana (6.01–9.16 mm/year), Texas (3.54–6.62 mm/year), and the US east coast where the rates are mainly higher than 3 mm/year [38]. Severe flooding in the San Jacinto River, Texas, in 1994 undermined over 29 pipelines at river crossings. Consequently, over 35,000 barrels of petroleum and related products were released into the environment [4]. There are more than 4000 platforms installed on the outer continental shelf in the Gulf of Mexico and the USA west coast, while they are not designed to deal

with sea-level rise. The sea level risk may also pose a significant danger to the coastal facilities, including tank batteries and ports [7]. According to the "Climate Change Science Program" report, 64% of the port facilities in the Gulf of Mexico in 2008 were affected by an increase in sea level by 61 cm [41].

Table 1. Climate change impacts on coastal and offshore petroleum infrastructures.

Climate Changes	Infrastructure	Impacts	Data From
Temperatures	Transportation infrastructure Extraction infrastructure	• Decrease availability of ice-based transportation and stability of buildings laid upon permafrost • Reduce load capacity of structures • Increase degradation of construction materials • Temperature extremes cause maintenance problems and increase the cost	[39–41]
Precipitation patterns	Oil and gas pipeline Oil refinery Storage tank Transportation infrastructure	• Soil shrinkage caused by drought has negative influences on oil and gas pipelines • Heavy rain and high humidity may result in the overload of air filters and further damage downstream equipment • Increase the risk of mold presence and weaken storage structures • Floods can damage roads, bridges, and ports in the coastal region	[7,8,42–44]
Sea level rise	Oil and gas platform Oil refinery Gas processing plant Oil and gas pipeline	• Oil and gas platforms are at risk of damage and disruption • Oil refineries and gas processing plants are vulnerable to shoreline erosion and seawater inundation • Increased degradation of pipelines and infrastructure	[4,7,41,45–47]
Extreme storm	Oil and gas platform Oil and gas pipeline Storage tank Oil refinery Gasoline supply station	• Overturn and damage platforms, drilling rigs, offshore pipelines, and mobile offshore drilling unit • Storm surge flooding can affect storage tanks • Wave height increase can cause wave inundation of decks and erosion and submergence of coastal infrastructure such as oil refineries • Surface damage to coastal infrastructure, e.g., gasoline supply station	[8,41,44,48–51]

Furthermore, Brown et al. [46] assessed the coastal energy infrastructure as potentially at risk in Europe. Results show 158 primary oil, gas, and tanker terminals located in the European coastal zone. In this region, oil and gas infrastructures are potentially at higher risk of sea-level rise. A similar study was conducted by Dismukes and Narra [47] to assess the potential dangers of coastal energy infrastructure from various fixed sea level rise outcomes and scenarios. With an increase in sea level of 1.83 m, more than 37 petroleum refining facilities might be at risk since they are located within the 2 km buffer regions [47]. About 8.9 million barrels per day (MMbpd) refining capacity may be influenced due to the future sea-level rise [47].

As discussed in the previous section, increased storm activities have been observed in many regions. Around 100 tropical disturbances develop over the Atlantic Ocean, 10 of which become tropical storms and 5 become hurricanes each year [48]. Furthermore, future anthropogenic warming will enhance tropical cyclones' wind speed and rainfall [49]. Storms and hurricanes endanger the offshore oil and gas infrastructure. In past studies, examples show extreme storm impacts on coastal and offshore petroleum infrastructure [50–52], as shown in Figure 1. For example, chemical and petrochemical facilities were hit and damaged by Hurricane Harvey in 2017, which released millions of pounds of toxic chemicals and fossil fuels [53]. Taking Hurricanes Katrina and Rita as an example, a damage assessment revealed that they destroyed 113 platforms, severely damaged 19 drilling rigs, and caused 19 mobile offshore drilling units to be adrift [54].

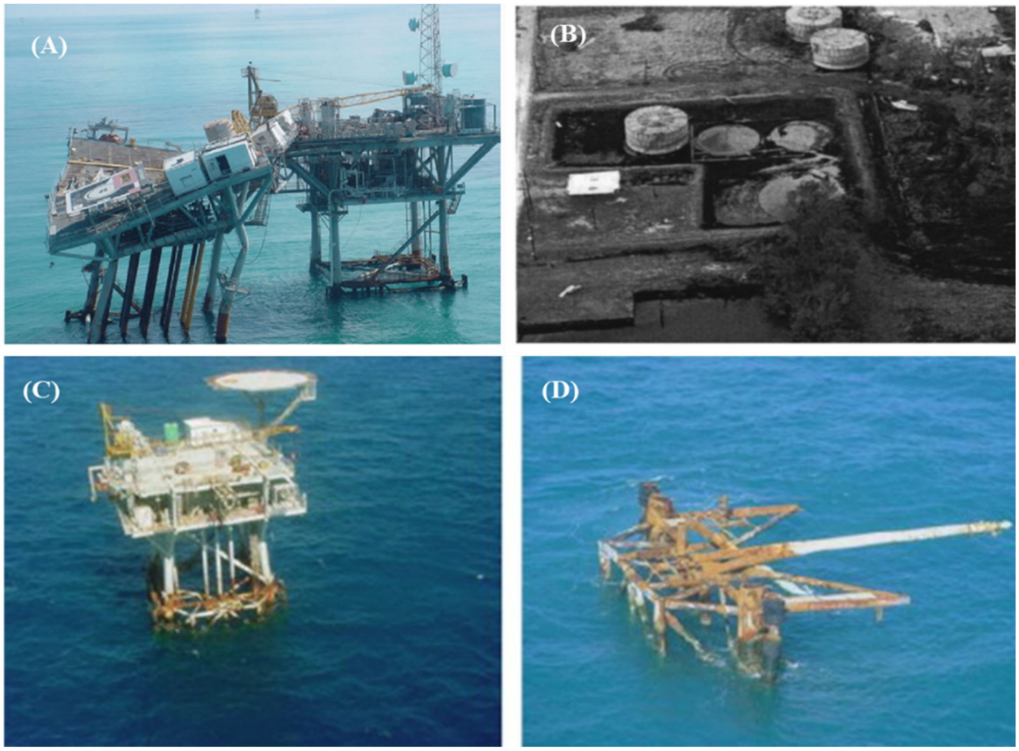

Figure 1. Examples of extreme storm impacts on coastal and offshore petroleum infrastructure: (**A**) offshore platforms were damaged during a hurricane off of Louisiana (reproduced under CC by 4.0 license, credit to Kaiser and Chambers [50]); (**B**) oil tanks were carried away by storm surge that caused over 1,750,000 L of oil release (reprinted with permission from"Alex Glostrum for the Louisiana Bucket Brigade", credit to Godoy [51]); (**C**,**D**) before and after operating platform were destroyed during the 2005 hurricane season (reprinted with permission from Elsevier, credit to Kaiser and Kasprzak [52]).

Additionally, the increase in wave heights accompanying hurricanes and tropical storms also contributes to the erosion and submergence of coastal infrastructure. The potential effects may also include damage to drilling riser, subsea wells, and production structures [7]. Offshore pipelines were also damaged during hurricanes. Statistically, Hurricane Andrew, Ivan, Katrina, and Rita damaged over 1105 pipelines and flowlines [41]. Due to storms, surface damage also occurred to the coastal oil and gas infrastructure. During Hurricane Rita, gasoline supply stations suffered failures, including damage to pumping stations and canopy, which disrupted gasoline supply [55].

4. Oil Spill Risks under the Changing Climate

4.1. Oil Spills Occurrence

The coastal and offshore oil spill incidents in the United States from 1991 to 2021 were collected from the US National Oceanic and Atmospheric Administration (NOAA), as shown in Figure 2. In these three decades, a total of 2182 oil spill incidents happened in the coastal and offshore regions in the USA [7]. There were 380 mystery spills for which the release sources are unknown [7]. Not including the mystery spills, the primary sources include tankers/barges, general shipping, wells/platforms, pipelines, and tanks/facilities. Of the reported incidents, 60.6% come from shipping vessels such as military and fishing vessels, bulk carriers, and pleasure crafts. Pipeline spills are the second most reported source (10.7%), and the others are followed by the order tanks/facilities (10.0%), tankers/barges (9.9%), and wells/platforms (8.8%). Although there were declines in the period 2011–2015, the spill incidents from four sources (i.e., generalships, pipelines, tanks/facilities, and wells/platforms) show an increasing trend in the last three decades. Furthermore, there is a

correlation between oil spills, population density, and the production and use of petroleum. The prominent locations of reported spills include the Gulf of Mexico and the region's nearby big cities (e.g., New York, San Francisco, Houston, and Seattle), which matches the population density and the production, consumption, and shipment of oil [9].

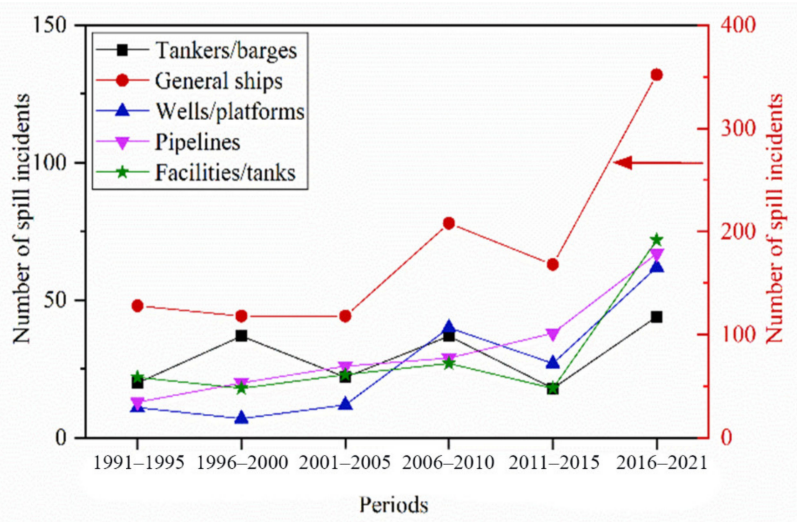

Figure 2. Numbers of reported oil spills in the United States from 1991 to 2021.

4.2. Potential Impacts of Climate Changes

In coastal and offshore regions, oil spills are often caused by accidents involving ships, barges, tankers, pipelines, platforms, and refining and storage facilities [56]. Equipment breaking down and natural disasters, including hurricanes and storm surges, are one of the major causes. As discussed in the previous sections, the intensity of extreme storms has increased. The climate risk that negatively influences the coastal and offshore infrastructure has also intensified.

These changes can cause severe complications and many problems to these infrastructures, increasing the oil spill risks. Sea level rise can increase the probability of erosion, disruption, and damage to oil and gas platforms, refinery industries, and pipelines. The floods accompanied by extreme rainfall events may also cause damage to onshore and offshore pipelines and infrastructures. During the severe flooding in the coastal area of Saga low flatland area, Japan, in 2019, the oil tank in an ironworks factory was flooded and consequently caused the release of over 110,100 L of quenching oil [44]. Compared to 1991–1995, the oil spill incidents from pipelines and wells/platforms increased by 51 and 50 in 2016–2021, respectively [44] (Figure 2).

Furthermore, extreme storms challenge and endanger the oil and gas infrastructure. The damages significantly increase the risks of oil spills to infrastructure [8]. For instance, there were 81 oil spill events in southwest Louisiana due to Hurricane Katrina, and the estimated release would be 22,000 bbls of crude oil [57]. In the two weeks after Hurricane Ida, there were 55 spill events, including a spill near a fragile nature reserve [58]. Furthermore, the impacts of oil spills may also be accentuated due to climate changes. Because of the decrease in ice coverage caused by global warming, oil spills will, in some cases, result in greater area coverage and shoreline exposure [59]. In summary, although the influences of climate changes on the frequency of oil spills are still unclear, climate changes can increase oil spill risks in the coastal and offshore regions. Based on the above discussion on the climate risk and its impact on the oil and gas infrastructure, there is an immense need to develop a decision support system that would optimize the oil spill management while considering the climate change dynamics.

5. Oil Spill Modeling and Decision Support Approach

Oil spill models have been extensively used to simulate the fate and transport of oil spills on a global scale. The results form the basis for evaluating the environmental, economic, and health impacts [60]. All of them are crucial for responding to oil spills, especially considering the impacts of climate change. This is because hydrodynamics, meteorological and environmental conditions influence the spilled oil's transport processes in the coastal and offshore regions. Many oil spill models have been developed and widely applied to forecast the trajectory and fate of oil spills (e.g., CDOG [61], OSCAR [62], and MEDSLIK-II [63]). Keramea et al. [60] summarized 18 oil spill models and concluded that the majority of models are capable of demonstrating the probability that an oil spill may affect a specific area and identifying the most sensitive regions at risk from oiling. These oil spill modeling approaches are applied in practical projects. For instance, the EU project Arctic Climate Change, Economy, and Society (ACCESS) conducted an oil spill trajectory modeling study in the Arctic and found that sea ice is strongly correlated with the fate of oil spills [59]. Moreover, the oil-shoreline interaction is also considered in many models to make response plans and assess environmental impacts. However, most oil spill models have been developed for the marine environment. Only a few models (e.g., COZOIL, OILMAP, and SOCS) focus on predicting the oil transport on shorelines [64].

Decision support approaches have been developed to support coastal and offshore oil spill response [65–68]. Many of them include Geographical Information System (GIS) as a component to create spatial decision support systems [69]. There are some models for oil risk assessment, such as the Fuzzy logic-based model (a quantitative approach) [70], multi-criteria analysis [71], and scenario analysis [72]. Many existing models usually separately consider response operations and spilled oil's transport and weathering processes, but they have significant interactions [68]. Some novel decision support systems are developed to provide more comprehensive support for oil spill response [68,73,74]. For instance, Ye et al. [73] developed a simulation-based multi-agent particle swarm optimization (SA-PSO) approach that integrates oil transport and weathering simulation, cleanup, recovery response simulation, and optimization approaches (as shown in Figure 3). Agent-based modeling (ABM) is first applied for the oil spill response operation and oil weathering simulation, which comprises multiple types of agents and given specific rules for behavior simulation. Particle swarm optimization (PSO) is used to receive the outputs from the ABM section, generate the optimal choices, and then check with the stop criteria. The outputs will be regarded as the final decision when meeting the criteria. Otherwise, they will be sent back to ABM for further iteration. These models have been applied in several cases, while more field validations are expected to further evaluate their performance and reliability in real-world oil spill incidents.

For over two decades, the oil industry mainly focused on mitigation plans regarding greenhouse gas emissions reductions instead of the guidelines for avoiding the damage and losses to the oil sector caused by climate change [73–75]. Katopodis and Sfetsos [8] summarized the most recognized prevention and mitigation measures for climate change damage and losses. The oil extraction methods should review and upgrade design thresholds of offshore structures such as oil platforms and rigs to make them more resilient to storm surges and hurricanes. For the coastal oil refining and storage facilities, safe protection and relocation of crucial components should be applied to reduce the potential damage caused by storms and flash flooding. It is also crucial to conduct the waterproofing of equipment and buildings and adequate emergency response. Moreover, when the oil and gas infrastructures are damaged and/or fail due to climate change impacts, it may result in significant economic losses and interruption of critical services. Therefore, there is a need to improve the resilience of infrastructure, which includes prevention and absorptive capacity to reduce or withstand the impact of perturbation and the ability to recover from disruption [42] rapidly. However, only a few publications focus on resilience and adaptation measures for critical infrastructure in the energy sector, especially the oil and gas

sector, to address climate change impacts [4,76,77]. Therefore, it is recommended to further extend the studies on climate change resilience and recovery.

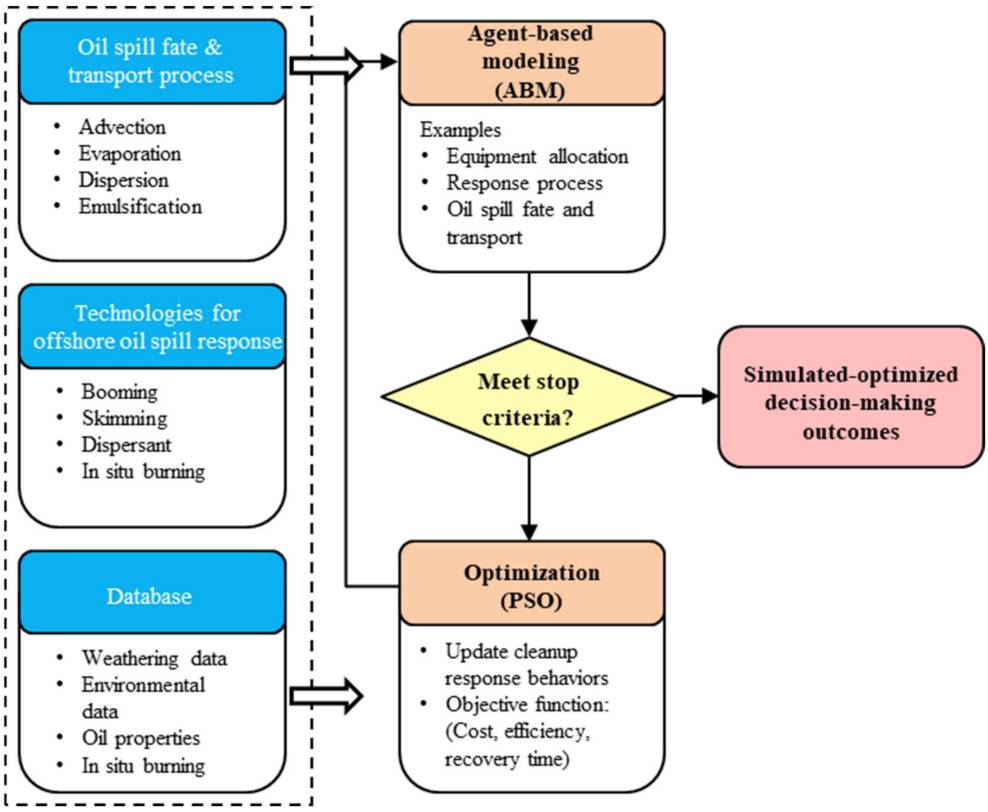

Figure 3. Framework of the simulation-based multi-agent particle swarm optimization (SA-PSO) approach.

Many efforts have been made to mitigate the impact of oil spills [68,78–80] using responsive techniques methods. For instance, the countermeasures or cleanup methods include natural attenuation, physical/mechanical recovery (e.g., booms, skimmers, pressure washers), application of spill treating agents (e.g., oil dispersants, solidifiers, washing agents), in situ burning, and bioremediation [81–85].

6. Research Gaps and Future Perspectives

This study has performed an overview of how climate change affects the coastal and offshore petroleum infrastructure and associated oil spill risks and how to adapt and mitigate the loss and damage caused by climate change. Further research is still required to evaluate the impacts of climate change properly. There are some challenges faced by coastal and offshore oil and gas sectors under climate change as follows:

1. There is a lack of comprehensive risk assessment capable of assessing the risks caused by climate change and accurately identifying and reducing vulnerabilities of oil and gas infrastructure located in coastal and offshore regions [4]. Therefore, to address this challenge, it is highly recommended to develop quantitative risk assessment methods based on data-driven approaches, which consider climate change an important trigger for such oil spill accidents. Furthermore, the risk assessment results should be applied to select the possible prevention and mitigation strategies for achieving the desired safety level.
2. It is crucial to ensure that infrastructure is resilient to climate change. Existing infrastructure should be retrofitted to address the physical impacts of climate change. At the same time, new designs should be prioritized according to improved standards that set out climatic design values. The current designs consider technical and regulatory standards (e.g., building codes) that are assumed to account for climate resilience

considering the climatic exhibits stationarity values (i.e., independent of time) and stationary return levels (i.e., return period of extreme events) [86]. However, forecasted climate changes should also be incorporated in planning phase to strengthen the infrastructure. Moreover, appropriate measures for existing infrastructure will depend strongly on the remaining economic life. It is suggested to further extend the studies on climate change resilience and recovery of existing infrastructures.

3. The overall knowledge of climate change impacts the frequency and amount of oil spills is limited. Additional studies are suggested to collect more data on oil spill incidents, including location, source, spillage amount, and reason. After considering the variations in primary climate factors (e.g., temperature, precipitation, extreme storm, and sea level), their correlation with oil spill occurrence can be identified. By combining comprehensive risk assessments, this work can deliver a concrete understanding of the impact chains of climate changes on the infrastructure, which should account for physical damages and impacts on society and the environment.
4. Most oil spill models have been developed for the marine environment. Only a few models (e.g., COZOIL, OILMAP, and SOCS) focus on predicting the oil transport on shorelines [64]. It is recommended to improve them further and apply them to predict the spilled oil distribution in marine and shoreline environments. Such analysis can be applied to support the oil spill response.
5. Decision support tools play a crucial role in oil spill response operations. However, many existing tools consider response operations and spilled oil's transport and weathering processes separately. Recently, some novel oil spill modeling and risk assessment have proved efficient and regarded as promising methods [68,74,87]. Future decision support tools can be developed by including response optimization considering oil weathering and improving forecast oil spill modeling by integrating multiple modules into an entire system.

7. Conclusions

This study presents the trends of global climate changes, including temperature, precipitation, flood, extreme storm, and sea level. Moreover, the article identifies how these climate change drivers are expected to affect the coastal and offshore oil and gas infrastructures. These impacts have been observed in many regions, including the United States, Europe, and the Arctic region. The reported oil spill incidents in the United States from 1991 to 2021 are also investigated to identify the main sources and the relationship with climate change. Although climate change's impact on the frequency of oil spills is still unclear, climate change can increase oil spill risks in the coastal and offshore regions. The following are the significant points that are concluded from this study:

1. When considering the climate change impacts, mitigation and adaptation options should require upgrading design thresholds of facilities to protect and relocate the crucial infrastructure.
2. It is critical to develop comprehensive risk assessments that can assess the risks caused by climate change and accurately identify and reduce oil and gas infrastructure vulnerabilities in coastal and offshore regions.
3. To minimize the oil spill impacts, decision support tools should integrate the oil transport and weathering model with the response planning and optimizing approach and apply efficient countermeasures for building and conducting the efficient and cost-effective response.
4. Overall, it concludes that climate change represents a serious threat to the coastal and offshore oil and gas infrastructure and contributes to the oil spill risks, which requires appropriate approaches being taken to prevent and mitigate the negative impacts.

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