Climate Change and Fate of Arctic Oil Spills

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Abstract

To investigate how the fate of oil released in the Arctic Ocean may change with a warmer climate, we have performed ensembles of oil spill simulations using Arctic environmental information (winds, currents, ice cover, etc.), covering the periods 2009-2013 and 2050-2054. Three different scenarios have been investigated: a well blowout, a shipping accident and a pipeline rupture. For each scenario, approximately 700 simulations were performed, with all parameters kept constant except the start date, which was chosen to be every five days during the two five-year periods covered by the available data. In this way, the underlying environmental data was sampled, allowing us to obtain statistical information on the influence of the climate on the footprint and fate of an arctic oil spill.

The results mainly show that partial or full ice cover has the effect of reducing the spread of oil, due to damping the effects of wind and waves, and the ice increasingly controlling oil movement. Evaporation is also reduced. The length of oiled shoreline for the well blowout scenario is found to be almost twice as large in the future scenarios, while for the pipeline rupture and the tanker accident the amount of oil on the shore is slightly higher in the present, although there is little or no change in the length of oiled shoreline.

1 Introduction

The goal of this study is to investigate the effect of a future with a warmer climate on the footprint and fate of an arctic oil spill. Even if the climate is warmer, that does not necessarily mean that any given day, or indeed any given year, will be warmer in the future, but rather that global average temperature will be higher. Thus, any single simulation of an oil spill at a given time and place is not by itself interesting in the context of climate change. By performing a large number of simulations, spread out in time over a period of several years, we can generate statistical data and investigate how an "average oil spill" in the future may compare to one in the present.

Using environmental driver data (currents, winds, temperature, ice) for the two periods 2009 - 2013 and 2050 - 2054, we have performed statistical runs using the OSCAR (Oil Spill Contingency And Response) numerical oil spill model. Three different scenarios have been simulated, a well-blowout at about 100 m depth off the north east coast of Greenland, a tanker accident with surface spill in the Kara Strait, and a submerged pipeline leak at 16 m depth near Varandey Bay.

1.1 The OSCAR Oil Spill Model

OSCAR is a state of the art oil spill trajectory model for predicting the fate and effects of released oil, for example from a platform, a pipeline or a vessel. The model accounts for weathering, the physical and chemical processes affecting oil at sea, as well as biodegradation. The development of models for these processes is strongly coupled with laboratory and field activities at SINTEF on fate and effects of oil.

Subsurface oil well blowouts in OSCAR use a near-field model which includes a multi-phase integral plume model (Johansen, 2000; Johansen et al., 2003). This model incorporates the buoyancy effects of oil and gas, hydrocarbon dissolution, hydrate formation, gas expansion and also includes the effects of the ambient water stratification, and cross flow on the dilution and rise time of the plume. Droplet size distribution due to turbulent break-up near the plume outlet is predicted using a model developed by Johansen *et al.* in 2013 (Brandvik et al., 2013; Johansen et al., 2013), accounting for interfacial tension between oil and water, oil viscosity, flow rate and outlet dimensions.

The OSCAR model computes surface spreading of oil, slick transport, entrainment into the water column, evaporation, emulsification and shore interactions to determine oil drift and fate at the surface. In the water column, horizontal and vertical transport by currents, dissolution, adsorption, settling and biodegradation are simulated. The varying solubility, volatility, and aquatic toxicity of oil components are accounted for by representing oil in terms of 25 pseudo-components (Reed et al., 2000), which represent groups of chemicals with similar physical and chemical properties. By modelling the fate of individual pseudo-components, changes in oil composition due to evaporation, dissolution and biodegradation are accounted for in the toxicity of the dissolved oil fraction. There is a biodegradation rate for each of the pseudo-components for the dissolved water fraction, droplet water fraction, surface and sediments.

The OSCAR model uses a pseudo-Lagrangian model where each model particle is tracked through the flow field, which is calculated from currents, wind, and ice if relevant. Buoyancy and sinking of oil droplets due to density differences or oil mineral aggregates are also included.

The properties of the spilled oil are an important part of the input to OSCAR. The viscosity is important for correct determination of the oil slick properties, and the droplet size distribution in the event of a blowout, with droplet size distribution in turn determining what fraction the oil will surface, and when. Viscosity and chemical composition are also important in modelling the formation of emulsions. On the surface, a water-in-oil emulsion can form, which will have quite different properties from the pure oil. Chemical composition of the oil is also relevant for evaporation, and toxicity if impact is to be studied. Both the crude oils considered in this study have previously been characterised for use in OSCAR.

1.2 The SINMOD Hydrodynamic Model

Current, wind and ice data are required as input to the OSCAR model. The SINMOD hydrodynamic model was used to produce the current and ice data (Slagstad and McClimans, 2005). SINMOD is based on the primitive Navier-Stokes equations and is established on a z-grid, using a constant-depth discretisation. The vertical turbulent mixing coefficient is calculated as a function of the Richardson number, Ri, and the wave state. The flow becomes turbulent when Ri is smaller than 0.65 (Price et al., 1986). Near the surface, vertical mixing due to wind waves is calculated from wind speed and fetch length. Horizontal mixing is calculated according to Smagorinsky (Smagorinsky, 1963).

The SINMOD model area used to generate the hydrodynamic data for this study is shown outlined in red in Figure 1. The model area has a spatial resolution of $4\,\text{km} \times 4\,\text{km}$, and the dataset produced has a temporal resolution of 2 hours, giving a total size of around 4 TB for the full 10 years of data. Boundary conditions were taken from a larger model domain, at $20\,\text{km} \times 20\,\text{km}$ resolution. A total of 8 tidal components were imposed by specifying the various components at the open boundaries of the large-scale model. Tidal data were taken from TPXO 6.2 model of global ocean tides (Egbert et al., 1994) (see also `http://volkov.oce.orst.edu/tides/global.html`.

For the present climate simulation (2009-2013), atmospheric data from the ERA-Interim Reanalysis (Dee et al., 2011) has been used. For the climate change case (2050-2054), the atmospheric forcing fields come from a regional model system run by the Max Planck Institute, REMO (Keup-Thiel et al., 2006). This model is configured to cover the model domain of SIN-MOD and has a grid resolution of approximately $0.22°$.

The ice model in SINMOD is a Hibler formulation (Hibler III, 1979), and has two state variables: average ice thickness, h, and ice compactness, A. The equation solver uses the elastic-viscous-plastic mechanism as described by Hunke and Dukowicz (Hunke and Dukowicz, 1997). Ice compactness denotes the area fraction of a grid cell that is covered with ice, which is essentially the same as coverage. The remaining fraction, $1 - A$, is regarded as open water.

2 Scenarios and Locations
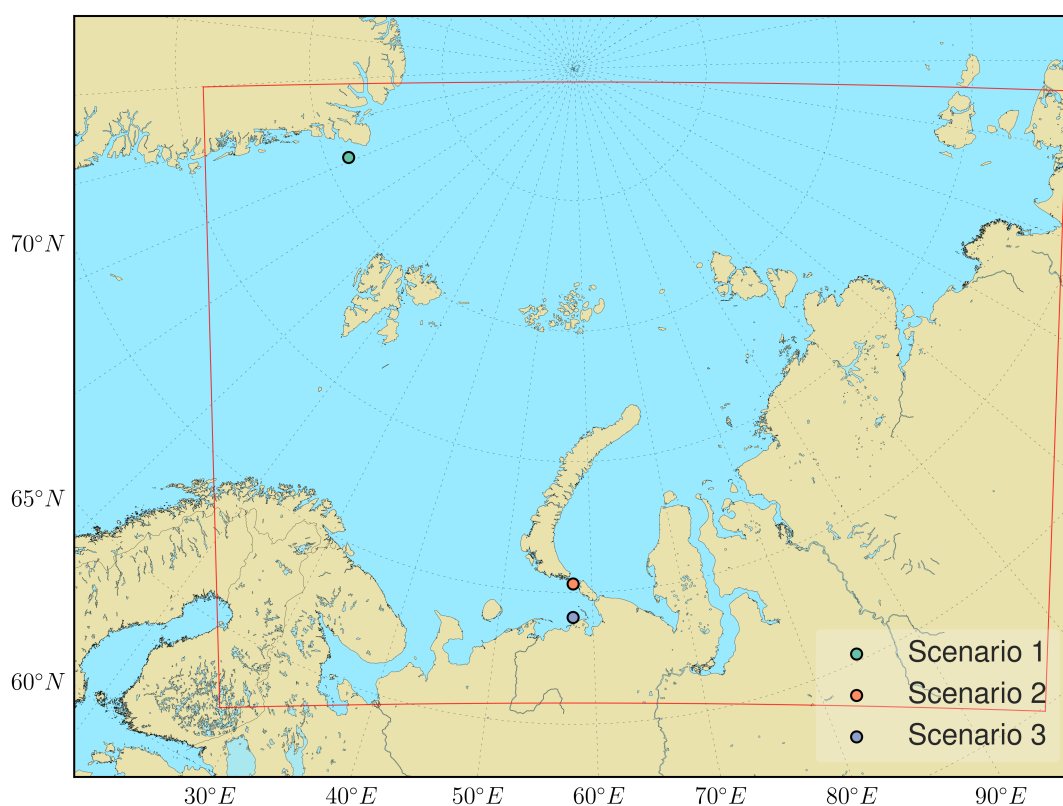
Figure 1: Locations of the three scenarios: Well blowout (Scenario 1) off the coast of Greenland, shipping accident (Scenario 2) in the Kara strait, and pipeline rupture (Scenario 3) near Varandey Bay. The model area which was used by the SINMOD hydrodynamic model is shown outlined in red.

Three scenarios were selected to be used as case studies:

1. A well blowout off the Northeast coast of Greenland

2. A shipping accident in the Kara Strait

3. A pipeline rupture near Varandey Bay

For each of these scenarios, 698 simulations were performed, with the results presented in Section 4. A description and brief discussion of each scenario follows here. We would like to

stress that these scenarios are fictitious, and were made up to show how the footprint of an oil spill might differ under a climate change scenario. These scenarios are not meant to represent the most likely oil spill scenarios in the Arctic, and do not take into account expected changes in activities and shipping routes.

2.1 Scenario 1: Well Blowout, Coastal Greenland

Table 1: Scenario parameters for Scenario 1: well blowout off the coast of Greenland.

Location	10.9865 W, 80.8161 N
Release diameter	0.6604 m
Release rate	10000 metric tons per day
Release duration	50 days
Total release amount	500000 metric tons
Release depth	96 m
Sea depth at release location	97 m
Oil type	Statfjord C blend
Simulation duration	50 days

The first scenario is a well blowout, similar in flow rate and total amount released to the Deepwater Horizon event, in the Gulf of Mexico in 2010, although the area considered here is much more shallow. The exact flow rate of the Deepwater Horizon release is not known exactly, with estimates ranging from around 2500 tons per day, up to 12500 tons per day (McNutt et al., 2011). In the well blowout simulations performed here, we have used a rate of 10000 metric tons per day, for 50 days, although modern permitting standards require that a capping stack must be available to be delivered in 5 days. The flow rate used can probably be said to be a high estimate for a well blowout at this location. The location of the release is shown on the map in Figure 1, and the scenario is summarised in Table 1.

We have selected to use the properties of crude oil from the Statfjord C field for the modelling. The Statfjord C Blend crude oil is regarded as a paraffinic medium crude oil with a density of 0.834 g/mL (API gravity 38). The fresh oil has a medium content of wax (4.1 % by weight) and low asphaltenes (0.09 % by weight) compared with other crude oils in the Norwegian sector. The oil exhibits a medium evaporative loss and forms relatively stable water-in-oil emulsions with high water content (approximately 80 %).

Average ice coverage in an area around the release point is shown in Figure 2 (top), with a comparison of present and future conditions. The most noticeable difference is that the open-water season is longer in the future. In the years 2009-2013, there are on average around 50 days with less than 30% ice coverage, while in the years 2050-2054, there are about 105 days with ice cover at less than 30%. At less than about 30% ice cover, oil moves as in open water. In the years 2009-2013, there are on average about 260 days with more than 70% ice cover, while for the years 2050-2054 there are about 180 days at higher than 70%. When the ice coverage is higher than about 70%, the movement of the oil is largely controlled by the ice, and spreading on the surface is strongly reduced.

2.2 Scenario 2: Shipping Accident, Kara Strait

In this case, the scenario is a tanker accident in the Kara Strait, the strait between Novaya Zemlya and Vaygach Island, which separates the Kara Sea from the Barents Sea. The strait is quite narrow, about 55 km across, and quite shallow, around 50 meters at the deepest, and the currents can be quite strong, frequently reaching 1.5 m/s in the current data used to drive

the oil spill simulations in this study. The scenario assumes that a tanker leaks 40000 metric tons of crude oil over a period of 14 days, and the simulations are run for a total of 50 days. A constant leak rate and a fixed position for the leaking vessel have been used in this scenario. The location of the release is shown on the map in Figure 1, and the scenario is summarised in Table 2.

Table 2: Scenario parameters for Scenario 2: shipping accident in the Kara Strait.

Location	57.8862 E, 70.3296 N
Release rate	2857 metric tons per day
Release duration	14 days
Total release amount	40000 metric tons
Release depth	Surface release
Sea depth at release location	39 m
Oil type	Russian Crude
Simulation duration	50 days

The chosen oil, Russian crude oil (2010), is regarded as a paraffinic crude oil with a density of 0.856 g/ml (API gravity 33.7), with medium wax content (3.9 % by weight), and has a asphaltene content of 0.39 % by weight. The oil exhibits medium evaporative loss and forms stable water-in-oil emulsion (about 80% water content) after a short time of weathering at sea.

Average ice coverage in an area around the release point is shown in Figure 2 (middle), with a comparison of present and future conditions. The most noticeable differences are that the open-water season is longer in the future, and that maximum ice cover during winter is lower for the future. In the years 2009-2013, there are on average around 180 days with less than 30% ice coverage, while in the years 2050-2054, there are about 260 days with ice cover at less than 30%. At less than around 30% ice cover, oil moves largely as in open water. Furthermore, during the years 2009-2013, there are on average around 100 days per year with ice cover higher than 70%, while for the years 2050-2054 the average year does not reach 70% ice cover.

2.3   Scenario 3: Pipeline Rupture, Varandey

The final scenario considered is an oil spill from a pipeline leading to a loading terminal at sea. Such a pipeline could for example be damaged by gouging from an iceberg. We assume that a large leak in such a pipeline would be quickly detected, leading to only limited amounts of oil leaking out. In this scenario, at total of 416 metric tons (3000 barrels) have been assumed to leak from a position 1 m above the sea bed, over a period of 2 days. The selected oil, Russian crude oil, is the same as in Scenario 2. The location of the release is shown on the map in Figure 1, and the scenario is summarised in Table 3.

Average ice coverage in an area around the release point is shown in Figure 2 (bottom), with a comparison of present and future conditions. The conditions are naturally quite similar to those for Scenario 2, which is located nearby. Average ice cover is lower in the future, with the years 2009-2013 showing an average of around 100 days at above 70% ice cover, compared to around 20 days for the years 2050-2054.

3   Simulation Procedure

As mentioned in the introduction, climate change and global warming do not necessarily mean that any given day, or any given year, will be warmer in the future. Instead, it means that
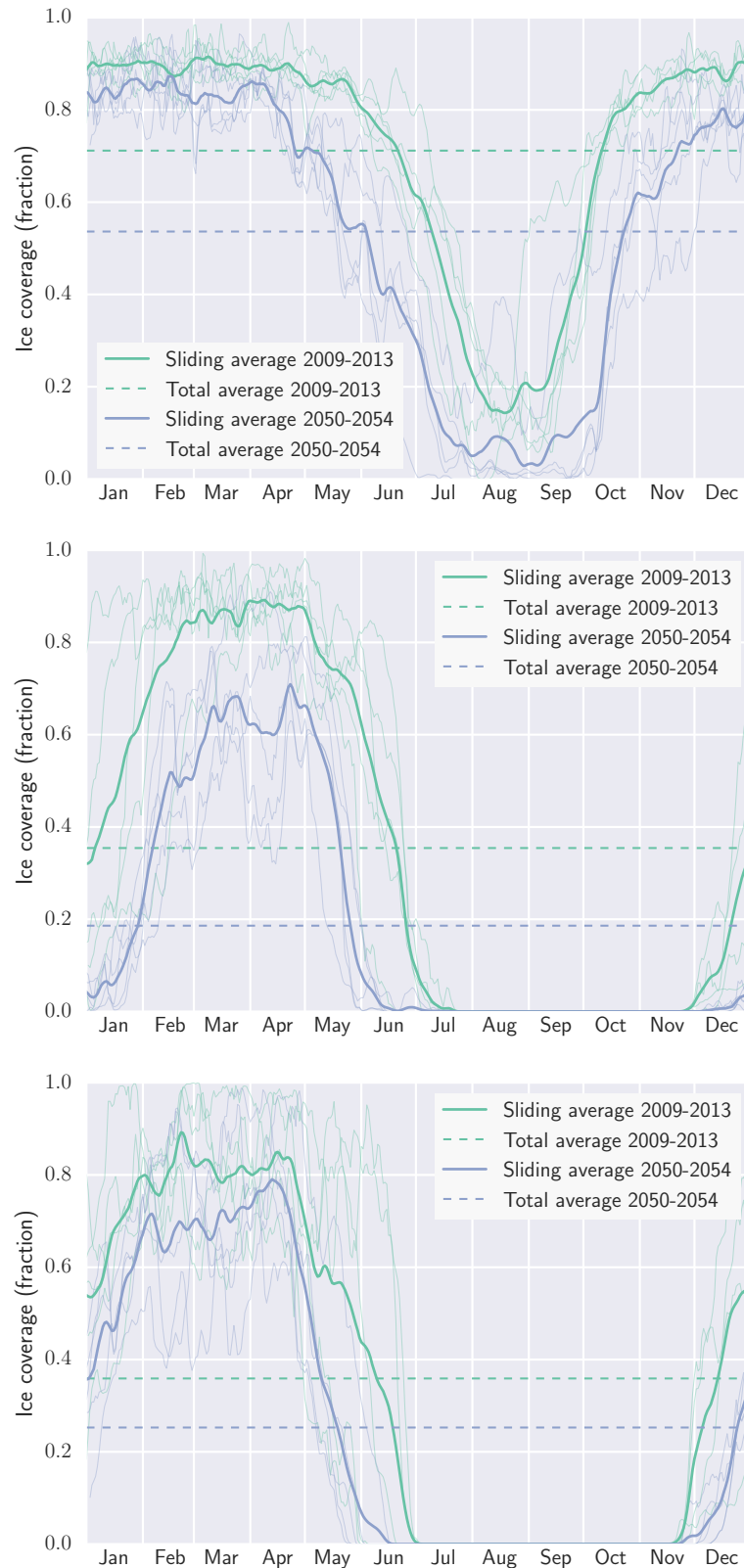
Figure 2: Ice coverage (fraction) in a 160 km × 160 km area centered on the release point, showing from the top Scenarios 1, 2 and 3. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed line show the total average over five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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Table 3: Scenario parameters for Scenario 3: pipeline rupture near Varandey.

Location	57.8862 E, 69.0528 N
Release rate	208 metric tons per day
Release duration	2 days
Total release amount	416 metric tons
Release depth	16 m
Sea depth at release location	17 m
Oil type	Russian Crude
Simulation duration	50 days

for most (but not necessarily all) areas, average temperatures will be higher. In order to investigate the effect of higher average temperatures on the fate of an oil spill, we need to perform a large number of simulations spread out over a period of several years. For this study, we have used the two five-year periods 2009 - 2013 and 2050 - 2054. In this way, we sample from the distribution of climate data, and produce a distribution of possible fates of an oil spill.

For each of the three scenarios studied here, we have performed a 50-day simulation starting every 5 days for the duration of both the two five-year periods. Thus, if the first simulation had a start date of January 1, 2009, it would run until February 20, 2009. The next simulation would have a start date of January 6, 2009, and run until February 25, etc. These two simulations would then see partially different environmental data, with the difference in the results being dependent on the type of scenario. After repeating this process to cover the whole five years, we will have collection of results from partially overlapping simulations, as well as for several years, which will allow to study both seasonal differences and differences from the present to the future.

The procedure is essentially a form of Monte Carlo averaging, i.e., an average over an ensemble of simulations where at least part of the input is in some sense random. The environmental data which is given to the model as inputs (currents, winds, ice, temperature and salinity) are not independent, and it is not easy to generate random realisations of these fields which are still physically consistent. However, by using sequences of data taken from the two five-year datasets, we are sampling from the underlying probability distribution. It could probably be discussed whether some other sampling scheme than the regular intervals used here would be better. For example, when calculating averages based on all the samples, simulations which take place during calm weather are given equal weight as those which take place during adverse weather conditions. In reality, it could for example be more likely for a spill, at least one caused by a shipping accident, to take place during bad weather. Regular sampling was nevertheless chosen, because it is trivial to implement, easy to explain and it has the distinction of being commonly used in contingency analysis during planning of new activities.

The simulation results from the OSCAR model include four dimensional (x, y, z, t) concentration fields giving concentration per component for droplets and dissolved chemicals, as well as three dimensional (x, y, t) grids for oil on the sea surface, on the shore and in the sediments. Additionally, some aggregated quantities are available as time series. These include amounts of evaporated oil, oil on the sea surface, submerged oil, oil on the shore, oil in the sediment and amount which has been biodegraded.

These last six quantities make up what is known as the mass balance, because it gives information about the fraction of the total mass which is found in any given "environmental compartment". During the development of a spill, oil can move from one compartment to another. For example, oil on the surface can be mixed down by waves and submerged, sub-

merged oil can resurface, stranded oil can be washed out to sea, etc. The exception is that oil which has been evaporated or biodegraded is removed from the simulation. Note that also oil which is trapped at the ice-water interface is considered to be at the surface in the mass balance calculation.

For each scenario, 698 simulations were performed, half in the period 2009 - 2013 and half during 2050 - 2054, giving a total of 2094 simulations. Depending on the scenario, one simulation takes about an hour to two and a half hours to complete, giving a total of about 150 days of CPU time. The simulations were for the most part performed on a 32-core compute node running linux, with 28 simulations running in parallel, allowing the simulations to be completed in a little over 5 days. The compute node was fitted with 10 TB of fast access disk space, allowing the entire environmental dataset to be kept on the node and used directly.

4   Results

4.1   Surface

Table 4: Summary of results for surface oil. The table shows the average (μ) and standard deviation (σ) over the two five-year periods, for all three scenarios, of the amount (in tons) of oil at the surface, the area (in km^2) covered by oil thicker than 100 μm and the total area (in km^2) covered by oil. The averages and standard deviations are calculated from the values at the end of each 50-day simulation.

	Scenario 1				Scenario 2				Scenario 3			
	Present		Future		Present		Future		Present		Future	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Surface (tons)	303k	36.4k	270k	57k	10600	9350	7390	8180	35.4	56.5	25.7	49.1
Thk. oil (km^2)	566	310	606	282	11.9	11.9	15.3	23.1	0.088	0.27	0.076	0.25
Tot. area (km^2)	1840	2420	4250	5520	856	2040	1110	2560	15.7	29.3	19.1	38.4

In Figure 3, amount of oil on the surface, area of thick oil (thicker than $100\,\mu$m) and total area covered by oil are shown for Scenario 1, the well blowout. Each quantity is shown at the end of a 50-day simulation, and as a function of start date of that simulation. The thin lines shown each individual year, while the thick lines show a five-day sliding average over a five-year period. The years 2009 - 2013 are shown in green, and the years 2050 - 2054 are shown in blue. The same for Scenario 2, the tanker accident, is shown in Figure 4, and for Scenario 3, the pipeline leak, in Figure 5.

In all three scenarios, there is a clear trend showing less oil on the surface during the summer months. Since oil typically has lower density than water, oil droplets will rise to the surface, and once at the surface will remain there unless wind and waves cause the oil to be mixed down. When there is ice cover, the effects of wind and waves are reduced or removed, meaning that oil which reaches the surface in full ice cover is more likely to remain at the surface. Note that surface oil here includes oil which is trapped at the water/ice interface. Due to a longer period of open water, there is on average less oil on the surface in the future scenarios.

When comparing the surface oil data for Scenario 1 (Figure 3) to the ice cover for that area (Figure 2, top), the same trend of a longer summer season in the future can be seen, and the correlation is quite clear. For Scenario 2, comparing the surface oil plot (Figure 4) to the ice cover (Figure 2, middle), the same trend is observed. For Scenario 3, with surface oil shown in Figure 5 and ice cover shown in Figure 2 (bottom), the longer ice-free period in the future is visible, but the correlation to the surface oil data is less clear. Note that in this scenario, the difference between the maximal ice cover in the present compared to the future is modest, with ice cover frequently dipping below 70% during winter for both periods.

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In Table 5, the average (μ) and standard deviation (σ) are shown for the two five-year periods, for all three scenarios, of the amount (in tons) of oil at the surface, the area (in km^2) covered by oil thicker than $100\,\mu$m and the total area (in km^2) covered by oil. In all three scenarios, the average amount of oil on the surface is lower in the future, and the total area covered by oil is higher in the future. Note also that for all three scenarios, the standard deviation of the total area increases in the future.

That the average total area is larger in the future is expected. Oil which remains on the surface will tend to move as a slick. When the oil is dispersed into the water column, however, different droplet sizes will rise with different speeds. Smaller droplets will tend to stay submerged longer, while larger droplets will rise faster. Since the current near the surface often changes relatively quickly with depth, this leads to spreading over a larger area whenever oil is mixed down into the water column.

It is interesting to note that both the area covered by thick oil and the total area are highly variable, especially in Scenarios 2 and 3. From the thin lines showing the individual years in Figure 4 (middle), it can be seen that in some cases the area covered by thick oil can reach $150\,$km^2, which is 10 times the average for the future scenarios. Similarly, for Scenario 3 it can be seen from Figure 5 (middle) that the area covered by thick oil can reach much higher values than the average. In this case, the maximum for the future scenarios is $3\,$km^2, which is around 40 times the average. Under the right circumstances, this high variability could certainly occur in the present scenarios as well. In any case, it serves to illustrate the dramatic difference that can be observed in two spills which are separated by a few days, but otherwise identical in all respects. This is especially true for shorter spills, such as Scenario 3 (2 days) and Scenario 2 (14 days). For a longer spill, such as Scenario 1 (50 days), the continuous release of oil over a long period will serve to smooth out short term changes in environmental data.

4.2 Stranded

Table 5: Summary of results for stranded oil. The table shows the average (μ) and standard deviation (σ) over the two five-year periods, for all three scenarios, of the amount (in tons) of oil on the shoreline and the length (in km) of shoreline affected by oil. The averages and standard deviations are calculated from the values at the end of each 50-day simulation.

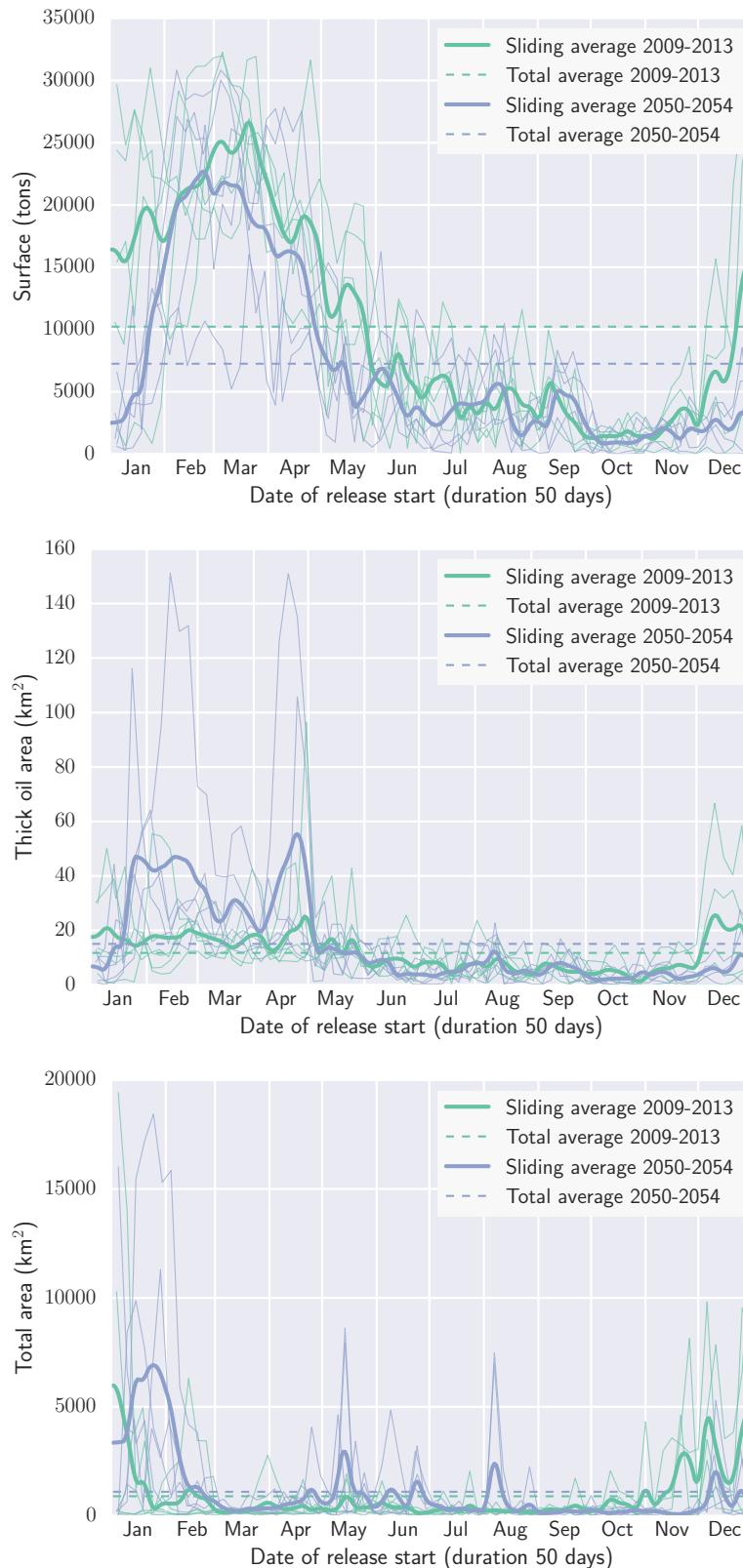|	Scenario 1				Scenario 2				Scenario 3			
	Present		Future		Present		Future		Present		Future	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Stranded (tons)	1730	1910	4750	3700	1500	998	1170	895	35.9	45.8	27.0	35.9
Length (km)	216	200	518	324	267	150	262	173	26.3	31.7	21.5	27.4

Oil on the shore in Scenario 1 (well blowout), is shown in Figure 6, with the total length of shoreline affected by oil shown on top, and amount of oil on the shore on the bottom. Each quantity is shown at the end of a 50-day simulation, and as a function of start date of that simulation. The thin lines show each individual year, while the thick lines show a five-day sliding average over a five-year period. The years 2009 - 2013 are shown in green, and the years 2050 - 2054 are shown in blue. The same for Scenario 2, the tanker accident, is shown in Figure 7, and for Scenario 3, the pipeline leak, in Figure 8. The averages and standard devations are summarised in Table 5.

For Scenario 1, we see a quite significant increase in the average between the present and the future, with a total average of 1720 tons of stranded oil and 213 km of oiled shoreline for 2009-2013, compared to 4900 tons and 529 km for 2050-2054. The standard deviation of both
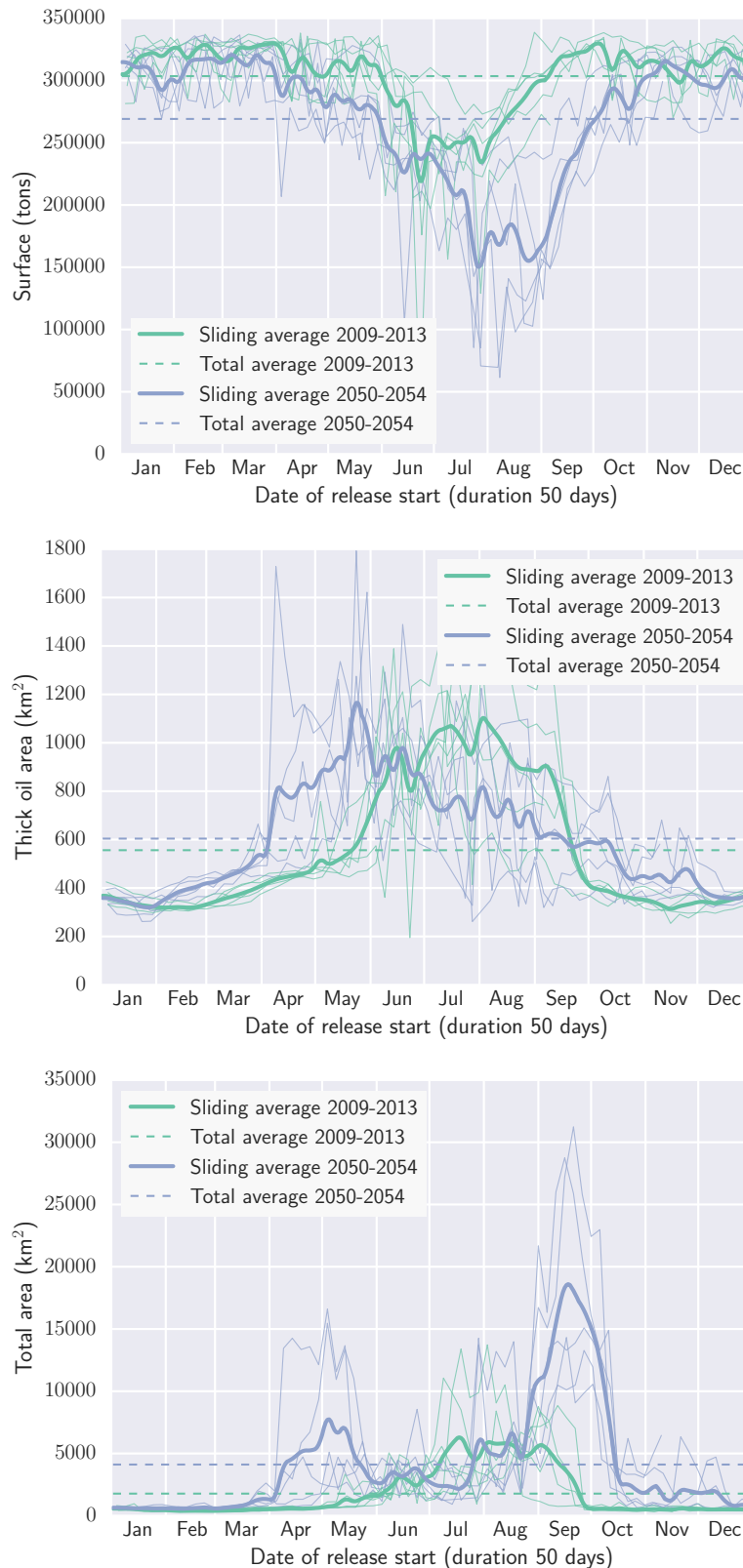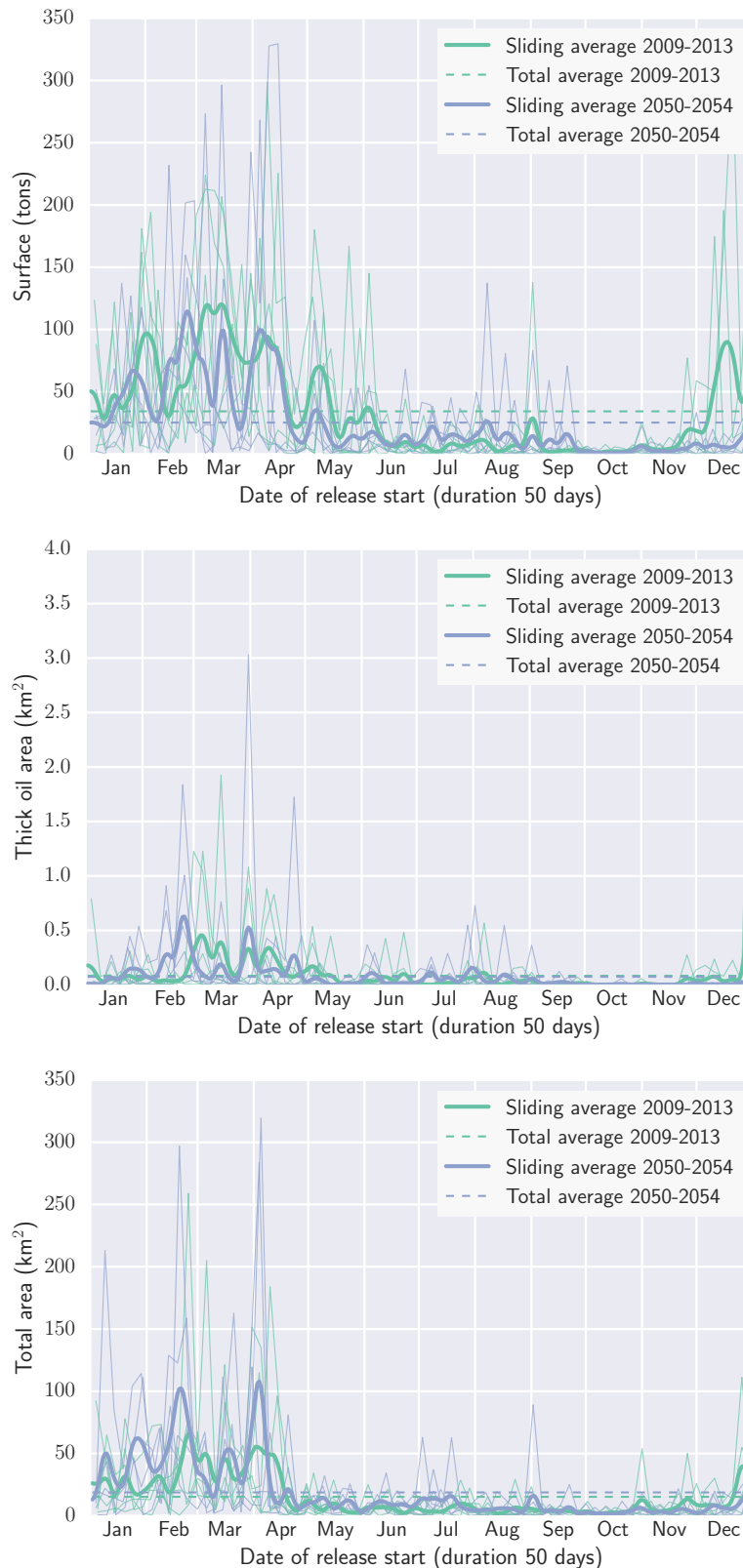
Figure 3: (Scenario 1) From top to bottom: Amount of oil (in metric tons) on the surface, area (in km^2) covered by oil thicker than 100 μm, and area (in km^2) covered by oil. In each case, the value at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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Figure 4: (Scenario 2) From top to bottom: Amount of oil (in metric tons) on the surface, area (in km²) covered by oil thicker than 100 μm, and area (in km²) covered by oil. In each case, the value at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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Figure 5: (Scenario 3) From top to bottom: Amount of oil (in metric tons) on the surface, area (in km²) covered by oil thicker than 100 μm, and area (in km²) covered by oil. In each case, the value at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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of these quantities are also larger in the future. Looking at length of affected shoreline and total amount of oil on the shore (Figure 6), and comparing to ice cover (Figure 2, top) we observe that both quantities go down in the winter season when ice coverage is high.

Looking at Scenarios 2 and 3, the differences between the present and the future are much smaller. For Scenario 2, the seasonal trends in oil on the shore (Figure 7) are less clear, while for Scenario 3 (Figure 8), there is a clear reduction in both amount of oil and length of shoreline affected during the open water season (see Figure 2, bottom). This trend is opposite to what was observed for Scenario 1, meaning that in one case, the ice cover serves to protect the coastline, while in the other, the ice keeps the oil trapped against the shore.

5   Discussion

The conclusion from the case studies is that the same trend can be observed in all three scenarios: during periods with low ice coverage, there is in general more spreading and a less concentrated surface slick. For individual years, this can be seen as more spreading in summer than in winter, and for the full ensemble of simulations, there is on average more spreading in the future scenarios than in the present. However, for almost all of the endpoints considered here, such as amount of oil on the surface and length of oiled shoreline, the variation between summer and winter is larger than the variation between the present and the future.

The difference in spreading has implications for consequences of a spill, as well as response options. More spreading means larger affected area, but also lower average concentrations over that area. It is also easier to respond to a thicker surface slick, however the presence of ice may limit the available response options.

The probability of oil spill accidents in the Arctic is expected to increase in concert with increases in transport and resource exploration and extraction activities. The results reported here suggest that future oil spills in a warming climate will result in greater areal coverage and in some cases increased shoreline exposure, due to reduced ice coverage. These two considerations point towards a significant increase in environmental risk, defined as the probability of an event, in this case an oil spill, weighted by the magnitude of the resulting environmental injury. A comparative environmental risk assessment would therefore be a natural follow-on to the present study.
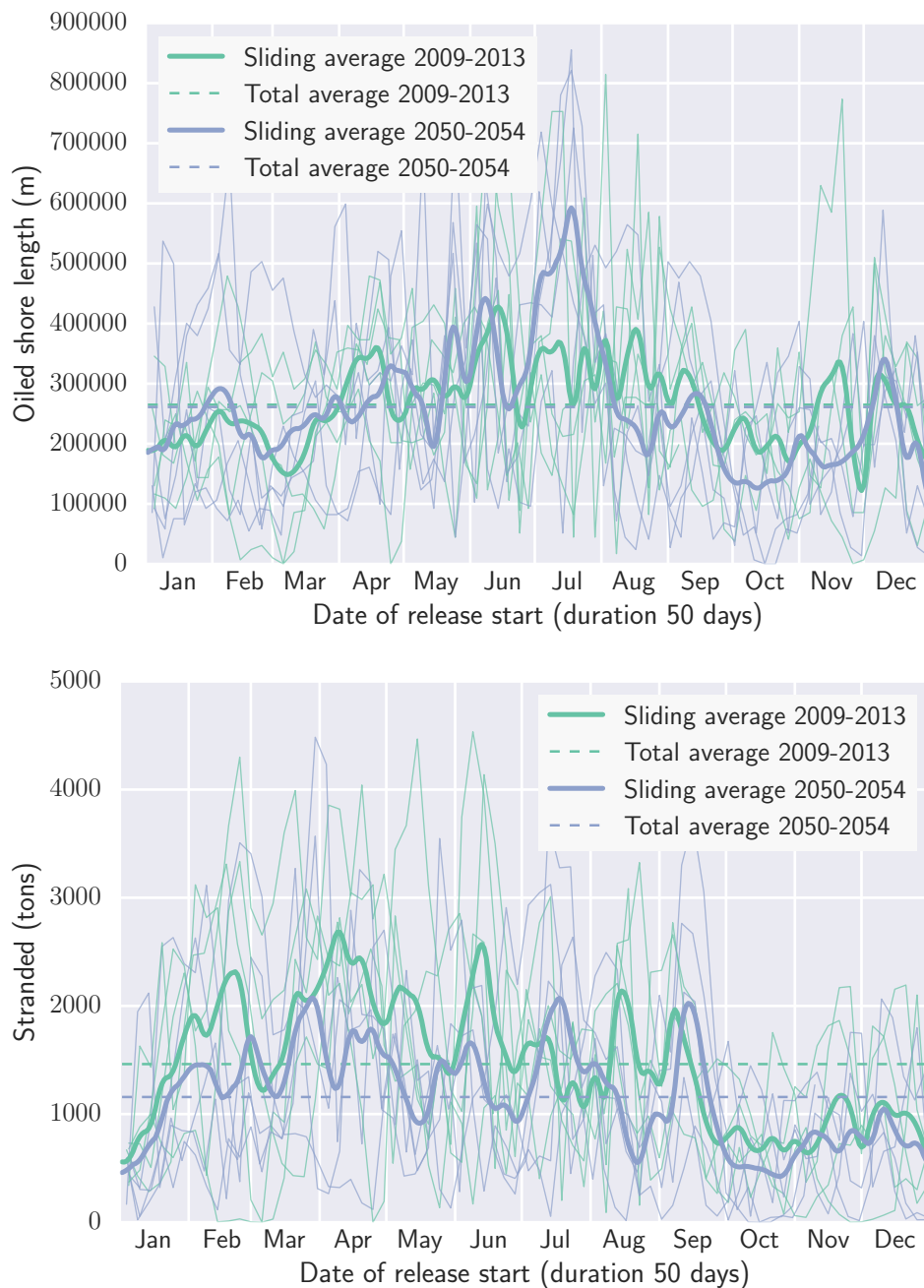
Ensemble simulations, such as those performed in this study, make up an important part of planning by allowing us to study a range of possible outcomes. They can also be used operationally, for longer term prediction of oil trajectories, outside of normal forecast ranges, as was done, for example, during the Deepwater Horizon (Barker, 2011). However, modelling the interactions of oil and ice, and especially modelling oil spill response in ice covered waters, are topics that need more research.
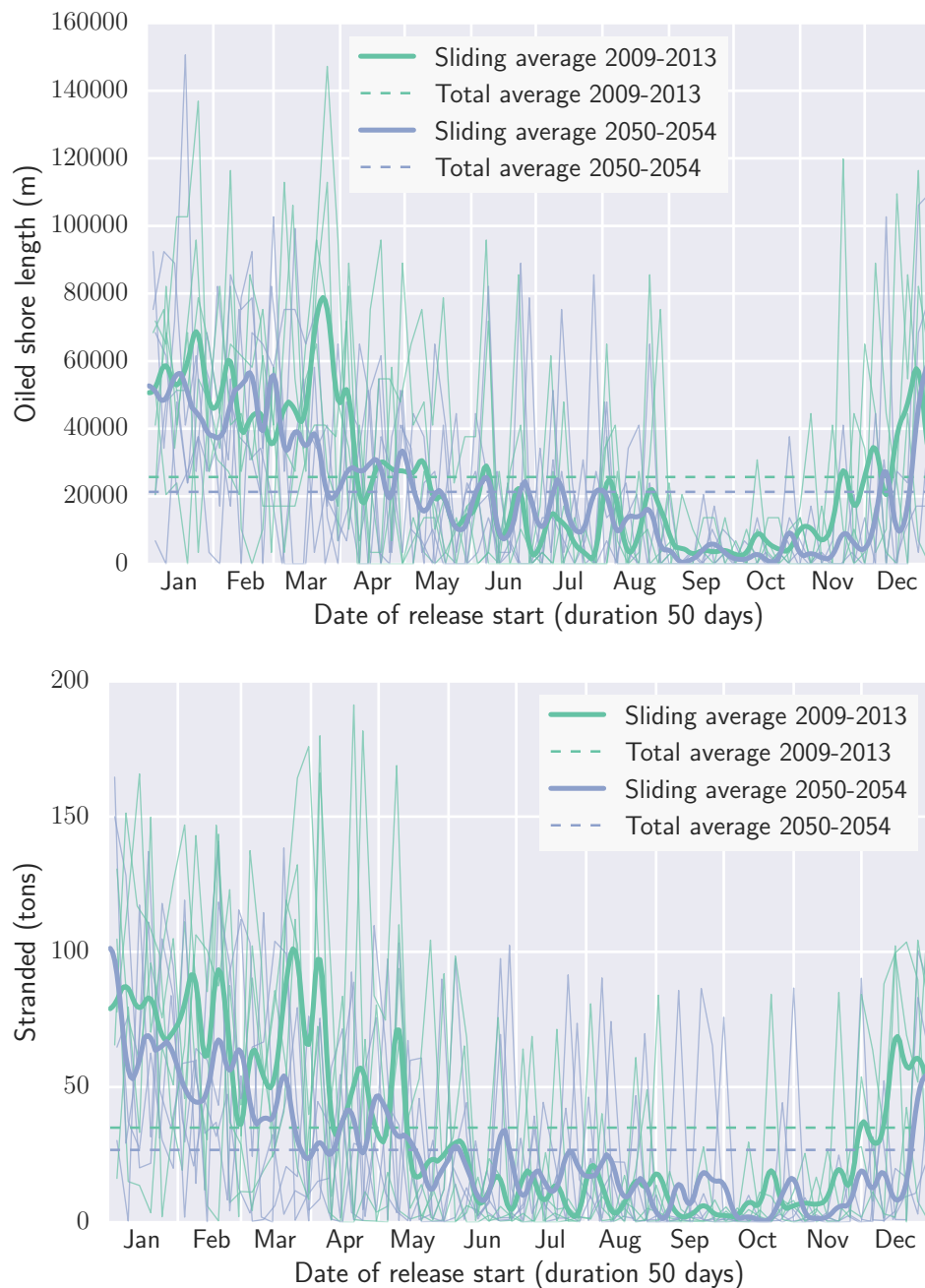
6   Acknowledgements
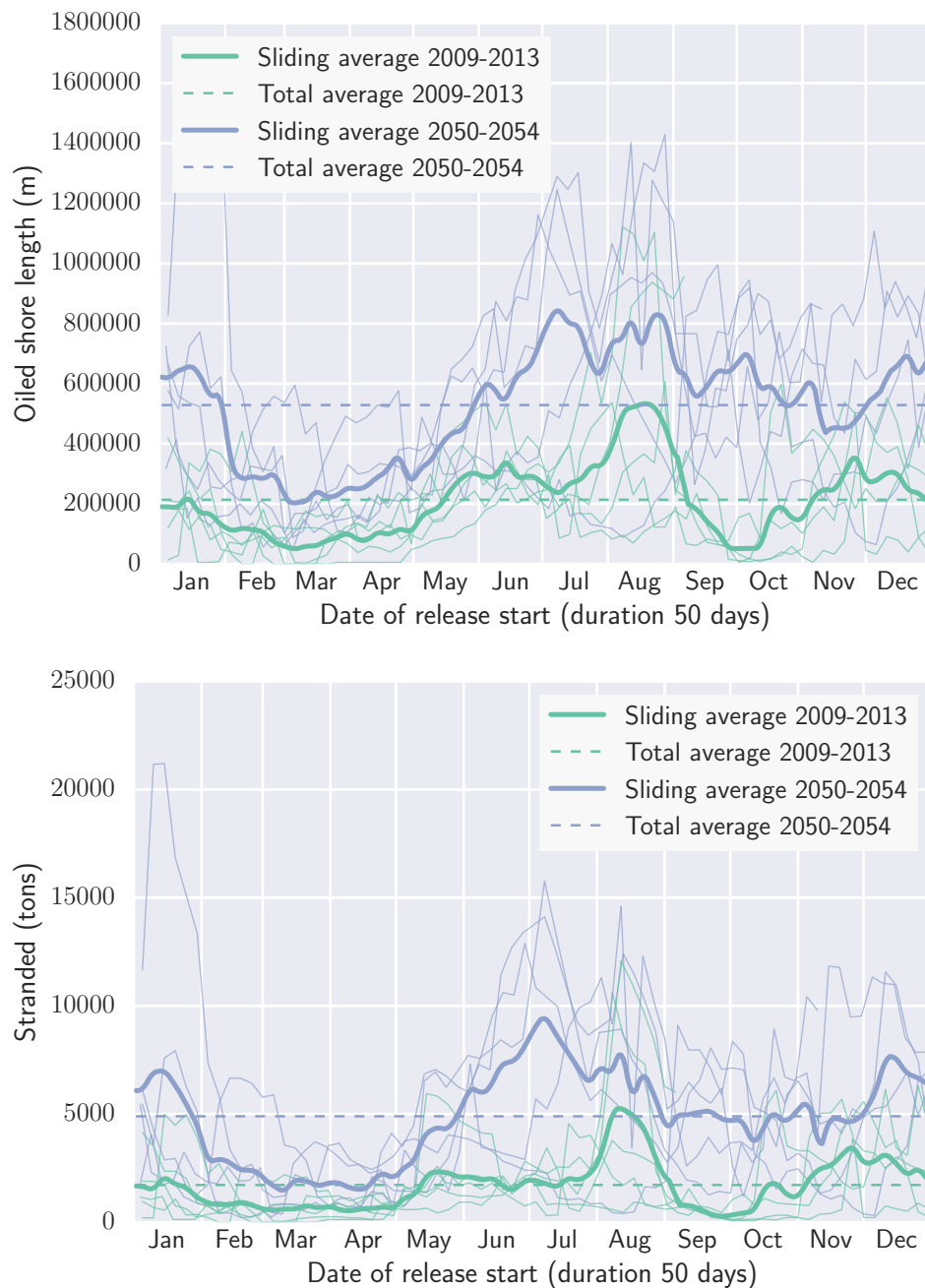
Figure 6: (Scenario 1) From top to bottom: Length (in m) of shore affected by oil, and amount (in metric tons) of oil on the shore. Both values are at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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Figure 7: (Scenario 2) From top to bottom: Length (in m) of shore affected by oil, and amount (in metric tons) of oil on the shore. Both values are at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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Figure 8: (Scenario 3) From top to bottom: Length (in m) of shore affected by oil, and amount (in metric tons) of oil on the shore. Both values are at the end of each 50 day simulation, shown as a function of start date for the simulation. The thin lines show data for the individual years, the thick lines show a five-day sliding average of five years, and the dashed lines show the total average of five years, with 2009-2013 shown in green and 2050-2054 shown in blue.

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