Stochastic analysis of deep sea oil spill trajectories in the Great Australian Bight

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Commissioned by: **The Wilderness Society South Australia Inc.**

An independent, not-for-profit environmental advocacy organisation, financially supported by its members, the Wilderness Society South Australia (TWS SA) has campaigned to protect wilderness in South Australia for over thirty years.

The recently proclaimed Marine Parks, covering the Great Australian Bight and the State's coastal waters, include sanctuary zones so that the marine environment as well as the fishing, tourism, recreational, social and economic futures of the region are secure.

TWS SA commissioned this modelling because it believes that South Australians have a right to see an independent analysis of the risk to their futures that intended deep sea drilling for oil in the Great Australian Bight presents.

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Executive summary

The Great Australian Bight (GAB) to the south of Australia has been targeted by industry as a new opportunity for the potential discovery of fossil fuels. British Petroleum (BP), joined by Norway's Statoil, applied to the Federal Department of Environment for assessment of a proposed oil exploration drilling program in Commonwealth waters of the GAB. The GAB exploration campaign led by BP has been controversial due to a range of factors, including concerns regarding the company's environmental record (particularly the Deepwater Horizon spill that occurred in the Gulf of Mexico in 2010) and the risks posed to the environmental, social and economic values of the region by the proposed deep water drilling.

The Wilderness Society South Australia has expressed serious concerns regarding likely impacts on the environmental values of the marine ecosystems in the GAB and over the oil spill response capabilities in a region where the oil industry is not established nor has significant support resources available locally like in the Gulf of Mexico.

Furthermore, BP has not disclosed key information relating to their environmental impact assessment of deep water well failure. This report presents an assessment of socio-economic and ecological impacts of deep water oil spill scenarios based on best available information and industry-standard numerical modelling methods.

The GAB is a body of water located off the coast south of Australia. The Southern Ocean is one of the windiest parts of the planet with sea surface wind increasing in more southerly latitudes. The GAB is also known for its highly energetic wave climate with ground swells regularly experienced year round from the Indian and the Southern Ocean into the Bight basin. The GAB is an important breeding and feeding ground for a range of marine species. Specifically, it is an important calving and mating area for the endangered Southern Right Whale and the threatened Australian Sea Lion. Several species of sea birds inhabit the GAB such as the Amsterdam, Tristan and Grey-headed albatross, as well as the Southern and Northern Giant petrel. The endangered Loggerhead and Leatherback sea turtles are also commonly found in the area. South Australia has established a network of 19 marine parks in order to protect marine habitat, biodiversity, ecological processes and the sustainability of marine activities.

The South Australian fishing industry significantly contributes to the regional economy with a total value of seafood production in 2012-2013 estimated around $442 million, of which aquaculture contributed nearly 55 % with Tuna being the largest sector in the state's aquaculture industry. Spencer Gulf and St Vincent Gulf create ideal breeding conditions for the King Prawn and other crustaceans. Of all the wild-catch fisheries, Rock Lobster is estimated to be the most valuable, followed by Prawn and Abalone. Tourism is also a valuable contributor to the South Australian economy with a combined $1.2 billion estimated for 2013-2014 in Yorke, Eyre and Fleurieu Peninsulas, Kangaroo Island and the Limestone Coast.

In this study we are considering the potential impacts of an oil spill in the GAB caused by the blowout of an oil drilling rig that leads to the uncontrolled release of crude oil at the sea bed into the water column. We consider two seasons (summer and winter) and four oil spill scenarios. An oil spill scenario is characterised by the spill location, a release duration, a flow rate and the crude oil type. The selection of scenarios, based on best information available to us, is discussed in this report. In the framework presented in this study, an oil slick is driven by oceanic currents and winds and is treated as a large number of independent particles whose paths and mass are recorded in time. While studying the trajectory of an individual oil slick is a deterministic investigation, for this study we propose a stochastic analysis. By analysing the progress of a large number of trajectory simulations, the potential severity of environmental impacts resulting from an oil spill can be assessed.

Regardless of the oil spill release scenario, the numerical model predicts that in the short term, in the event of a blowout in the GAB, crude oil lost in the marine environment is likely to impact the shores of Western Australia should the event occur in summer whereas it would most likely reach the Eyre Peninsula and Spencer Gulf in South Australia if the incident should happen during winter. In the long term though, the numerical model predicts that remaining droplets of oil at the sea surface would progressively leave the GAB and transit towards the Tasman Sea through Bass Strait and around Tasmania.

Under summer conditions, for a blowout scenario representing a spill of 5,000 barrels of oil per day for 87 days (scenario 2A), the model predicts that within four months an area of roughly 213,000 km^2 would have an 80 % chance to have a surface oil thickness above levels likely to trigger the closure of fisheries. This area extends from the proposed petroleum exploration area towards the coast of Western Australia near the Twilight Marine Reserve. During winter and within four months under the same spill scenario, this area covers a surface of approximately 265,000 km^2 from the proposed exploration well to the entrance of Spencer Gulf, reaching the Eyre Peninsula and Kangaroo Island. We propose a detailed oiling analysis for key locations in Western Australia and South Australia. Of all the sites investigated in the oiling analyses, the Twilight Marine Reserve was the most impacted under summer conditions. During winter, West Coast Bays Marine Park, Lower Yorke Peninsula Marine Park and Western Kangaroo Island Marine Park show the highest levels of oiling.

Although the parameters characterising the oil spill are subject to some variability, we aim to describe different possible deep sea well failure scenarios based on best information available and past events. Regardless of the oil spill scenario, the model predicted that at a minimum, there is a 70 % to 80 % likelihood for oil droplets reaching the Australian coastline.

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I Introduction

I.1 Background information

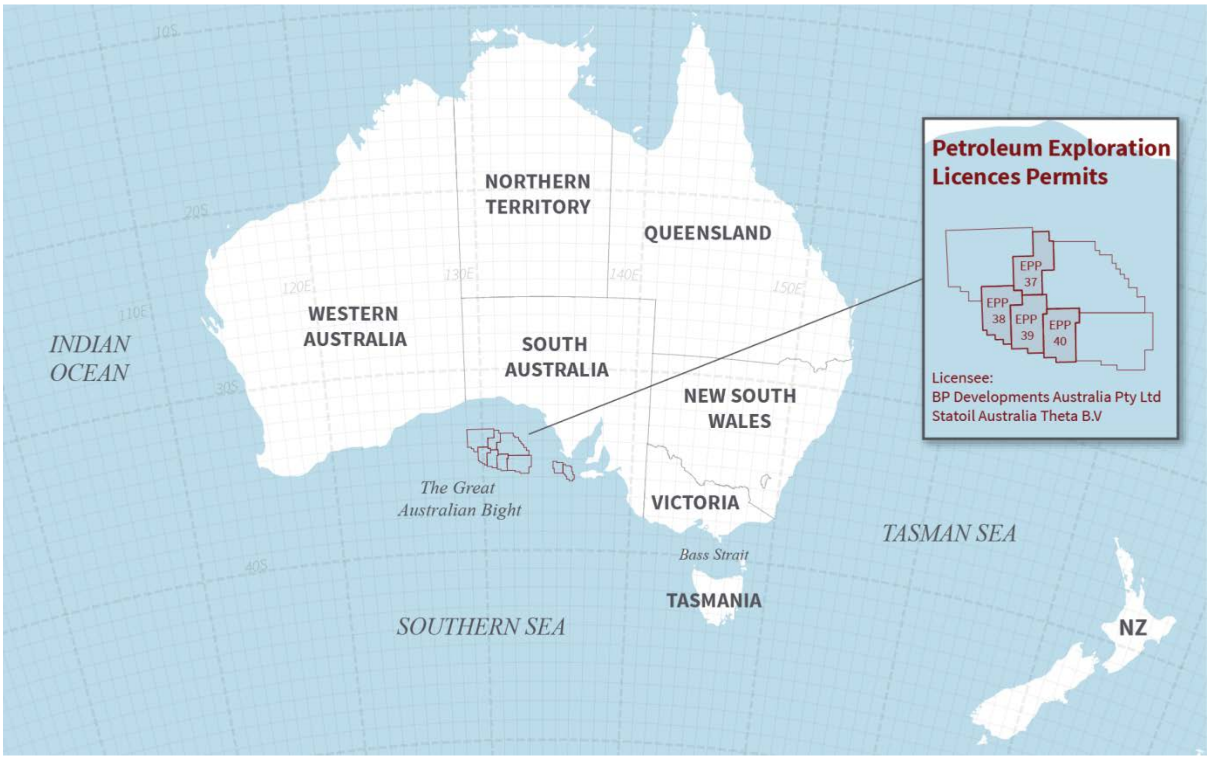

Figure 1: Petroleum exploration permits in the Great Australian Bight to the south of Australia and specific licences granted to BP.

The Great Australian Bight (GAB) at the south of Australia has been identified as a purported opportunity for the potential discovery of fossil fuels. British Petroleum (BP) has stated its view that it regards the GAB as one of the most prospective frontier basins in the world. The Bight Basin comprises a series of Middle Jurassic-Cretaceous depocentres that developed during the break-up of Australia and Antarctica (Geoscience Australia, 2007). The main depocentres extend over water depths between 100 and 5,000 m and are relatively unexplored.

The Australian Government has granted permit areas in its Commonwealth waters for offshore petroleum exploration to the oil and gas industry. Particularly, BP applied to the Federal Department of Environment for assessment of a proposed oil exploration drilling program in Commonwealth waters of the GAB (BP 2012). The exploration drilling campaign is proposed to start in 2016 in the Petroleum Exploration Permits (EPP) 37, 38, 39 and 40 (Figure 1). The first well named ‘Stromlo’ is planned to be drilled in October 2016 (SMH, 2015).

The GAB exploration campaign led by BP has been controversial due to a range of factors, including the environmental and social values of the region, the risk posed by deep water drilling operations and the concerns regarding the company’s environmental record particularly in regards to its involvement in the Deepwater Horizon (DWH) oil spill that occurred in the Gulf of Mexico in 2010 following the loss of control over the Macondo oil well. In the event that such a large event were to occur in the GAB, The Wilderness Society South Australia (TWS) has expressed serious concerns over the oil spill response capabilities in a region where the oil industry is not established nor has significant support resources available locally like in the Gulf of Mexico. In its Environment Protection and Biodiversity Conservation Act 1999 (EPBC) Referral of proposed action (BP, 2012), BP did not disclose key information relating to its environmental impact assessment of deep water well failure. Specifically, BP did not disclose the release rates and oil type used for the study which was claimed to be commercial material in confidence and exempt from the Freedom of Information Act public release as BP trade secrets. Moreover, both Australian Government officials (Department of the Environment, 2013b) and TWS claim that the blowout duration used for the numerical modelling supporting BP's assessment is based on a relatively optimistic scenario.

This report presents an assessment of socio-economic and ecological impacts of deep water oil spill scenarios based on best available information and industry-standard numerical modelling methods.

I.2 Lessons from the Gulf of Mexico

During the Deepwater Horizon MC252 Spill (DWH oil spill), oil and gas were discharged approximately 1.5 km below the sea surface into the Gulf of Mexico for a total period of 87 days (OSAT-1, 2010). The immediate cause of the Macondo well blowout was a failure to contain hydrocarbon pressures in the well. The flow from the well overwhelmed the mud-gas separator system which caused a first explosion in the evening of April 20th, 2010. (National Commission DWH, 2011). While the flow rate of oil entering the marine environment remained inaccurate for almost a month, it was only after BP released a video of oil and gas streaming from the end of the broken riser that responders began to realise that the flow rate was much larger than initially anticipated (with initial estimates ranging from 1,000 to 6,000 bbl/day). It was later estimated that 4.9 million barrels (bbl) of oil had escaped from the Macondo well with a flow rate reaching 62,200 bbl/day in April 2010 and dropping to 52,700 bbl/day in July 2010 when the well was capped (McNutt et al., 2011)

By April 30th, the first oiled bird recovery was reported and the Louisianan Department of Wildlife and Fisheries, along with the Department of Health and Hospitals, began closing fisheries and oyster grounds in state waters. State fisheries closures spread to Alabama, Mississippi and Florida during June 2010 (National Commission DWH, 2011). During the DWH oil spill, concerns over seafood contamination from oil and dispersant compounds led to a closure of over 230,000 km^2 in the Gulf of Mexico to fishing (NMFS, 2010).

Within the first week following the spill, BP, Coast Guard and responders started deploying dispersants on the surface oil slick. Within a month, around 300,000 gallons (more than a million litres) of the dispersant Corexit were sprayed on the water surface (National Commission DWH, 2011). Never before has such a volume of dispersant been applied to respond to a spill. To put this in context, about 6,000 gallons were used during the Exxon Valdez spill which resulted in 250,000 bbl of crude oil released in the Alaskan waters (Skinner and Reilly, 1989). By May 2010, dispersant was directly applied at the wellhead 1.5 km below the sea surface. During the DWH oil spill response, a total of 1.84 million gallons (nearly 7 million litres) of dispersants were applied both at the surface and directly on the sea floor (OSAT-1, 2010).

To contain the spill several strategies were adopted. First, a containment dome was lowered to the sea floor but failed at collecting the spilling oil as methane gas in contact with cold water formed slushy hydrates and closed the funnel in which the oil was to be contained. Then, three attempts at dynamic kill (or top kill, e.g. releasing heavy drilling mud in the damaged blowout preventer) failed to lower the pressure within the well. By early June a collection device was installed by BP and

15,000 bbl/day of crude oil was collected by the Discoverer Enterprise. However, as the flow rate of the spill was much larger that the collection rate, a second vessel collecting and burning an extra 10,000 bbl/day had to be mobilized. The two vessels' joint capacity of 25,000 bbl/day was however still insufficient (National Commission DWH, 2011). It is only by July 15th, 2010, 87 days after the spill began, that oil stopped leaking into the Gulf of Mexico, at which time BP successfully installed a capping stack on the damaged well (OSAT-1, 2010). Well integrity tests were carried out as a significant risk of underground blowout remained. An underground blowout causing the sands around the wellhead to liquefy could potentially have resulted in the loss of a significant portion of the 110 million bbl reservoir into the Gulf (National Commission DWH, 2011). In September 2010, 152 days after the blowout, the Macondo 252 well was officially declared dead when the first relief well drilled within four months finally intercepted the initial damaged well.

An interagency team, led by the Department of the Interior of the United States and the National Oceanic and Atmospheric Administration (NOAA), developed an Oil Budget Calculator to determine what happened to the oil (Lubchenco et al., 2011). The DWH spill oil budget estimated that of the 4.9 million bbl predicted to have escaped from the Macondo wellhead:

- 25 % was directly recovered, burned or skimmed from the water surface,
- 25 % had naturally evaporated or dissolved in the environment,
- 24 % was dispersed naturally (16 %) and chemically (8 %) as microscopic droplets in the Gulf waters
- 26 % of residual amount was still on the sea surface or stranded on the shoreline

By August 2010 studies show that most of the remaining oil had disappeared from the water column with less than 1 % of water samples containing MC252 polycyclic aromatic hydrocarbons (PAHs) levels above the US Environmental Protection Agency's aquatic life benchmarks (OSAT-1, 2010). Most of the residual amount of oil remaining in the environment (26 %, nearly 1.3 million bbl) that rose to the sea surface, and spent approximately one month at sea (OSAT-2, 2011), remained on or just below the surface as a light sheen and eventually became stranded near the shoreline as weathered tar balls (Lubchenco et al., 2011). The important shoreline clean-up effort along the impacted Gulf Coast removed much of the stranded oil residue. Oil was deposited along the shoreline in three zones: the subtidal, intertidal and supratidal (OSAT-2, 2011). Three types of located oil residue remained particularly challenging to collect, including supratidal buried oil, small surface residue balls and oil mats submerged by sand and sediments. Two years after the blowout, 634 of the 3,007 surveyed shoreline segments in the Eastern states still did not meet the endpoint criteria (OSAT-3, 2013) defined in the Deepwater Horizon Shoreline Clean-up Completion Plan (SCCP, 2011) because of periodic remobilization of submerged or buried weathered oil deposits. Identified mechanisms of weathered oil remobilization include cross-shore transport in the intertidal and nearshore subtidal zones, longshore transport and simple uncovering of material across tidal zones (OSAT-3, 2013).

In April 2014, 4 years after the incident, BP announced that it was ending its active clean-up activity of the Gulf Coastline after having collected 100,000 tonnes of material (BP, 2014) of which 10 to 15 % was residual oil (equivalent to approximately 100,000 bbl). However, the efforts to restore the Gulf are still ongoing, five years after the event (GECRC, 2015).

II The Great Australian Bight

The GAB is a body of water located to the south of Australia. It extends from Western Australia (WA) through South Australia (SA) to Victoria and covers an area of approximately 2,000 km in longitude and 1,000 km in latitude. This marginal sea is bounded by the Southern Ocean to the south, the Australian landmass to the north, the Indian Ocean to the west and Bass Strait to the east, connecting the GAB with the Tasman Sea between Tasmania and Australia.

II.1 Sea surface currents

The GAB has been described as a transit zone for sea surface mass transport between the Indian Ocean and the Southern Pacific Ocean (Lebreton et al., 2012). Sea surface water leaks from the Indian Ocean, transits in the Great Australian Bight and eventually enters the Tasman Sea and the Southern Pacific Ocean through Bass Strait and South of Tasmania. To the west, the Bight basin receives warm water from the Leeuwin Current that pushes water southward from tropical latitudes along the coast of WA. In the south, the colder Antarctic Circumpolar Current, mainly driven by strong winds, circulates eastward around Antarctic waters. Similarly to the Leeuwin current, the East Australian Current transports warm tropical water southward along the east coast of Australia from Queensland to Victoria (Figure 2). During summer, the prevailing easterly winds (see next section on wind climate) force the coastal waters offshore, generating three wind-driven upwelling centres spanning a distance of approximately 800 km along SA (Kämpf et al., 2004) forming the Great South Australian Coastal Upwelling System (GSACUS). Amongst this series of upwelling systems is the Bonney upwelling along the Bonney coast between Portland in Victoria and Kangaroo Island. Enriched nutrients are pushed to the surface, sustaining a rich ecosystem and feeding ground for Blue and Southern Right whales (Butler et al., 2012).

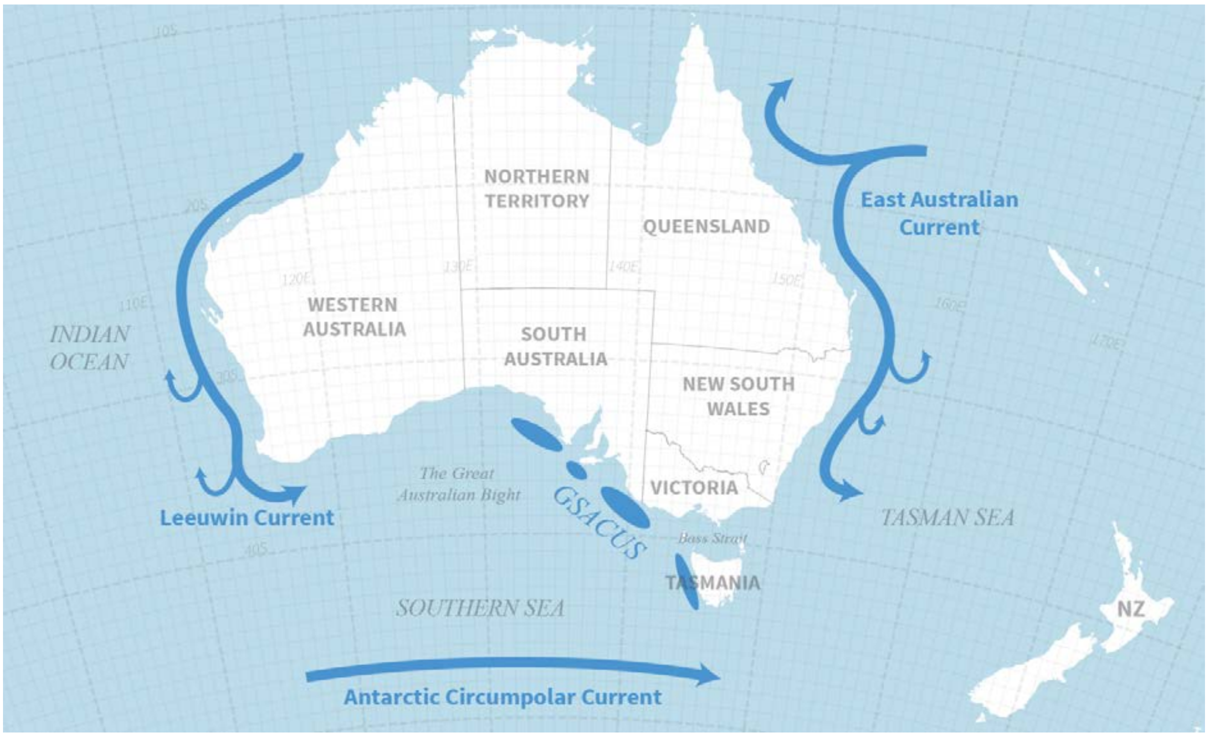

Figure 2: Predominant sea surface currents around the GAB and the Great South Australian Coastal Upwelling System (GSACUS). Upwelling locations adapted from (Kämpf, 2010).

II.2 Sea surface winds

The GAB is exposed to a relatively strong wind climate. The Southern Ocean is one of the windiest parts of the planet with sea surface wind increasing in more southerly latitudes. To describe the wind climate at the area of interest for this study, we extracted sea surface wind data from the 1948-present NCEP/NCAR global reanalysis (Kalnay, 1996) distributed by the Earth System Research Laboratory (ESRL) of NOAA. Here, we present a statistical analysis of a 20-year wind speed and direction time series for the global model node located at 35^{o}S, 130^{o}S. Table 1 shows the historical distribution of modelled wind speed between January 1994 and December 2014. The dataset was split in two parts between summer months (October to March) and winter months (April to September). While nearly half of the modelled velocities range from 5 to 10 m/s (Force 4 to 5 on the Beaufort scale) for both seasons (53 % in summer and 43 % in winter), much stronger winds occur more frequently in winter. For more than a third of the winter season, the wind blows at speeds above 10 m/s. Velocities above 15 m/s (Force 7 and higher on the Beaufort scale, moderate to strong gales) account for nearly 10 % of modelled wind speeds as opposed to roughly 3 % in summer. Extreme weather conditions and storm force winds (velocity above 20 m/s, Force 9 and higher on the Beaufort scale) occur in average for 1 % of the time during winter seasons.

Table 1: Wind speed distribution from NCEP/NCAR reanalysis at 35^{o}S, 130^{o}E (1994-2014).

Beaufort	**0 – 3**	**4 – 5**	**6 – 7**	**7 – 8**	**9**	**> 10**
Wind speed	0 – 5 m/s	5 – 10 m/s	10 – 15 m/s	15 – 20 m/s	20 – 25 m/s	> 25 m/s
Summer	21.9 %	52.6 %	22.6 %	2.8 %	0.1 %	0.006 %
Winter	19.9 %	42.9 %	27.8 %	8.4 %	0.9 %	0.053 %

One can observe significant seasonality in the climate when looking at the distribution of wind. Figure 3 shows wind roses for summer (left) and winter (right) depicting the seasonal wind direction and speed distributions for the time period 1994-2014 at the area of interest. In summer, the wind generally blows from the east and south-east while in winter, the usually stronger wind blows from the West and to a lesser extent from the North. As discussed in Section II.1, the prevailing easterly winds during the summer season are responsible for several upwelling systems along the south east coast of Australia. The most prominent of these occurs along the Bonney coast and is regularly observed between November/December and March/April (Butler et al., 2012).

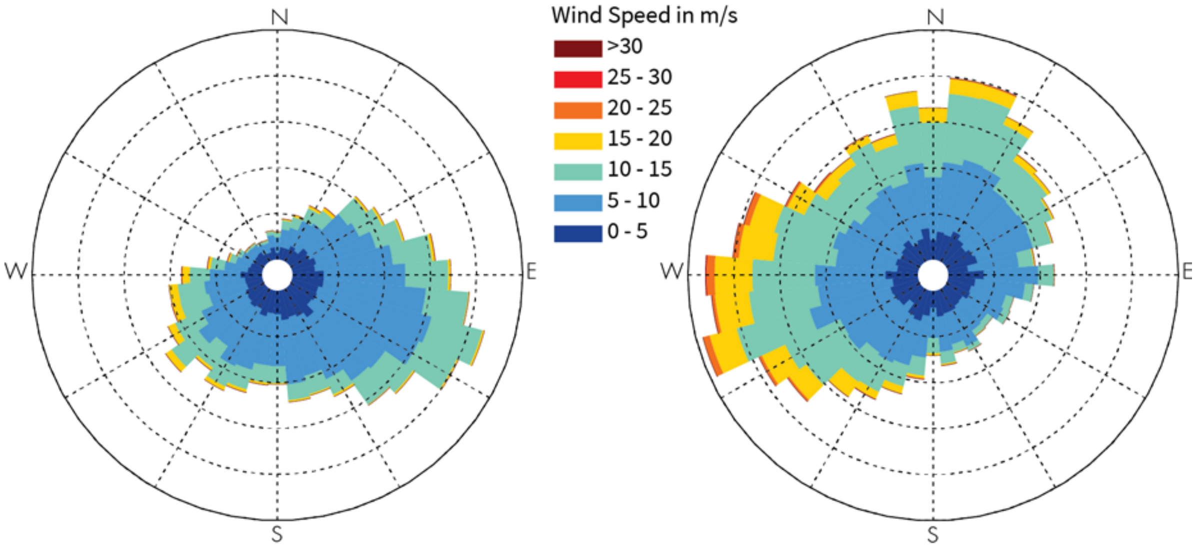

Figure 3: Modelled wind speed and direction roses for summer (left) and winter (right) at 35^{o}S, 130^{o}E for the period 1994-2014 (NCEP/NCAR global reanalysis).

II.3 Wave climate

The GAB is widely known for its highly energetic wave climate with ground swells regularly experienced year round from the Indian Ocean and the Southern Ocean into the Bight basin. For this study we use the global Wavewatch III (Tolman, 2002) model reanalysis from 2005 to 2012 to describe the wave climate in the GAB and present a statistical analysis between the summer and winter seasons at 35°S, 130°E near the area of interest. The Wavewatch III version 2.22 global hindcast reanalysis data product is distributed by the Marine and Modelling Marine Branch of NOAA.

The numerical model predicts significant wave heights[1] between 2.9 m and 3.7m for summer and winter respectively. By comparison, the 100-year return period significant wave height calculated from the Australian Region Geosat wave dataset at the same location ranges between 2.5 and 3.0 m (CSIRO, 2015).

The maximum modelled significant wave height in the area of interest was nearly 8 m in summer and above 10 m in winter during the 7-year period 2005-2012 (Table 2). The wave climate in the GAB is seasonal with larger waves occurring in winter as expected. Table 3 shows the distribution of modelled wave events sorted by significant wave height for the period 2005-2012 at the area of interest. During summer, the significant wave heights are between 2 and 4 m three-quarters of the time and above 4 m for 10 % of the time. However in winter, swell episodes with amplitude above 4 m are much more frequent and account for over a third of modelled wave heights. The area of interest is mainly exposed to south-westerly ground swell propagating inside the bight with peak periods averaging between 12.3 s and 13.4 s in respectively summer and winter (Table 2).

Table 2: Key characteristics of the wave climate in the Great Australian Bight from the global Wavewatch III reanalysis (2005-2012 at 35°S, 130°E)

	Summer	Winter
Significant wave height - average	2.9 m	3.7 m
Significant wave height - max	7.7 m	10.8 m
Peak wave period - average	12.3 s	13.4 s
Peak wave direction - average	SW (220.8°)	SW (227.2°)

Table 3: Distribution of significant wave height from the Wavewatch III global reanalysis at 35°S, 130°E for the period 2005-2012 for summer and winter

Significant wave height (m)	0-2	2-4	4-6	6-8	8-10	>10
Summer	14.7 %	74.5 %	9.8 %	0.98 %	0 %	0 %
Winter	3.9 %	62.1 %	27.8 %	5.6 %	0.53 %	0.04 %

A more detailed analysis of wave climate frequency and directional spectrum is given in Appendix A. We derived the average time interval between swell events from time series of significant wave height (Table 4). We consider this analysis relevant to this study as the extreme marine physical climate in the GAB is one of the main concerns in regards to the oil spill response plan proposed by BP. Swell events with a significant wave height above 3 m are relatively frequent all year round

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[1] The significant wave height corresponds to the amplitude trough to crest of the highest third of the waves within a random ocean wave spectrum. This value is commonly used as it statistically represents the wave height felt by an observer at sea.

within the Bight with an average time interval between 1.8 to 3.1 days depending on the season. As discussed earlier, episodes of larger swell are much more frequent in winter with events having a significant wave height above 5 m weekly and above 6 m every two weeks on average.

Table 4: Average time interval between swell events in summer and winter at the area of interest as a function of significant wave height, derived from the 2005-2012 significant wave height time series from the NOAA Wavewatch III global reanalysis data product.

	Summer	Winter
Hs > 3m	3.1 days	1.8 days
Hs > 4m	10.1 days	3.8 days
Hs > 5m	25.1 days	6.9 days
Hs > 6m	77.5 days	14.3 days

II.4 Marine habitat

The GAB is a breeding and feeding ground for various marine species. Particularly, the Department of Environment of the Australian Government lists several endangered marine species that may occur within the proposed GAB drilling areas (BP, 2012). Amongst them are several species of sea birds such as the Amsterdam, Tristan and Grey-headed albatrosses as well as the Southern and Northern Giant petrels. The endangered Loggerhead and Leatherback sea turtles are also commonly found in the area.

The GAB Marine Park at the Head of the Bight in South Australia is an important calving and mating area for the endangered Southern Right Whale (SACES, 2014). The Encounter Coast situated around Victor Harbour is also a significant habitat for Southern Right whales. The endangered Blue Whale is also drawn to the region, particularly around the Bonney upwelling area between Ceduna and Portland. The Bonney upwelling occurs during summer with the prevailing south-east winds and exhibits a distinct colder-water flora, and rich assemblages of sessile filter feeders such as sponges, bryozoans and corals. It provides a feeding ground for seabirds, fishes, whales as well as other higher order predators such as fur seals and penguins (Butler et al, 2002). Specifically, the upwelled nutrients stimulate the bloom of Phytoplankton, providing an abundance of food for migrating Blue whales. Figure 4 shows the commonly accepted Southern Right Whale and Blue Whale habitat in the GAB from data curated by the Department of Environment, Water and Natural Resources (DEWNR) of South Australia (DEWNR, 2005a and DEWNR, 2005b).

Another iconic species of the GAB region is the Australian Sea Lion, listed as vulnerable under the Commonwealth EPBC Act 1999 in 2005 and as a threatened species in both SA and WA (DSEWPaC, 2013). While the original range for the species is unknown, the Australian Sea Lion now only breeds in the coastal and offshore waters of SA. Most breeding colonies of Australian Sea Lion are small with less than 50 pups produced per season. Only a few colonies, all in South Australia, produce more than 200 pups per season. The estimated total pup production per season is 2,432 (Gales et al., 1994). Between 1987 and 2010, population estimates have ranged from 9,900 to 14,700 (Gales et al., 1994; Dennis and Shaughnessy, 1996; DEWHA, 2010). Figure 4 shows the reported Australian sea-lion breeding colonies in the GAB (DEWNR, 2012a).

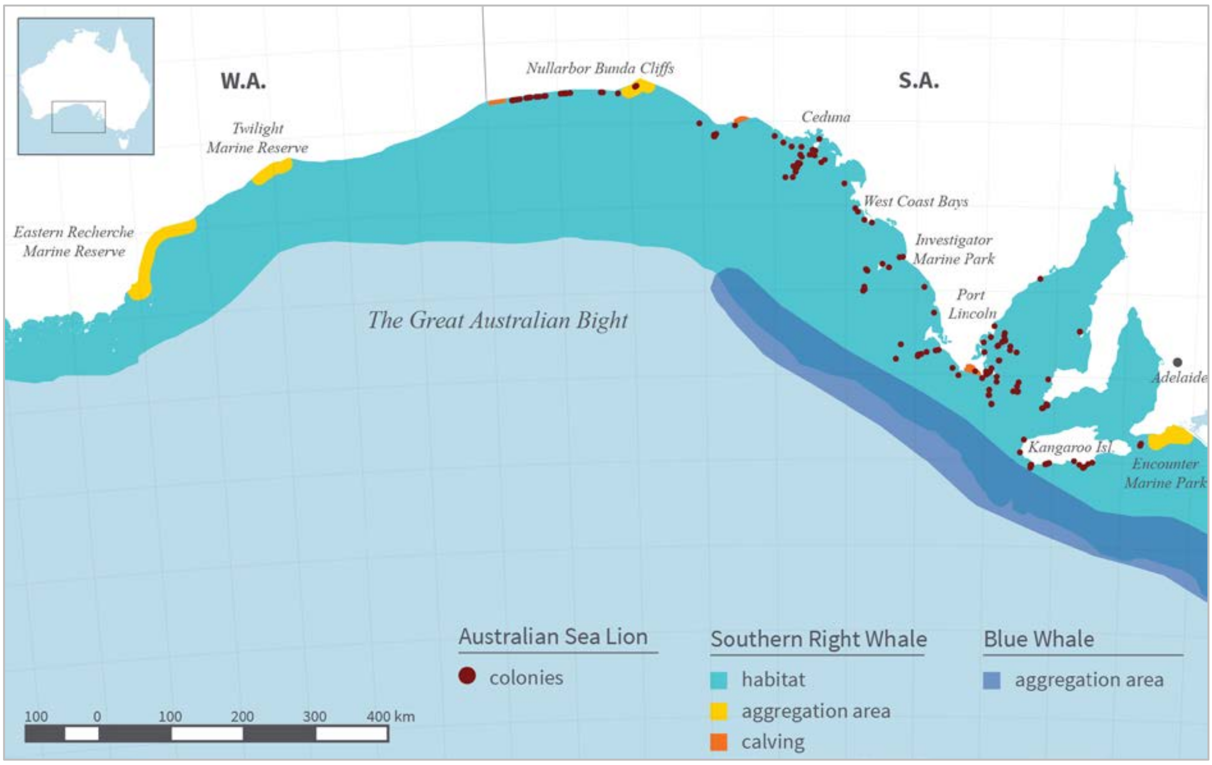

Figure 4: Habitat of iconic endangered marine species in the GAB.

II.5 Socioeconomic aspect

The South Australian fishing industry is an important contributor to the regional economy. During 2010-2011, the total volume of production of SA’s commercial wild fisheries was worth an estimated $197 million per year in 2010-2011 (Knight and Tsolos, 2012) and $199 million per year in 2012-2013 (EconSearch, 2014). The SA Research and Development Institute (Ward et al., 2012a) lists the following significant commercial fisheries: Abalone, Blue Crab, Marine Scalefish, Pipi, Prawn, Rock Lobster, Sardine and Charter Boat. Of all the wild-catch fisheries, the Rock Lobster is estimated to be the most valuable, followed by Prawn and Abalone. Additionally, the aquaculture industry is well established in the region with farms of Abalone, Pacific oysters, Southern Bluefin Tuna, Yellowtail Kingfish, Mussels and Algae production. The aquaculture industry was estimated to contribute to nearly 55 % of the state’s total value of sea food production in 2012-2013 with $243 million per year of which Tuna accounted for 63 % (EconSearch, 2014).

In particular, the Spencer Gulf and St Vincent Gulf creates ideal breeding conditions for the King Prawn and other crustaceans (Blue Crab, Lobster). The two gulfs are both shallow embayments located in temperate locations. The paucity of freshwater influx combined with high levels of evaporation during summer leads to increased levels of salinity offering a favourable breeding habitat for King Prawns (PIRSA, 2014).

The main fisheries of SA are shown in Figure 5 (Dixon et al., 2012, PIRSA, 2012, PIRSA, 2013, PIRSA, 2014, Ward et al., 2012b)

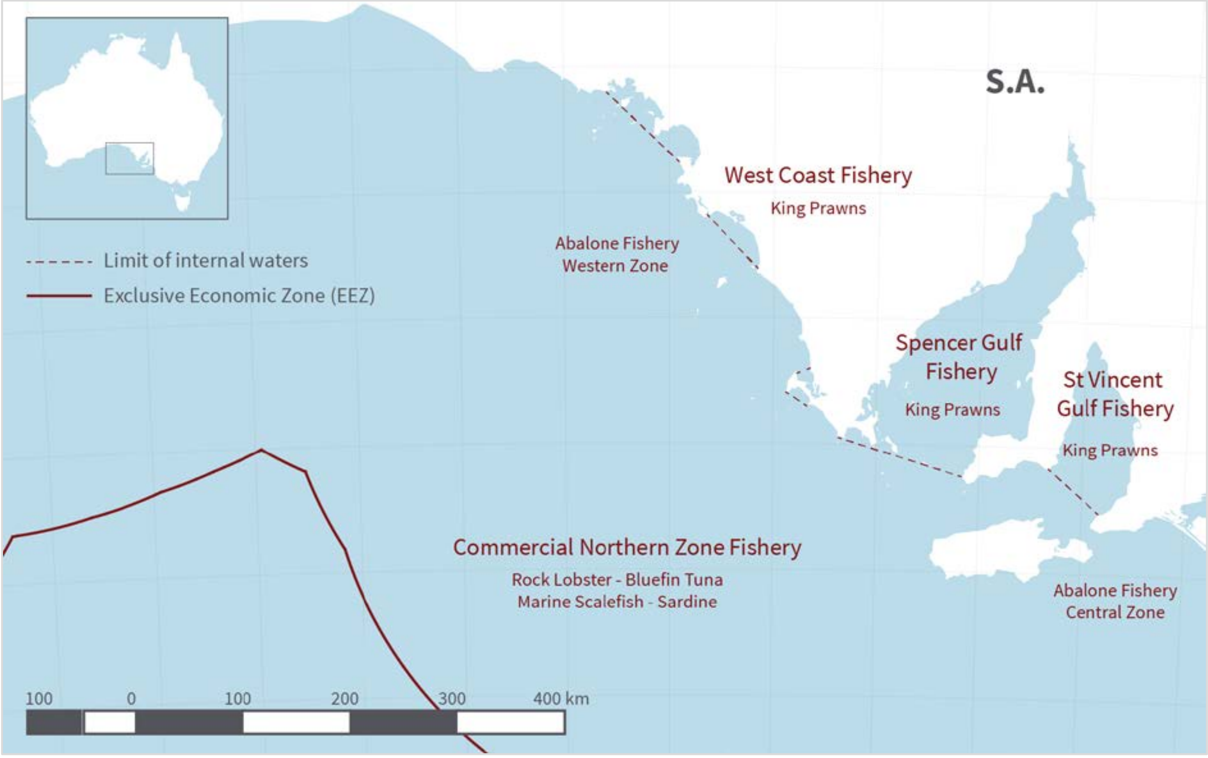

Figure 5: Main fisheries in SA.

In 2009, South Australia established a network of 19 marine parks in order to protect marine habitat, biodiversity, ecological processes and the sustainability of marine activities. The marine parks cover an area of 26,655 km^2 and include 44 % of South Australia's waters (DEWNR, 2012b). Within the marine parks, Sanctuary Zones (approximately 6 % of state controlled waters) have been established to provide protection and conservation for habitats and biodiversity, principally by prohibiting the removal and harm of plants, animals and marine products (SACES, 2014).

South Australia has been successful at developing nature based tourism and ecotourism in particular regions, with prime examples being Kangaroo Island and The Coorong (SACES, 2014). Tourism is a major contributor to the economy in the region with a combined $1.2 billion per year for 2013-2014 (Deloitte, 2015) in Yorke ($236 million), Eyre ($293 million) and Fleurieu ($360 million) Peninsulas, Kangaroo Island ($134 million) and the Limestone Coast ($259 million). Employment from the tourism industry in the region containing marine parks is estimated to directly and indirectly account for nearly 10,000 full-time equivalent jobs (EconSearch, 2012). The creation of highly protected marine ecosystems is expected to further provide a strong base for developing ecotourism in South Australia in the longer term by supporting the growth of activities such as whale and dolphin watching, shark watching, scuba diving and boating (SACES, 2014). In a recent study, the “Great Southern Reef” covering an area of nearly 71,000 km^2 along more than 8,000 km of temperate coastline across South Australia was estimated to generate $10 billion per year in fishing and tourism related activity (Bennett et al., 2015).

Figure 6 shows the current marine parks and commonwealth marine reserves in the GAB area. The state marine parks are represented in different shades of green according to their respective International Union for Conservation and Nature (IUCN) regulation code with IUCN IA being the most restrictive category.

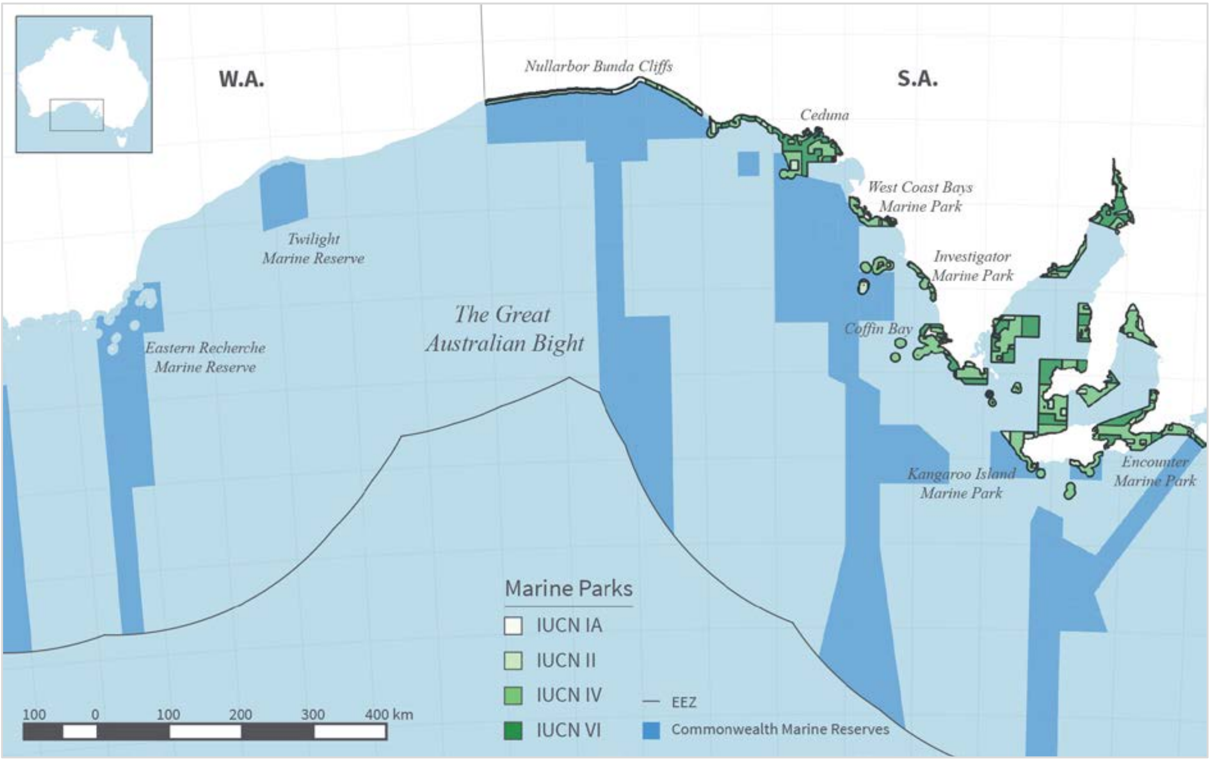

Figure 6: State marine parks and Commonwealth marine reserves in the GAB.

III Deepwater oil spill scenarios

In this study we are considering the potential impact of an oil spill in the GAB caused by the blowout of an oil drilling rig that leads to the uncontrolled release of crude oil at the sea bed into the water column. This represents an event analogous to the type of spill that occurred in 2010 during the DWH oil spill in the Gulf of Mexico. In terms of numerical modelling scenarios, an oil spill is characterised by the following key parameters:

- Release location
- Release duration
- Flow rate
- Crude oil type

Here we discuss the different oil spill scenarios that we considered for this study based on best-available information on BP's petroleum exploration campaign scheduled to start October 2016.

III.1 Release location

We estimated the location of the first exploration well based on information provided by BP's head of exploration for Asia-Pacific during an oil industry conference in Melbourne in 2015. Drilling is proposed to take place in the first well, named “Stromlo”, from October 2016 at a water depth of approximately 2.2 km and 3 km into the seabed (SMH, 2015). To estimate the release location, we overlaid the four petroleum exploration permit areas granted to BP Developments Australia Pty Ltd (EPPs 37, 38, 39 and 40), the 3D seismic survey area conducted as part of the campaign (BP, 2013a) and the 2.2 km isobaths from bathymetric data distributed by Geoscience Australia (Whiteway, 2009).

The estimated release location was placed at the intersection between the 2.2 km isobaths and the centre of EPP 39 at latitude 34.92^{o}S and longitude 130.58^{o}E. However, to confirm that the exact release location would not drastically influence our probabilistic analyses, we produced several probabilistic maps in which the release location was located on the 2.2 km isobaths in EPP 38 and EPP 40. The comparison between the different location release scenarios is presented in Appendix B.

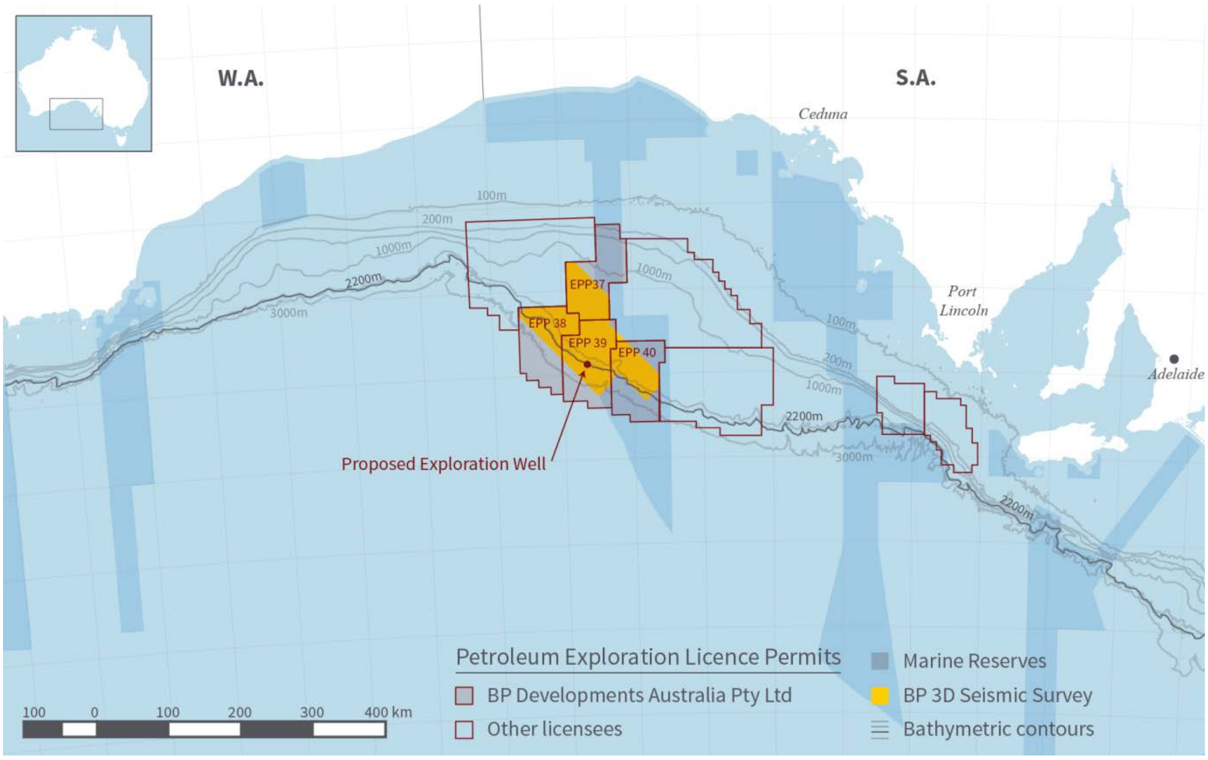

Figure 7: Estimated location for the exploration well "Stromlo" located in EPP 39 at a depth of 2.2 km. The location was selected using best available information (permits area, seismic survey area and disclosed information on depth of proposed well)

III.2 Release duration

Estimating the release duration for a deep water oil spill associated with a loss of well control event requires calculating the minimum time for the relief equipment to arrive on site and perform the blowout kill operations. In the EPBC Act Referral of proposed action (BP, 2012), details on BP's oil spill trajectory modelling study indicates two release duration scenarios: 35 days corresponding to the time required to place a capping system on the damaged well and 158 days which is the estimated time to drill a relief well. BP further detailed the logistics for both response plans under Freedom of Information Act (BP, 2013b). However, the numerical modelling results were only presented for the 35 day duration as BP purports that this duration is the most credible worst case scenario. Australian Government officials later questioned the choice for this duration and claimed it to be relatively optimistic (Department of the Environment, 2013b)

The 35 day duration scenario was based on detailed logistics for the mobilisation and installation of a capping stack from Oil Spill Response Limited (OSRL) in Singapore and the Containment Response System (CRS) from BP in Houston (BP, 2013b). The logistic studies for both response plans predicts a critical path duration of 32 days (OSRL, Singapore) and 29.5 days (CRS in Houston) for the relief equipment to arrive on site and be installed. The critical paths are synthetized in Table 5 and Table 6.

Table 5: Capping schedule – critical path to mobilise and install on site a capping stack from OSRL Singapore (BP, 2013b)

Days after incident occurs	Event	Duration
0	OSRL callout initiated	
+12	Capping stack equipment loaded on installation vessel and ready to depart from Singapore docks	12 days
+20	Transport from Singapore to Perth	8 days
+23	Unload, test equipment and load on vessels	3 days
+28	Transport from Perth to incident site	5 days
+32	Install cap and close well	4 days

Table 6: Capping schedule – critical path to mobilise and install on site the CRS from BP in Houston (BP, 2013b)

Days after incident occurs	Event	Duration
0	CRS callout initiated	
+14	Mobilise installation vessel, mobilise and transport CRS from Houston to Perth.	14 days
+25	Load and transport equipment from Perth to incident site	11 days
+29	Install cap and close well	4 days

While the industry has learned from mistakes made during the DWH oil spill catastrophe in 2010, where it took 87 days to cap the well after trying several response strategies (containment dome, top kill, collection device and finally capping stack), the duration BP estimated to transport the capping stack equipment from Perth to the well site and kill the spill has been particularly contested. TWS expressed concerns in regards to the time to transport and install the capping system on site which is mainly based on experience in the Gulf of Mexico where the oil industry is widely established and more so where the physical marine environment is significantly different with a much lower probability of severe storms at the exploration site. It should also be noted that in the event of the Gulf of Mexico oil spill, it took three days from finishing installing the capping system to get authorization to shut the stack as a risk of an even more catastrophic underground blowout at the wellhead remained. It is only 152 days after the blowout that the Macondo well was officially declared dead as BP achieved drilling the first relief well in September 2010 (National Commission DWH, 2011). For the proposed GAB exploration well, BP projected the drilling of a relief well to take 158 days, however the outcomes of BP's numerical modelling study for this duration has not yet been published.

For this study, we also investigate two release durations based on BP's purported worst credible case scenario and on the time it took to install the capping stack at the Macondo well. While best practice should be to take a conservative approach and use a release duration equivalent to the time required to drill a relief well (158 days), we have decided to use the two following scenarios to better compare with BP's modelling assessment, assuming the capping system would be sufficient to kill the damaged well.

- Duration 1: 35 days (BP's purported 'worst credible case' scenario)
- Duration 2: 87 days (DWH oil spill duration)
- *Duration 3: 158 days, not modelled (BP's advised timeframe to drill a relief well)*

III.3 Flow Rate

The predicted flow rate during a loss of well control event is influenced by several factors: the conduit through which the reservoir fluids can flow to get to surface, the pressure of the reservoir, the type of fluid and the amount of open hole drilled into the reservoir (BP, 2011). For the proposed GAB exploration well, BP did not provide the flow rate used for its numerical modelling study of deep water oil spill scenarios. Since the predicted flow rate is mainly based on the pressure of the reservoir and the diameter of the well, this information was claimed to be commercial material in confidence and exempt from Freedom Information Act public release.

For this study we estimate the flow rate associated with a loss of well control from previous reported discharge flow rates. For the Gulf of Mexico oil spill in 2010, the flow rate of oil entering the marine environment was estimated to have reached 62,200 bbl/day in April 2010 and dropped to 52,700 bbl/day in July 2010 (McNutt et al., 2011).

In the shallow waters of the Timor Sea, North West of Australia, the Montara well blowout incident in 2009 has been estimated by Geoscience Australia to have released 2,000 bbl/day and about 3,000 bbl/day by the Western Australian Greens party (MCI, 2010). An Environmental Impact Assessment published for another BP oil exploration prospect in the Cardhu reservoir in the North Sea investigated a pumping rate of 45,000 bbl/day (BP, 2011).

Only about 10 wells have been drilled in the eastern part of the Bight Basin at water depths between 70 m and 260 m and the GAB remains a frontier region with offshore areas largely unexplored. Considering the lack of information in regards to pressure reservoir in the GAB, we investigate two flow rate scenarios for this study, optimistic and pessimistic flow rates similar to the release durations. For the worst case scenario, we decided to use a flow rate below the volume estimated during the DWH spill to take into account potential response operations in the event of deep water well failure.

- Flow rate A: 5,000 bbl/day, optimistic
- Flow rate B: 50,000 bbl/day, pessimistic

Combining the two release durations with the two flow rate scenarios we compare the four discharge scenarios investigated during this study (1A, 1B, 2A and 2B) with historical data on oil spill events worldwide (Figure 8).

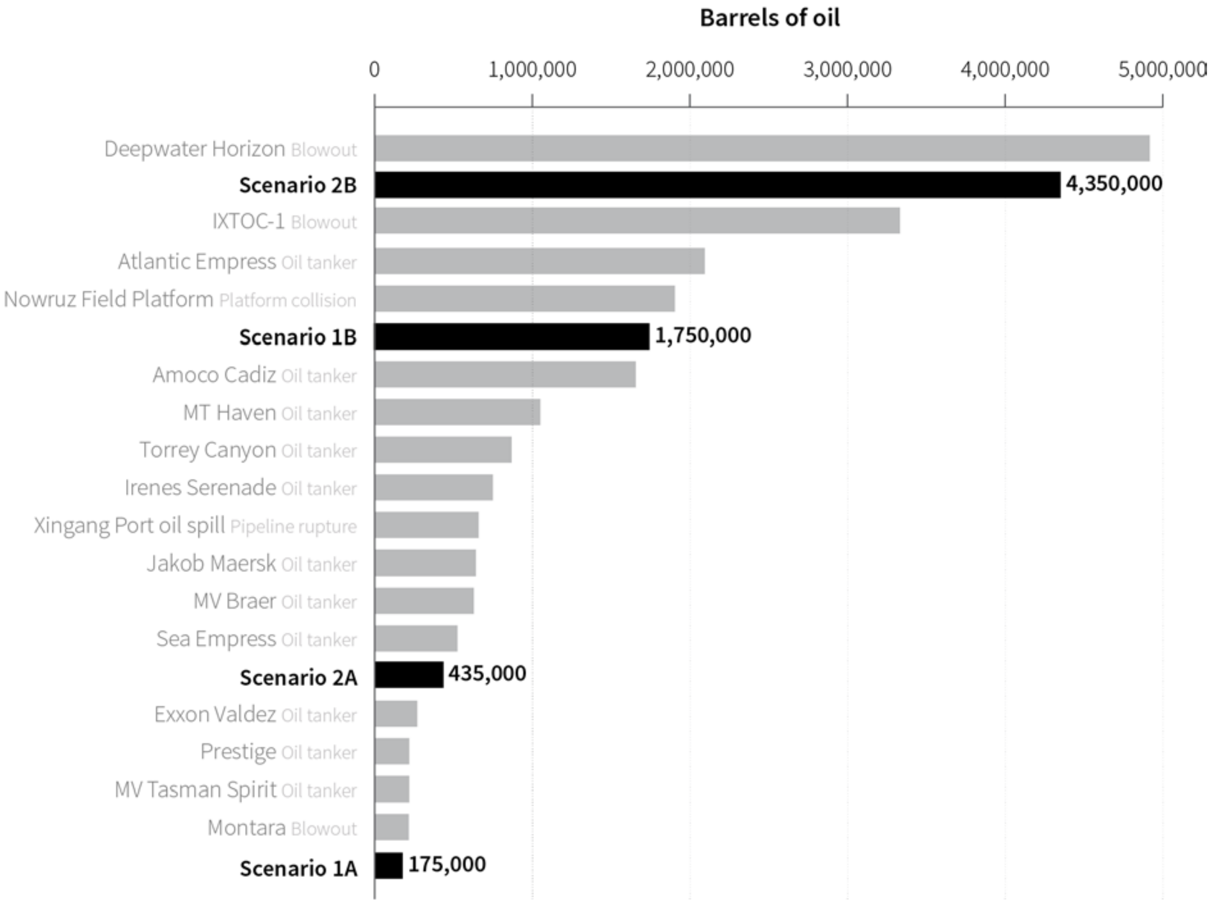

Figure 8: Comparison of the modelled volume scenarios (1A, 1B, 2A and 2B) and major historical oil spill events worldwide. Volumes are expressed in barrels. (McNutt et al., 2011, Etkin, 1999, MCI, 2010, ITOPFL, 2013)

III.4 Crude Oil Type

Given the deep waters of the Bight basin is a frontier oil and gas exploration area with no previous hydrocarbon discoveries, the properties of potential hydrocarbons and hydrocarbon phase remain uncertain (BP, 2012). According to BP's petroleum systems analysts and geologists, the GAB is likely to be predominantly gas-prone with condensate to gas ratios varying from dry gas to volatile oil.

A distinction is frequently made between non-persistent oils, which, because of their volatile nature and low viscosity, tend to disappear rapidly from the sea surface, and persistent oils, which dissipate more slowly and usually require a clean-up response. As a general rule, the lower the specific gravity of the oil the less persistent it will be (Lenting and Pratt, 1998).

BP initially published results for a volatile oil scenario with an American Petroleum Institute (API) gravity range between 36 and 48. However, as the best practice for environmental impact assessments is to investigate conservative oil types (with no or very low weathering processes) and because oil spill preparedness and response planning should be based on hydrocarbon type that has the potential for the worst environmental consequences, BP eventually released modelling results for an "oily" case scenario corresponding to hydrocarbons with an API gravity ranging from 27 to 33 (BP, 2013b). This information was provided to the Australian Government that has been publically obtained through Freedom of Information.

Crude oils of different origins vary widely in their physical and chemical properties. The main physical properties that affect the behaviour and the persistence of oil spilled at sea are the specific gravity, distillation characteristics, viscosity and pour point (ITOPFL, 2002). Table 7 gives the conversion between the API gravity ranges estimated by BP and the corresponding specific gravity and density of oil.

Table 7: Conversion table between API gravity used by BP, specific gravity and density.

API	27	33	36	48
SG	0.89	0.86	0.84	0.79
ρ (kg/m^3)	889	859	839	789

While a conservative approach would be to use non-weathering oil for an impact assessment, to achieve a more realistic understanding and compare our results with BP’s modelling assessment we used the weathering characteristics of a typical medium crude equivalent to BP’s ‘oily case’ scenario which takes into account the weathering of lighter compounds but contains a significant portion of persistent compounds. We considered an oil type with the following crude compounds:

Table 8: Three-compound crude used as oil type for this study, proportion and main behaviour at sea

	Light Compounds	Medium Compounds	Heavy Compounds
Proportion	22 %	26 %	52 %
Behaviour at sea	Evaporate	Naturally disperse and evaporate	Persistent

A detailed explanation on how the weathering processes are generally treated in the numerical model is given in the next section of this study.

IV Numerical modelling of marine oil spills

IV.1 Fate of oil at sea

The fate of spilled oil in water bodies is governed by physical, chemical, and biological processes (Wang, Shen and Zheng, 2005). This includes the chemical properties of the crude oil itself as well as the environmental conditions (Sebastiao and Guedes Soares, 1995) which are site and time dependent.

When liquid oil is spilled on the sea surface, it spreads to form an oil slick (Wang, Shen, & Zheng, 2005). However, such slicks are not evenly distributed, but rather spread irregularly on the water as bands or tarballs with clean water in between. (NOAA, 2013)

The physical and chemical changes that spilled oil undergoes are collectively known as 'weathering'. (ITOPFL, 2002). These processes include:

- **Advection** which is the transport of oil horizontally or vertically and depends primarily on the hydrodynamics, meteorological and environmental conditions. (Wang, Shen, & Zheng, 2005).

- **Evaporation** of the oil from its liquid to gas state and is the primary initial process involved in the removal of oil from sea. (Sebastiao and Guedes Soares, 1995).

- **Dispersion**, the process of forming small droplets of oil which become incorporated into the water column and are then driven by current, wave and wind action (Wang, Shen, & Zheng, 2005). Besides evaporation, the rate of natural dispersion largely determines the life of an oil slick on the sea surface (Sebastiao and Guedes Soares, 1995).

- **Emulsification** which involves the dispersion of water droplets into the oil medium (Sebastiao and Guedes Soares, 1995). Emulsification and evaporation lead to decreased oil-water density difference, and increased pour point (Reed, et al., 1999). Emulsification is a key process in determining spill lifetime as well as the window of opportunity for spill response (Nordvik et al., 1995). However, reliable computations of emulsion formation, stability, and associated viscosity at present require laboratory or field observations. (Reed, et al., 1999).

- **Spreading** of low pour point oil released on water is probably the most dominant process in the first stage of the spill (Sebastiao and Guedes Soares, 1995). Spreading is important in determining the fate of spilled oil through evaporation, emulsification, and natural dispersion. Release conditions are also relevant in determining initial spreading. Underwater releases, for example, result in very different initial surface distributions of oil than surface releases (Reed, et al., 1999).

- Other processes are **dissolution**, **sedimentation** by sinking, **photo-oxidation** (Ferreira, Cabrai and Junior, 2003) and also **biodegradation** (Sebastiao and Guedes Soares, 1995).

Although the individual processes causing these changes may act simultaneously, their relative importance varies with time (ITOPFL, 2002) as illustrated in Figure 9.

It is well known that advection, dispersion and evaporation are the dominant processes in oil weathering, mostly governed by environmental forces (Reed, et al., 1999) and are the ones considered by mathematical models for quantitative estimation of oil spills at sea (Ferreira, Cabrai and Junior, 2003).

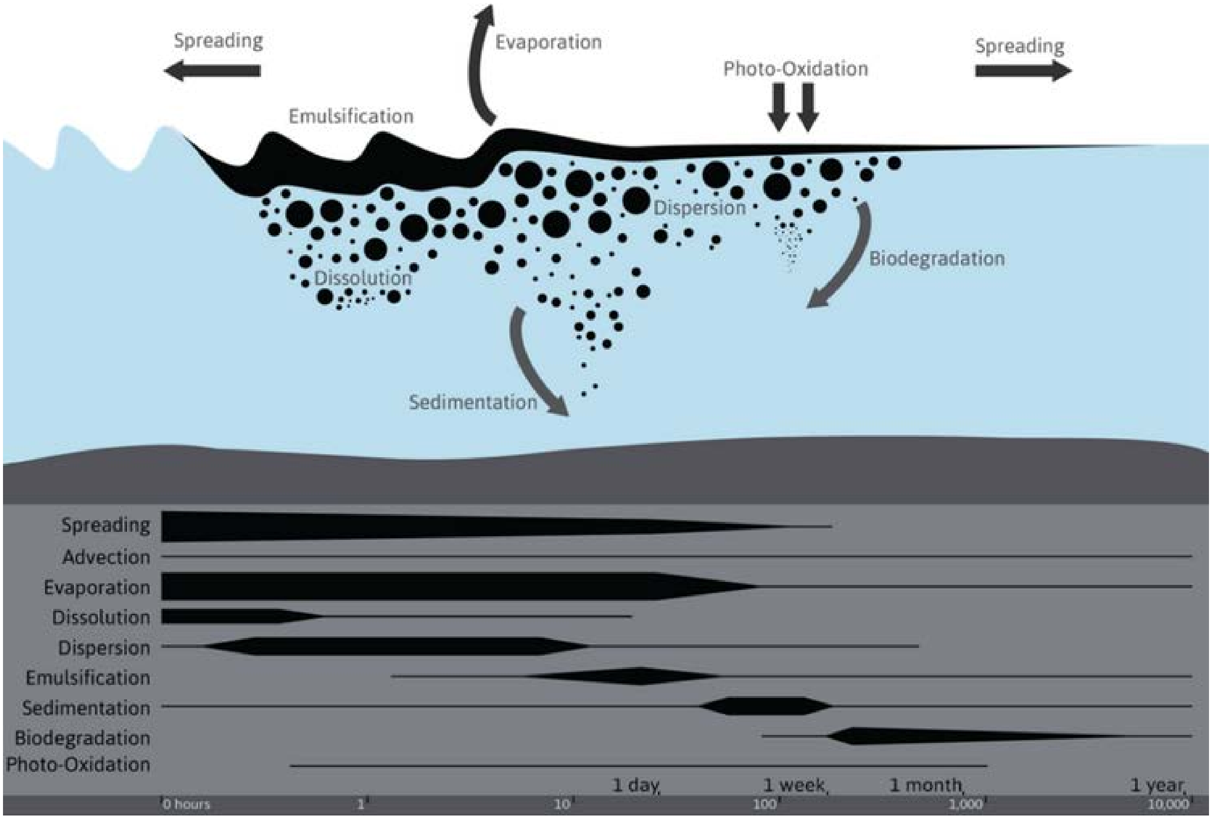

Figure 9: Physical and chemical processes causing change in oil characteristics of a typical medium crude oil under moderate sea conditions, adapted from ITOPFL (2002). The schematic at the bottom shows the relative importance of weathering processes of an oil slick over time. The width of the line shows the relative magnitude of the process in relation to other contemporary processes. Adapted from Hazardous Materials Response and Assessment Division.

IV.2 Trajectory modelling

Numerical modelling of oil spill dispersion generally uses a Lagrangian approach (Reed, et al., 1999). In this framework, an oil slick is driven by oceanic currents and winds and treated as a large number of independent particles whose paths and mass are recorded in time. While studying the trajectory of an individual oil slick is a deterministic investigation, for this study, we propose a stochastic analysis. By analysing the progress of a large number of trajectory simulations, the potential severity of environmental impacts resulting from an oil spill can be assessed (Ferreira, Cabrai and Junior, 2003). A probabilistic approach is presented by simulating thousands of events randomly scattered through 20 years of environmental hindcast data and then by computing the relative frequency of a given target being reached by a spill.

IV.2.a Dispersal model

The oil spill dispersal model used in this study is the publicly available General NOAA Oil Modelling Environment (GNOME). GNOME was designed for the rapid modelling of pollutant trajectories in the marine environment (Beegle-Krause, 2001). The model has been extensively tested and verified (NOAA, 2012). GNOME resolves a forward Euler scheme to predict the overall movement of spill particles as they are forced by oceanic currents, wind and diffusion according to the equation (Beegle and Kraus, 1999):

$$\frac{\partial X}{\partial t} = U_h + k_w U_w + D$$

Where $\frac{\partial X}{\partial t}$ is the particle displacement, U_h, the hydrodynamic forcing velocity, k_w, the windage coefficient (typically between 1 and 4 %), U_w the wind forcing velocity and D, the turbulent diffusion component.

For this study, we built two different models: a local, fine resolution (1/12°) model covering the GAB to predict short term local impacts and a larger, coarser resolution (1/3°) model integrating parts of the Southern Ocean, Bass Strait and the Tasman Sea to evaluate long term impacts and estimate how far droplets of oil can travel within a 6-month time period.

The extent of both models is shown in Figure 10 and further details on coverage and resolution is given in Table 9.

Table 9: Numerical model grid descriptions for both fine and coarse resolution model used in this study.

	Longitude	Latitude	Resolution	Average cell area
GAB model	120E – 140E	40S – 30S	0.08 degree	~ 60 km^2
Southern Sea Model	100E – 180E	50S – 30S	0.32 degree	~ 960 km^2

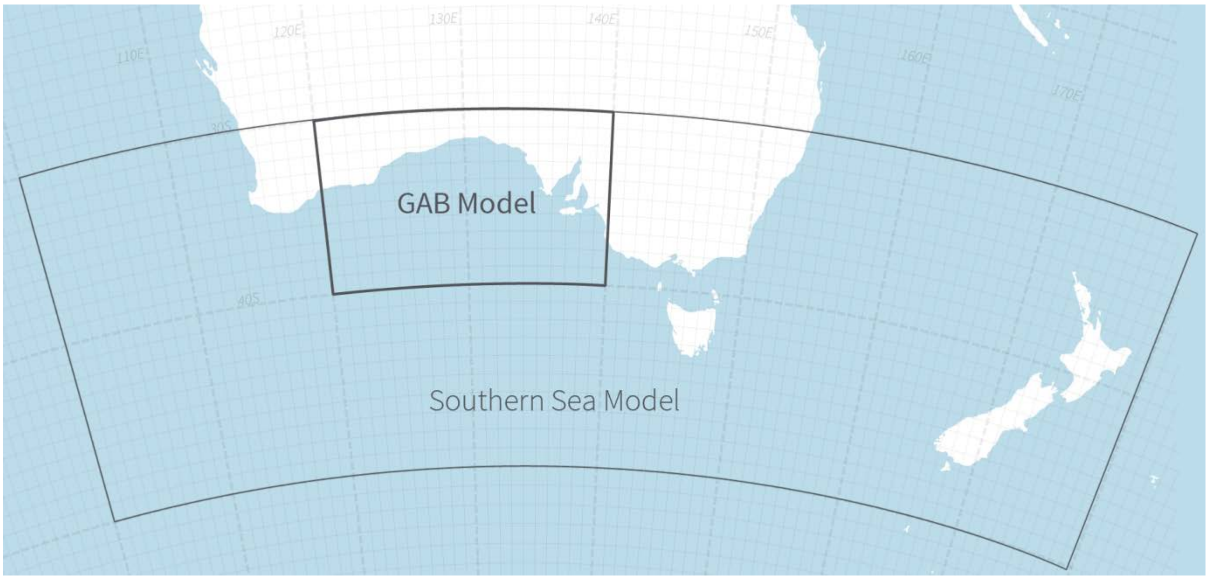

Figure 10: Fine resolution model grid around the GAB and coarse resolution model including the Southern Sea, Bass Strait and the Tasman Sea.

IV.2.b Environmental forcing

Sea surface current data is extracted from the 1992-present HYCOM/NCODA 1/12^{o} reanalysis (experiment 19.0, 19.1, 90.9, 91.0 and 91.1, Cummings and Smedstad, 2013, Cummings, 2005, Fox et al., 2002) distributed by the Naval Research Laboratory (NRL) of the US Navy. The system is configured using the Global Hybrid Coordinate Ocean Model (HYCOM, Chassignet, et al., 2007) version 2.2 and the output is served on a uniform grid. The HYCOM model is forced by the US Navy's Operational Global Atmospheric Prediction System (NOGAPS) and includes wind stress, wind speed, heat flux, and precipitation. The model provides systematic archiving of daily three-dimensional ocean circulation on a global scale with output data archived back to 1992. Latitudinal and longitudinal sea surface current components were extracted from January 1st, 1994, to December 31st, 2014, at a 12 hourly time step and a spatial resolution of 0.08 degrees (7-9 km depending on location). Tidal forcing is not represented in HYCOM. Therefore model artefacts could occur for regions where tide-driven circulation is significant such as in the shallow waters of Spencer Gulf or St Vincent Gulf. While the modelled particles are mainly transported by sea surface currents, the numerical model integrates wind forcing (or windage) by adding an advection term proportional to wind speed and direction. Sea surface wind induced advection is typically about 3 % of the wind speed based on analytical derivation and empirical observations of oil spreading out in the direction of the wind (Stolzenbach, Madsen, Adams, Pollack and Cooper, 1977). It is noted that the windage is reduced as the oil weathers and spends more time below the surface (NOAA, 2012). Based on observation and experience (Lehr and Simecek-Beatty, 2000), a random windage value between 1 to 4 % was taken for this modelling exercise with a wind persistence (the amount of time before the random value is reset) of 15 minutes. Sea surface wind data was sourced from the 1948-present NCEP/NCAR global reanalysis (Kalnay, 1996) distributed by the Earth System Research Laboratory (ESRL) of NOAA. We extracted data from January 1st, 1994, to December 31st, 2014, at a 6 hourly time step and a spatial resolution of 2.5 degrees. Finally an additional diffusion term is applied to the trajectory particles. Random spreading is simulated using a simple 'random walk' approach with a square unit probability (Csanady, 1973). We used a random diffusion factor of 100,000 cm^2/sec (horizontal eddy diffusivity as recommended for the default GNOME setting). In GNOME diffusion and spreading are treated as stochastic processes. Gravitational and surface tension effects are ignored, as these are only important during the first moments of a spill. Complex representation of sub-grid diffusion and spreading effects are ignored. (NOAA, 2012).

IV.2.c Weathering

GNOME uses a relatively simple 3-phase evaporation algorithm where the pollutant is treated as a three-compound substance with independent half-lives (Boehm et al., 1982). The concept of a 'half-life' is helpful in defining removal rates of less persistent oils. A half-life is the time required for a quantity of oil to fall to half its original value, consequently non-weathering oils are represented by an infinite half-life parameter. Since the exact characteristics of the potential crude oil material below the GAB's seafloor remains unknown to date, scenario (BP, 2013b), we modelled the behaviour of a typical medium crude oil using three main compounds as detailed in Table 8. This is similar to BP's 'oily case'. The lighter compound representing mostly gas and volatile components are likely to evaporate or be naturally dispersed within the first hours after entering the marine environment. Larger polycyclic aromatic hydrocarbons will likely disperse within the first days after surfacing. Finally, the residual oil, mostly heavy components such as tar, is much more persistent at sea. The half-life parameters for each compound are given in Table 10.

Table 10: Three-compound substance and associated half-lives for the crude oil type used for this study

	Light component	Medium component	Heavy component
Proportion	22 %	26 %	52 %
Half-Life in hours	14.4	48.6	$1.0\text{x}10^9$

IV.2.d Beaching

Beaching is the process of oil washing up on shore and either adhering or being remobilised by wind and/or wave activity. The re-floatation half-life is a parameter which empirically describes the adhesiveness of the oil to the shoreline. It is a function of substrate porosity, the presence or absence of vegetation, the inherent stickiness of the oil, and other physical properties and environmental processes (Danchuck, 2009). Re-floatation half-life values such as those provided by (Torgrimson, 1980) are generally given in terms of the number of hours over which half of the oil on a given shoreline is expected to be removed if (1) there is an offshore wind or diffusive transport and (2) the sea level is at the same level or higher than the time when the oil was beached. Since it is based on observations of removal rates from previous spills, the half-life method does not represent the detailed physics of the remobilization process, but is commonly used due to the complexity of trying to model shoreline-oil interactions at large scales. Oil re-floatation half-lives are different for each shoreline type depending on substrate, vegetation and oil type (Torgrimson, 1980). Values typically used for mud, sand and vegetation are 1, 24 and 8760 hours respectively. This parameter, along with the other environmental data, allows re-floatation of oil after it has impacted a given shoreline. (NOAA, 2012). The re-floating half-life parameter was set to a standard 24 hour in our model.

IV.3 Stochastic modelling

IV.3.a Probabilistic analysis

Model runs can be automated to produce a large number of trajectories under variable marine climate conditions. The full environmental forcing dataset was separated in two seasons: summer (from October to March) and winter from (April to September). A thousand spills per scenario and per season were simulated with different starting times within the corresponding months over the 20-year long database. The resulting trajectory database was then statistically analysed. NOAA's Trajectory Analysis Planner (TAP) computes probabilistic quantities from a large number of pre-computed trajectories (NOAA, 2000). TAP was designed to assist with the following planning tasks (Samuels et al., 2013):

- Assessing potential threats from possible spill sites to a given sensitive location,
- determining which shoreline areas are most likely to be threatened by a spill,
- calculating the probability that a certain amount of oil will reach a given site within a given time-period and
- estimating the levels of impact on a given resource from a spill.

In this study we focus on two main analyses: an impact analysis and a response time analysis. The impact analysis consists in locally evaluating how many spills raised the oiling thickness above specific thresholds within a given time after the incident. Whereas the response time analysis looks into what the minimum time was for the exceedance of a specific oiling threshold at a given location for a combined 95 % of spill trajectories.

IV.3.b Oiling thresholds

Similarly to BP's numerical modelling assessment, we consider different oiling thresholds for the sea surface and for the shoreline. Additionally, we introduce the type of impact as an additional factor for the analysis. A socioeconomic and an ecological threshold for both shoreline and sea surface were defined using recommended values by NOAA (2013). The different oiling thresholds investigated in this study are detailed in Table 11. At the sea surface the socioeconomic threshold was set at 0.01 g/m^2 which would correspond to a barely visible sheen of oil on the water surface. This level would likely trigger the closure of fisheries as fishing is prohibited in areas with any visible oil to prevent contamination of fishing gear and catch. On the shoreline, the socio economic threshold at 1 g/m^2 (~500 tarballs per acre of shoreline) corresponds to a level that would require an active beach clean-up operation. Ecological thresholds were defined according to minimum oiling levels likely to mortally impact wildlife at sea (10 g/m^2) and on the shoreline (100 g/m^2, French, 1996).

Table 11: Oil thickness thresholds for surface and shoreline (socioeconomic and ecological) used in this study. Adapted from (NOAA, 2013).

Oil Description	**Sheen Appearance**	**Approximate Sheen Thickness**		**No. of 1 inch Tarballs**	**Impact**
Oil Sheen	Barely Visible	0.00001 mm	0.01 g/m^2	~5-6 tarballs per acre	Socioeconomic (Surface)
Heavy Oil Sheen	Dark Colours	0.01 mm	10 g/m^2	~5,000-6,000 tarballs per acre	Ecological (Surface)
Oil Sheen/Tarballs	Dull Colours	0.001 mm	1 g/m^2	~500-600 tarballs per acre	Socioeconomic (Shoreline)
Oil Slick/Tarballs	Brown to Black	0.1 mm	100 g/m^2	~50,000-60,000 tarballs^{s} per acre	Ecological (Shoreline)

As a comparison, for its stochastic modelling analysis, BP (2012) used a single surface oiling threshold of approximately 4 g/m^2 (as 5 µm thick oil sheen, using the given API of 36-48 for the volatile oil case) and a single shoreline oiling threshold of 80 g/m^2 (as 0.1 l/m^2, given the same API) which represents approximately more than 40,000 1-inch tarballs per acre of coastline. In response to the submitted EPBC Act referral, the Department of the Environment has recommended BP to lower its initial oil thickness threshold as previous EPBC assessments have included oil spill modelling at a threshold of 1 g/m^2 on the basis that it should be the threshold for biological impact (Department of the Environment, 2013a).

It is of critical importance to understand that the risk assessment derived from the stochastic analysis is highly dependent on the oiling threshold initially considered.

V Analysis of oil spill trajectories

Here we present the numerical modelling results for the four deep water oil spill scenarios for both winter and summer in the GAB. The analysis of 1,000 modelled spill trajectories per season is detailed in this section. First, we provide an impact analysis by computing the proportion of spill trajectories that reached the different oil thickness thresholds introduced earlier in this report. Secondly, we assess a response time analysis by predicting how fast and how far the oil can travel within a maximum period of six months. Finally we focus the analysis on twelve different areas of particular interest for their socioeconomic and/or ecological values.

V.1 Impact analysis

An impact analysis is the most obvious way of assessing a trajectory analysis. Given a set of trajectories, an impact analysis calculates the proportion of spills that reach an oil thickness level exceeding a fixed level of concern. Care is to be taken when interpreting these results. They represent the probability of a given area to reach a certain oiling threshold, not the extent of an oil spill at a particular time. As an example, if in the early stage of a spill, one trajectory extends westward and another eastward, the resulting impact analysis for the two trajectories will show a horizontal extent, west to east with an impact probability of 50 %. This does not mean that an oil spill has 50 % chance of having this extent, but that for locations inside the extent, there is 50 % chance to be reached by oil (alternatively going west or east).

Here we describe the numerical model results for the four oil spill scenarios presented earlier in this report. While the full impact analysis is mapped in Appendix C, we summarize the main results in this section and demonstrate how the release flow rate and the selected season for the simulations are the main factors governing the impact.

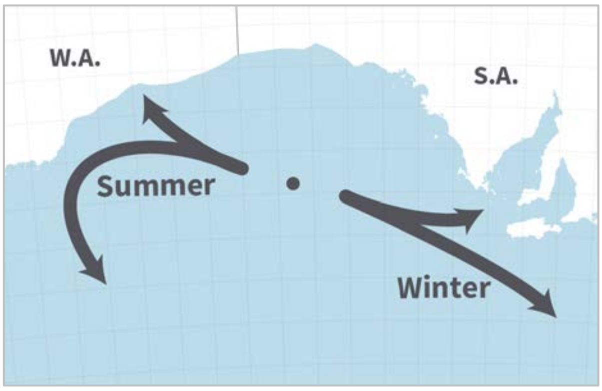

Figure 11: Schematic of general oil transport at the sea surface depending on the modelled season.

When looking at the pathways of modelled oil particles, one can observe clear seasonal trends between summer and winter (See Figure 11). Trajectories that started during the summer months usually show a sea surface transport of oil towards north-west whereas trajectories starting during the winter months are generally concentrated in the eastern side of the Bight basin. In that sense, regardless of the oil spill release scenario, the numerical model predicts that in the short term, in the event of a blowout in the GAB, crude oil lost in the marine environment is likely to impact the shores of WA should the event occur in summer whereas it would most likely reach the Eyre Peninsula and Spencer Gulf in SA if the incident should happen during winter. In the long term though, the numerical model predicts that remaining droplets of oil at the sea surface would progressively leave the GAB and transit towards the Tasman Sea through Bass Strait and around Tasmania. Table 12 summarizes the key findings for each scenario.

Table 12: Key findings from the impact analysis by oil spill scenario and by season. The scenarios are sorted by degree of severity.

Scenario	Summer	Winter
1A 5,000 bbl/day 35 days	Very likely socioeconomic impact at sea in the Commonwealth waters of WA. Potential socioeconomic impact on the shoreline of WA.	Very likely socioeconomic impact at sea in SA’s fisheries and state marine parks. Potential socioeconomic impact on the shoreline from West Coast Bays to Kangaroo Island.
2A 5,000 bbl/day 87 days	Very likely socioeconomic impact at sea in the Commonwealth waters of WA. Likely socioeconomic impact on the shoreline of WA.	Very likely socioeconomic impact at sea in SA’s fisheries and state marine parks. Likely socioeconomic impact on the shoreline from West Coast Bays to Kangaroo Island.
1B 50,000 bbl/day 35 days	Very likely socioeconomic impact on the shoreline in WA. Potential ecological impact at sea in Southern Whale aggregation areas of WA.	Very likely socioeconomic impact on the shoreline from West Coast Bays to Kangaroo Island. Potential ecological impact at sea at the entrance of Spencer Gulf.
2B 50,000 bbl/day 87 days	Very likely socioeconomic and potential ecological impact on the shoreline in WA. Likely ecological impact at sea in whale aggregation areas of WA.	Very likely socioeconomic impact on the shoreline from West Coast Bays to Kangaroo Island. Likely ecological impact at sea at the entrance of Spencer Gulf. Possible ecological impact on the shoreline of Kangaroo Island.

Figure 12 and Figure 13 respectively depict the probability of socioeconomic impact at sea after four months for scenario 2A (5,000 bbl/day, 87 days) during summer and winter with an oiling threshold of 0.01 g/m^2 (socioeconomic threshold) corresponding to a level that would likely trigger the closure of fisheries. The socioeconomic impact analysis is overlaid with state marine parks and Commonwealth marine reserve areas. Under summer conditions and within four months, the model predicts that an area of roughly 213,000 km^2 would have an 80 % chance to have an oil thickness level above the socioeconomic threshold at the surface. This area extends from the proposed exploration well towards the coast of Western Australia near the Twilight Marine Reserve. During winter, within four months, the area where at least 80 % of the trajectories raised the oil thickness level above the socioeconomic threshold represents a surface of approximately 265,000 km^2 covering the offshore waters around the proposed exploration well to the entrance of Spencer Gulf, reaching the Eyre Peninsula and Kangaroo Island.

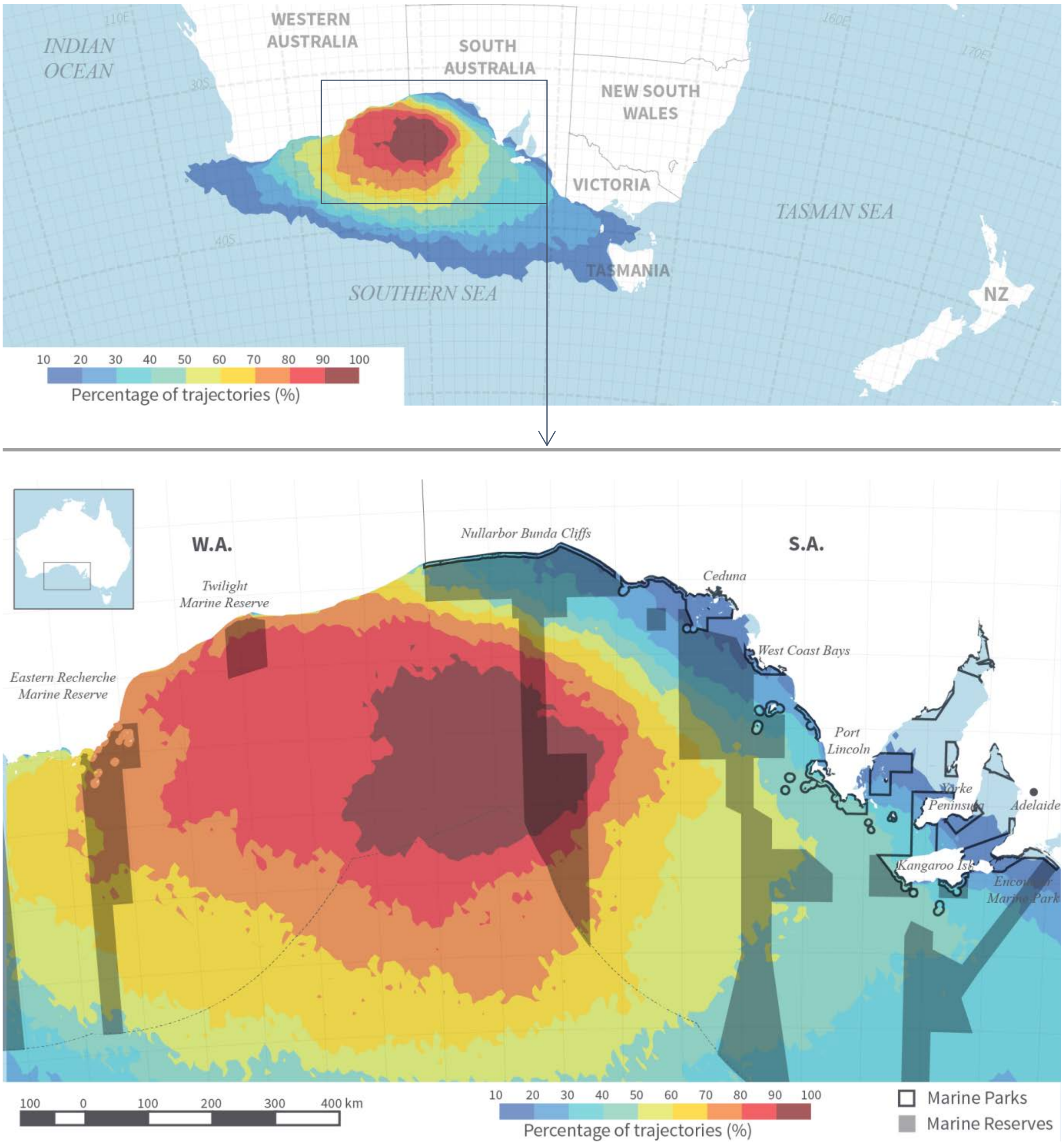

Figure 12: Socioeconomic impact analysis for summer after 4 months (scenario 2A with oiling threshold of 0.01 g/m^2).

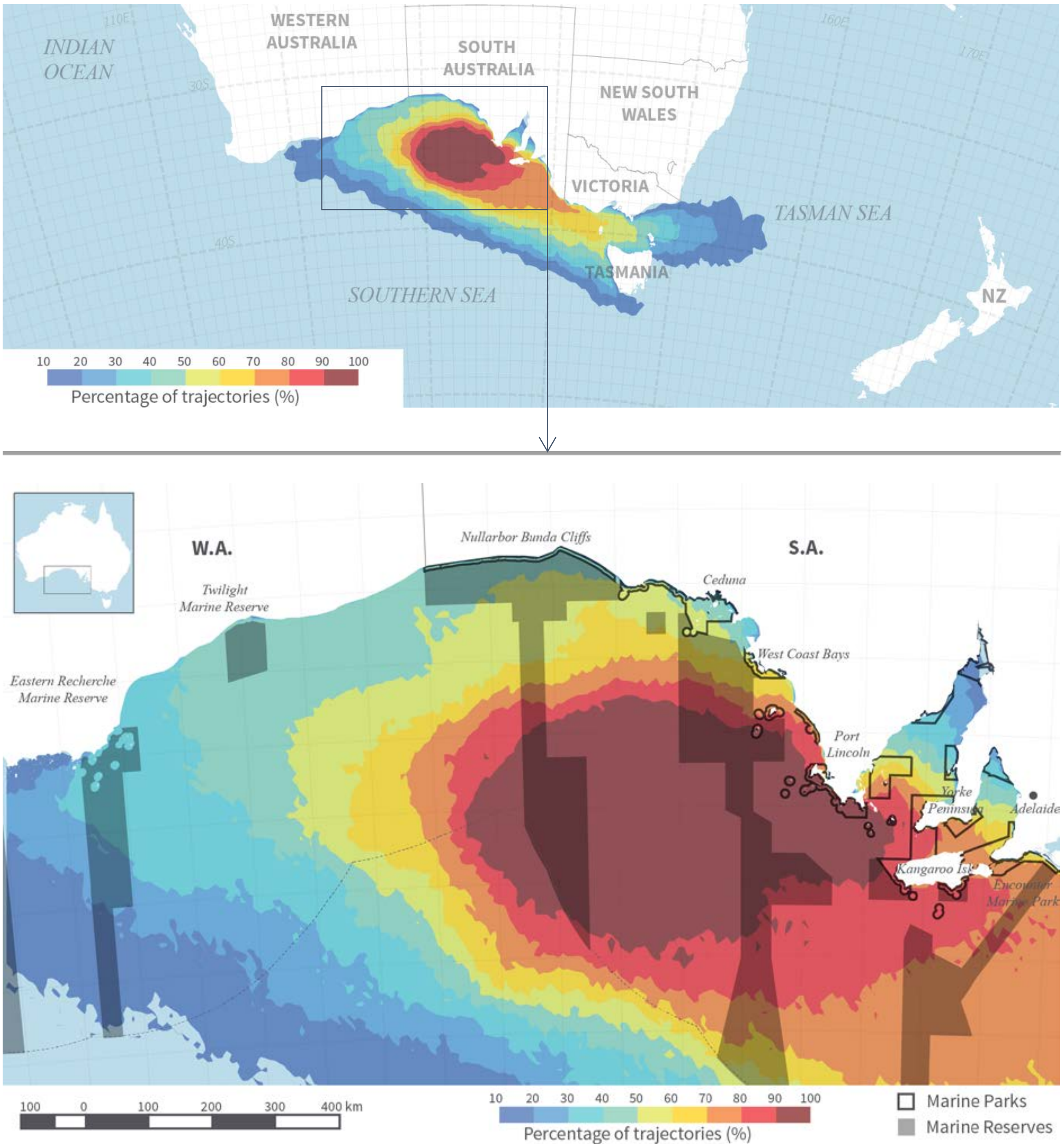

Figure 13: Socioeconomic impact analysis for winter after 4 months (scenario 2A with oiling threshold of 0.01 g/m^2).

When looking at the results for the other scenarios in Appendix C, the socioeconomic impact for the surface waters is relatively similar within the three-month time frame. This is because the oil thickness level of 0.01 g/m^2 is easily reached for the large volumes and durations of all four spill scenarios simulated in this study. However when looking at longer term impacts, scenario 1B and 2B show a much wider probabilistic plume spreading to the Tasman Sea. There is a higher probability for oil droplets to reach these waters over time since the oil volume released in these scenarios is one order of magnitude higher than the two others. In particular, the model predicts a 10 % chance for residual oil to reach the West Coast of New Zealand’s South Island within six months during winter under scenario 2B. Also, it is interesting to note the significant long term difference in probabilistic plume aspect between summer and winter. In winter, most of the modelled trajectories entered the Tasman Sea through Bass Strait whereas in summer, the trajectories were homogeneously distributed between North and South of Tasmania while drifting westward, making the island much more impacted during this season.

Scenarios 1A and 2A rely on a rather optimistic oil spill flow rate of 5,000 bbl/day and shows no or very low probability of oil thickness levels above ecological threshold. The model predicts that for most trajectories the residual oil will disperse at the sea surface sufficiently enough to not reach an oil thickness above 10 g/m^2. However, when considering a higher spill release flow rate (scenario 1B and 2B, 50,000 bbl/day), similar to what occurred during the DWH oil spill, the predicted ecological impact is far more significant. For scenario 2B, in summer and within four months, the numerical model predicts a 16,000 km^2 area with an 80 % chance of having an oil thickness above levels known to mortally impact wildlife, as opposed to 14,000 km^2 in winter. Under scenario 2B in summer, the Twilight Marine Reserve in WA, an important seasonal calving habitat for the threatened Southern Right Whale and foraging site for the threatened White Shark and the migratory Flesh-footed Shearwater, has a greater than 50 % chance of being impacted with lethal oil thickness levels (Figure 14). In winter, the modelled probability of reaching the ecological threshold in the coastal waters at the entrance of Spencer Gulf ranges from 30 % (Yorke Penisula) to 70 % (Eyre Penisula and Kangaroo Island) within four months (Figure 15).

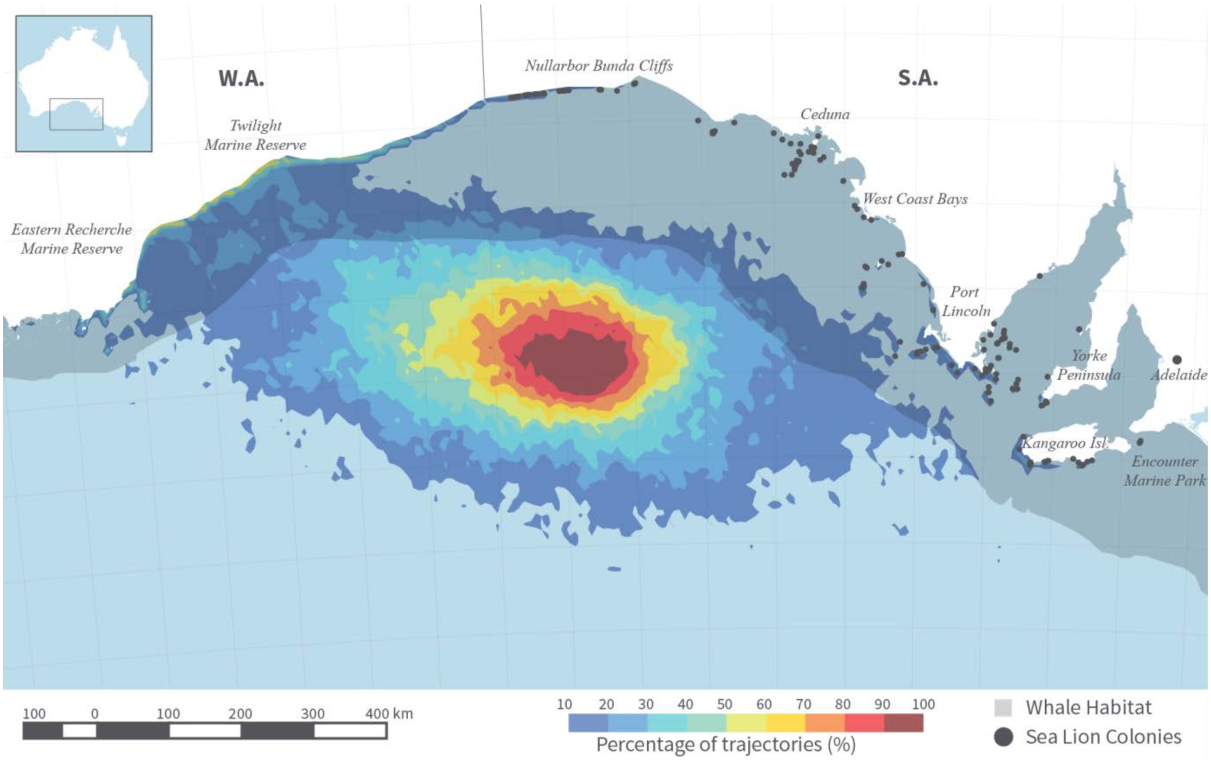

Figure 14: Ecological impact analysis for summer after 4 months (scenario 2B with oiling threshold of 10 g/m^2).

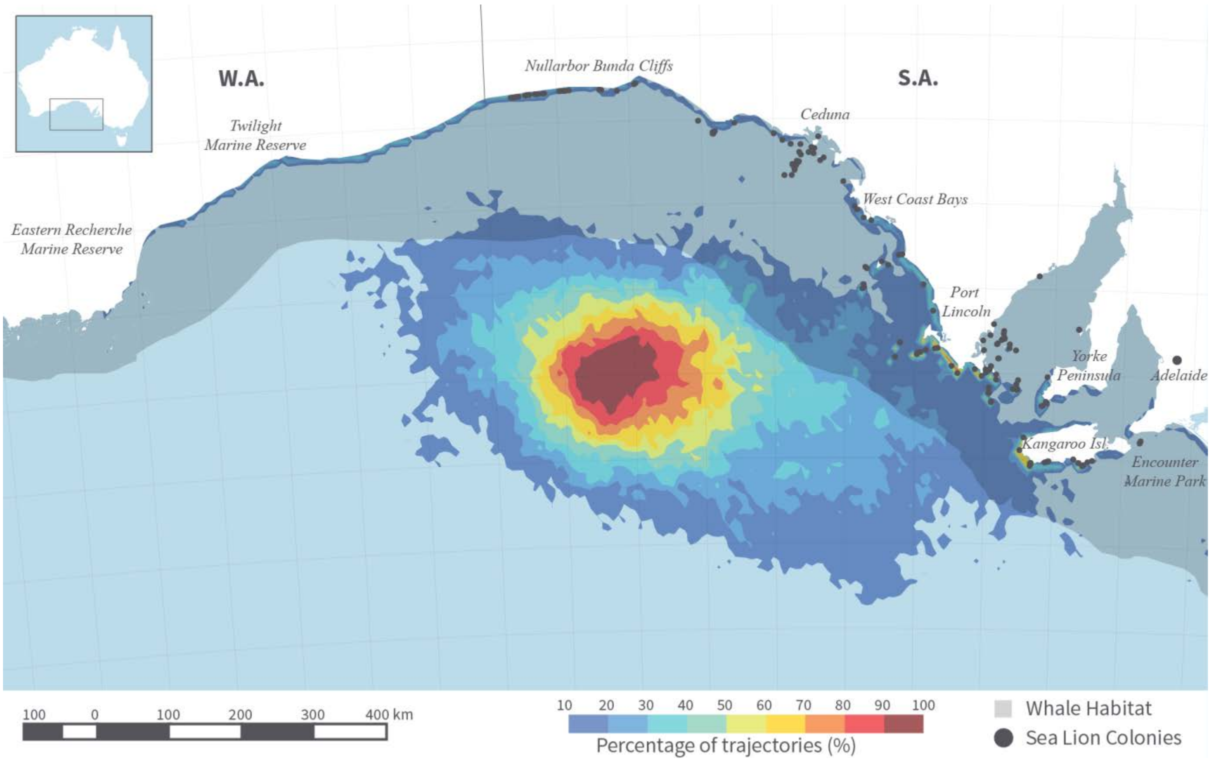

Figure 15: Ecological impact analysis for winter after 4 months (scenario 2B with oiling threshold of 10 g/m^2).

V.2 Response time analysis

A response time analysis looks at how quickly the combined area of oil spills above a certain oil thickness threshold spread, allowing for careful emergency response planning. Here we present the result for an oil thickness above the sea surface socioeconomic threshold of 0.01 g/m^2. We have decided to focus the analysis on the minimum oiling thresholds introduced in this study as it helps to show how fast oil droplets can travel within and without the GAB. Figure 16 and Figure 17 show the travel time of the combined 95 % of trajectories that increased the oil thickness above the socio-economic threshold at sea after one, three and six months under summer and winter conditions. The contours plotted in these figures show the extent of the socioeconomic threat zone where fisheries could potentially be impacted for the most optimistic oil spill scenario (scenario 1A, solid line) and the most pessimistic scenario (scenario 2B, dashed line) investigated in this study. While the travelling time contours for the two scenarios are very similar for the first month, the socioeconomic threat zone spreads over a larger area with time as more oil is released in the numerical model.

In summer, the model predicts an area that could potentially be exposed to levels above socioeconomic impact at sea, reaching the coast of WA within one month (Figure 16). The area stretches from the border between SA and WA to the Eastern Recherche, a Commonwealth marine reserve. Within three months, modelled oil particles could have travelled as far as Cape Leeuwin in the west and the entrance of Bass Strait in the East. Within six months, oil particles could have reached Tasmania, Port Philip Bay and entered the Tasman Sea.

Figure 16: Travelling time of the socioeconomic threat zone under summer conditions. Scenario 1A in solid line and scenario 2B in dashed line

Under winter conditions, the modelled trajectories are generally showing a westward oil transport at the sea surface. After one month, modelled particles have reached the Eyre Peninsula and Kangaroo Island at the Entrance of Spencer Gulf (Figure 17). Within three months, oil droplets could already have travelled beyond Tasmania and after six months, model particles are well present in the Tasman Sea. Particularly, the model shows that New Zealand shores can also be affected as the socio economic threat zone extends towards Fiordland and the West Coast under scenario 2B.

The full response time analysis including the two other scenarios and different oil thickness thresholds is given in Appendix D for winter and summer conditions.

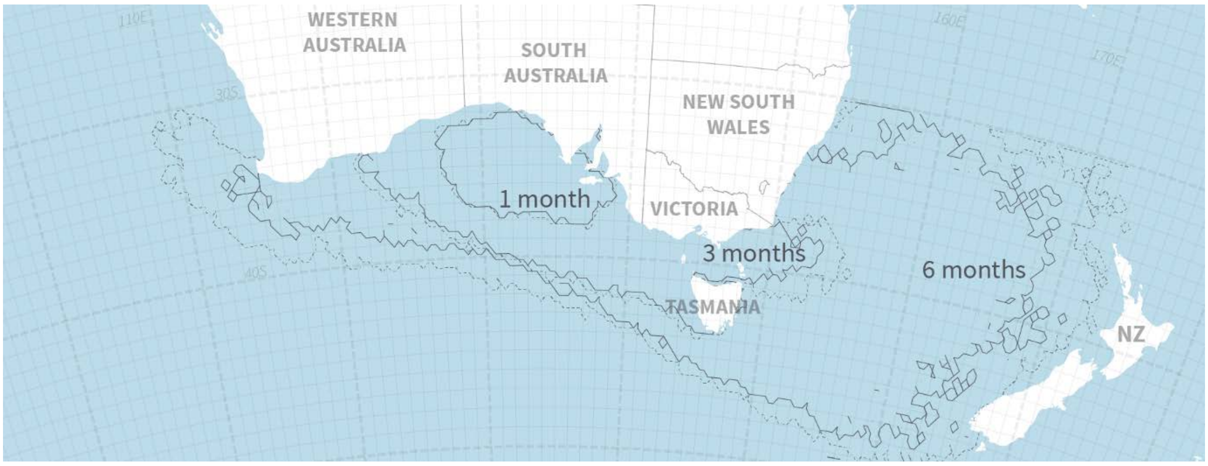

Figure 17: Travelling time of the socioeconomic threat zone under winter conditions. Scenario 1A in solid line and scenario 2B in dashed line

V.3 Oiling analysis

Here we provide an oiling analysis for specific areas of interest in WA and SA. The oiling analysis gives details on the probability of reaching different oil thickness thresholds for individual coastal sites and informs on the average and maximum modelled oil density that a key location can be exposed to. Figure 18 shows the areas of interest selected for this study.

While further analysis should take into account coastal dynamics, particularly tidal driven circulation inside and around Spencer Gulf, with a higher resolution model, information was extracted at the nearest model cell for each site.

Figure 18: Selected coastal locations for the oiling analysis

Of all the sites investigated in the oiling analyses, the Twilight marine reserve in WA was the most impacted under summer conditions. The average oiling level ranges from 6.6 g/m^2 to 121.4 g/m^2 depending on the modelled scenario. The maximum oiling level was recorded for 423.8 g/m^2, four times higher than the ecological threshold on the shoreline. The probability of severe biological impact ranges from 20 % under scenario 1A to 67 % under scenario 2B. Although to a lesser extent, the Eastern Recherche marine reserve in WA is also significantly impacted under summer conditions with oil thickness levels between 0.9 g/m^2 and 15.2 g/m^2 on average with a maximum recorded at 58.8 g/m^2. During winter, West Coast Bays Marine Park, Lower Yorke Peninsula Marine Park and Western Kangaroo Island Marine Park show the highest level of oiling with respectively 1.3 g/m^2 to 22.2 g/m^2, 1.3 g/m^2 to 26.3 g/m^2 and 2.7 g/m^2 to 44.7 g/m^2. Of all the analysis sites, the maximum oil thickness was recorded for the Western Kangaroo Island Marine Park with 367.1 g/m^2 and 70 % probability of at least reaching the surface ecological impact under scenario 2B.

V.3.a Eastern Recherche (Commonwealth Marine Reserve)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	75	27	< 1	< 1	0.9	5.3
	1B	75	70	27	< 1	8.8	53.0
	2A	78	46	< 1	< 1	1.5	5.9
	2B	78	73	46	< 1	15.2	58.8
Winter	**1A**	36	1	< 1	< 1	0.3	1.7
	1B	36	27	1	< 1	2.6	17.2
	2A	53	15	< 1	< 1	0.8	2.8
	2B	53	51	15	< 1	8.1	27.6

V.3.b Twilight (Commonwealth Marine Reserve)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	74	64	20	< 1	6.6	18.3
	1B	74	72	64	20	66.5	183.0
	2A	76	67	37	< 1	12.1	42.4
	2B	76	73	67	37	121.4	423.8
Winter	**1A**	47	23	5	< 1	3.1	18.1
	1B	47	43	23	5	30.7	181.0
	2A	62	50	24	< 1	9.7	35.2
	2B	62	61	50	24	97.1	352.0

V.3.c Head of Bight – Nullarbor Bunda Cliffs

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	42	14	< 1	< 1	1.2	8.8
	1B	42	37	14	< 1	12.4	88.4
	2A	47	18	< 1	< 1	1.5	9.2
	2B	47	42	18	< 1	15.3	92.0
Winter	**1A**	52	29	< 1	< 1	1.6	10.0
	1B	52	49	29	< 1	16.0	99.8
	2A	73	52	2	< 1	2.7	12.1
	2B	73	71	52	2	26.9	121.2

V.3.d Ceduna

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	30	< 1	< 1	< 1	0.2	0.7
	1B	30	21	< 1	< 1	1.56	7.3
	2A	32	< 1	< 1	< 1	0.2	0.6
	2B	32	23	< 1	< 1	1.73	5.7
Winter	**1A**	44	1	< 1	< 1	0.3	1.1
	1B	44	32	1	< 1	2.6	10.9
	2A	74	5	< 1	< 1	0.3	1.1
	2B	74	68	5	< 1	3.2	11.4

V.3.e West Coast Bays (Marine Park)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m²)	
		0.01 g/m²	1 g/m²	10 g/m²	100 g/m²	Average	Maximum
Summer	1A	40	9	< 1	< 1	0.9	4.8
	1B	40	31	9	< 1	8.8	47.8
	2A	43	15	< 1	< 1	1.3	5.4
	2B	43	39	15	< 1	13.4	53.6
Winter	1A	59	21	< 1	< 1	1.3	8.6
	1B	59	45	21	< 1	12.5	85.8
	2A	86	42	6	< 1	2.2	14.6
	2B	86	80	42	6	22.2	146.1

V.3.f Investigator (Marine Park)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m²)	
		0.01 g/m²	1 g/m²	10 g/m²	100 g/m²	Average	Maximum
Summer	1A	42	14	< 1	< 1	1.1	5.7
	1B	42	38	14	< 1	10.7	57.2
	2A	55	27	< 1	< 1	1.5	7.6
	2B	55	51	27	< 1	14.8	75.9
Winter	1A	74	26	< 1	< 1	1.0	4.8
	1B	74	59	26	< 1	9.6	48.4
	2A	92	53	< 1	< 1	1.9	7.3
	2B	92	86	53	< 1	19.0	73.3

V.3.g Coffin Bay

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m²)	
		0.01 g/m²	1 g/m²	10 g/m²	100 g/m²	Average	Maximum
Summer	1A	40	16	< 1	< 1	1.5	8.2
	1B	40	33	16	< 1	14.6	81.6
	2A	48	29	< 1	< 1	2.1	8.0
	2B	48	44	29	< 1	20.9	79.6
Winter	1A	56	15	< 1	< 1	0.9	5.3
	1B	56	45	15	< 1	9.5	52.5
	2A	74	31	< 1	< 1	1.5	5.5
	2B	74	61	31	< 1	14.6	55.1

V.3.h Port Lincoln

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	1A	18	1	< 1	< 1	0.2	2.0
	1B	18	8	1	< 1	2.3	20.3
	2A	30	3	< 1	< 1	0.5	3.0
	2B	30	20	3	< 1	4.9	30.2
Winter	1A	73	3	< 1	< 1	0.3	1.3
	1B	73	55	3	< 1	2.5	13.0
	2A	86	11	< 1	< 1	0.4	2.0
	2B	86	80	11	< 1	4.3	19.8

V.3.i Lower Yorke Peninsula

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	1A	47	9	< 1	< 1	0.8	5.7
	1B	47	38	9	< 1	7.8	57.2
	2A	62	28	< 1	< 1	1.8	7.4
	2B	62	54	28	< 1	18.2	74.4
Winter	1A	85	32	< 1	< 1	1.3	9.7
	1B	85	78	32	< 1	12.9	97.2
	2A	90	57	4	< 1	2.6	11.9
	2B	90	85	57	4	26.3	118.6

V.3.j Kangaroo Island (Marine Park)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	1A	55	27	< 1	< 1	1.5	9.1
	1B	55	49	27	< 1	15.4	91.0
	2A	70	47	2	< 1	3.1	15.9
	2B	70	63	47	2	31.2	158.6
Winter	1A	88	60	3	< 1	2.7	14.1
	1B	88	75	60	3	26.6	140.9
	2A	90	70	7	< 1	4.5	36.7
	2B	90	83	70	7	44.7	367.1

V.3.k Encounter (Marine Park)

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	28	4	< 1	< 1	0.4	1.9
	1B	28	22	4	< 1	4.1	18.7
	2A	46	9	< 1	< 1	0.7	6.4
	2B	46	36	9	< 1	6.7	64.0
Winter	**1A**	75	18	< 1	< 1	0.7	5.3
	1B	75	60	18	< 1	7.2	52.5
	2A	76	34	< 1	< 1	1.3	7.4
	2B	76	72	34	< 1	13.0	74.4

V.3.l Adelaide

Season	Scenario	Percentage of trajectories above thresholds (%)				Oiling level (g/m^2)	
		0.01 g/m^2	1 g/m^2	10 g/m^2	100 g/m^2	Average	Maximum
Summer	**1A**	8	< 1	< 1	< 1	0.1	0.3
	1B	8	3	< 1	< 1	0.9	2.6
	2A	11	< 1	< 1	< 1	0.1	0.4
	2B	11	5	< 1	< 1	1.0	3.6
Winter	**1A**	61	12	< 1	< 1	0.5	2.2
	1B	61	48	12	< 1	5.0	21.8
	2A	67	21	< 1	< 1	0.8	3.8
	2B	67	57	21	< 1	8.2	38.5

VI Conclusion

We conducted an oil spill trajectory analysis based on modelled probabilistic quantities derived from 1,000 spill scenarios under two different seasons at an offshore site in the GAB, using industry standard numerical modelling techniques. Whilst the parameters characterising the oil spill are subject to some variability, we aimed to describe different possible deep sea well failure scenarios based on best information available and past events. We demonstrated that the oil spill flow rate and the modelled season were the main factors influencing the oiling levels at various sites of the Australian coastline.

In case of a blowout event in the GAB, the modelling system implemented for this study can be re-used to assess a real time simulation of the fate of oil at sea and assist in emergency response operations. This study could be refined with further investigations such as studying the fate of neutrally buoyant oil compounds (heavy crude) that could remain somewhere along the water column and never surface and/or nesting the regional model structure with finer local grids around headlands and gulfs to provide a better resolution when assessing an oiling analysis on specific sites. Specifically, the numerical model does not take into account tidal circulation within the environmental forcing. While tidal forcing is commonly neglected in offshore deep waters, it can have a significant effect on particle trajectories inside gulfs, estuaries and harbours. Turbulent eddy diffusion is treated using a random path with a commonly accepted eddy diffusivity value.

In the catastrophic event of a deep sea well failure in the GAB, our model predicted that the shores of WA would directly be impacted should the incident occur in summer whereas in winter, it would mostly be the coastline of SA and oil would probably travel as far as Victoria and Tasmania. Depending on the oil spill scenario, modelled oil thickness reached levels as high as 424 g/m^2 on the shoreline. Regardless of the scenario, the model predicted 70 % to 80 % chance for oil droplets reaching the coastline of Australia.

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Appendix A: Wave spectrum analysis

Here we describe in more detail the wave climate frequency and directional spectra from the 2005-2012 global wave model reanalysis at the area of interest. The full wave frequency spectrum is shown in Figure 19 depicting the average total annual number of hours per swell event characteristics as a joint probability between significant wave height and wave peak period. While typical ground swell events in the GAB usually have a period ranging between 12 s to 14 s and a significant wave height from 2 m to 3 m, the GAB is frequently exposed to larger, more energetic ground swells with peak wave period between 14 s and 18 s and significant wave height ranging from 2 m to 8 m.

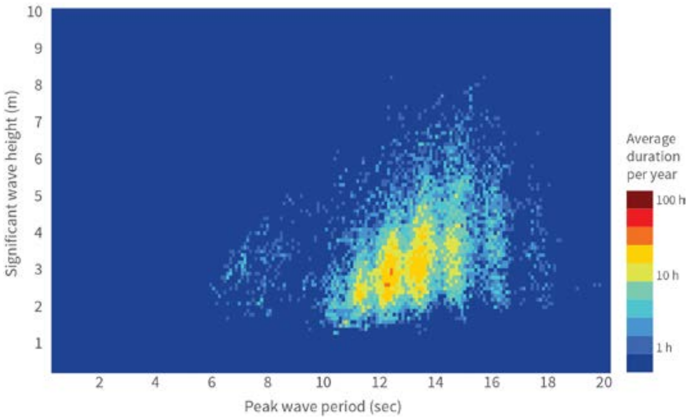


Figure 19: Wave energy frequency spectrum described in average number of hours of occurrence per year as a function of wave period and wave direction. (NOAA Wavewatch III reanalysis, 2005-2012 at 35°S, 130°E)

When looking at the full time series between 2005 and 2012 at the area of interest, one can see how extreme wave events occur mostly in winter. Figure 20 shows significant wave height and peak wave direction at 35°S, 130°E from the global wave model reanalysis. The raw model data is presented with the fortnight average clearly showing the seasonal variations in wave climate at the area of interest. The fortnightly averaged significant wave height ranges from above 2 m in summer to 4 m in winter. While most waves travel from the South West, the temporal average in peak wave direction also shows a slight seasonal variation with waves generally coming with a more southern direction during the summer (around 220° as opposed to 227° in winter).

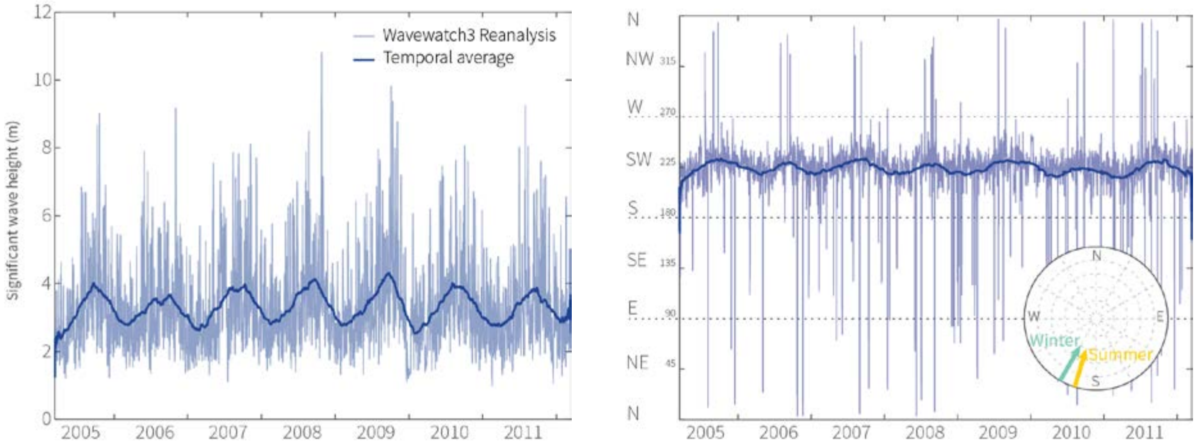


Figure 20: Full significant wave height (left) and peak wave direction (right) time series between 2005 and 2012 at 35°S, 130°E (NOAA Wavewatch III). The bolder line is the fortnightly average clearly showing the seasonal changes in wave climate between summer and winter.

Appendix B: Model Sensitivity

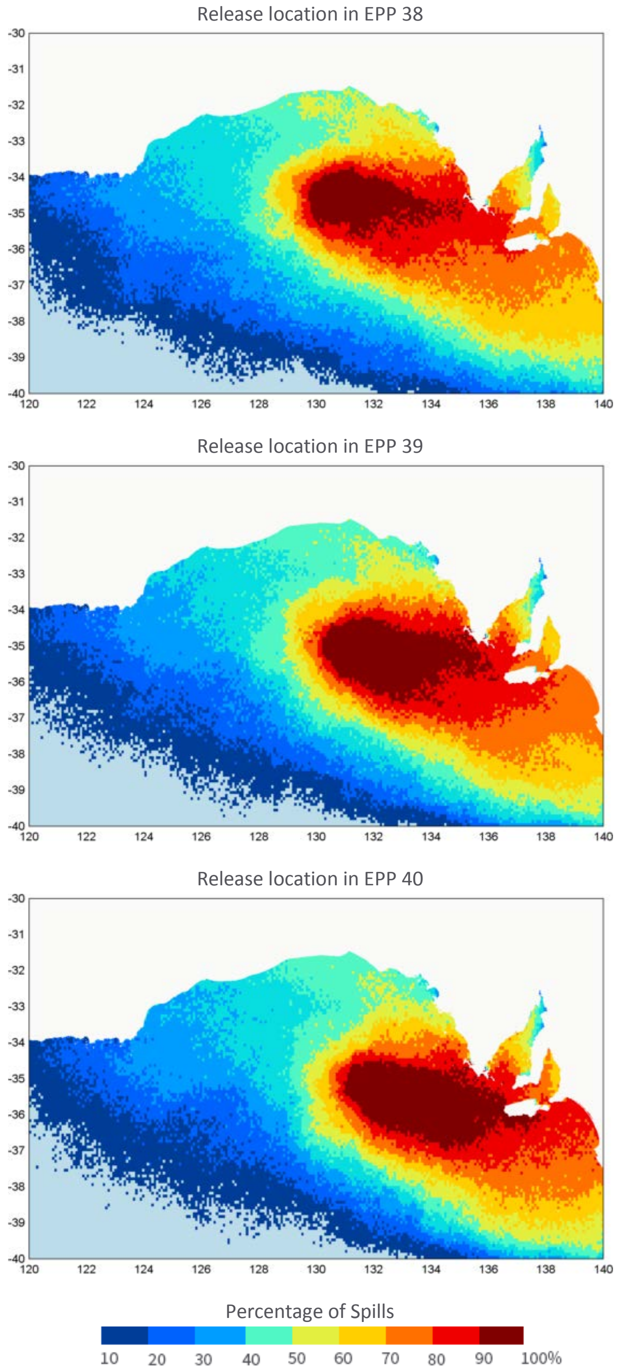
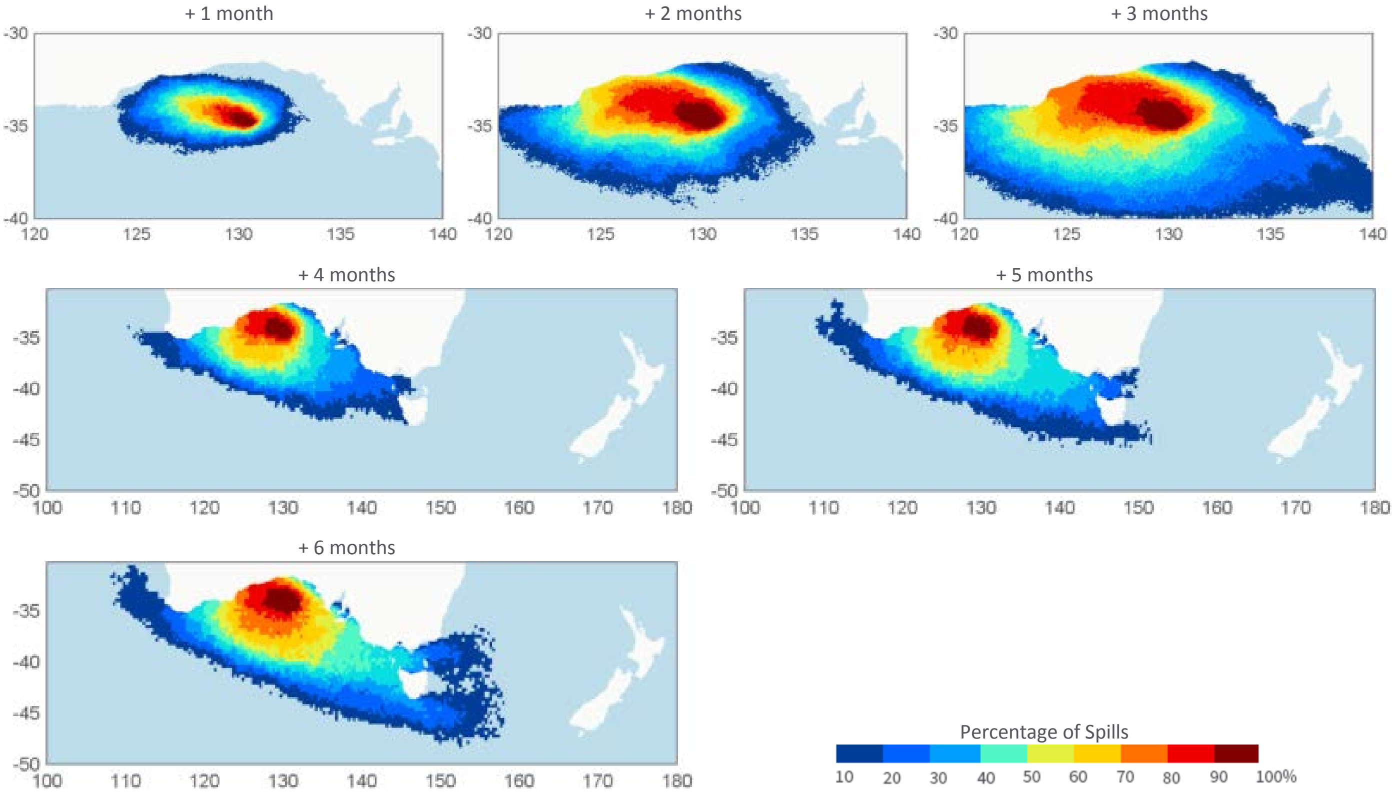


Figure 21: Comparison of different release locations for summer seasons after 6 months for an oiling threshold of 0.01 g/m^2.

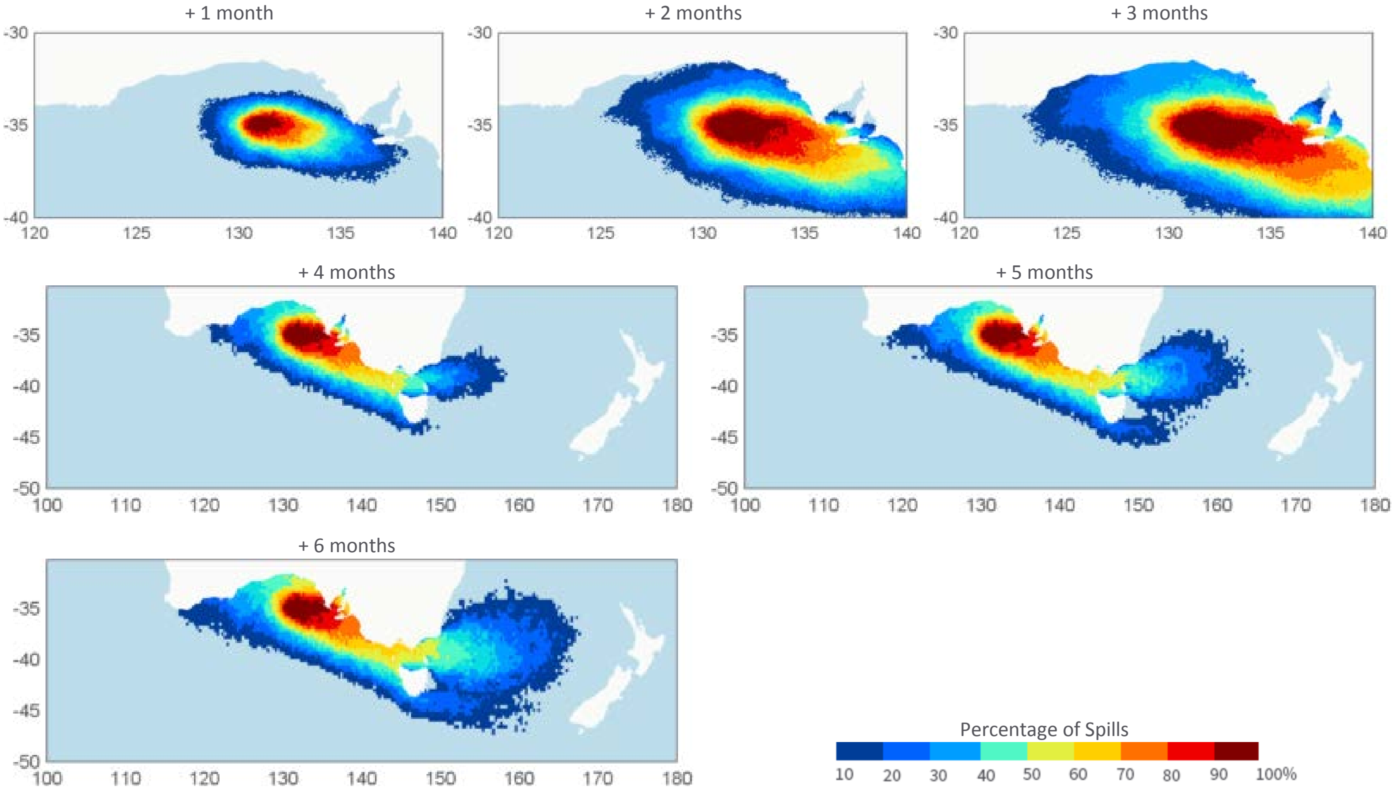
Appendix C: Impact Analysis

Scenario 1A: oiling threshold at 0.01 g/m2 (socio-economic impact threshold at sea, fisheries closure)

- Summer season

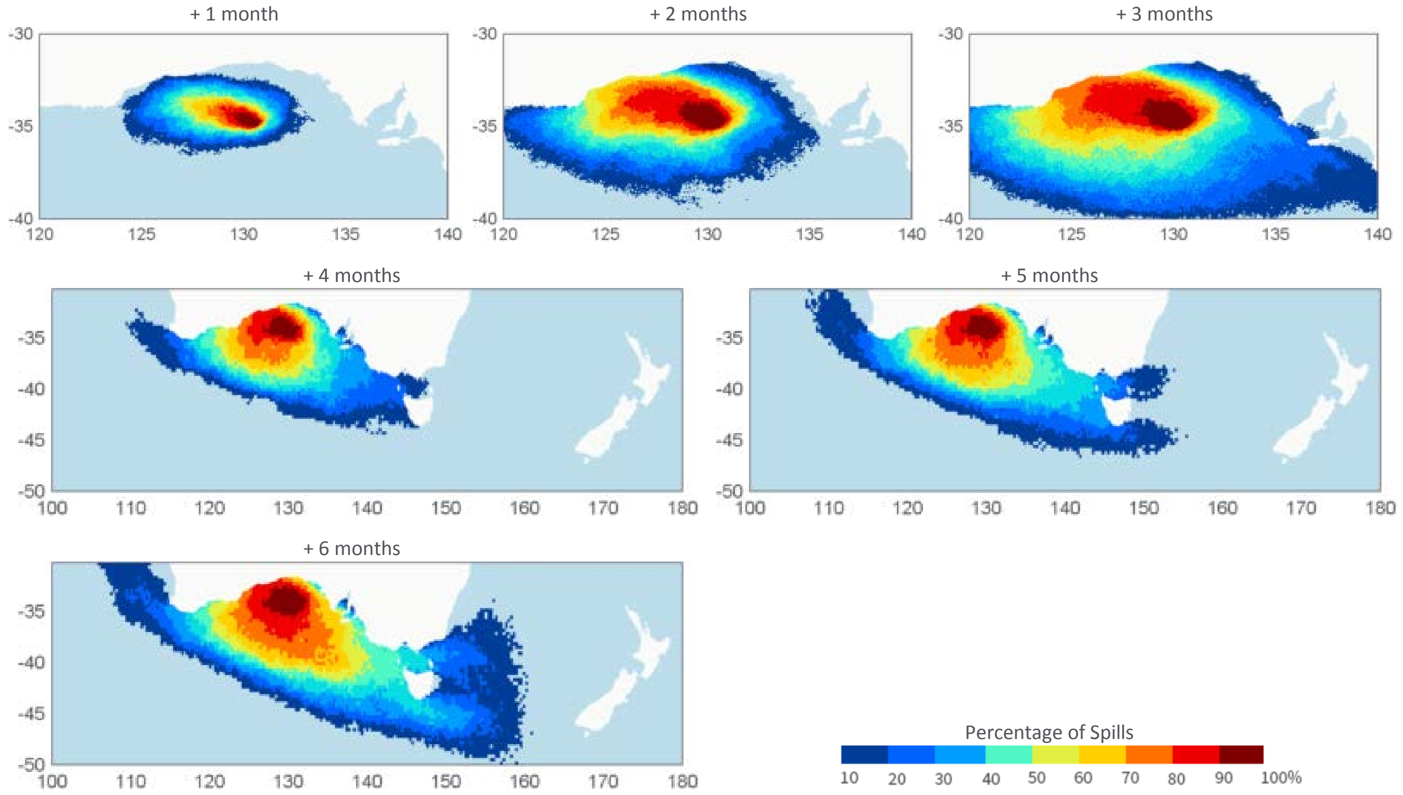


- Winter season

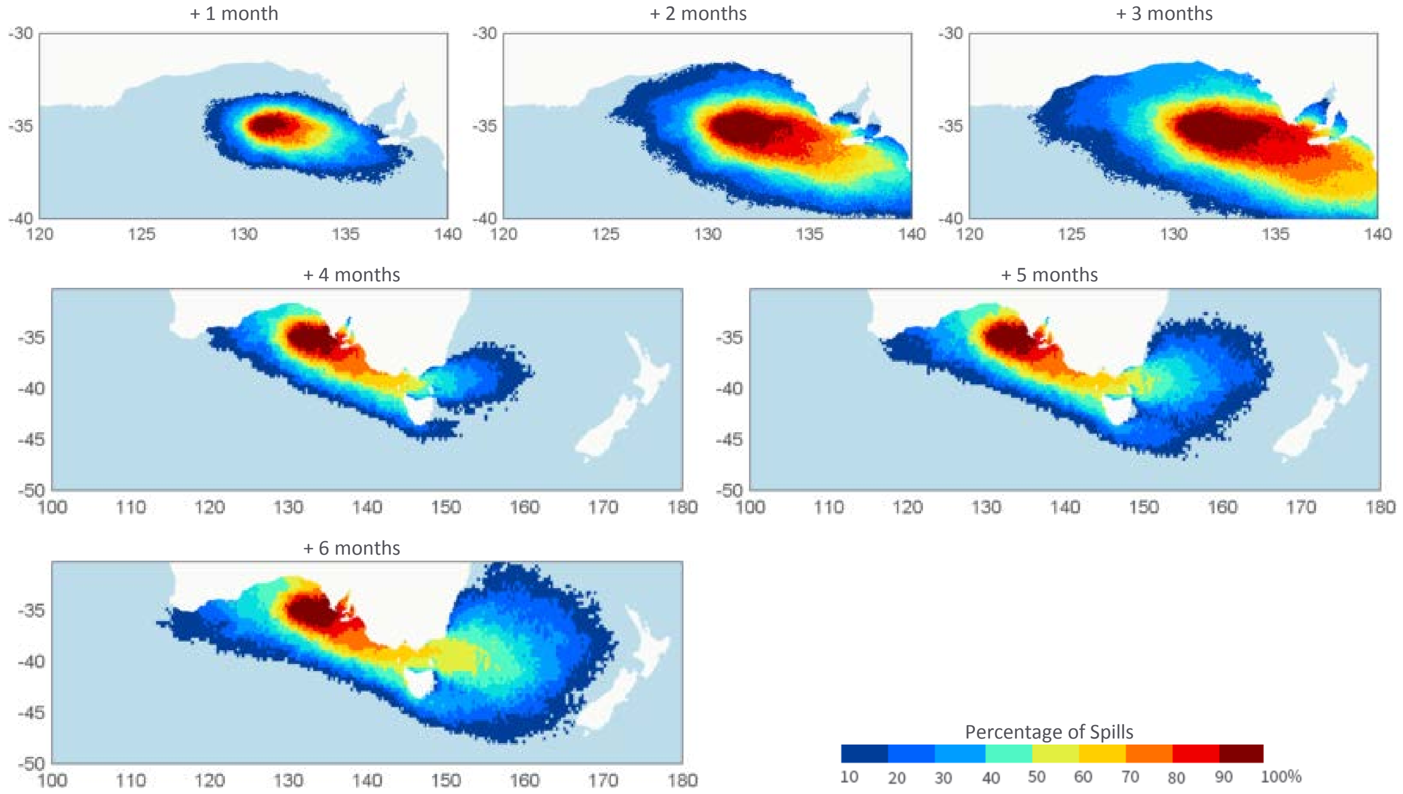


Scenario 1B: oiling threshold at 0.01 g/m2 (socio-economic impact threshold at sea, fisheries closure)

- Summer season

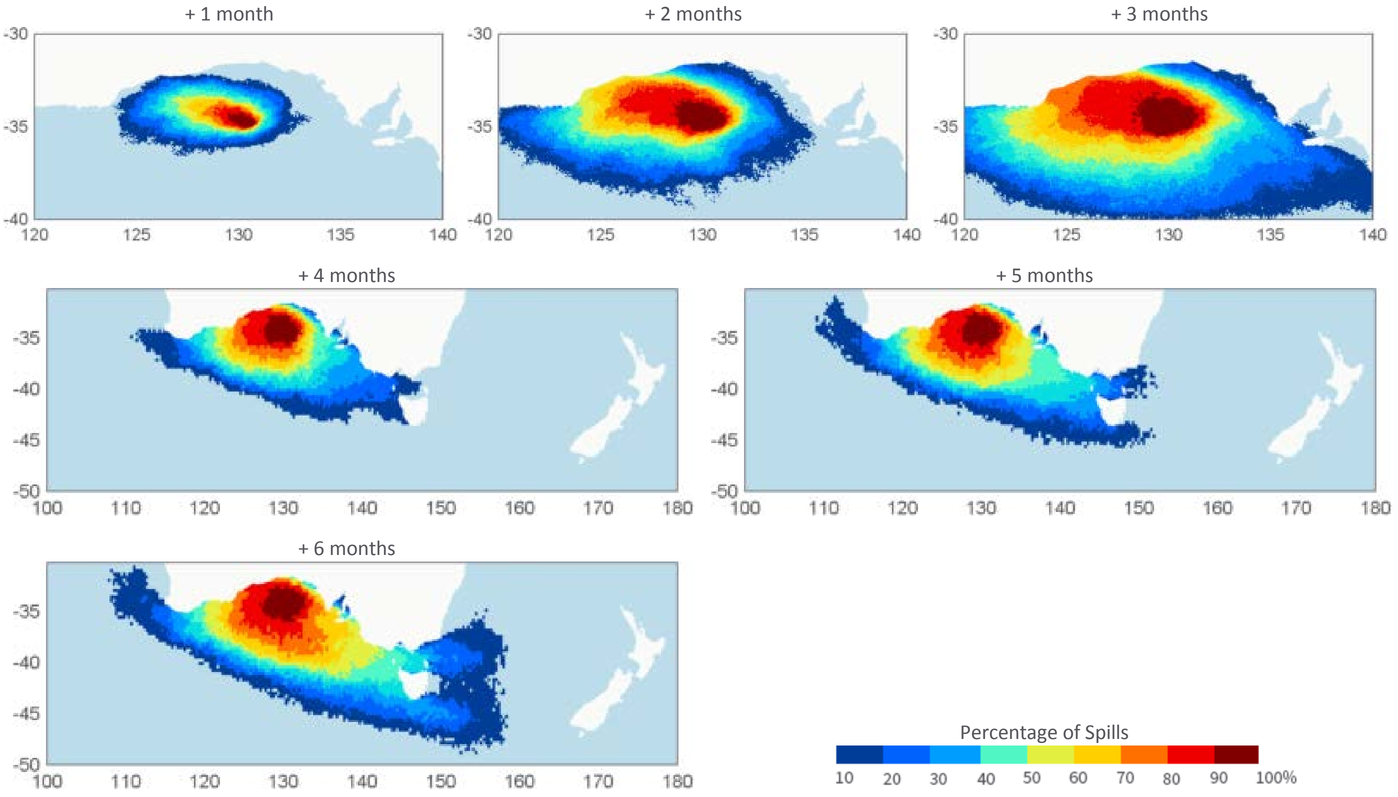


- Winter season

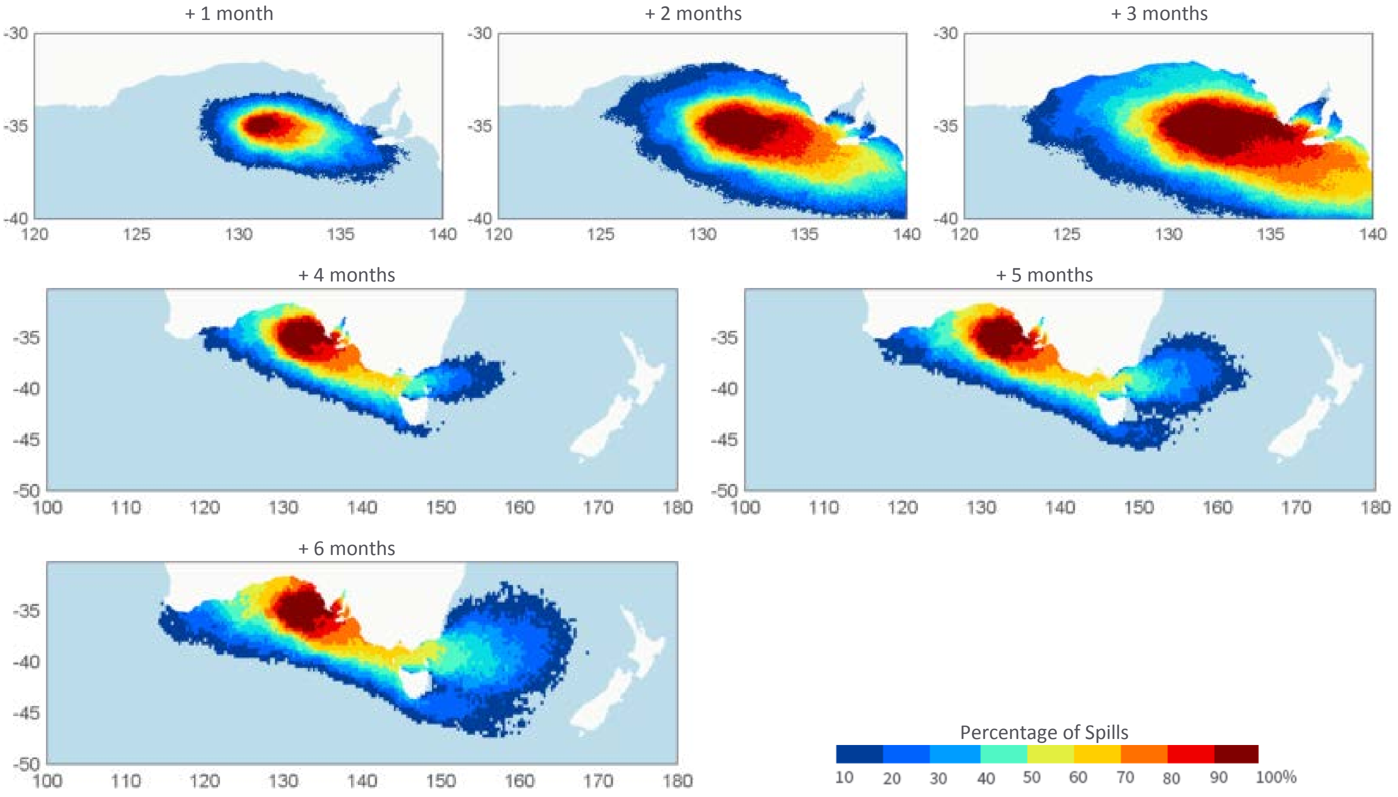


Scenario 2A: oiling threshold at 0.01 g/m2 (socio-economic impact threshold at sea, fisheries closure)

- Summer season

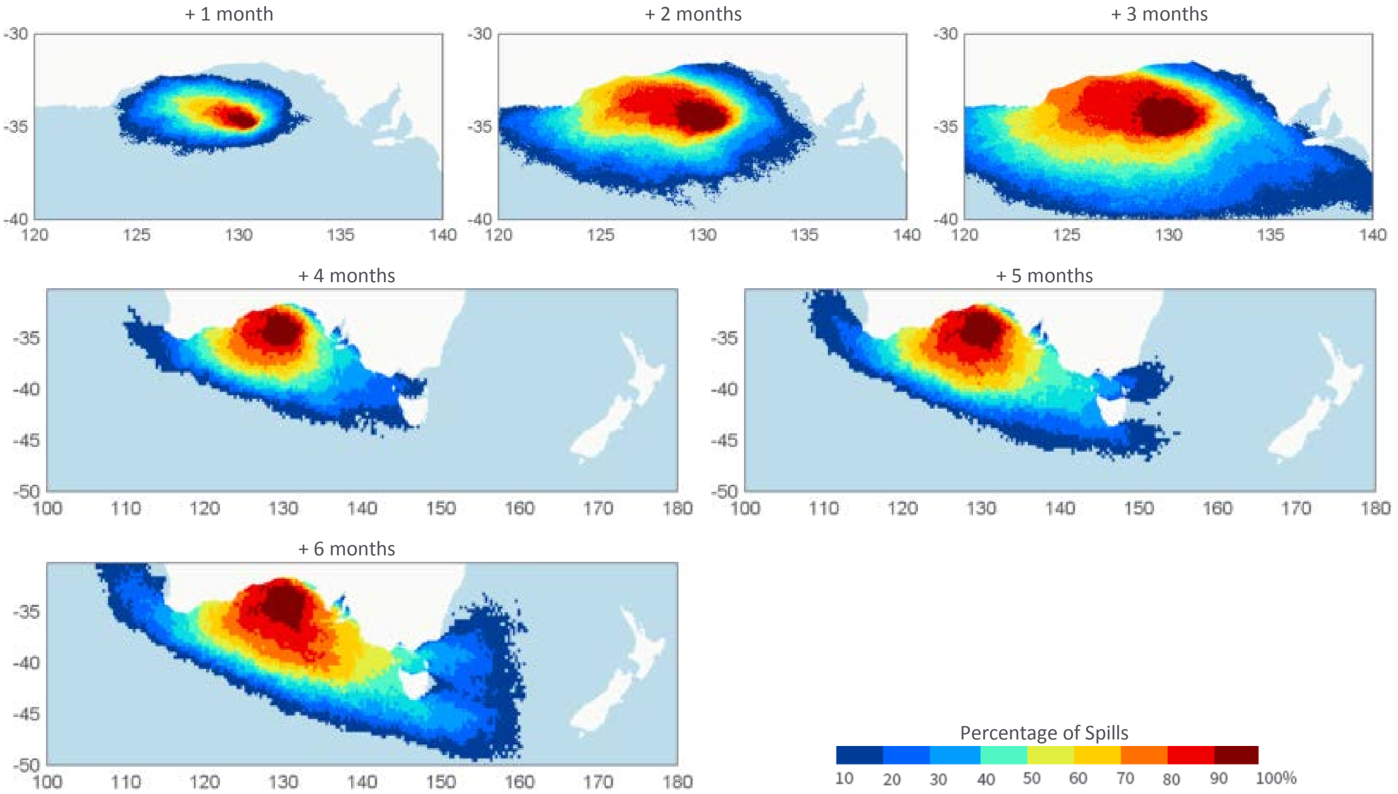


- Winter season

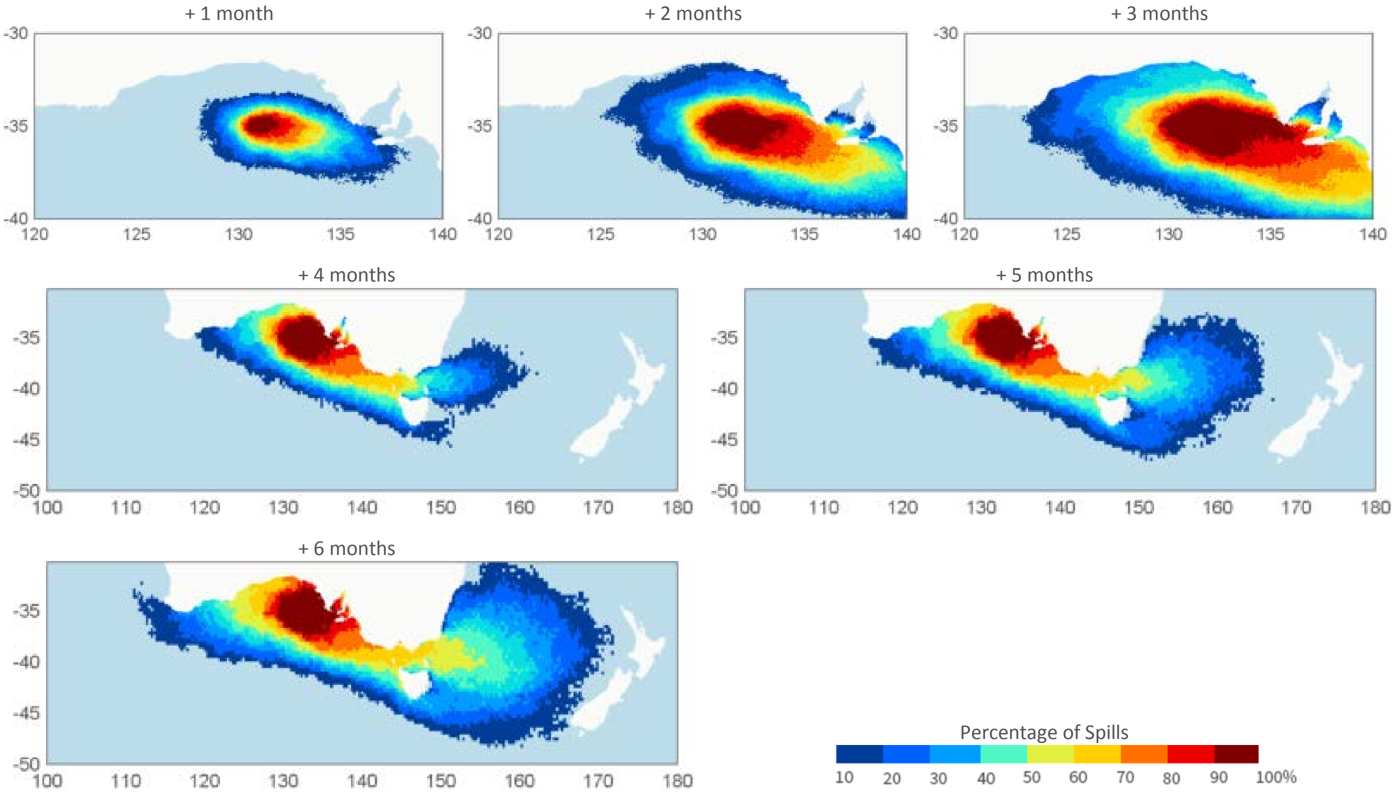


Scenario 2B: oiling threshold at 0.01 g/m2 (socio-economic impact threshold at sea, fisheries closure)

- Summer season

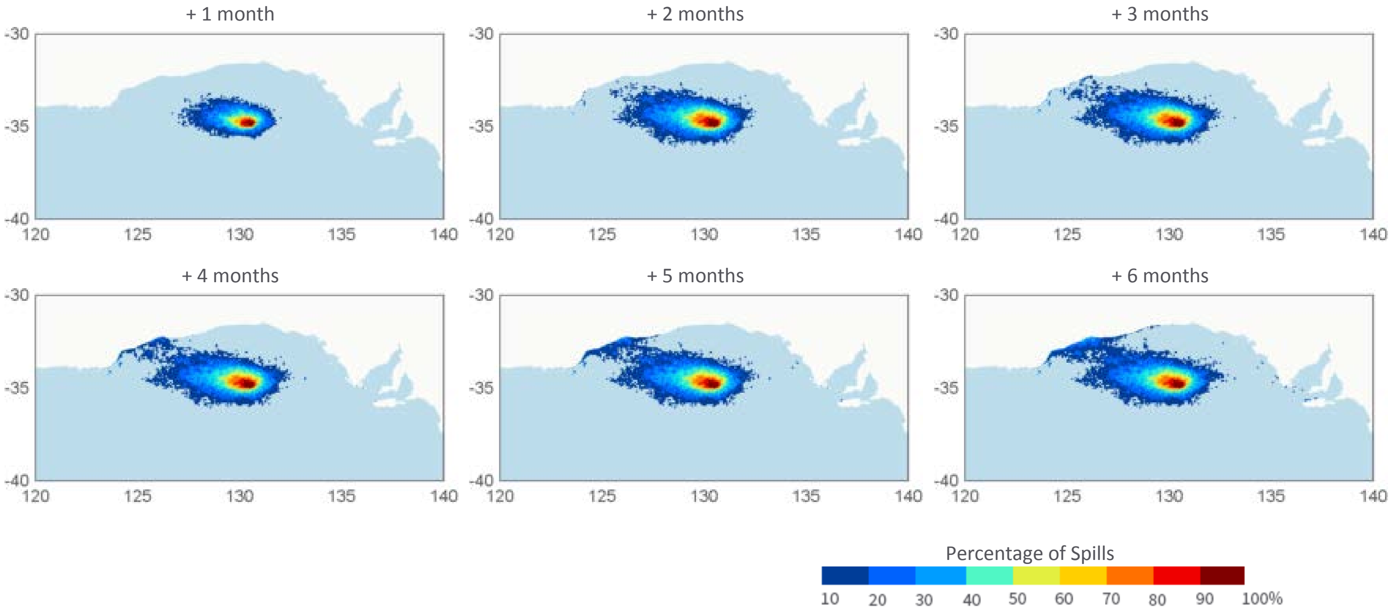


- Winter season

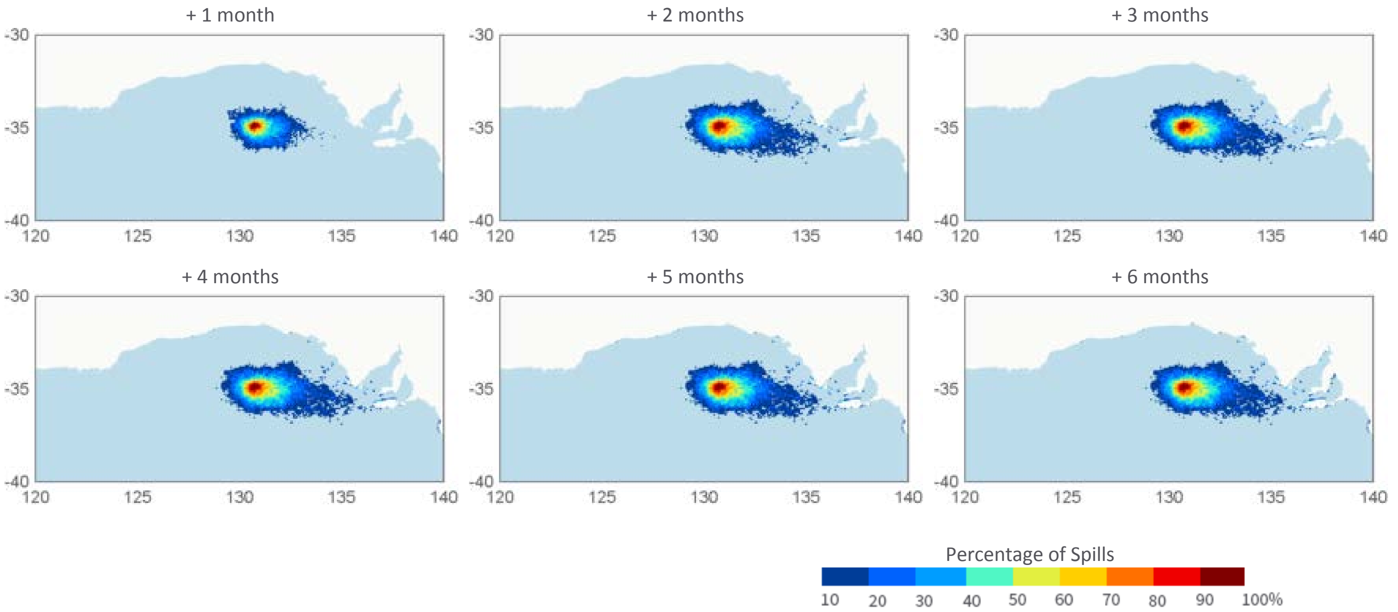


Scenario 1A: oiling threshold at 1 g/m2 (socio-economic impact threshold on land, coastal clean-up)

- Summer season

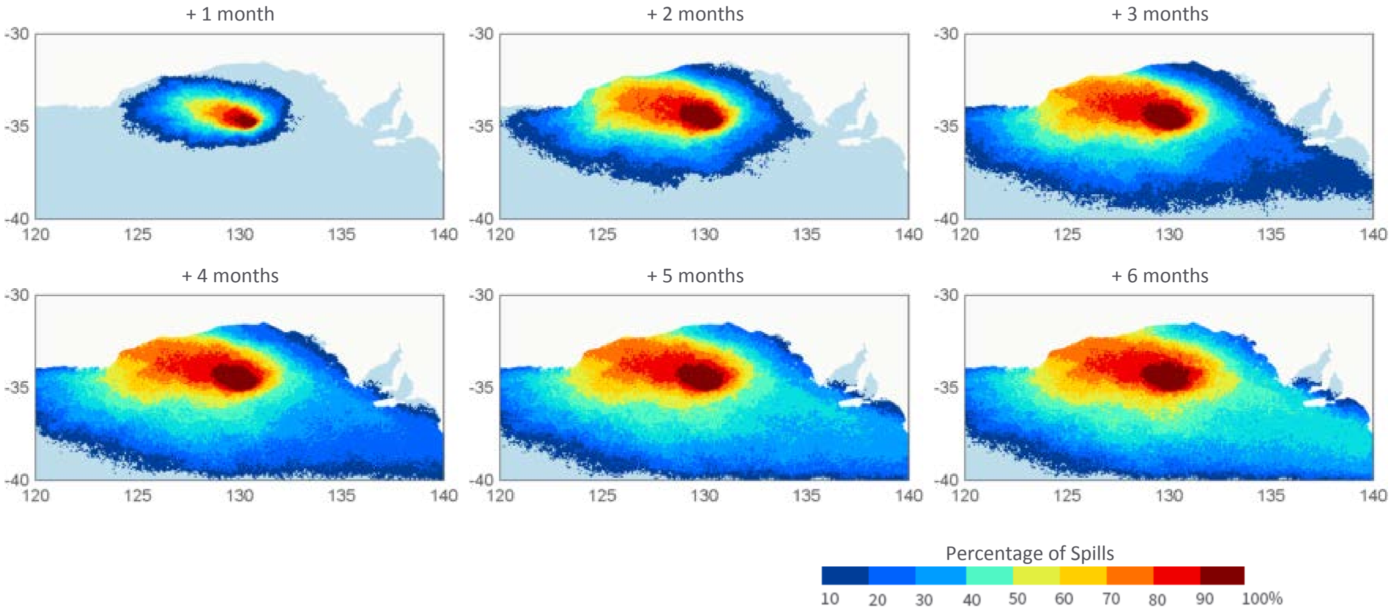


- Winter season

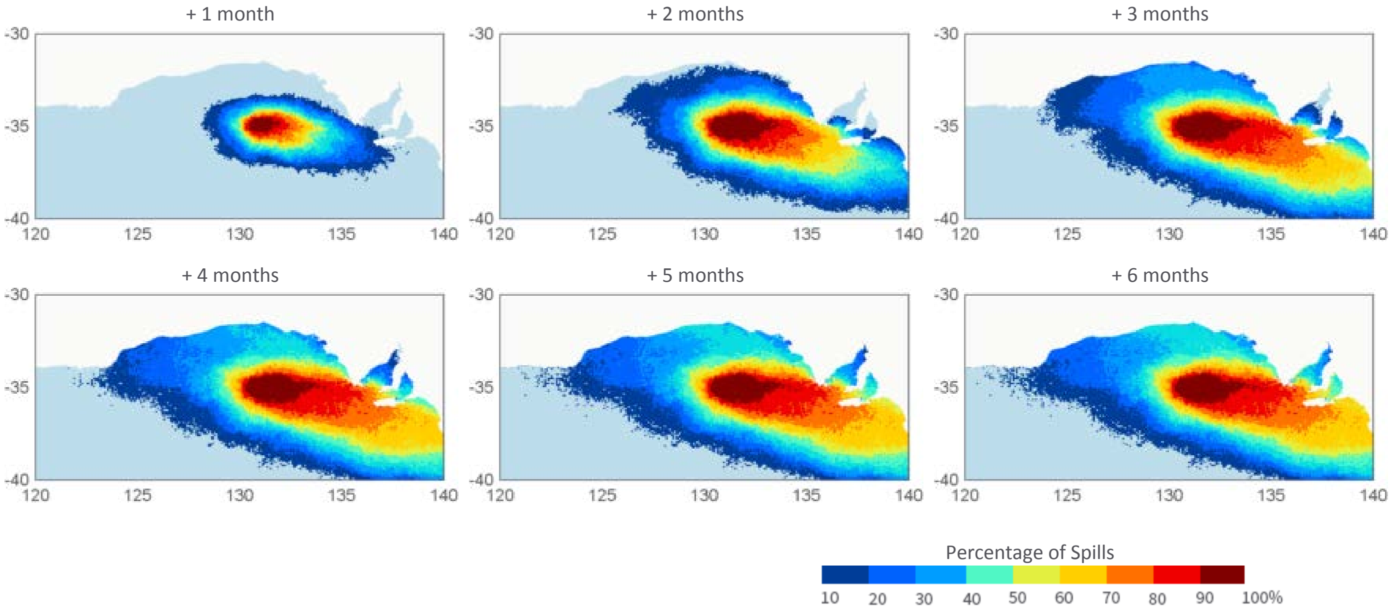


Scenario 1B: oiling threshold at 1 g/m2 (socio-economic impact threshold on land, coastal clean-up)

- Summer season

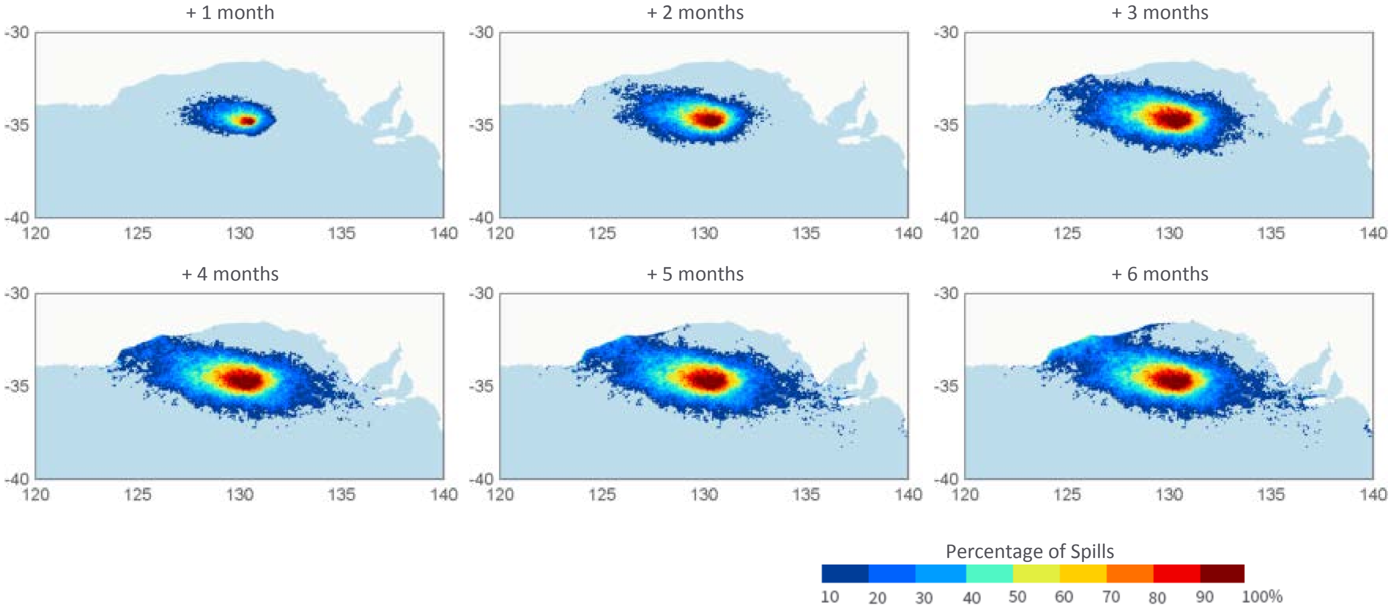


- Winter season

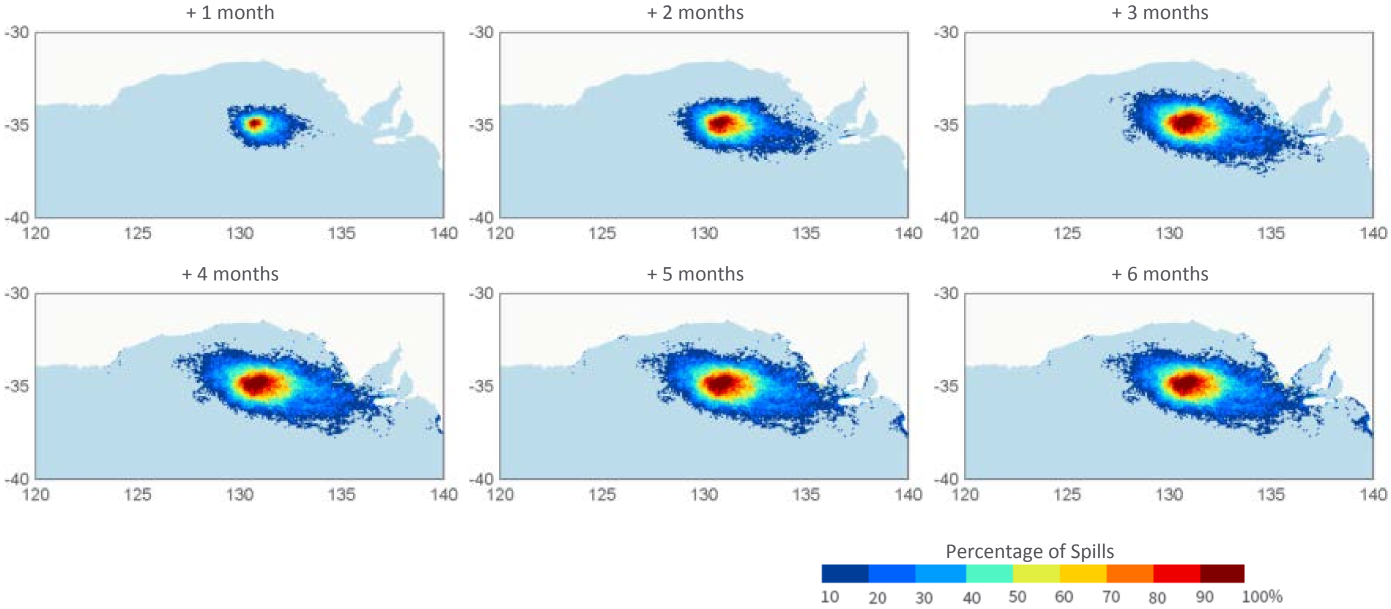


Scenario 2A: oiling threshold at 1 g/m2 (socio-economic impact threshold on land, coastal clean-up)

- Summer season

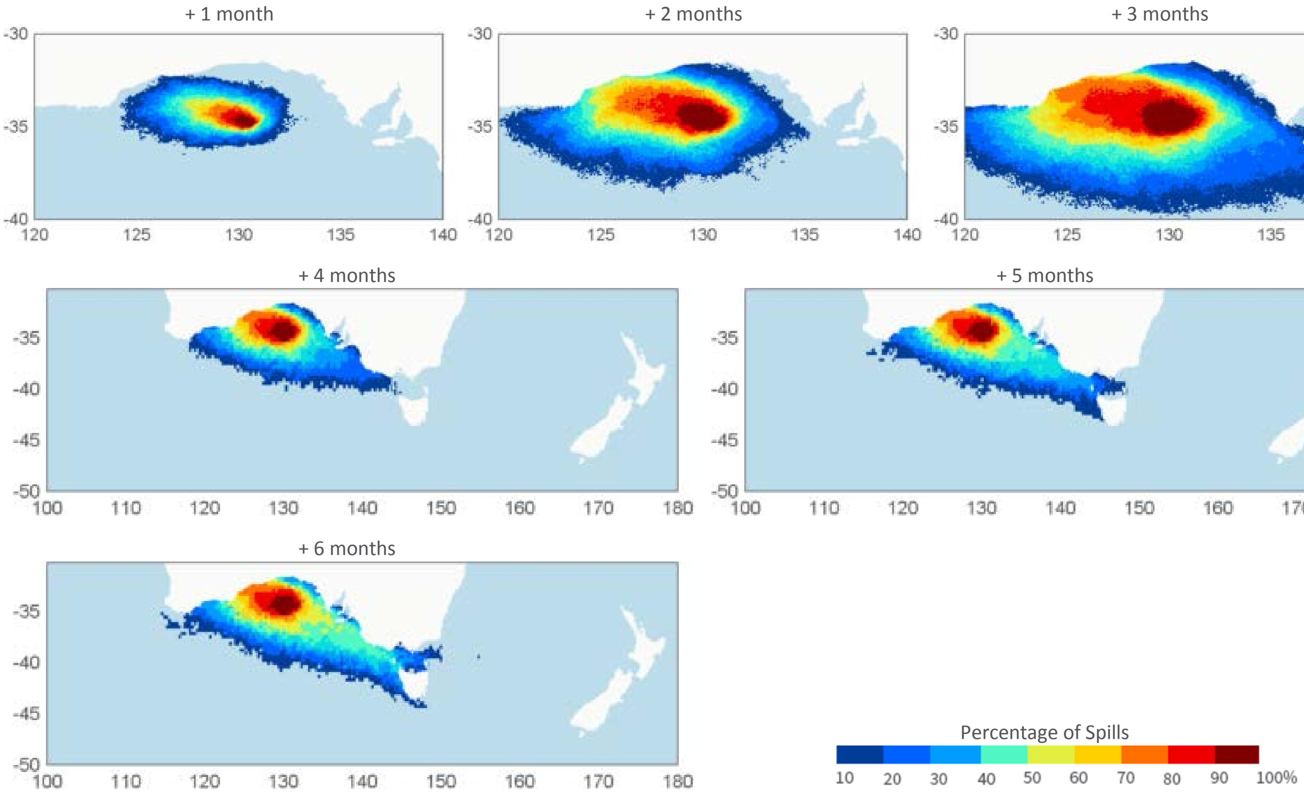


- Winter season

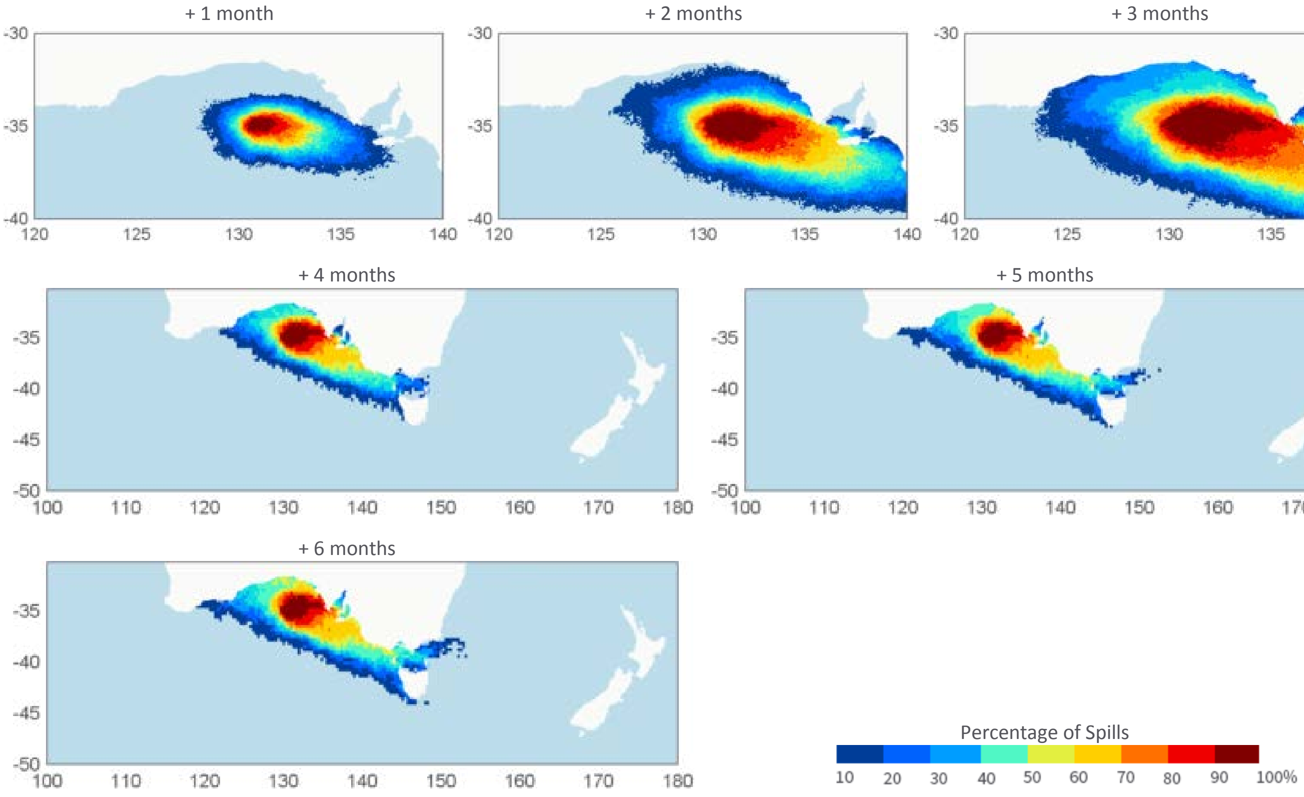


Scenario 2B: oiling threshold at 1 g/m2 (socio-economic impact threshold on land, coastal clean-up)

- Summer season

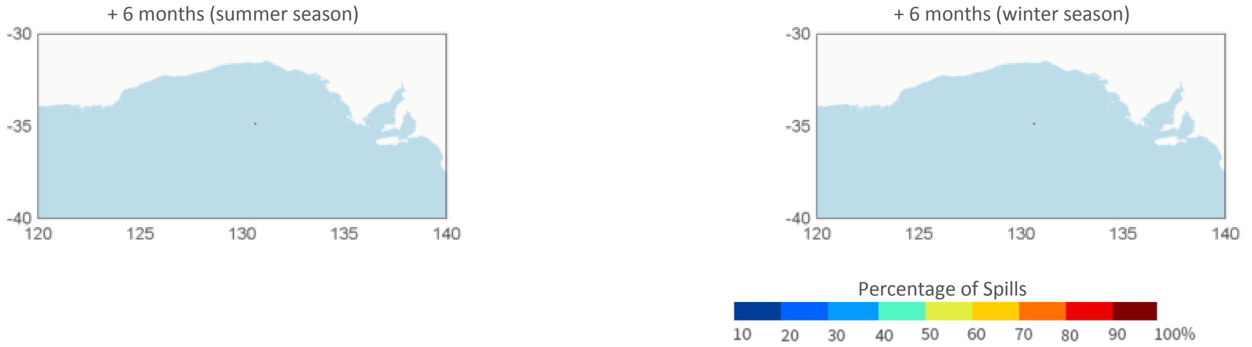


- Winter season



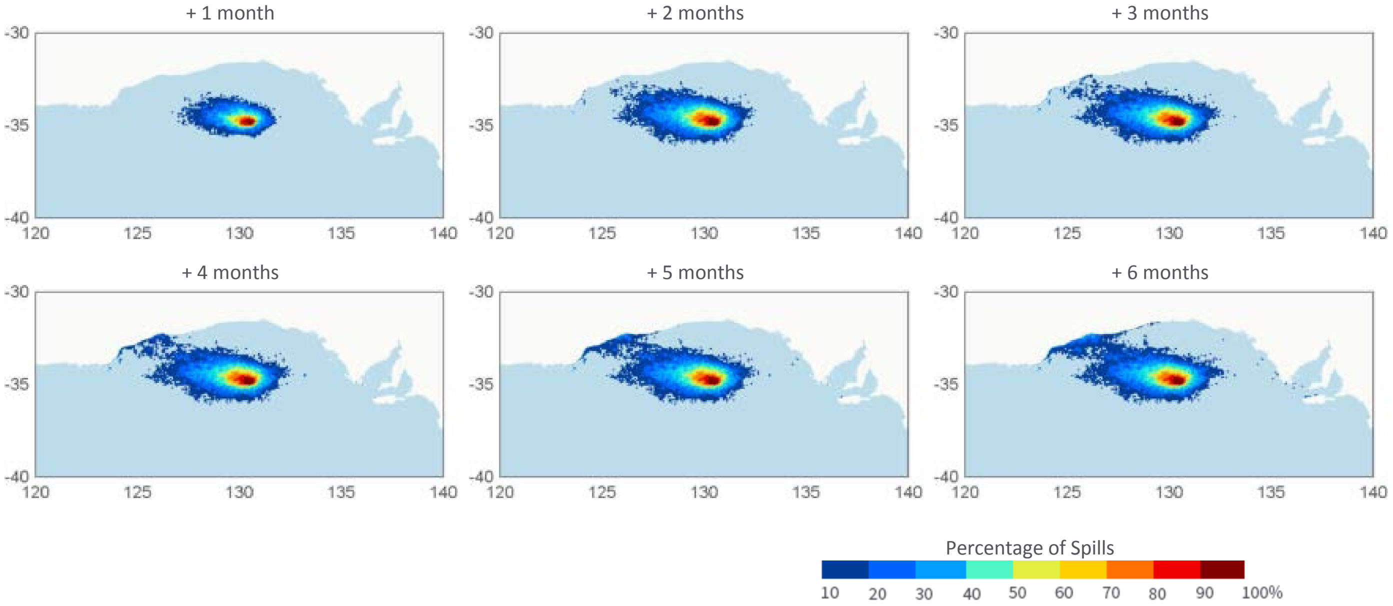
Scenario 1A: oiling threshold at 10 g/m2 (ecological impact threshold at sea, mortal impact on sea birds and wildlife)

- Less than 10 % of spills reached this level of concern in scenario 1A for both winter and summer

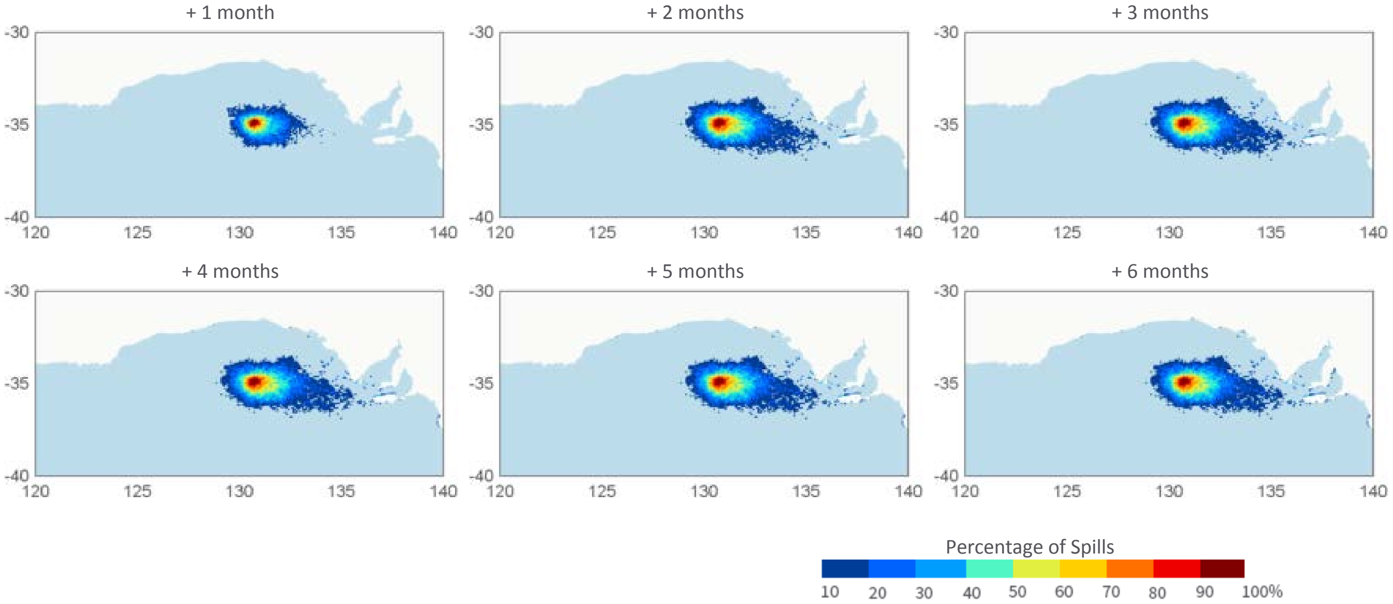


Scenario 1B: oiling threshold at 10 g/m2 (ecological impact threshold at sea, mortal impact on sea birds and wildlife)

- Summer season

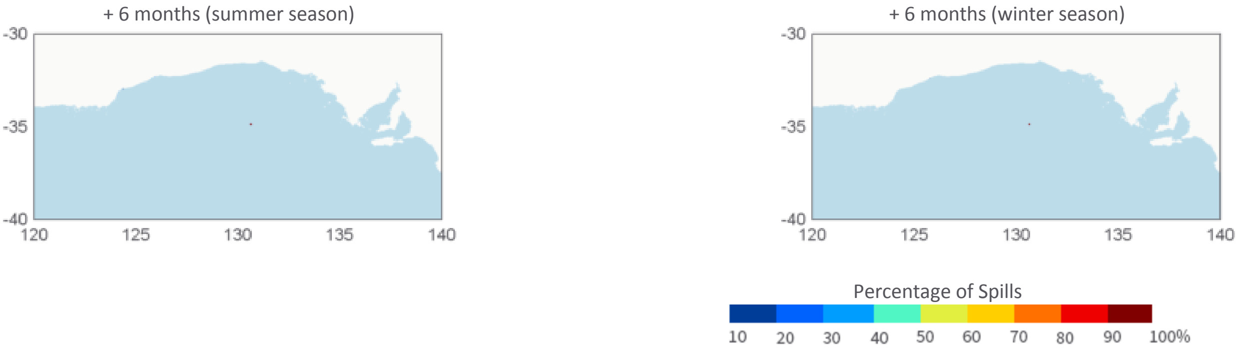


- Winter season



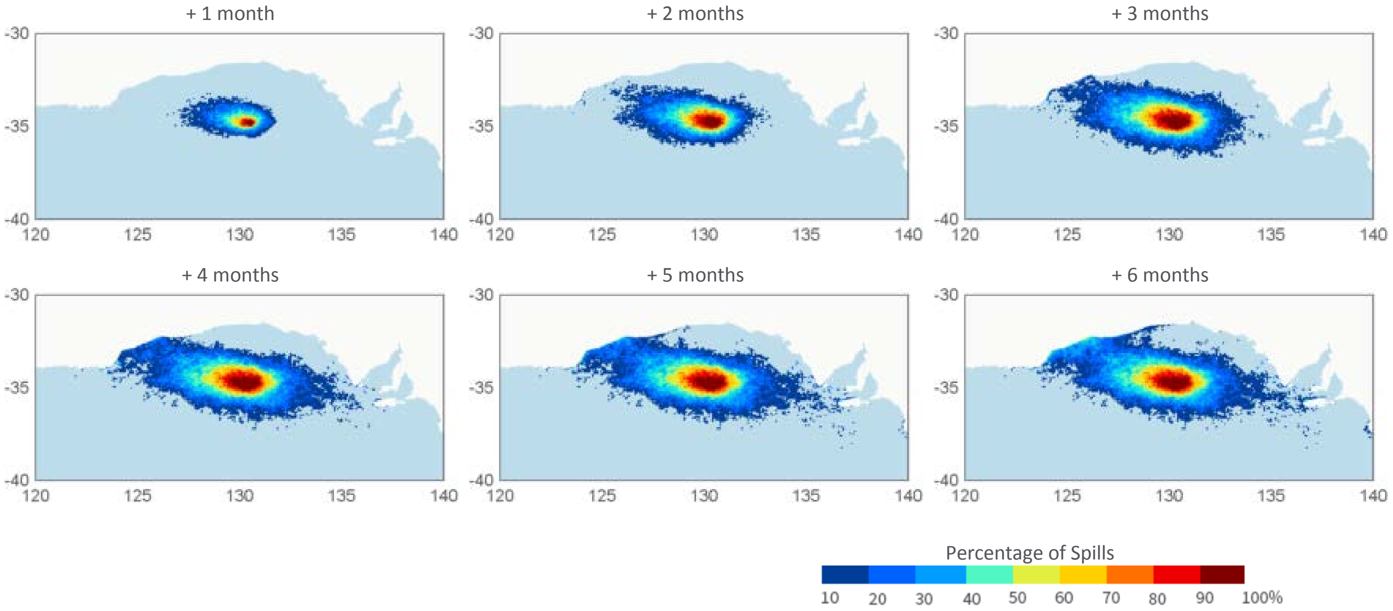
Scenario 2A: oiling threshold at 10 g/m2 (ecological impact threshold at sea, mortal impact on sea birds and wildlife)

- Less than 10 % of spills reached this level of concern in scenario 2A for both winter and summer

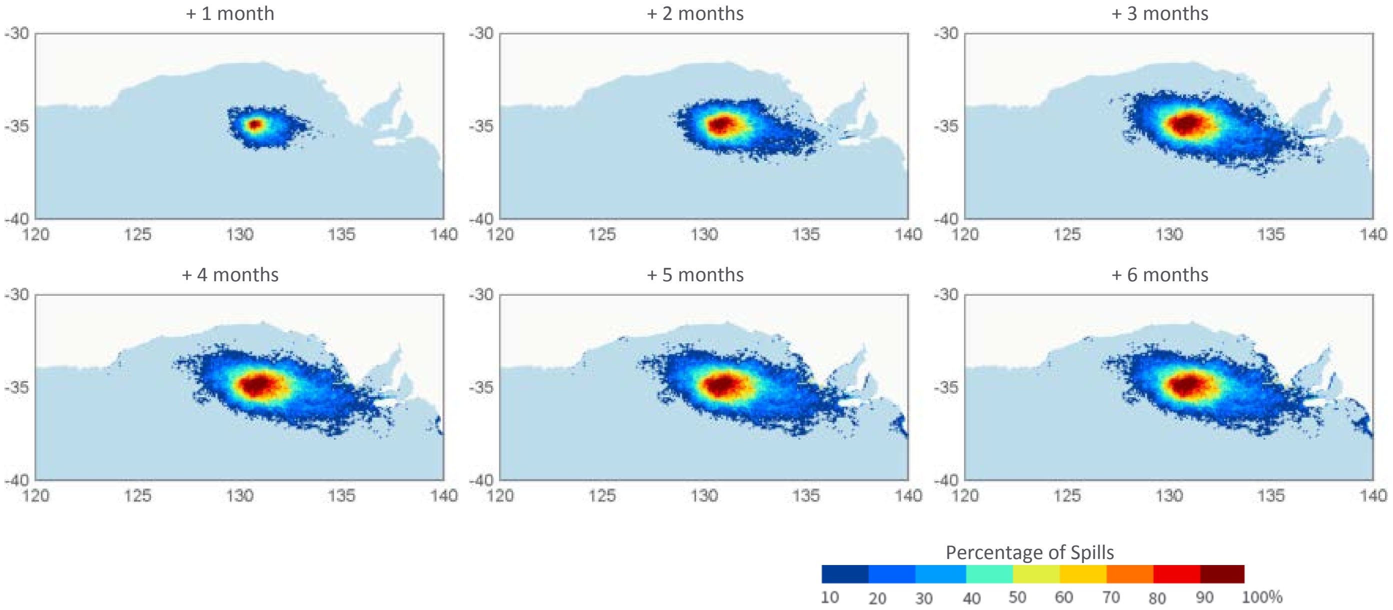


Scenario 2B: oiling threshold at 10 g/m2 (ecological impact threshold at sea, mortal impact on sea birds and wildlife)

- Summer season

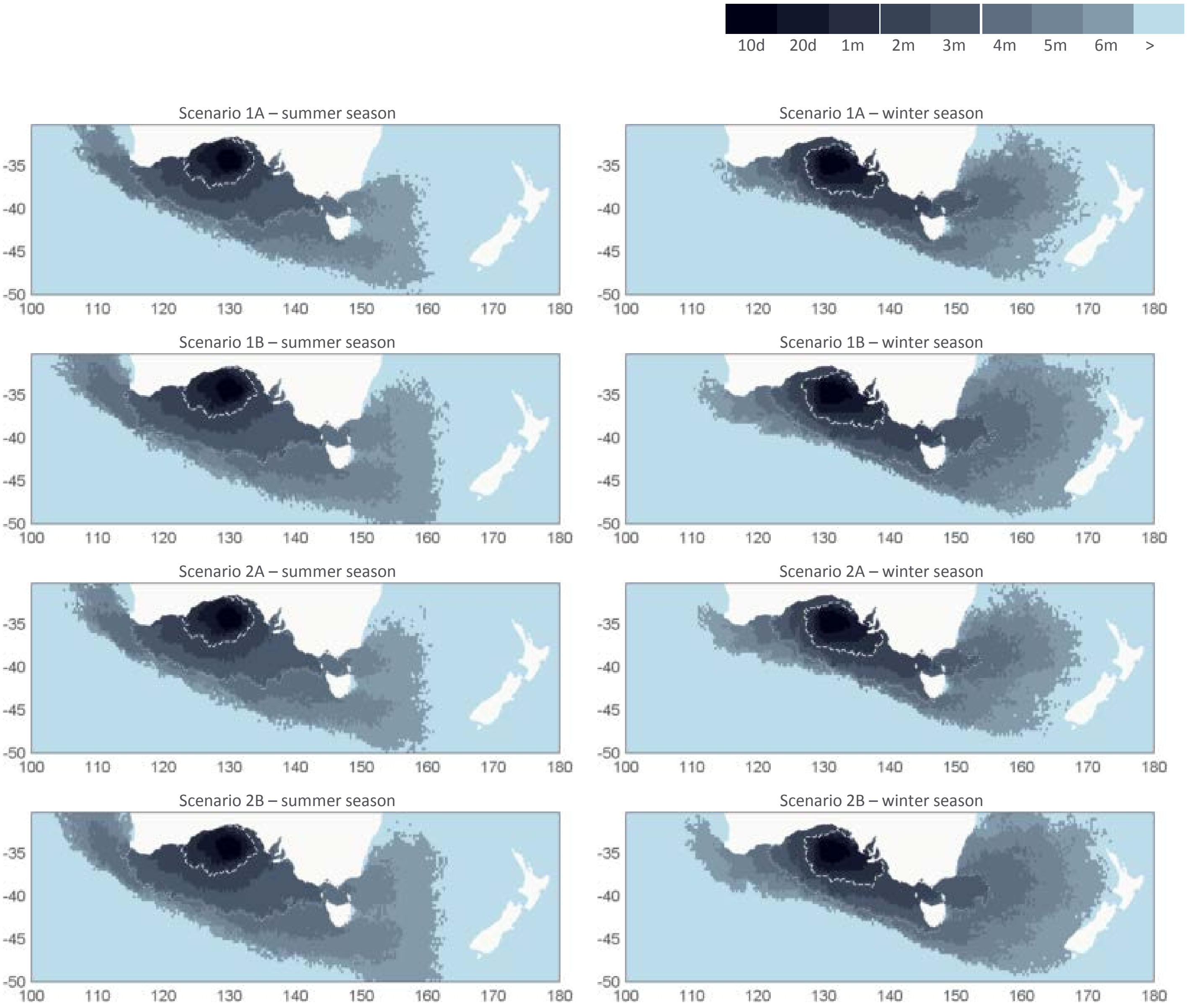


- Winter season



Appendix D: Response time analysis

Socio-economic threshold at sea (0.01g/m^2): minimum travelling time for 95 % of trajectories



Scenario 1A – summer season

Scenario 1A – winter season

Scenario 1B – summer season

Scenario 1B – winter season

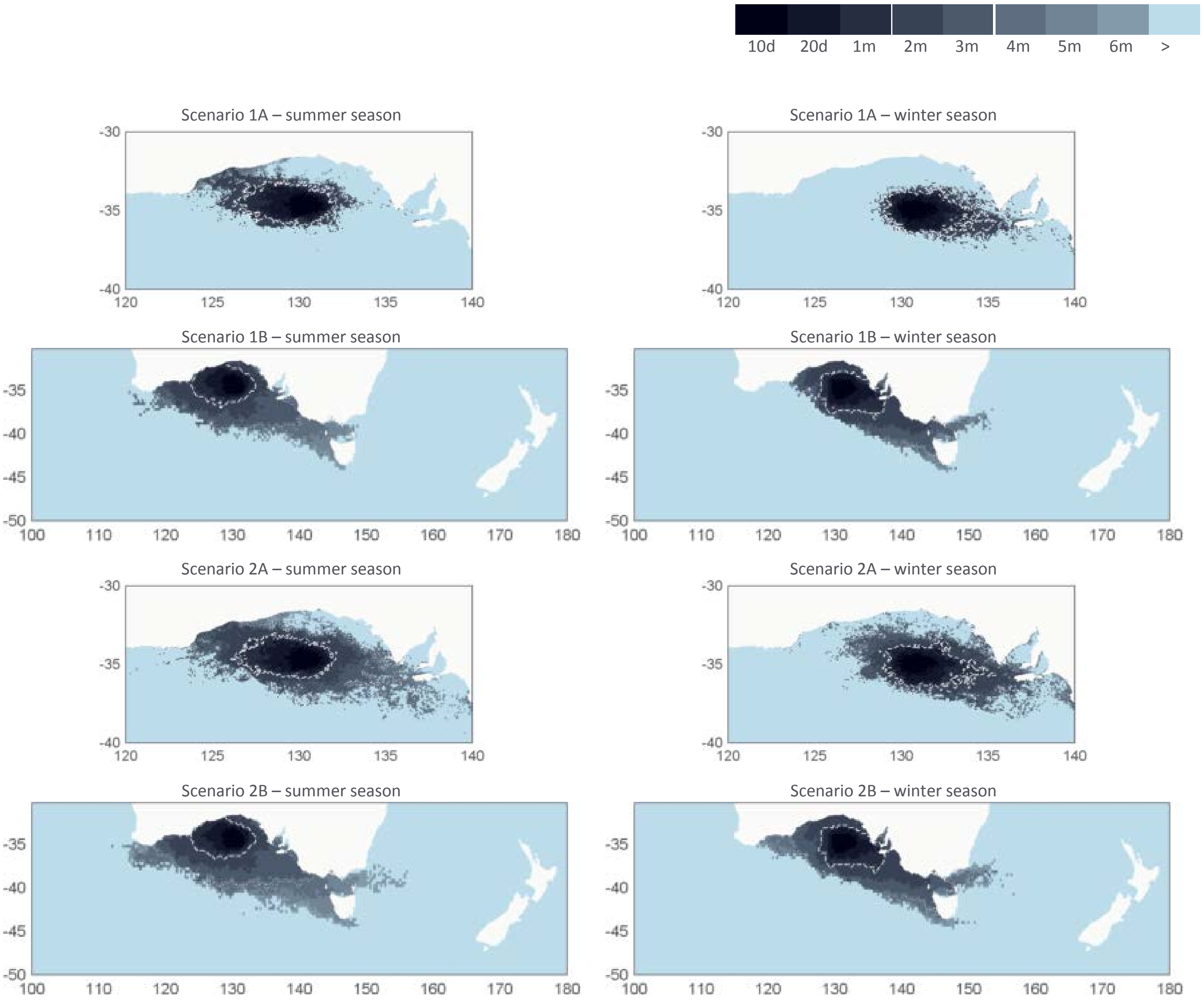
Scenario 2A – summer season

Scenario 2A – winter season

Scenario 2B – summer season

Scenario 2B – winter season

Socio-economic threshold on land (1g/m^2): minimum travelling time for 95 % of trajectories



Scenario 1A – summer season

Scenario 1A – winter season

Scenario 1B – summer season

Scenario 1B – winter season

Scenario 2A – summer season

Scenario 2A – winter season

Scenario 2B – summer season

Scenario 2B – winter season

Ecological threshold at sea (10g/m^2): minimum travelling time for 95 % of trajectories