Spatio-temporal analysis of global marine oil tanker spills over half a century

Naa Sackeyfio
ITOPF
naasackeyfio@itopf.org

Abstract

For the past five decades, ITOPF has reported comprehensively on the temporal trends of oil tanker spills and other industry publications have provided insights based on temporal analysis. Spatial distribution and trends of accidental oil spills from tankers have also been analysed and reported to some extent, mainly focussing on large spills and the major oil spills in history. There, however, remains a paucity of information on the spatial distribution of oil tanker spills globally, particularly for past decades. This is unsurprising considering the uncertainty of location information in some historical reports. The analyses of both spatial and temporal dimensions of historical oil spill data are significant in the assessment of risk for the improvement of safety in marine waters. Today, Automatic Identification Systems (AIS), remote sensing and Geographic Information Systems (GIS) are all being explored to detect spill locations and expand knowledge on oil spills.

This paper provides a global overview of the spatial distribution of accidental marine oil tanker spills of size 7 tonnes and over, based on ITOPF's spills database, and explores spatio-temporal patterns over 50 years using GIS. The main purpose of this study is to produce maps that represent actual spill occurrence and highlight areas of high and low densities as accurately as possible rather than to emphasise on spatial statistics. The results emphasise the dramatic decline in oil tanker spills globally over half a century and show spatial variations in oil spills over the period. They also show a strong relationship between oil movement and oil tanker spills when frequency of oil spills in the various regions is compared with world seaborne trade data over ten years.

1 Introduction

Accidental oil spills from tankers account for a small percentage of global marine oil pollution. They can however involve significant releases of oil and can have marked, albeit generally short-term, environmental and socio-economic impacts. Monitoring of oil tanker spills is therefore of prime importance to maritime organisations and relevant regulatory bodies. In the past few decades, there has been a great deal of interest in understanding trends and patterns in the distribution of oil spills to inform remediation strategies for environmental management. Many studies have also been carried out to assess the risk of oil spills which is essential in providing the basis for pollution response planning. The information provided by ITOPF on global temporal distribution of accidental marine oil tanker spills informs many marine studies and supports reviews at both local and international levels. The corresponding spatial information also has potential to improve management systems. Unfortunately, spatial data is not always as accurate as temporal data for historical marine oil spills. The point in time, usually the date, when incidents occurred are often well documented. On the other hand, geographic coordinates are not always available for incidents. Spills are sometimes reported by countries or major seas and oceans and the aggregation does not allow thorough analysis that could reveal true spatial patterns in the data. It is therefore encouraging that more accurate and complete granular spatial data on marine incidents is becoming available with the development of AIS and improved accessibility to remote sensing images, applications and products. The use of GIS for visualising and analysing the data has proved highly useful in understanding spatio-temporal trends in marine spills and for effective monitoring (Ivanov & Zatyagalova, 2008; Stevens, 2015).

The main source of data for this study is ITOPF's database on global accidental oil tanker spills, the same source for its annual oil tanker spill statistics publication. ITOPF's database is representative of global spills from tankers as various sources of information are explored in the collation of data and information has been gathered consistently over the years.

ITOPF is a not-for-profit organisation with the primary role of responding to ship-sourced spills. ITOPF maintains a database of accidental spills of persistent and non-persistent oil from tank vessels, including combined carriers, FPSOs and barges since the early 1970s. The information is gathered from published sources, such as the shipping press and other specialist publications, as well as from vessel owners, their insurers and from ITOPF's own experience at incidents. The data held includes the name of vessel involved, the type of oil spilled, the volume spilled, location and cause of the incident. With regards to location of spills, exact coordinates are not always available for oil spills, hence approximate locations are sometimes used. This is often not an issue from a global perspective but can be problematic when analysing data at regional or local scales.

This study shows the spatial distribution of marine oil tanker spills globally from 1970 to 2019 by mapping known locations of oil spills recorded by ITOPF in GIS. It also provides a relative density map to show where oil spills are concentrated. The study further analyses spatio-temporal maps for different decades and compares oil spill occurrence with oil movement.

The oil movement dataset used for this study was obtained from the United Nations Conference on Trade and Development's statistics database. According to the UNCTAD secretariat, the data was compiled based on data supplied by reporting countries, as published on the relevant government and port industry websites and by specialist sources.

2 Method

Historical data for oil tanker spills of size 7 tonnes or more that occurred between 1970 and 2019 was extracted from the ITOPF database. Spills of less than 7 tonnes in size were excluded because reporting for this category of spills is not reliable. Approximate geographic coordinates were assigned to records that were missing coordinates, but which had specific location descriptions. Records without any specific spatial descriptions were omitted. Nearly 90% of the records held in the database for large (>700 tonnes) and medium (7-700 tonnes) spills had adequate geographic information thus were included in the dataset for this study. Marine spills were separated from inland spills using Select By Location and Near tools in GIS.

Mapping and spatial analysis were done using Esri ArcGIS Pro. Heat map symbology (which utilizes the Kernel density method) was chosen for density mapping because this study seeks to highlight concentrated spill locations based on distribution rather than identify statistically significant spatial clusters. Also, the ArcGIS Kernel Density tool provided the possibility of weighting some features, like large spills, more heavily than others for further analysis.

For this study, temporal data was mostly analysed by decades, spatial data was analysed by continents, oceans/major seas and countries. Oil tanker spills were analysed by spill size classes; large (>700 tonnes) and medium (7-700 tonnes). The ocean boundaries were modified from version 2 of the International

Hydrographic Organization (IHO) Sea Areas shapefile[1]. The categorisation was done for the sake of simplicity and based on location of seas and distribution of spill data.

3 Results and Discussion

Over one thousand eight hundred oil tanker spills of size 7 tonnes and over that occurred between 1970 and 2019 are recorded in ITOPF's database. Approximately 90% of these records are plotted in GIS as they have adequate geographic coordinates and/or descriptions; 8% being inland spills, mostly occurring in and around the Mississippi River, and the remaining 82% being marine spills. Analysis of the marine spills are presented below.

3.1 Geographic distribution of marine oil tanker spills

The marine oil tanker spills are recorded in the waters of over one hundred countries, territories and regions around the world. The one-to-one dot distribution map in Figure 1 below shows the locations of marine oil tanker spills recorded between 1970 and 2019. Generally, spills are clustered close to shorelines and randomly dispersed across the oceans. Approximately 80% of marine spills recorded are within 10 nautical miles of shore.

Figure 1 Oil tanker spills >7 tonnes (1970-2019).

To highlight the main areas of clustering within the spill data, it was displayed as a heat map (generated at a search radius of 25 points and scale of 1:150,000,000). The brighter colours in the heat map below represent areas with high spill count (Figure 2).

[1] Details on Ocean/Sea boundaries (IHO) and modifications can be found in the Supporting Tables and Graphs section.

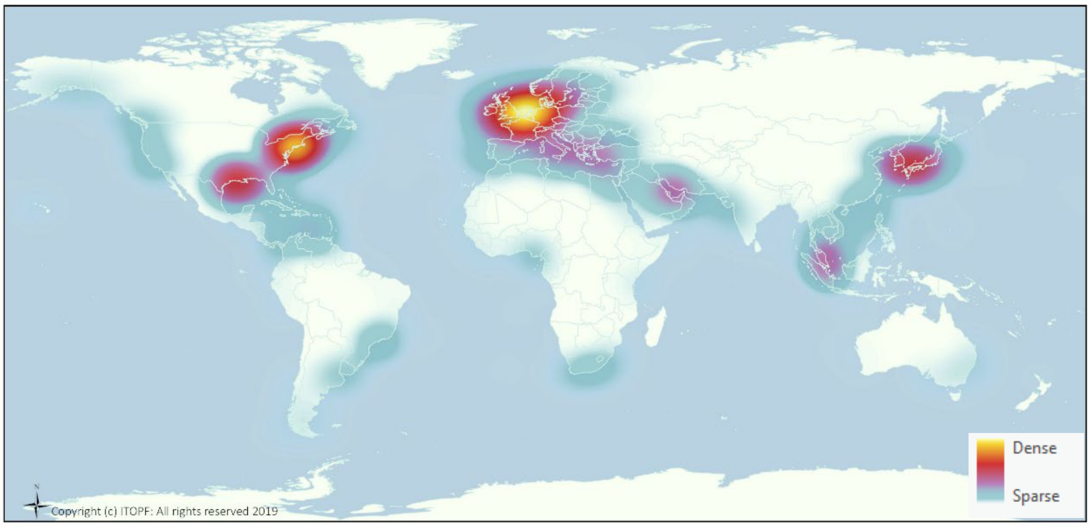


Figure 2 Oil tanker spills >7 tonnes (1970-2019).

The heat map shows Northwest Europe, precisely, around the Strait of Dover as the region with the highest concentration of spills. This is followed closely by Northeast USA. Relatively high density of spills can also be seen in areas of Southeast USA, East Asia (south of Japan sea), most areas in West Europe and around the Baltic. With the known tanker traffic in the Bosphorus, Hormuz and Malacca straits within South Europe, Persian Gulf and South east Asia respectively, it is unsurprising that high spill densities are apparent in these regions as well. There are also some distinct patches indicating spill clusters in The Caribbean and to a lesser extent South of Africa, Southeast Brazil, West USA and Gulf of Guinea in Africa.

When viewed at slightly different zoom levels (all showing the full extent of world map) to assess any significant differences that may occur as a result of the redefinition of density, the region with the highest concentration of spills changed. At the chosen default scale of 1:150,000,000 the area with the highest density of spills was around the Strait of Dover, however at a larger scale of approximately 1:110,000,000 and beyond, the area around northeast USA had the highest spill density. Similarly, maintaining the default scale and reducing the default search radius from 25 to 18 points or below changed the area with the highest density from the Strait of Dover to northeast USA. This can be explained by the fact that the spill cluster in Northwest Europe is distributed when the map is zoomed in or the search radius is reduced. Northwest Europe and northeast USA can therefore be said to be the regions where the highest concentrations of oil tanker spills have been recorded in the five decades. Density remained relatively constant in all other areas throughout the assessment.

Also, when relative density was weighted by spill size (spills greater than 700 tonnes weighted 2 and those less than or equal to 700 tonnes weighted 1), thus making large spills contribute double the feature count to the calculation of density, there was very little change. The main areas of clustering remained the same, however, their intensities changed slightly.

3.2 Spatio-temporal trends in marine oil tanker spills

An illustration of the number of spills recorded in the different continents over the five decades is shown in Figure 3. A decrease over time can be observed for all regions. It can however be seen from Figure 4 that Europe has experienced the most decline, with the most rapid decline occurring between the 1970s and 1980s. The highest number of spills for the five decades was recorded in North America, however, over the last three decades, most spills have been recorded in Asia (Figures 3 & 4). This decade, less than ten spills were recorded in each continent except Asia, where more than 30 spills were recorded.

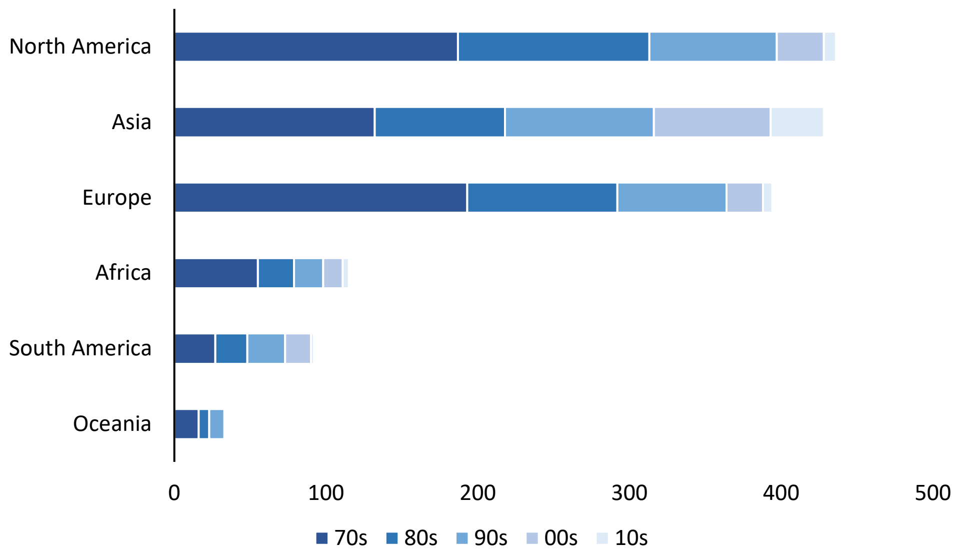


Figure 3 Oil tanker spills >7 tonnes (1970-2019) by continents.

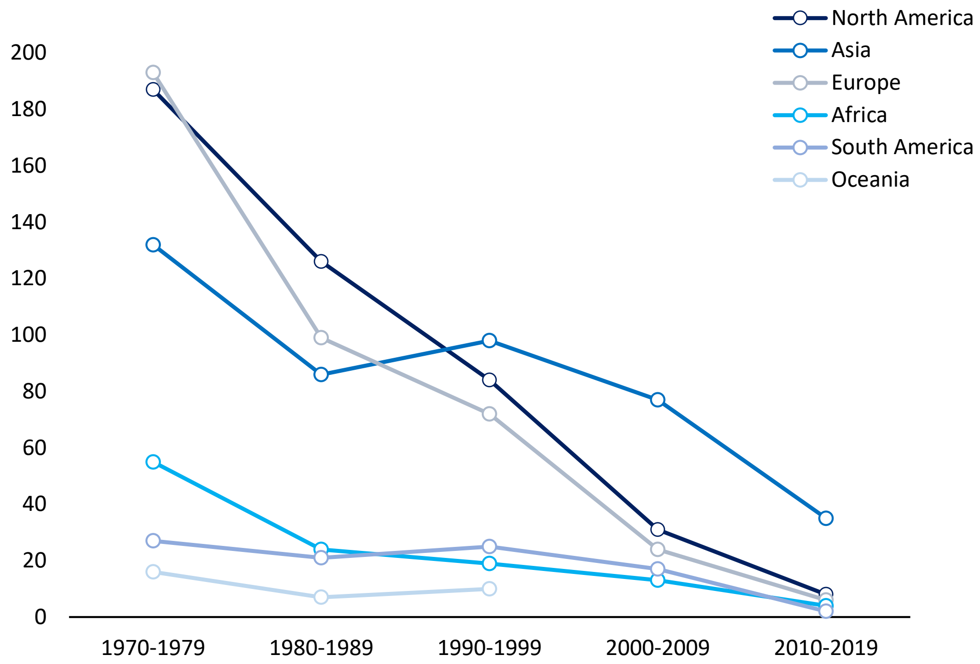
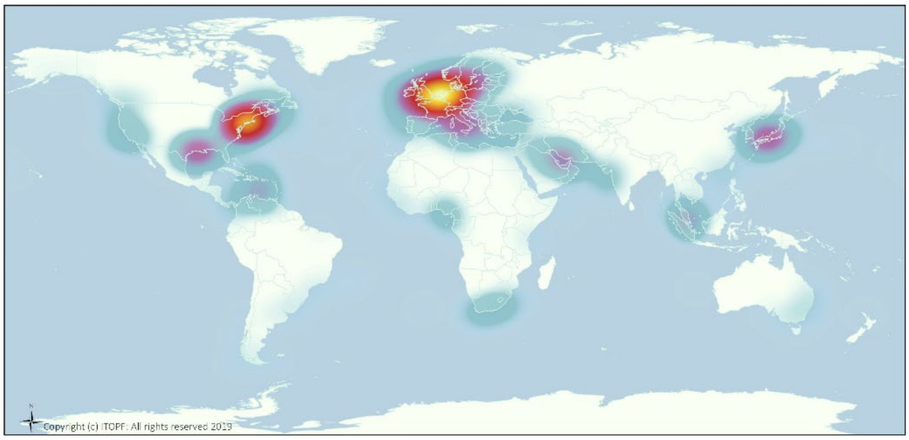
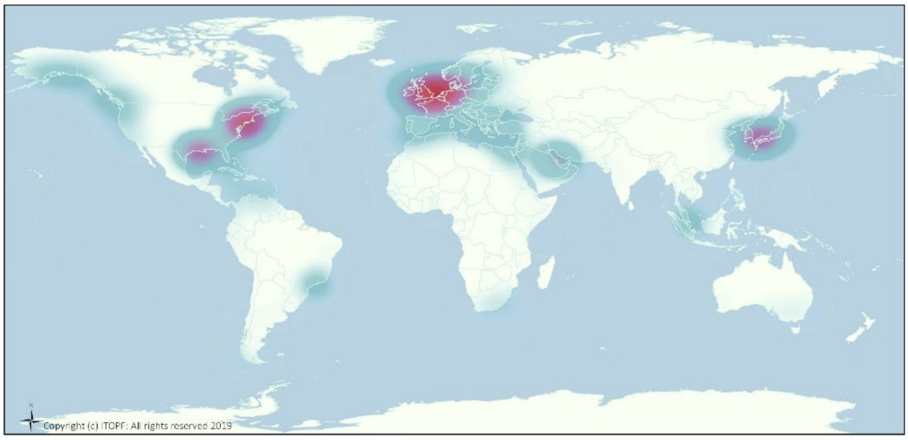
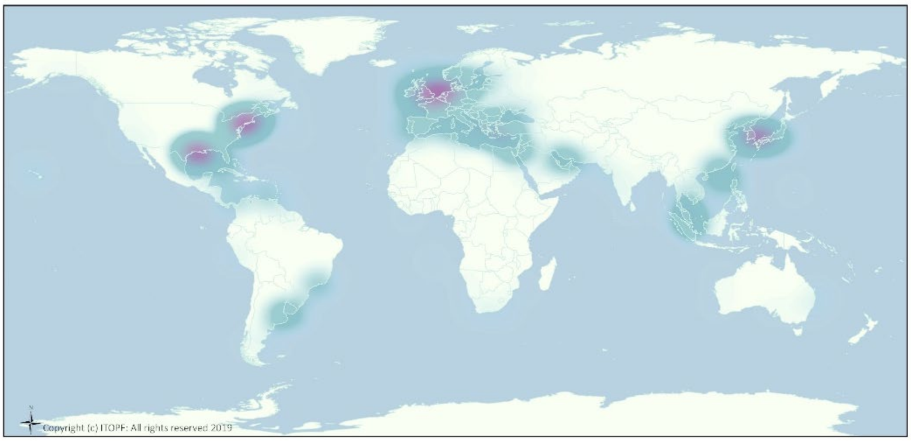


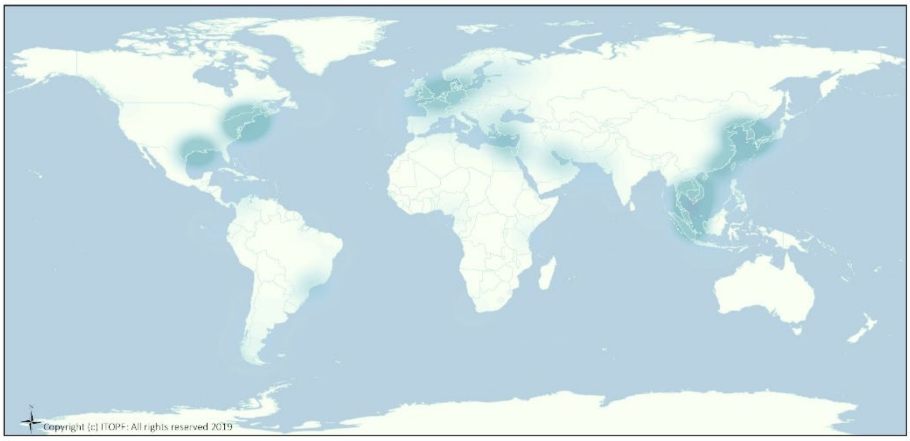
Figure 4 Oil tanker spills >7 tonnes (1970-2019) by continents.

To compare differences in spatial clusters over time, the following sets of maps, were exported from an interactive time enabled heat map produced for this study. They show relative densities in various regions around the world per decade. The first set (Figure 5) uses constant rendering to ensure the definition of density applied for the range of data in the first decade remains constant throughout the analysis so different periods can be compared equally. The second set (Figure 6) uses dynamic rendering which recalculates density based on the range of data per decade. This method allows us to identify regions where the highest density of spills was recorded in different decades. Search radius, scale and colour range were kept constant.

Map set 1 

Decade	Maps (using constant rendering)
1970s	
1980s	
1990s	

2000s



2010s

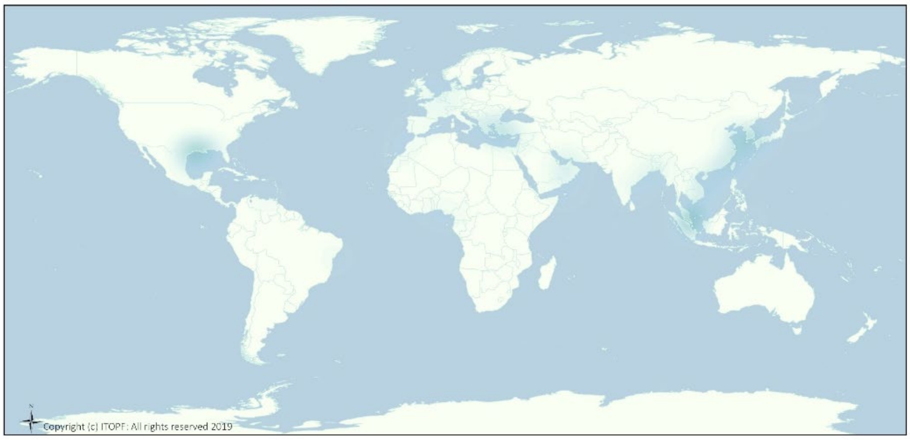
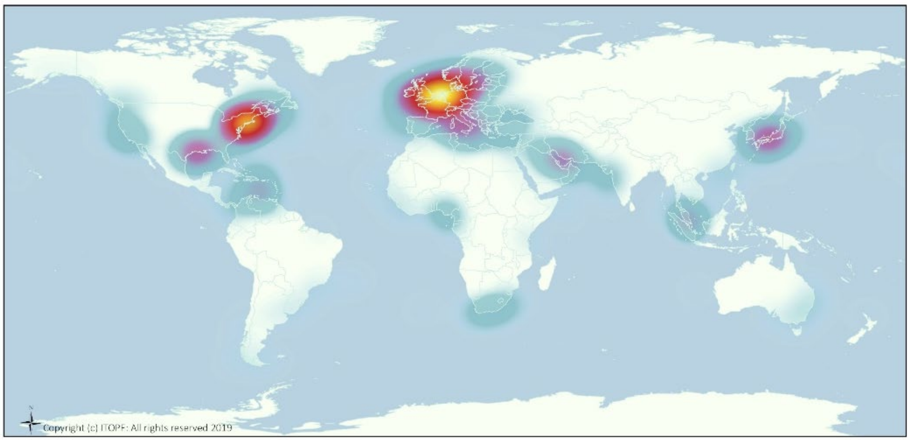


Figure 5 Oil tanker spills >7 tonnes per decade (1970-2019).

Map set 2

Decade	Maps (using dynamic rendering)
1970s	

1980s

1990s

2000s

2010s

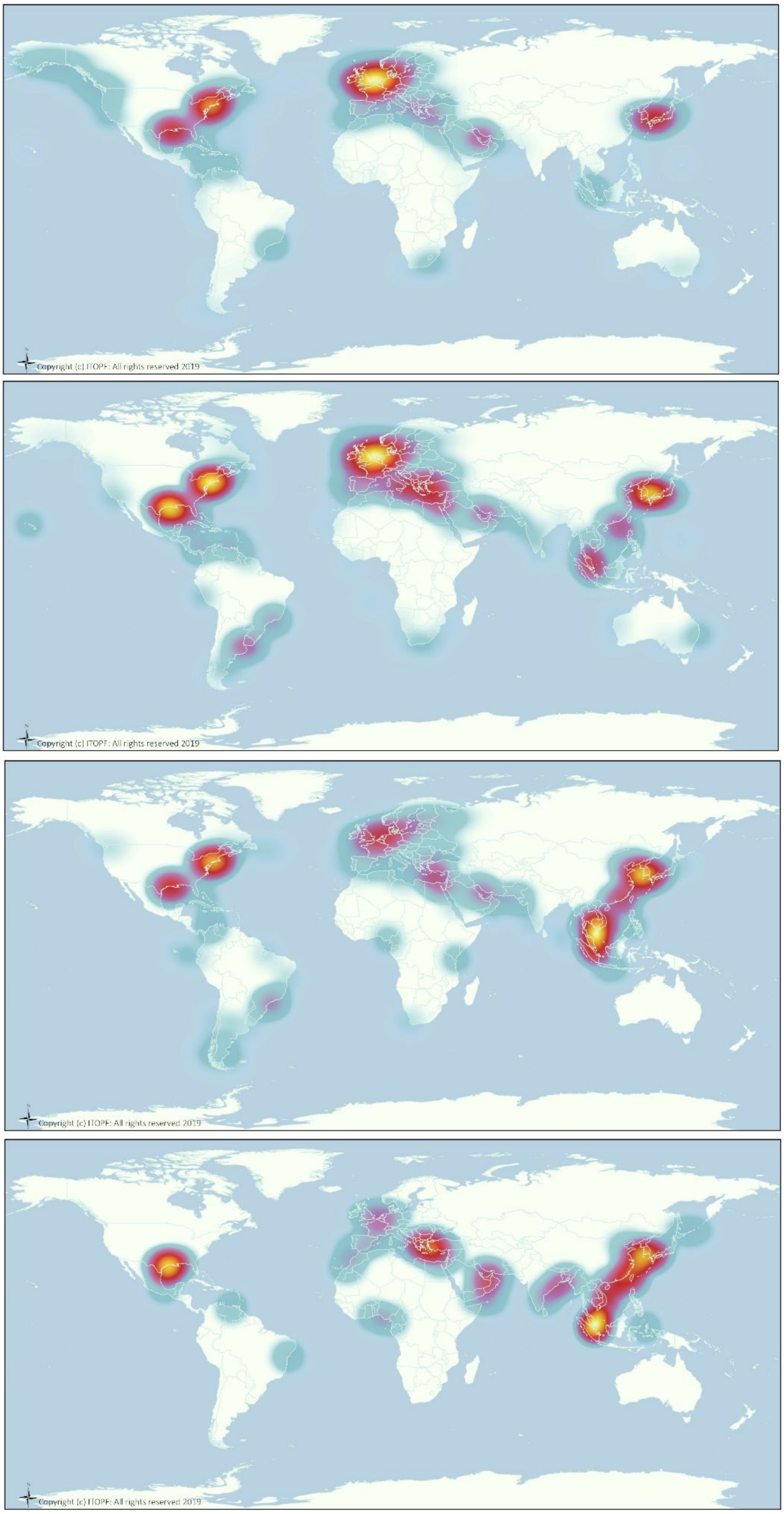


Figure 6 Oil tanker spills >7 tonnes per decade (1970-2019).

Generally, map set 1 emphasises the dramatic decline in accidental marine oil tanker spills globally. A comparison of the 1970s map to the 2010s map (both produced using the same density definition) shows a significant positive change. Nonetheless, accidents may occur so long as we continue to transport oil around the globe. Deeper analysis with focus on recent decades is therefore crucial to provide insights to help manage current spill risks.

Map set 2, which has different density definitions for the various decades, show the regions of high spill density for the different decades. Changes in East and South USA, West Europe and East/South Asia are compelling and validates inter-continental trends shown in Figures 3 and 4 and discussed above.

Analysis of the spill data at country level provides further information on trends in the various regions. Considering data over the 50-year period, spills recorded in the top ten countries shown in Figure 7 below constitute 50% of all spills analysed. The changes in their positions over the decades are detailed in the chart. Interestingly, seven of these countries are off the list this decade, being replaced by China, Singapore, Vietnam and others. It is however worth noting that with less than 100 spills recorded this decade, a 'few' spills are enough to get a country into the top ten. The relevance of a 'league table' (drawn from the dataset for this study) in analysing geographical trends for any period beyond the 2000s is therefore inconclusive.

The USA has consistently been reported as the country with the highest frequency of spills (Huijer, 2005 & Musk, 2012). In her study, Huijer (2005) argued that this could be attributed to the heavy shipping traffic which could mean a higher risk of accidental spills, as well as reliable reporting of spills in USA. Nonetheless, spills recorded in USA, have reduced by over 90% in the five decades.

		1970s	1980s	1990s	2000s	2010s
1	USA	1	1	1	1	1
2	JAPAN	2	3	4	10	6
3	UNITED KINGDOM	3	2	3	9	
4	NETHERLANDS	5	4			
5	SOUTH KOREA		7	2	4	6
6	CANADA	6	5			
7	ITALY	4		10		
8	SWEDEN	7	10			
9	FRANCE	8				
10	BRAZIL		8	8	5	

Position	1-2	3-4	5-6	7-8	9-10	Out of top 10

Figure 7 Top 10 countries where oil tanker spills >7 tonnes were recorded (1970-2019).

3.3 Geographical distribution of oil spills by sizes

Generally, large (>700 tonnes) and medium (7-700 tonnes) spills are evenly distributed at a ratio of about 1:2 respectively across the various continents.

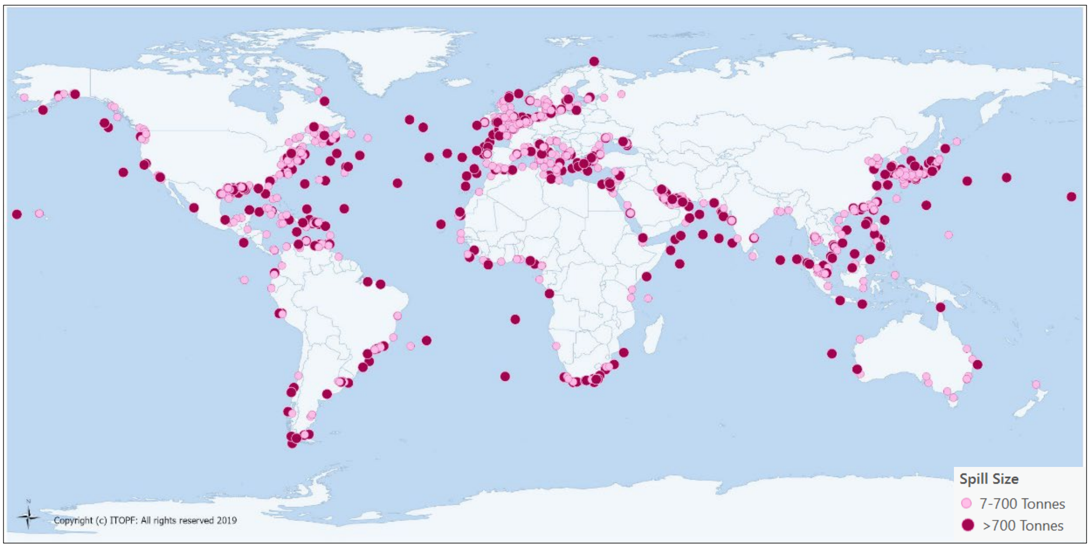


Figure 8 Medium (7-700 tonnes) and large (>700 tonnes) oil tanker spills from 1970-2019.

Approximately two thirds of the spills recorded in most of the oceans and seas (based on the modified ocean boundary classifications) are medium spills. In the North Sea however, over 90% of the over 100 spills recorded since 1970 are medium spills. On the other hand, in the South Pacific and Indian oceans more than half of the spills are large. Figure 9 shows the proportion of large to medium spills in the various oceans/seas where more than 10 spills have been recorded[2].

Also, as noted above, there was negligible change between the relative density map of spills with no attribute weighting and the map generated weighting data by spill size, confirming the even distribution of spills across the globe.

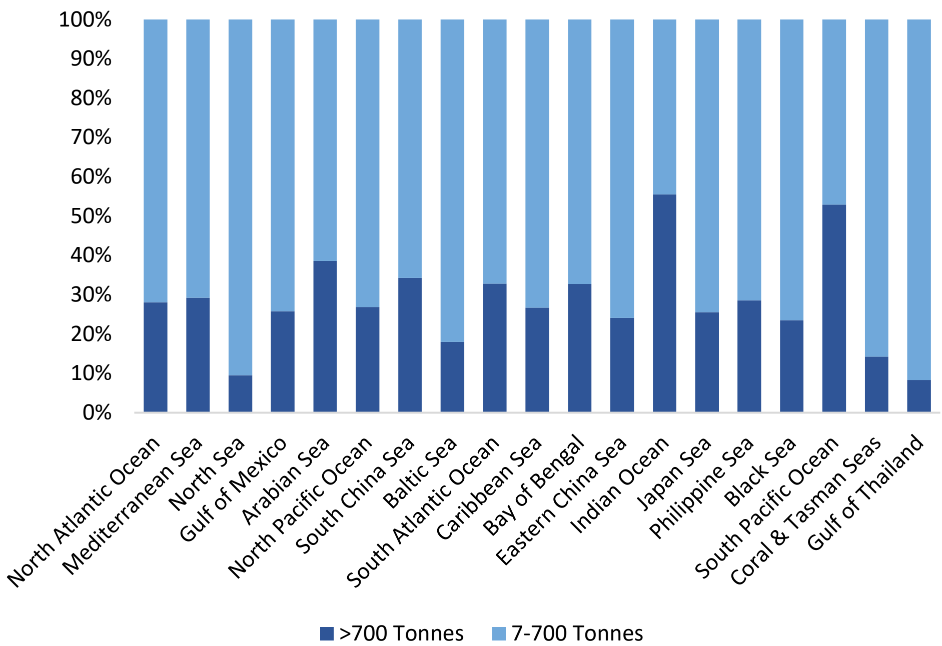


Figure 9 Medium (7-700 tonnes) and large (>700 tonnes) oil tanker spills from 1970-2019.

[2] Only Arctic ocean is excluded due to the low number of spills recorded.

3.4 Oil spills versus oil movement

The current rate of oil tanker spills globally is significantly lower than recorded in previous decades. The probability that one will occur in a specific place has been linked to several factors, with the most common being vessel traffic and shipping routes (Moldan & Dehrman, 1989; Woolgar, 2000; Stevens, 2014).

To investigate the eastward shift of the densest spill area in recent decades, data on world seaborne trade by regions[3] for a period of ten years (2008 to 2017) was analysed, together with marine tanker spills data for the same period. Figure 10 below shows the average crude oil, petroleum products and gas, loaded and unloaded versus the average number of spills per region over the ten-year period. It emphasises the correlation between the two factors.

Globally, the frequency of oil tanker spills has been shown to decrease despite growth in seaborne oil trade. However, the analysis in Figure 10 implies that increased oil movement could indeed indicate increased risk in some regions. Further observations over a longer period might help to elaborate this. Unfortunately, world seaborne trade data by types of cargo and by group of economies is available from 2006 only.

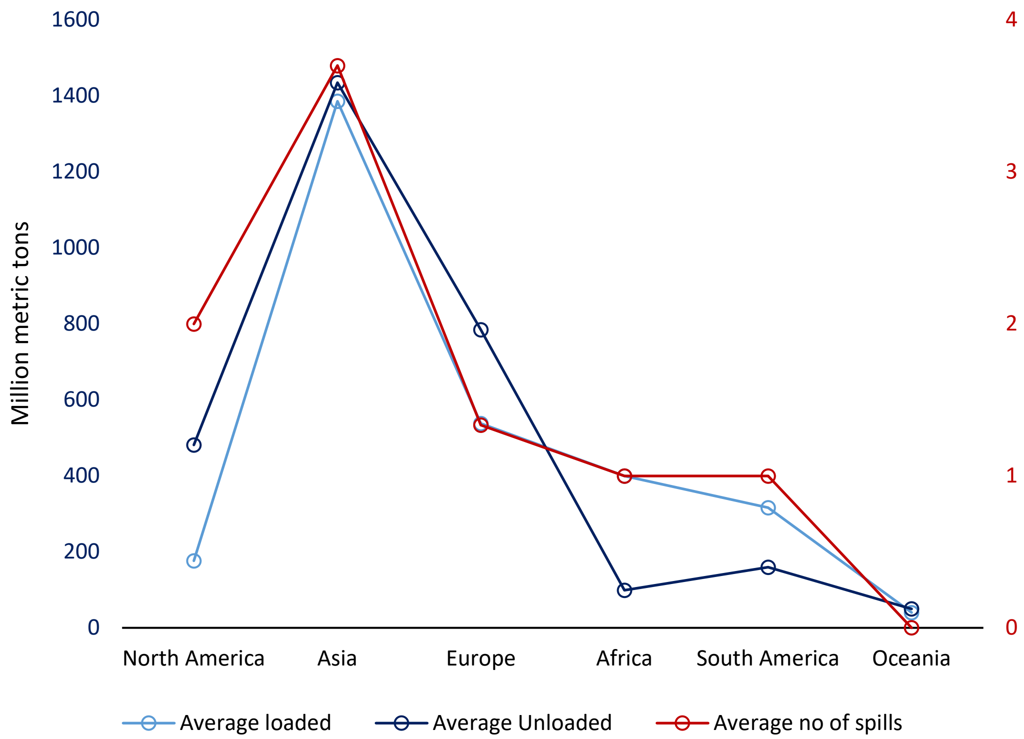


Figure 10 Average crude oil, petroleum products and gas loaded/unloaded vs average number of spills >7 tonnes (2008-2017).

4 Conclusion

Oil tanker spills have occurred across the globe with about 80% clustered near shorelines. Data recorded for half a century shows Northwest Europe and Northeast USA as the areas with highest relative density of spills. In the last 3 decades however, most spills were recorded in Asia. At country

[3] Source: UNCTADstat database.

level, the highest number of spills for each decade was recorded in USA. Nonetheless, there has been over 70% reduction in number of spills in Asia and over 90% in the rest of the world between the 1970s and 2010s.

The proportion of large (>700 tonnes) and medium (7-700 tonnes) spills in the various continents and oceans/seas are generally equal, occurring at a ratio of about 1:2 respectively. It is thus unsurprising that attribute weighting by spill size had negligible effect on relative density of spills on maps. The main areas of clustering were unchanged.

When compared with oil movements for a ten-year period, oil tanker spills were generally higher in regions where the volume of crude oil, petroleum products and gas loaded and unloaded were higher. This does not conclusively suggest higher probability of oil spills in high oil-movement areas as a combination of factors come into play in the evaluation of risk of oil spills. However, it highlights a strong relationship between the two factors.

The use of GIS allowed the efficient production of distribution maps and density analysis, revealing key spatial information about global oil tanker spills. The study has shown positive trends in oil spills across various regions in the world. This trend is likely to persist if spill incidents continue to be measured and consequently managed within the industry.

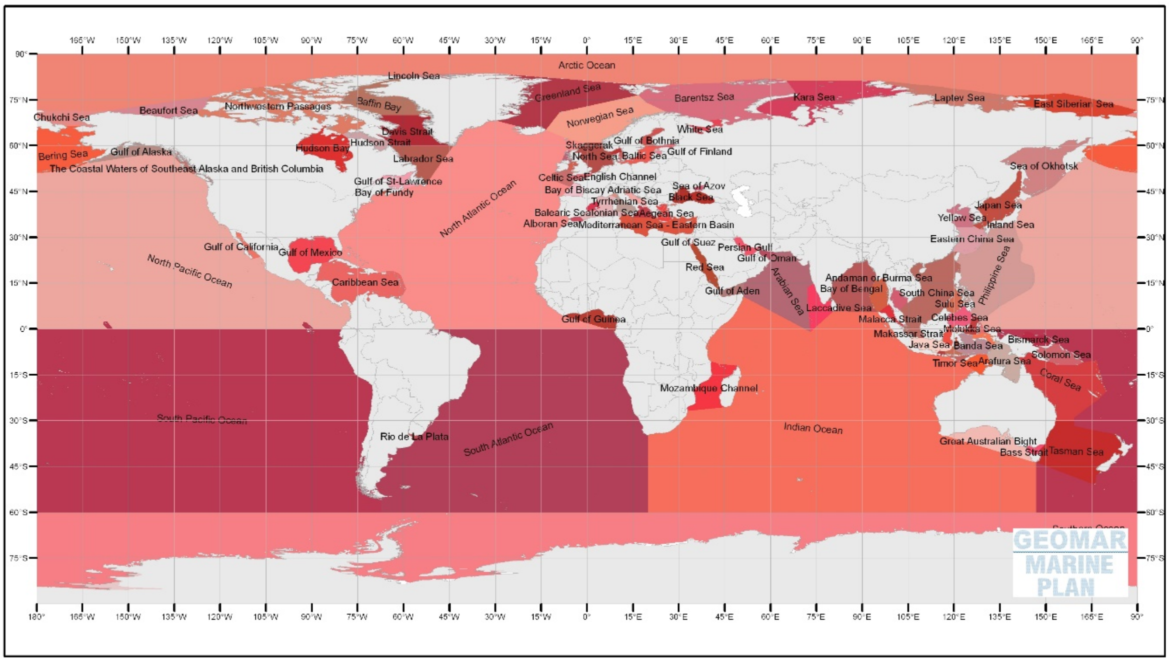
5 Supporting Tables and Graphs

Modified ocean/sea boundary classification.

Arabian Sea	Arabian Sea
	Gulf of Aden
	Gulf of Oman
	Gulf of Suez
	Laccadive Sea
	Persian Gulf
	Red Sea
Arctic Ocean	Barentsz Sea
	Davis Strait
	Norwegian Sea
Baltic Sea	Baltic Sea
	Gulf of Bothnia
	Gulf of Finland
	Kattegat
	Skagerrak
Bay of Bengal	Andaman or Burma Sea
	Bay of Bengal
	Malacca Strait
	Singapore Strait
Black Sea	Black Sea
	Sea of Azov
Caribbean Sea	Caribbean Sea
Coral & Tasman Seas	Bass Strait
	Coral Sea
	Tasman Sea
Eastern China Sea	Eastern China Sea
	Seto Naikai or Inland Sea
	Yellow Sea
Gulf of Mexico	Gulf of Mexico
Gulf of Thailand	Gulf of Thailand
Indian Ocean	Great Australian Bight
	Indian Ocean
	Mozambique Channel
Japan Sea	Japan Sea
Mediterranean Sea	Adriatic Sea
	Aegean Sea
	Alboran Sea
	Balearic (Iberian Sea)
	Ionian Sea
	Ligurian Sea
	Mediterranean Sea - Eastern Basin
	Mediterranean Sea - Western Basin
	Sea of Marmara
	Strait of Gibraltar
	Tyrrhenian Sea
North Atlantic Ocean	Bay of Biscay
	Bay of Fundy
	Bristol Channel
	Celtic Sea
	English Channel
	Gulf of Guinea
	Gulf of St. Lawrence
	Irish Sea and St. George's Channel
	Labrador Sea
	North Atlantic Ocean
North Pacific Ocean	Bering Sea
	Gulf of Alaska
	North Pacific Ocean
	Sea of Okhotsk
	The Coastal Waters of Southeast Alaska and British Columbia
North Sea	North Sea
Philippine Sea	Philippine Sea
South Atlantic Ocean	Rio de La Plata
	South Atlantic Ocean
South China Sea	Makassar Strait
	Molukka Sea
	South China Sea
	Sulu Sea
South Pacific Ocean	South Pacific Ocean

Ocean/sea boundaries (IHO)

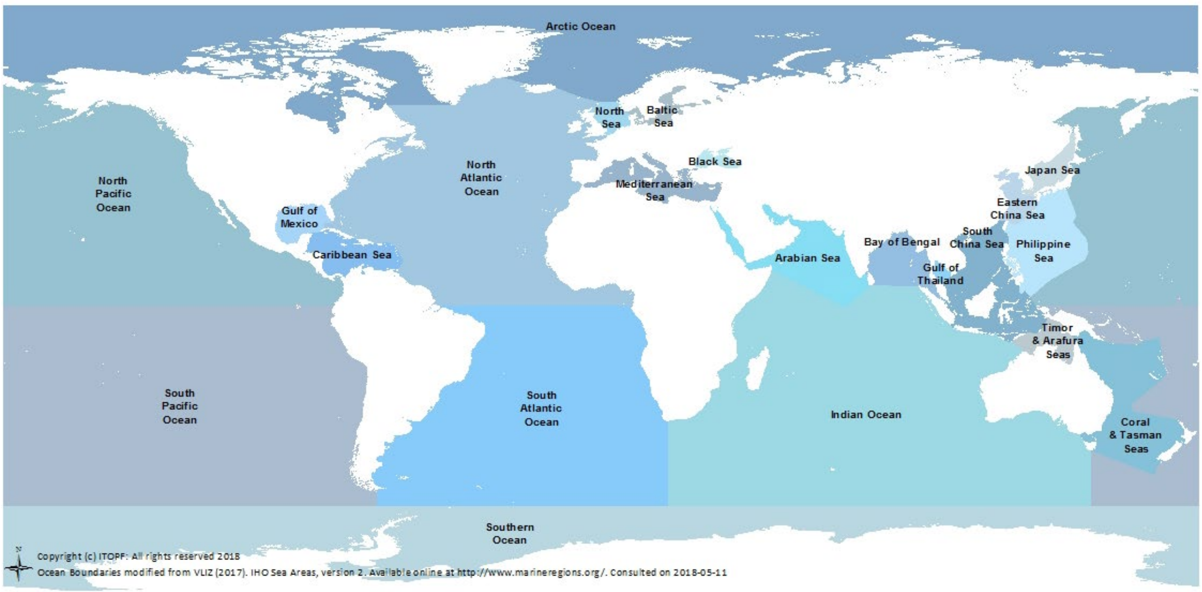
MARINE DIVISIONS: WORLD SEAS. INTERNATIONAL HIDROGRAPHIC ORGANISATION



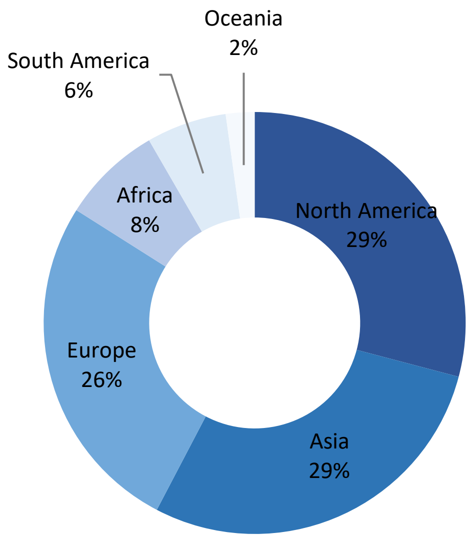
GEOMAR
University of Seville. Department of Human Geography

Source: Author based on VLIZ

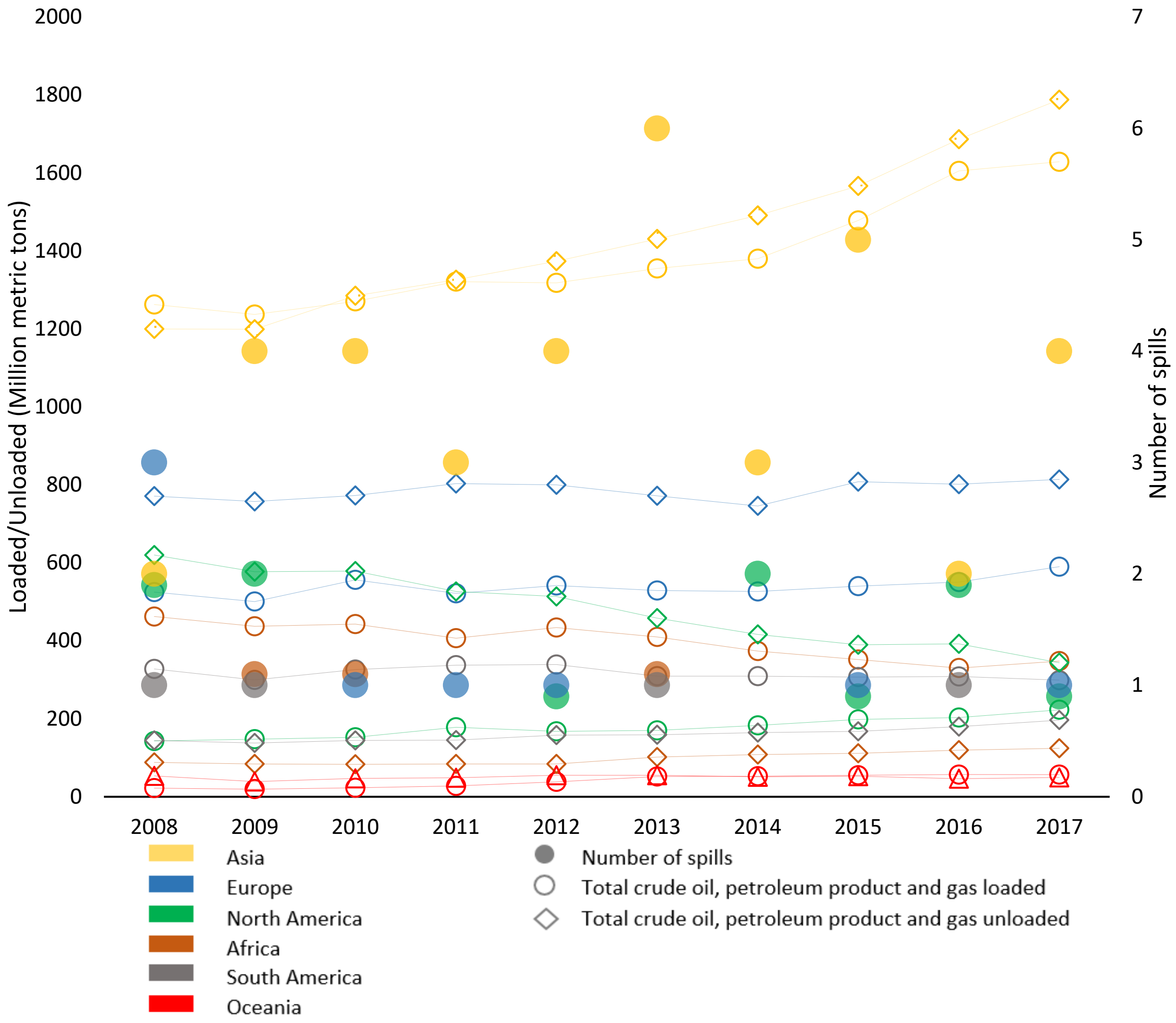
Modified ocean/sea boundaries



Percentage of oil tanker spills >7 tonnes (1970-2019) by continents.



Crude oil, petroleum products and gas loaded/unloaded vs number of spills >7 tonnes (2008 -2017), per year.



6 References

British Petroleum Company (2019). *BP Statistical Review of World Energy*. London, June.

Burgherr, P. (2007) 'In-depth analysis of accidental oil spills from tankers in the context of global spill trends from all sources'. *Journal of Hazardous Material* 140 (1–2), pp. 245-256. DOI: 10.1016/j.jhazmat.2006.07.030

Flanders Marine Institute (2017) *IHO Sea Areas, version 2*. Available at: http://www.marineregions.org/ (Accessed: May 2018).

Global Marine Oil Pollution Information Gateway (2005). *Facts on marine oil pollution*. Available at: http://oils.gpa.unep.org/facts/facts.htm (Accessed: March 2019).

Huijer, K. (2005) 'Trends in oil spills from tanker ships', *Arctic and Marine Oil spill Program (AMOP) Technical Seminar*. Calgary, Canada, 7-9 June.

Ivanov, A. and Zatyagalova, V. (2008) 'A GIS approach to mapping oil spills in a marine environment'. *International Journal of Remote Sensing*, 29 (21), pp. 6297-6313. DOI: 10.1080/01431160802175587

Moldan, A. and Dehrman, A. (1989) 'Trends in oil spill incidents in South African coastal waters'. *Marine Pollution Bulletin*, 20 (11), pp. 565-567. https://doi.org/10.1016/0025-326X(89)90358-5

Musk, S. (2012) 'Trends in oil spills from tankers and ITOPF non-tanker attended incidents', *Arctic and Marine Oil spill Program (AMOP) Technical Seminar.* Vancouver, British Columbia, Canada, 5-7 June.

Stevens, L. (2015) 'Visualising spill risk: understanding and assessing regions of heightened vulnerability associated with increased seaborne transport of oil', *International Oil Spill Conference.* Amsterdam, Netherlands, 24-26 March.

UNCTAD (2019) *UNCTADstat database. Maritime transport, World seaborne trade*. Available at: https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx (Accessed: December 2019).

Woolgar, L. (2008) 'Assessing the increasing risk of marine oil pollution spills in China', *International Oil Spill Conference*. Savannah, Georgia, 4-8 May.