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Influence of projected climatic conditions and varying lateral points of release on oil slick transport in a tide-dominated estuary

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Abstract

Oil spills in estuarine systems can strongly endanger habitats and water quality. However, the impacts of projected climatic conditions on oil spill transport in estuarine environments have received little attention. To address these key gaps, we analyse here a range of simulations for the Humber Estuary, UK, using coupled hydrodynamic and oil spill model. These simulations indicate that, for this well-mixed macro-tidal estuary: (a) the influence of projected sea level rise and river discharge on oil slick impacted area, slick length and overall distance travelled is relatively minor (< 10%); (b) magnitude of currents determines differences in dynamics between oil slicks released along the estuary length; and (c) differences in lateral current speed and direction are key determinants of the differences in the dynamics of oil slicks released along the estuary width. The implications of these findings for operational oil spill response in estuaries similar to the Humber Estuary are: (i) the need to be aware of dominant current direction in different segments of the estuary; and (ii) the need take cognisance of the interaction between oil slicks and estuary bank and how it influences overall distance travelled by oil slicks.

Keywords: oil spill; estuarine environments; climate change; sea-level rise; numerical model.

1. Introduction

Notwithstanding the growing use of renewables, oil still significantly contributes to economic activity. As a result, there still remains a continuous increase in the demand for crude oil and its derivatives (Wang et al. 2005; Chen et al. 2019). The production and transportation of crude and refined oil can undesirably lead to oil spills (Berry et al. 2012), making it a major contributor to marine and estuarine pollution (Cheng et al. 2011; Kang et al. 2016). Oil spills can severely affect fisheries and wildlife (Xu et al. 2013), public health (Noh et al. 2019; Sharpe et al. 2019) as well as areas with high touristic, social and environmental value (Olita et al. 2012). Considering the adverse economic, environmental and social impacts, it is no surprise that oil spills are regarded as one of the worst types of marine and estuarine pollution (Guo et al. 2018). Understanding the typical location of oil spills, their subsequent travel path and oil travel time to receptors is vital to mitigate the impact of oil spills (Al-Rabeh et al. 2000; Berry et al. 2012; Amir-Heidari and Raie 2018). Consequently, numerical oil spill models are often employed to understand oil spill transport, to minimize oil pollution impacts (Guo et al. 2018). An effective approach is by simulating an ensemble of hypothetical spill scenarios thereby providing a statistical measure of oil spill impact (Amir-Heidari and Raie 2018).

Despite increasing maritime transport of oil (Chen et al. 2019) and increasing risks that oil spills present to estuaries (Kennish 2002; Anifowose et al. 2016), estuaries have received much less research attention compared to coastal and pelagic environments (Murphy et al. 2016; Eke et al. Submitted). While it appears that there is substantial study on oil spills in estuaries, literature review reveals that many authors in this field have considered the term “estuary” to be synonymous with “bay”, “inlet”, “lagoon” and “sound” (Pye and Blott 2014). While estuaries, bays, lagoons and sounds are all sea inlets, they are different. Unlike estuaries, bays do not have significant input from freshwater (Savenije 2005). While lagoons are separated

from the sea by barriers and are shallower in comparison to estuaries (Miththapala 2013). While flow dynamics in estuaries are characterised as fast and strong, flow dynamics in Lagoons are characterised as sluggish (Miththapala 2013). A sound is the part of the sea, between two bodies of land. The generalisation of these water bodies as estuaries supports Murphy et al.'s (2016) claim that estuaries have received less research attention in terms of oil spill studies. Only Yan et al. (2012) and Eke et al. (submitted) have explicitly focused on oil spills in an estuarine environment. Yan et al.'s (2012) paper examines the impact of wind and time of release (with respect to peak ebb and flood) on oil spill trajectories. However, little work has been accomplished on the impact of river flow vectors and freshwater discharge in their study. Eke et al. work (in submission) examine the implications of interacting tidal currents and riverine flows on oil spill transport; and the influence of seasonal river discharge variability on oil spill transport. However, neither paper address key gaps in this field, especially: (a) the impact of projected future climatic conditions on oil spill transport; and (b) the influence of lateral points of release on oil spill transport. Considering the significant risks that oil spills present to estuaries, this study addresses these gaps.

Estuaries can be defined as semi-enclosed bodies of water in which incoming saline ocean water is diluted by freshwater (Kim et al. 2017). Transport and circulation in estuaries are tide-driven, wind-driven and density-driven (mainly driven by river discharge) (Nguyen et al. 2008). These processes are influenced by the relative effects of river input and tidal mixing (Pinet 2019). Based on the degree of mixing between freshwater and saline water estuaries can be classified into salt-wedge, highly stratified, partially mixed (weakly stratified) and well-mixed estuaries. Estuaries can also be classified by tidal range: micro-tidal (tidal range < 2m), meso-tidal (2 – 4 m) and macro-tidal (> 2m). The biological and physio-chemical processes (salinity regime, geomorphology, sedimentology, residence times, tidal water movements, turbidity and intertidal area) in estuaries are influenced by tidal range (Tweedley et al. 2016).

Consequently, estuaries are significantly influenced by climate change because they respond to several types of forcing e.g. momentum (i.e. wind stress); evaporation and precipitation (i.e. freshwater, heat and air-water fluxes of CO₂); streamflow quality and quantity; and sea-level changes (Najjar et al. 2010). This explains why projected climatic alterations, particularly changes in either freshwater river flow or in mean sea level have been observed to have a critical impact on estuaries and its processes (Whitehead et al. 2009; Ranasinghe et al. 2012; Rice et al. 2012; Pye and Blott 2014; Robins et al. 2014; Wu and Parson 2019). However, the influence of projected future climatic conditions on oil spill transport in estuarine environments, has not been studied.

Sea level rise has attracted much attention because it is influenced by climate change and because of its social, economic and environmental impacts. The change of global sea level has been caused by ocean heat uptake and thermal expansion, glaciers, Greenland ice sheet, Antarctic ice sheet and water storage on land (anthropogenic activities) (Church et al. 2013). Sea level change was typically observed by tidal gauges until the 1990s when satellite altimetry was employed (Cazenave and Nerem 2004). The use of satellite altimetry to track sea level change has improved the sea level predictions (Ariana et al. 2017). Because of two main limitations, tidal gauges were less accurate: (a) being located only on ocean islands and continental margins, they had poor spatial distribution; b) they are prone to vertical movement due to their attachment to land, as a result producing sea level changes that is unrelated to climate variations (Nerem and Mitchum 2002). In the last century, the global mean sea level has increased at a rate of +1 to +2 mm/year (Prandle and Lane 2015). However, since the use of satellite altimetry measurements, the upper range of global sea level rise has reached 3 mm/year (Bindoff et al. 2007; Robins et al. 2016). Observation of sea level in the 20th century indicates an increase of 1.4 mm/year around the UK (Lowe et al. 2018). To determine sea level change, Coupled Model Intercomparison Project (CMIP5) climate models and several

emission scenarios known as Representative Concentration Pathways (RCPs) are employed (Table S1; Meinshausen et al, 2011). The recent UK climate projection 2018 (UKCP18) report does not consider RCP6.0 scenario as it presents similar sea level rise at 2100 to RCP4.5 and in comparison, to other scenarios has poorer data availability in the CIMP5 database (Palmer et al. 2018). Mean sea level projection for the 21st century suggests sea level rise around the UK, although at spatially varying rates (Robins et al. 2014; Lowe et al. 2018). Much is known about the influence of sea level rise on flooding and inundation (Quinn et al. 2014), vertical mixing and salinity intrusion (Robins et al. 2016), sediment transport (Tessier et al. 2012), fluxes of nutrients (Robins et al. 2014; 2016) and behaviour of larger organisms (Chu-Agor et al. 2011; Fujii 2012) in tidal systems. It is critical to understand how projected sea level will influence oil slick transport.

The role of climate change on river discharge is poorly understood (Burn et al. 2012; Hannaford 2015). However, variations in rainfall and evapotranspiration due to climate change significantly impacts the hydrologic regime of water, particularly river discharge (Watts et al. 2015). The influence of increasing temperature to changes in rainfall through to river flow is a complex, non-linear process that is significantly influenced by catchment characteristics (Hannaford 2015). According to the UKCP18, the 21st century is expected to move towards hotter, drier summers and warmer wetter winters (Murphy et al. 2018). Robins et al. (2016) point out a relationship between increased UK winter rainfall and increased river flows in winter. Long trend analysis of UK river discharges (1961 – 2010) depicts higher discharges in winter compared to summer (Marsh and Dixon 2012; Hannaford 2015). Furthermore, Christerson et al.'s (2012) river catchment model predicts an increase and reduction in winter and summer discharge across the UK from 2011 to 2040 respectively. In a review of observed trends and projected 21st century climate change to UK estuaries, Robins et al. (2016) assign medium confidence to increases in winter flow by up to 25% and decreases in summer mean

flow by 40-80%. Several studies have been undertaken to explore the impact of projected river flow on solute transport (e.g. Robins et al. 2014); inlet-interrupted coastlines (Ranasinghe et al. 2012); and Anadromous fish (Ohlberger et al. 2018). Until now, the relative impact of projected sea level and river flow on oil spill transport in estuarine environments is poorly understood and there is no known study focusing on this important phenomenon; This study explores these areas.

Previous studies on oil spill transport in estuarine environments have considered various oil-release locations. Yan et al. (2012) and Eke et al. (submitted) modelled oil releases from 2 arbitrary locations along the estuary length. Both studies agree that the point of release along the estuary length influences oil slick impacted area. However, neither study considered how varying the point of oil release along the estuary's cross-sectional width will influence oil slick transport. Consequently, no known study has modelled the influence of varying deliberate or accidental lateral oil release locations on oil slick transport in a macro-tidal estuary. Considering the unpredictability of oil spills (Vethamony et al. 2007; Li et al. 2018) and the risks they present to estuaries and their ecosystems, it is critical to also address this key research gap.

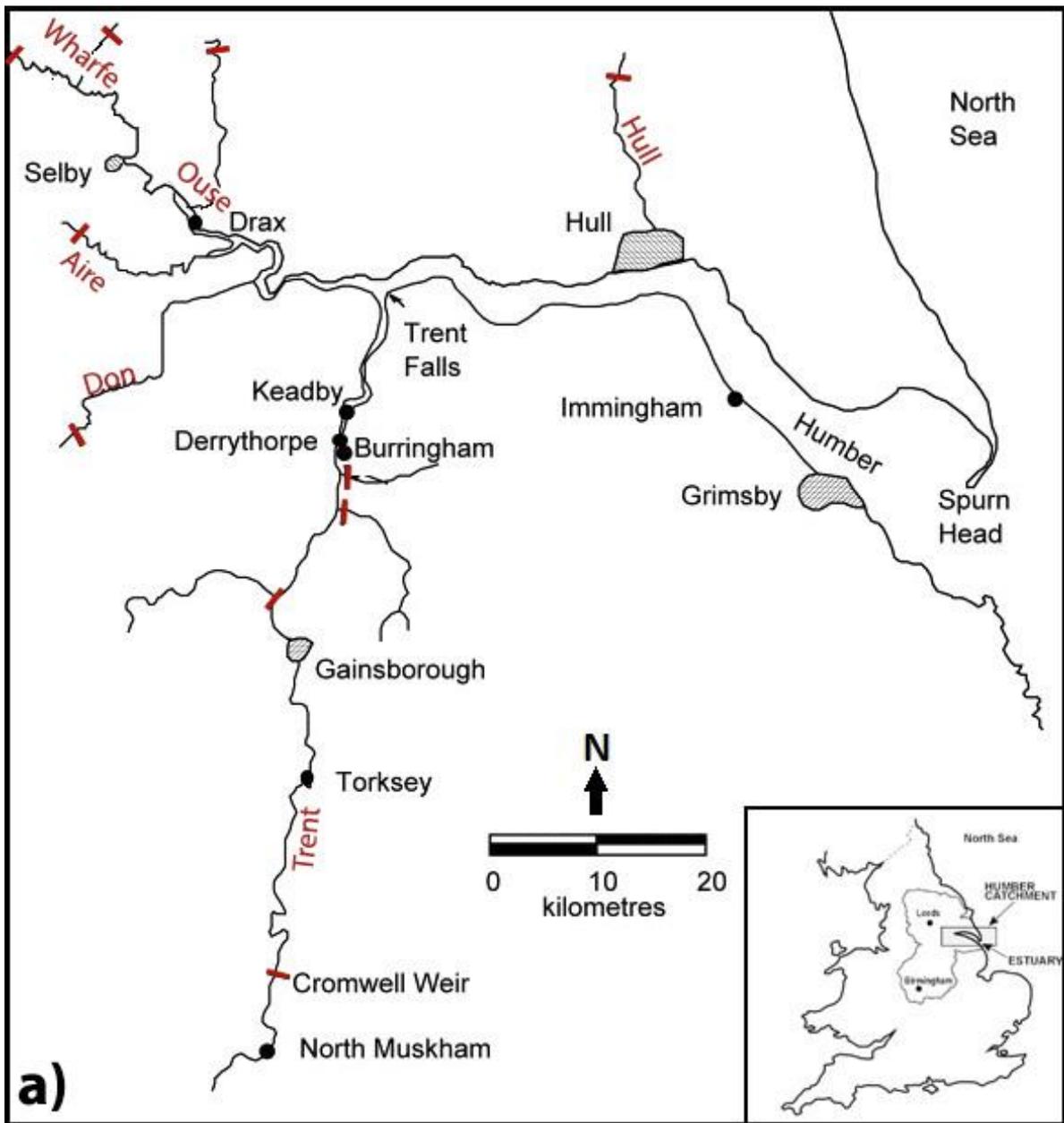
With the UK sea level projections expected to rise (Palmer et al. 2018) and river flow projected to decrease in summer and slightly increase in winter (Robins et al. 2016), it is important to understand how these factors will influence operational spill predictions particularly on the short-term (48 hours), as it accounts for the most volume of oil lost (Fingas 2013). Using numerical models, this study, for the first time, assesses the influence of projected climatic conditions on oil spill transport as well as the influence of varying lateral oil release locations on oil slick transport in the Humber tide-dominated estuary.

2. Study area

The Humber Estuary, located on the northeast coast of the UK, is one of the largest estuarine systems in the UK with a mean fluvial flow of $\sim 250 \text{ m}^3/\text{s}$, with Q10 and Q95 (i.e. 10th and 95th percentile flows) of 610 and 58 m^3/s respectively, over the period 1980 – 2015 (Townend and Whitehead 2003; Fujii 2007; Robins et al. 2018). These volumes are delivered from several rivers (R.) (including the R. Trent and the R. Ouse), with a combined catchment area of 24,240 km^2 (draining approximately 20% of England's landmass) (Yamanaka et al. 2010). Several smaller rivers such as the R. Hull, R. Ancholme and R. Freshney also discharge into the Humber Estuary. The estuary meets the North Sea at Spurn Head, located approximately 62 km downstream from the Ouse-Trent confluence at Trent Falls (Boyes and Elliott 2006) (Figure 1). The distance of tidal influence extends from the mouth to 120 km on the River Ouse and 147 km on the River Trent (Mitchell 2013; Skinner et al. 2015). The width of the Humber Estuary is approximately 8 km at the mouth (Spurn Head) and is less than 0.5 km upstream of Ouse-Trent confluence, making it a funnel-shaped estuary (Fujii 2007; Pye and Blott 2014). The large semi-diurnal macro-tidal estuary has a range that varies between 3.2 m (mean neap tidal range) and 6.4 m (mean spring tidal range) at Immingham, near the mouth of the Humber (Mitchell et al. 2003a; van der Wal et al. 2010). The tidally averaged water depth of the Humber Estuary varies between 3 m and 8 m in the inner estuary and at the mouth, respectively (Cave et al. 2003).

The Humber Estuary has one of the UK's biggest constellation of oil refining industries (Edwards and Winn 2006; Humber Nature Partnership 2015). In the outer Humber Estuary is the Tetney Monobuoy from which crude oil is unloaded and transferred through underground pipelines to the ConocoPhillips Ltd's Humber refinery (Cave et al. 2003). Furthermore, three marine terminal facilities, are located at the Southbank of the Humber (South Killingholme

Jetty, Immingham gas jetty and Immingham oil terminal) (Humber Nature Partnership 2015). Consequently, the Humber Estuary plays host to oil tankers which berth at the oil terminals (Cave et al. 2003). In 2001, over 40 million tonnes of oil and chemicals were transported in and out of the Humber (English Nature 2003) which makes it the main east coast port for crude hydrocarbon landing in the UK (Cave 2003). The estuary thus is prone to oil spill risk, and several incidents have occurred in the past. The Sivand tanker incident, which occurred on September 1983, spilled 6,000 tonnes of Nigerian light crude into the Humber Estuary (Little 1987). Also, 46 tonnes of crude oil spills from 9 different incidents have been recorded on the Humber Estuary between 1989 and 1997 (Cave et al. 2003). These oil spill records and the presence of oil refineries and transport along the Humber Estuary highlight the significance of this study.



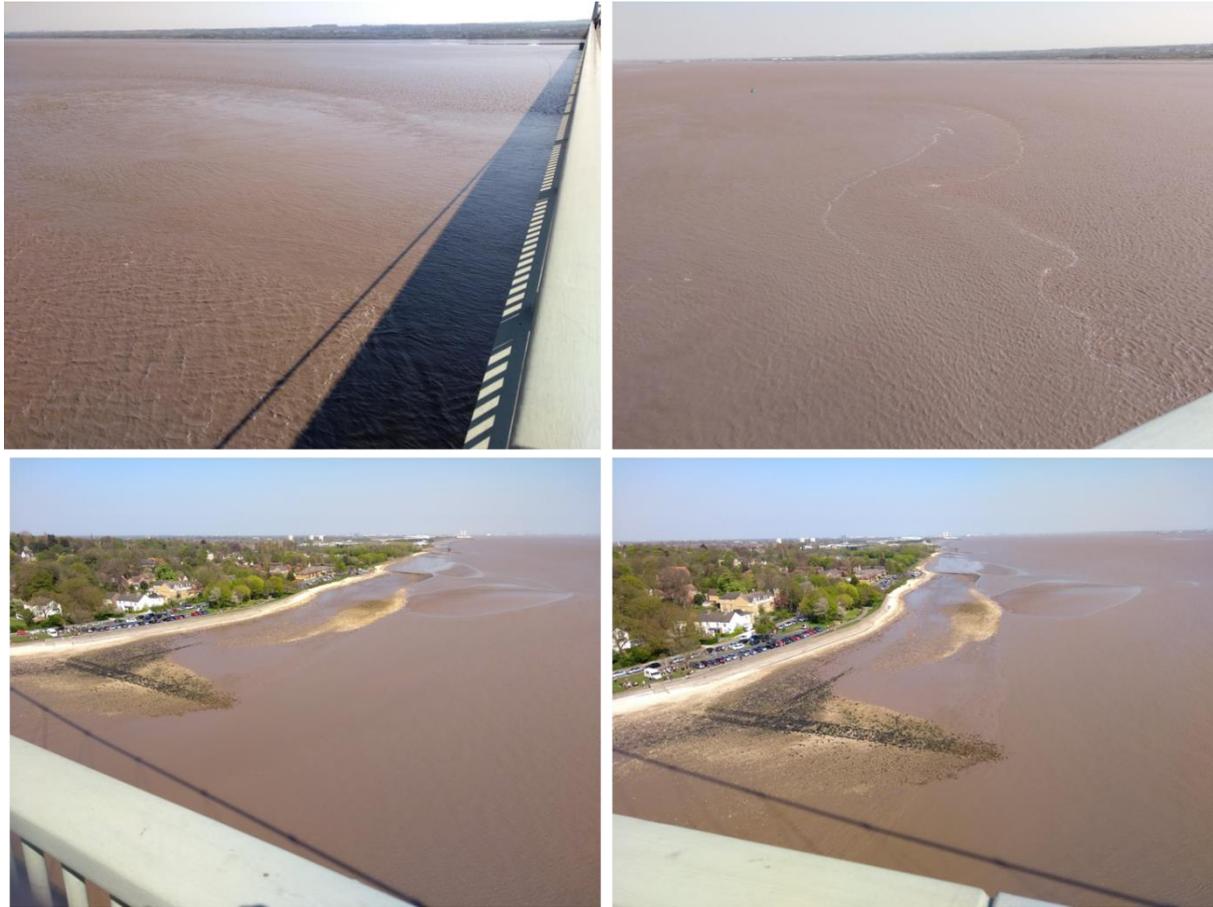


Figure 1: a) The Humber estuary system. Inset shows the location of the Humber estuary in the UK (Mitchell et al. 2003a; Edwards and Winn 2006). Rivers are indicated as red font and Tidal limits are indicated as red bars crossing the channel; b) Photo of the Humber Estuary depicting the estuary size and turbidity, and turbulent forms on the water surface (Photo taken from the Humber bridge by Damian Lawler).

3. Materials and methods

3.1. *Hydrodynamic model*

TELEMAC3D, a three-dimensional open-source finite-element model that solves the Navier-Stokes equations with or without hydrostatic pressure approximation (Stansby et al. 2016) was used to compute the hydrodynamics of the Humber estuary. TELEMAC3D uses a sigma transformation to resolve the vertical direction and unstructured triangular grid in the horizontal direction (Moulinec et al. 2011; Villaret et al. 2013). This study employs the hydrostatic pressure approximation due to the intense computational power demanded by non-hydrostatic pressure models. The impact of using hydrostatic pressure approximation on the reliability of

the model is expected to be relatively insignificant, as there is no indication that the processes (i.e. small-scale ocean processes; Marshall et al. 1997; Candy 2017) emphasised using non-hydrostatic pressure models influence estuarine oil slick transportation. Furthermore, the Humber estuary is a well-mixed estuary, consequently, this study's choice of the Navier-Stokes equation with hydrostatic pressure approximation to model the Humber Estuary will not have any significant impact of the reliability of the results as the effect of stratification and vertical acceleration is negligible in well-mixed estuaries (Martin and McCutcheon 1999; Valle-Levinson 2010). The model is implemented with 5 equidistant σ -coordinate layers in the vertical. The application of 5 σ -coordinate levels is sufficient and efficient for developing an operational oil spill system (Abascal et al. 2017). The resulting computational domain consists of 92,369 nodes and 183,925 elements, with a mean edge length of 54.57 m varying from 11 m to 803 m. Horizontal turbulence is resolved using the Smagorinsky model because it is best suited for tidal systems that involve highly non-linear flow (Rahman and Venugopal 2017). Vertical turbulence is resolved using Nezu and Nakagawa mixing length model as it offers a good representation of wind drift (Rahman and Venugopal 2017). A simulation time step of 45 seconds is employed which satisfies the Courant-Friedrichs-Lewy criterion. Chezy's law of bottom friction is employed as it is more suited for TELEMAC3D models applying the equidistant layer (Rahman and Venugopal 2017).

TELEMAC3D provides ready integration with TELEMAC's built-in oil spill model (GoEURY et al. 2014; Pham et al. 2016) (see below). In a previous study, we utilised TELEMAC3D to develop hydrodynamic models for representative summer (August 2017) and winter (February 2010) months in the Humber estuary (Eke et al. submitted). The open river boundary was driven by constant discharge obtained from literature (Mitchell et al. 1999; 2003b; Table S2). Tidal gauge measurements from the interaction of 34 tidal components at the estuary's mouth (at 541049, 402468 and 540841, 409420) were extracted from the Finite Element Solution

model (FES 2014; Lyard et al., 2016). The open offshore boundary was driven by 15-minute tidal height data extracted from the FES2014 model with respect to Mean Sea Level (see Eke et al. 2018). Because of limited current data, the hydrodynamic models were calibrated against 15-minute tidal height data collected from the representative summer and winter months at Immingham station; 2,976 and 2,688 measured and predicted values were compared for summer and winter respectively. In large estuaries, reasonable reproduction of the depth-averaged currents can be achieved if accurate bathymetry is employed and tidal elevation is accurately simulated (Prandle 2009). The Chezy friction coefficient was employed as the calibration parameter. The model performance was compared using three metrics: Root Mean Square Error, *RMSE*; coefficient of determination, *R*²; and regression coefficient, *b*. The calibrated results revealed that the best agreement between the measured data and model results were obtained with Chezy *C* of 70 m^{0.5} s⁻¹ (*RMSE* 0.623 m; *R*² 0.883 and *b* 0.966) in summer and 75 m^{0.5} s⁻¹ (*RMSE* 0.709 m; *R*² 0.852 and *b* 0.937) in winter respectively. For comprehensive calibration and validation procedure of the representative periods, see Eke et al. (submitted).

3.2 Oil spill models

The current generation of oil spill modelling tools employed to support operational oil spill response and impact assessment include GNOME (Zelenke et al. 2012); ADIOS2 (Lehr et al. 2002); OSCAR (Reed 2000); OILMAP (RPS ASA 2019); MEDSLIK (Alves et al. 2015; De Dominicis et al. 2013a; 2013b) amongst others. In this study, we employ the TELEMAC built-in oil spill model because of its ready integration with TELEMAC3D. The TELEMAC oil spill model is ideal for short-term forecasting of oil spill behaviour in continental water (lakes, rivers and estuaries) (Goery 2012; Goery et al. 2014). The two-dimensional oil spill model combines a Eulerian and Lagrangian approach to compute oil slick transport (Pham et al. 2016).

The model represents oil slicks as a set of hydrocarbon particles consisting of a mixture of discrete non-interacting hydrocarbon components (soluble and insoluble) (Goeury et al. 2014; Joly et al. 2014). TELEMAC accounts for advection, diffusion, spreading, evaporation and dissolution of the oil spill (Goeury et al. 2012). However, it does not model other key short-term weathering processes such as dispersion (considering TELEMAC is a two-dimensional oil spill model), buoyancy and emulsification. The TELEMAC oil spill model can, therefore, be considered as rudimentary with regards to modelling oil weathering processes. Consequently, the focus of this study is on oil spill transport in tide-dominated estuarine environment. TELEMAC's capability for simulating oil spill transport was validated by Goeury (2012) using the ERIKA oil spill incident that occurred in the Bay of Biscay in December 1999. Goeury (2012) study proves that Telemac's simulation of oil slick transport is not significantly impacted by the lack of considering dispersion, buoyancy and emulsification. For a comprehensive validation procedure of the TELEMAC oil spill model, see Goeury (2012).

3.3 Oil spill simulation design

Several scenarios were developed to assess the relative influence of projected climatic conditions (sea level rise and projected river flow) and varying points of release on oil slick dynamics in a tide-dominated estuary. To visualise the oil spill transport, a python script was utilised to convert the TELEMAC oil spill displacement output file (tecplot® format) into an ArcMap readable (.xyz) format. The TELEMAC oil spill displacement output file contained the xyz position of the oil spill particles at 15 minutes interval. The *measure tool* within ArcMap was employed to measure: (a) the oil slick impacted area on the water surface, (b) length of the oil slick over time (distance from one end of the slick to the other) and (c) overall distance travelled (maximum upstream and downstream displacement from the point of

release). We are interested in studying the dynamics of the oil slicks in the estuarine environment and these variables are useful to understand the relative influence of projected climatic conditions (sea level rise and projected river flow) and varying lateral points of release on oil slick transport. Constant wind speed and direction in time and space were applied to the oil spill simulation. The reliability of result is not significantly affected by the assumption of constant wind speed, as the influence of wind speed on oil slick transport is approximately 3% of the wind speed (Joly et al. 2014). In the TELEMAC oil spill model, when an oil particle reaches a shoreline (beaches), it may be deposited if the slick thickness is greater than the water level under the oil slick or the size of the bottom roughness is greater than the water level.

3.3.1 Sea level rise (SLR)

Mean sea level data was provided by the UK Meteorological Office Hadley Centre via the “UKCP user interface”. The data were obtained from the “marine projections for the UK” data source using the same baseline (1981 – 2000) used to develop the recent UK climate projection 2018 report. Mean sea level for medium emission scenario (RCP4.5) was extracted from grid square latitude 53.5°N longitude 0.08° (538064; 402380; coordinates are in OSGB 1936) (Figure S1). The influence of sea level rise was investigated using the Telemac hydrodynamic models for the representative summer and winter seasons (see Section 3.1).

To assess the relative influence of projected climatic conditions, we initially simulated an instantaneous oil release from an arbitrary location (L1; Figure 2) at high water during spring tide. L1 was chosen to reduce the chances of the oil slick leaving the computational domain. This therefore enables oil slick travel to be monitored within the 48-hour period. The oil is released under high water spring tide condition because it presents greater oil slick impacted area on water surface and distance travelled (Eke et al. submitted). The oil is released from this location under both representative summer and winter flows. In addition to oil slick transport

simulations under the representative summer (August 2017) and winter (February 2010) flows, sea level projections for 2030, 2050 and 2100 were also simulated for (Table 1). In line with Robins et al. (2014) and Kumbier et al. (2018) methodology, the hydrodynamic models for February 2030, 2050 and 2100 were developed by linearly adding sea level rise values to the tidal height readings at the open offshore boundary (Table 2). Each scenario simulates an instantaneous release of 10,000 m³ of Brent crude oil (883.6 kg m⁻³). A hypothetical oil spill volume to 10,000 m³ as this spill size represents a major oil spill and a more probable spill size which is large enough to illustrate the scale of response required for a major marine oil spill (DeCola et al. 2012) The Brent blend was chosen due to its proximity to the Humber Estuary, as it is located in the North Sea off the United Kingdom’s coast. The resulting simulated oil slick is monitored for a 48-hour period (over two semi-diurnal tidal cycles).

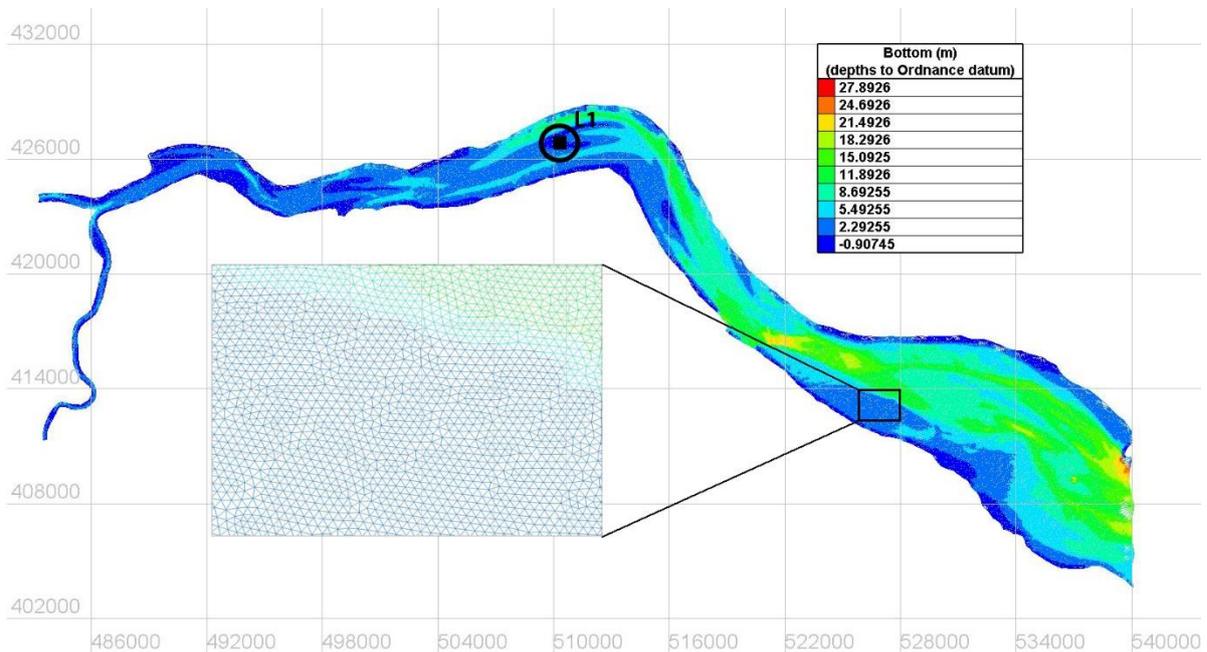


Figure 2: Computational domain for the Humber Estuary simulations showing release points for oil spill scenarios at L1 (510498; 426777) (coordinates are in OSGB 1936). Inset shows the detail of the computational mesh.

Table 1: Time-mean sea level rise with respect to 1981 – 2000 for scenario RCP4.5 (Met Office Hadley Centre 2018). Values in brackets indicate the 5th to 95th percentiles.

Year	Sea level rise (m)
2010	0.05 (0.04 – 0.07)
2017	0.08 (0.06 – 0.11)
2030	0.14 (0.10 – 0.19)
2050	0.25 (0.18 – 0.34)
2100	0.53 (0.36 – 0.81)

Table 2: Summary of oil spill simulations.

Run	Scenario	Flow input at river boundary (m ³ /s)	Tidal height at offshore boundary (m)
1.1	Summer (August 2017)	Q	H
1.2	Winter (February 2010)	Q	H
2.1	Summer SLR 2030	Q	H + 0.06
2.2	Winter SLR 2030	Q	H + 0.09
2.3	Summer SLR 2050	Q	H + 0.17
2.4	Winter SLR 2050	Q	H + 0.20
2.5	Summer SLR 2100	Q	H + 0.45
2.6	Winter SLR 2100	Q	H + 0.48
3.1	Summer (SLR + Flow) 2100	Q – 80%	H + 0.45
3.2	Winter (SLR + Flow) 2100	Q + 25%	H + 0.48
3.3	Summer Flow 2100	Q – 80%	H
3.4	Winter Flow 2100	Q + 25%	H

Note: Q is the typical freshwater flows from Rivers Ouse and Trent (Table S1); and H is the tidal height data extracted from the FES2014 model.

3.3.2 Projected fluvial discharge

Projected freshwater discharge data for the 21st century was obtained from literature. River catchment models project an increase of up to 25% in winter mean fluvial flow and decrease of 40 – 80% in summer mean fluvial flow by the year 2100 (Fowler and Wilby 2010; Christerson et al. 2012; Prudhomme et al. 2012). In a review of the impact of climate change on UK estuaries, Robins et al. (2016) assign medium confidence to this prediction. Consequently, an increase of 25% in winter mean flow and a decrease of 80% in summer mean flow is adopted for this study. In line with Robins et al. (2014) methodology, hydrodynamic models for projected river flow were developed by adding the projected flow values to freshwater discharge values at the open river boundaries (Table 2). In addition, projected river flow was also simulated in combination with corresponding sea level rise prediction for 2100 (Table 2).

3.3.3 *Varying lateral release locations*

The calibrated hydrodynamic model developed for the representative summer month (August 2017) was employed to assess the influence of lateral oil release location on oil slick transport. The summer month was chosen because it presents a unique oil transport scenario i.e. enables net upstream migration of oil slicks (Eke et al. submitted). Each scenario simulates an instantaneous oil release from one of 10 locations; 5 release locations placed upstream and downstream (Figure 3). Oil slick release locations along L2 (L2_a; L2_b; L2_c; L2_d; and L2_e) and L3 (L3_a; L3_b; L3_c; L3_d; and L3_e) situated 1,000 m and 350 m apart respectively. The difference in spacing was due to the funnel-shaped configuration of the Humber estuary: its wide mouth of approximately 8 km narrows to less than 0.5 km at the Ouse-Trent confluence (Fujii 2007). The oil was released under spring tide conditions, during both high and low tide with reference to the release locations. Spring tide condition was chosen because it presents greater oil slick impacted area and distance travelled (Eke et al. Submitted). Like the projected climatic condition design, each scenario simulates an instantaneous release of 10,000 m³ of Brent Crude oil, and the resulting simulated oil slick is monitored for a 48-hour period (over two semi-diurnal tidal cycles).

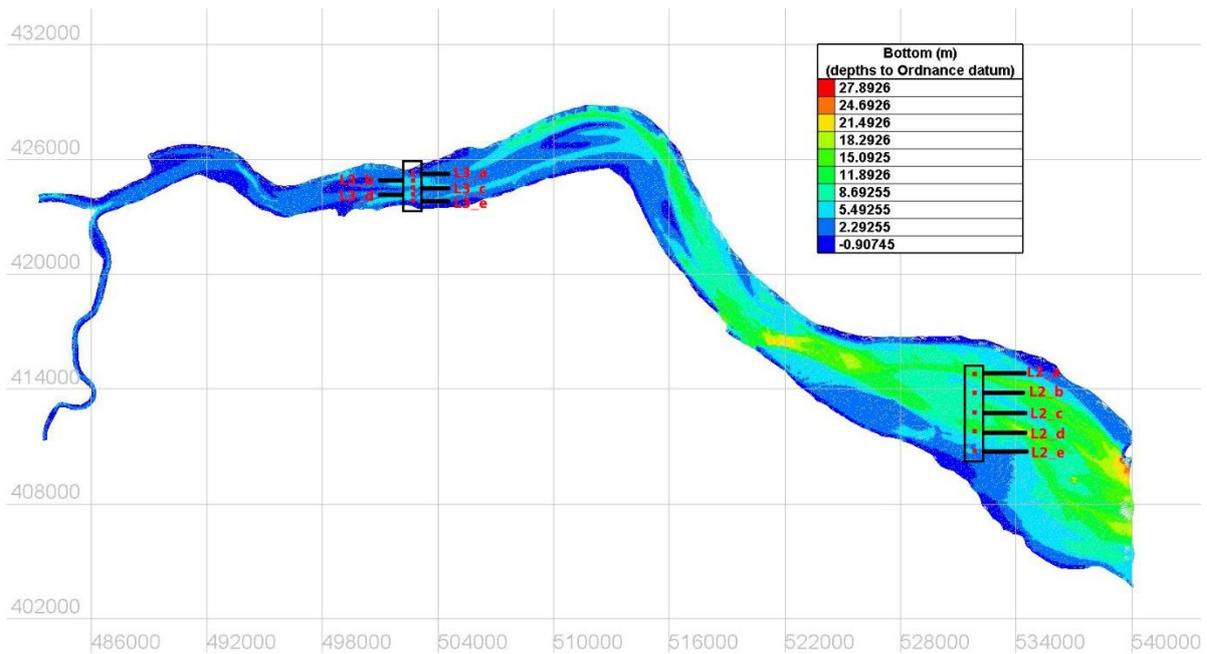


Figure 3: Outline for computational domain showing release location (red dots) for oil spill scenarios (coordinates are in OSGB 1936).

4. Results and discussion

4.1. Impact of sea level rise

We first present the results (Figures 4 – 6) for the projected climatic condition scenarios (released from L1; Figure 2). The influence of sea level rise on oil slick impacted area, length and distance travelled were analysed over the spill duration. Under summer conditions, maximum oil slick length was observed to peak at 2030 sea level spanning 15.55 km, slightly longer (8%) than the 2017 summer sea level scenario (Figure 4a; Table S3). Under winter conditions, maximum oil slick length was observed to increase with sea level rise by an average of 5% by 2100 (Figure 6b; Table S4). After 48 hours, the overall distance travelled by summer slicks peaked at 2030 sea level and by 2100 was about 3% less than the representative summer slicks scenario (Table S3). While the overall distance travelled by winter slicks was an average of 2% less than the representative summer scenario by 2100 (Table S4). After 48 hours, the oil slick impacted area peaked at 2030 sea level by 2% and 15% in summer and winter respectively

(Figures 5a; 5b). This greater impact of short-term sea-level rise is surprising, especially under winter conditions. This could possibly be due to the effect of sea level on tidal dynamics. Pelling et al. (2013) point out that the relationship between sea level and tidal dynamics can be non-linear. However, it can be concluded that the overall influence of sea level rise on oil slick impacted area, length and overall distance travelled is relatively insignificant (Tables S3, S4). Our findings agree with Prandle and Lane (2015) study which points out that the influence of sea level rise on estuarine processes is based on estuary characteristics (tidal range, dominant influence and water circulation), as a result, sea level rise of 1 m has little effect on large tide-dominated estuaries (e.g. the Humber Estuary). Furthermore, sea level rise has relatively greater influence on vertical mixing and saline intrusion than on tidal current (Prandle and Lane 2015).

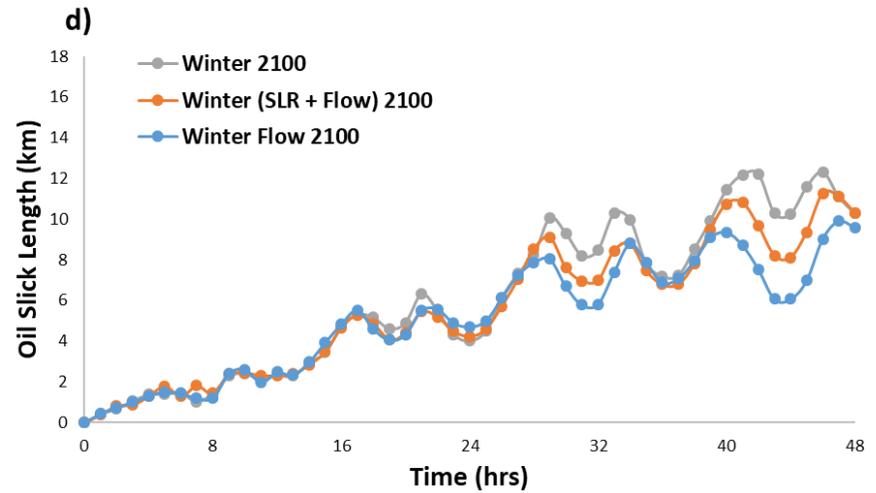
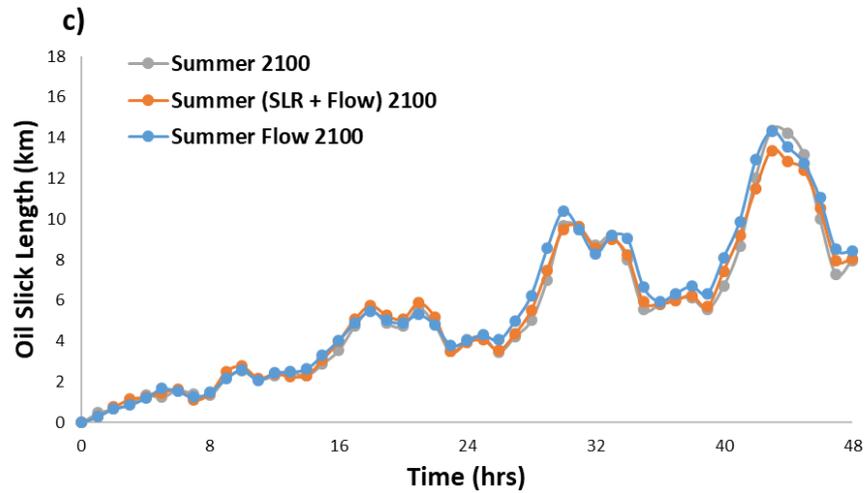
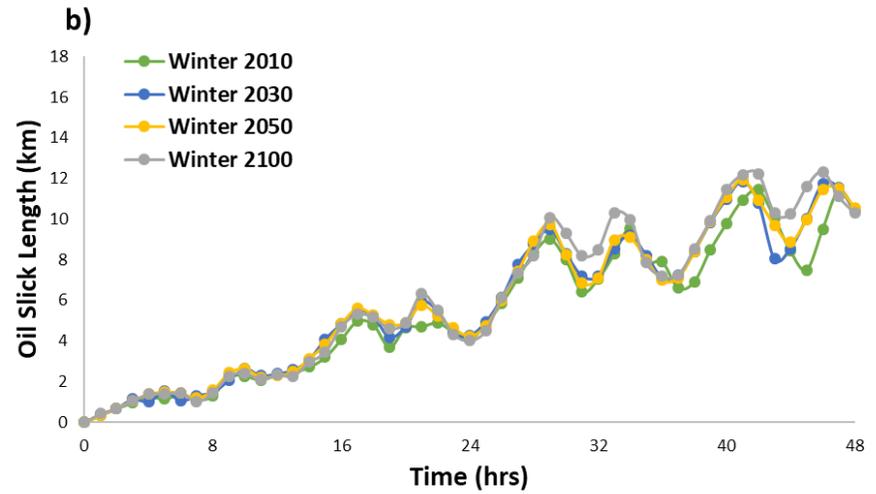
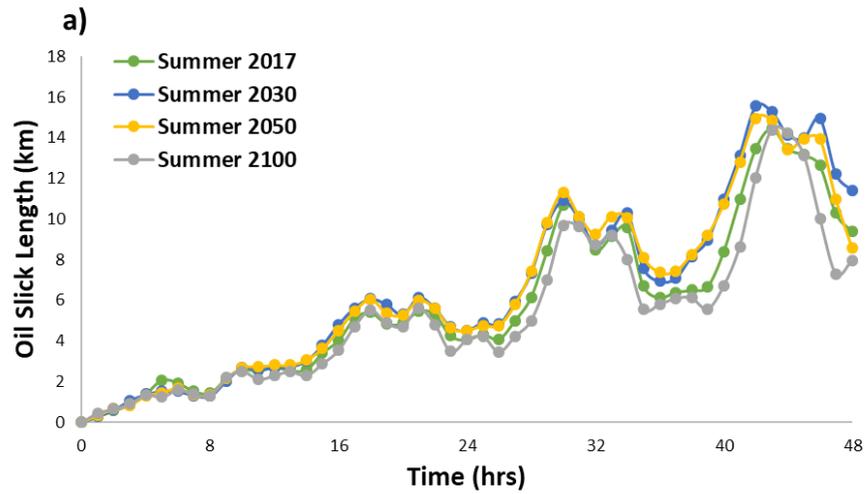


Figure 4: Oil slick length over time for a spill a) at summer sea level; b) at winter sea level; c) at 2100 summer scenarios; d) at 2100 winter scenarios.

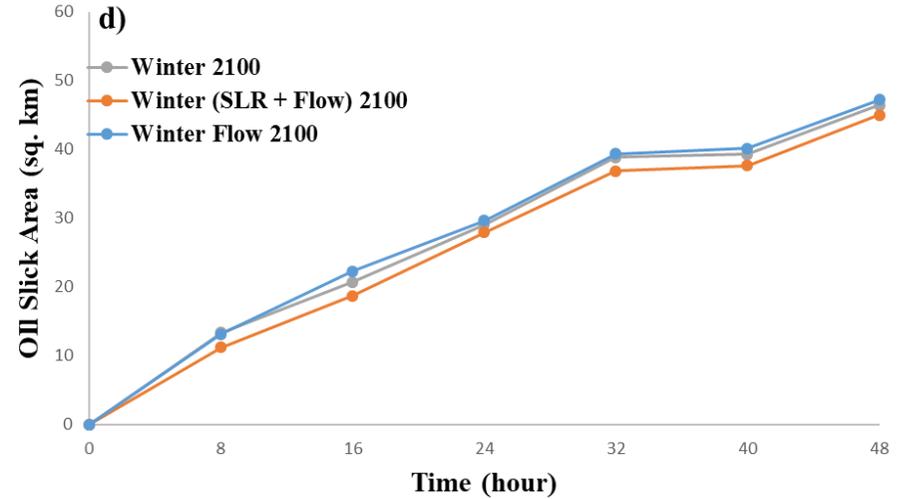
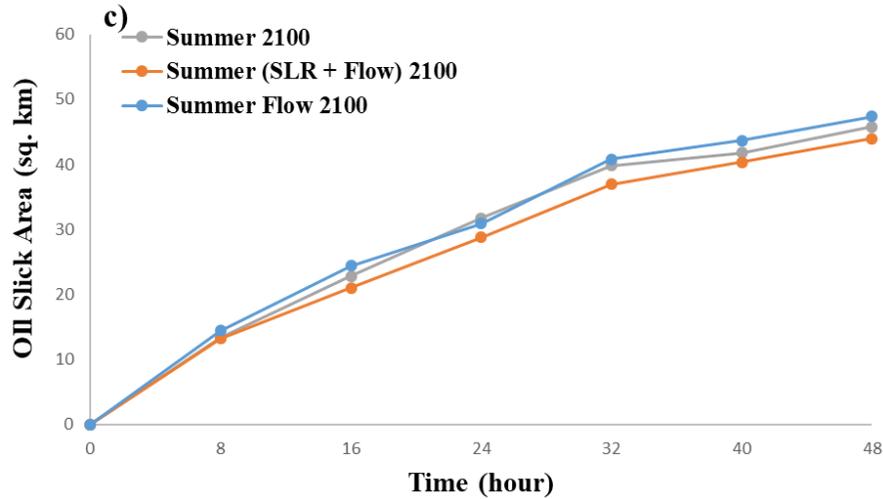
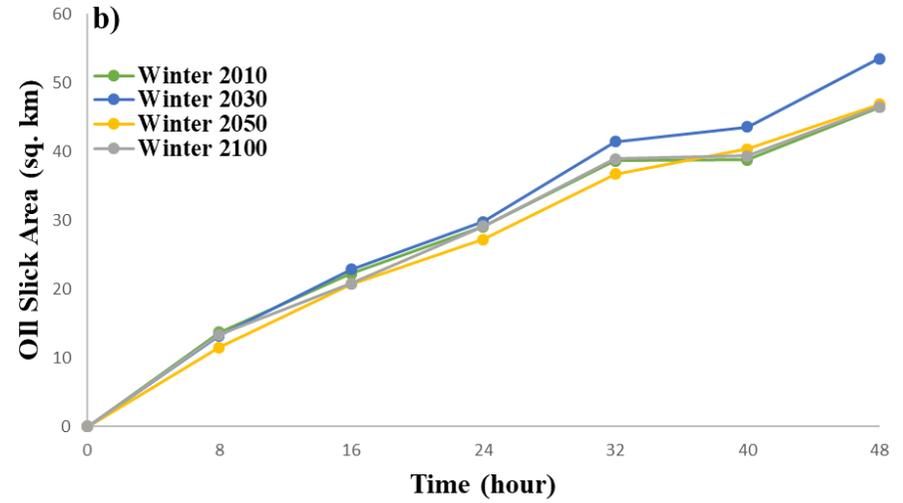
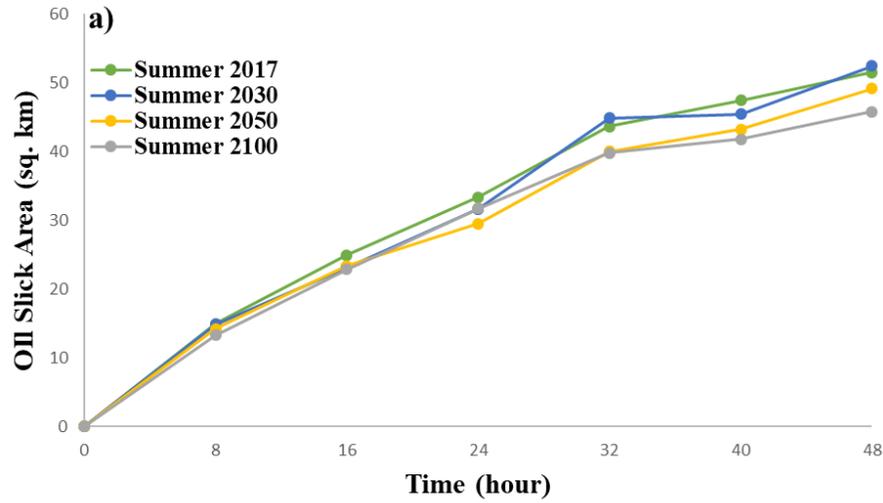


Figure 5: Area covered by simulated oil slick over time for a spill a) at summer sea level; b) at winter sea level; c) at 2100 summer scenarios; d) at 2100 winter scenarios.

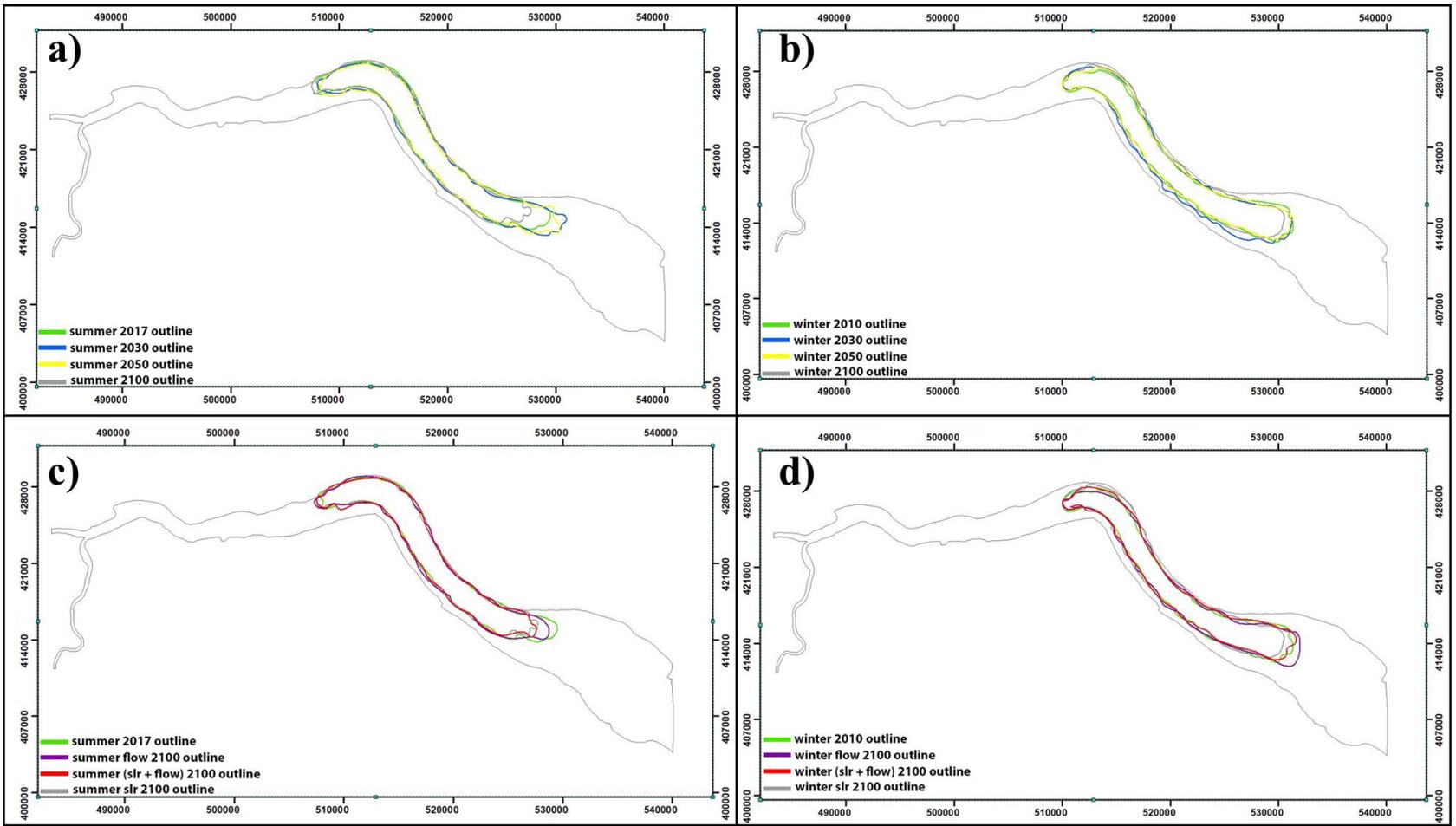


Figure 6: Outline of the area covered by oil slicks under: a) different summer sea level scenarios; b) different winter sea level scenarios; c) projected summer flow scenarios; and d) projected winter flow scenarios (coordinates are in OSGB 1936).

Although sea level does not significantly influence the area impacted by oil slick, oil slick length and distance travelled, the oil slick transport suggests that sea level influences upstream and downstream displacement to some degree (Figures 6a, 6b). Compared to summer slicks released under 2017 sea level, summer slicks released under 2030 and 2050 travelled further downstream, resulting in a displacement of 1.7 km and 1.6 km further downstream in 2030 and 2050 respectively. The difference in upstream displacement was negligible under 2030 and 2050 sea level respectively. Under 2100 sea level, summer slicks travelled further upstream (Figure 6a). Compared to the 2017 summer scenario, downstream displacement was reduced by 1.3 km while summer slicks were displaced further upstream by 0.5 km (Figure 6a; Table S5). Summer slicks are expected to spread upstream over repeated tidal cycles, however, due to the time of release and relatively high river flow, there was no upstream displacement from the release point under winter conditions. Downstream displacement of winter slicks was reduced by 0.2 km under 2030 and 2050 sea level and by 1.1 km under 2100 sea level (Figure 6b). Results suggest that the influence of sea level rise on oil slicks displacement is influenced by seasonal variations. Under summer conditions, relatively short-term sea level rise (2030 and 2050) displaces oil slicks further downstream while long-term sea level rise displaces oil slicks further upstream (Figures 6a, 6b; Table S5). This peak impact in the near-future scenarios presents a similar anomaly as observed for the slick area, which could again be related to the non-linear relation between sea level and tidal dynamics which is influenced by bathymetry and coastal development, both natural and anthropogenic (Pelling et al. 2013). However, under winter conditions, oil slicks are displaced further upstream with sea level rise (Figures 6a, 6b; Table S5). A commonality in both seasons is the ‘brake’ on downstream displacement by long-term sea level rise.

4.2. Impact of projected fluvial discharge

The Humber Estuary is characterised by relatively low summer fluvial flows and relatively high winter fluvial flows (Table S2). Alongside hotter drier summers and warmer and wetter winters, river flows in the 21st century are projected to decrease in the summer and slightly increase in winter (Robins et al. 2016). It was observed that a decrease in river flow will encourage further upstream transport of oil slicks (Figure 6c). Considering summer conditions in the Humber Estuary, an 80% decrease in river flow led to oil slicks displacement of 0.6 km further upstream (Table S5). This was 0.2 km further than when only sea level rise at 2100 was considered and 0.3 km further than summer slicks released under a combination of decrease in river flow and 2100 sea level (Figure 6c). Surprisingly, the summer (SLR + Flow) 2100 scenario (Figure 6c), exhibited less upstream displacement compared to under projected river flow (Table S5). This could possibly be because of the effect that combined sea level rise and decrease in river flow have on tidal asymmetry in the estuary. Decreases in river flow, sea level rise or a combination of both, restricted downstream displacement of summer slicks while resulting in an upstream transport of the entire oil slick (Table S5). Considering the upstream and downstream displacement, we conclude that sea level rise acts as a mitigating factor on the effect of projected river flow on the spreading of summer slicks.

Under winter conditions, after 48 hours, the 25% increase in river flows displaced oil slicks by 0.7 km further downstream (Figure 6d), while in the 2100 sea level scenario, downstream displacement of oil slick was reduced by 1.08 km (Table S5). However, the combination of increased river flow and sea level rise (SLR + Flow) displaced oil slicks by 0.4 km further downstream (Figure 6d). Results suggest that while increased winter flow will increase the downstream displacement of oil slicks, sea level rise acts as a mitigating factor. In both seasons, overall distance travelled by oil slicks were greater solely based on flow variability; by about

2% and 4% in summer and winter respectively (Tables S6; S7). Overall distance was reduced when sea level rise was taken into account. Projected river flows have different effects on the area covered by summer and winter slicks. After 48 hours, the area covered by summer slicks is reduced by 8% while the area covered by winter slicks is increased by 2% (Tables S6; S7). However, the combination of projected sea level and river flow will reduce the impacted area covered by both summer and winter slicks as well as the maximum oil slick length in both seasons (Tables S6; S7). Results suggest that projected river flow has a relatively insignificant impact on oil slick impacted area, length and overall distance travelled. Our findings agree with Prandle and Lane (2015) study. The authors point out that while a change of 25% (either increase or decrease) in river flow will have significant effects on both vertical mixing and salinity intrusion, in contrast, there is little effect on tidal currents in tide-dominated estuaries. This explains the relatively insignificant impact on oil slick impacted area, length and overall distance travelled as tidal current is the main driver of oil slick.

4.3 Longitudinal patterns along the estuary

Results show that the proximity of the oil release location to the estuary mouth influences the oil slick impacted area, as well as overall distance travelled. At low water, the area covered by oil slicks released near the estuary mouth (along L2; Figures S3.2a; S3.2b; S3.2c; S3.2d; S3.2e) was on average 168% larger than oil slicks released further upstream (along L3; Figures S3.4a; S3.4b; S3.4c; S3.4d; S3.4e; Figure 7; Table S8). While after 48 hours, the overall distance travelled by oil slicks released near the estuary mouth at low water was 56% larger than oil slicks released further upstream (Table S8). This could possibly be explained by stronger currents observed at the estuary mouth (Figure 8; S4; Table 3). We now know that for this macro-tidal estuary, oil slick impacted area and overall oil travel distance will decrease as the point of release moves further upstream because of decreasing current velocities. Since the

amount of oil released is the same in all scenarios, the oil impacted area suggests that the oil slicks remain denser (more concentrated) as the point of release is further upstream. Oil slicks released at high water could not be compared as slicks released near the estuary mouth leave the computational domain (Figure S6).

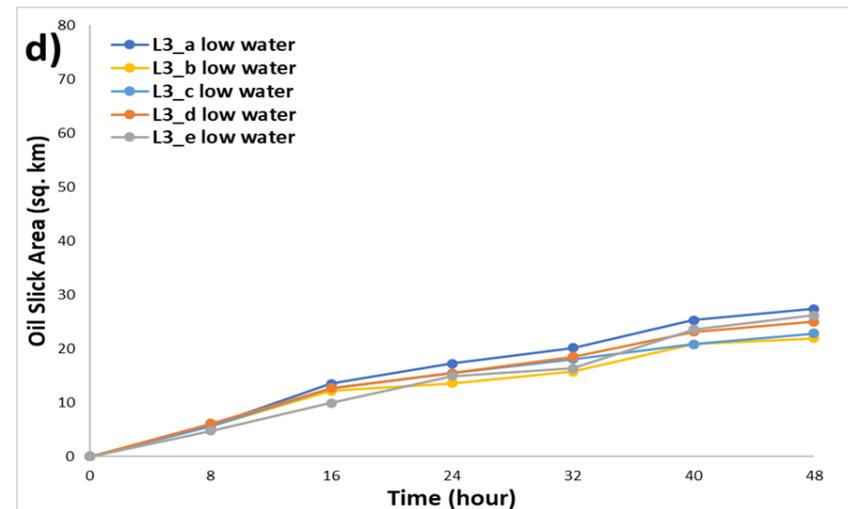
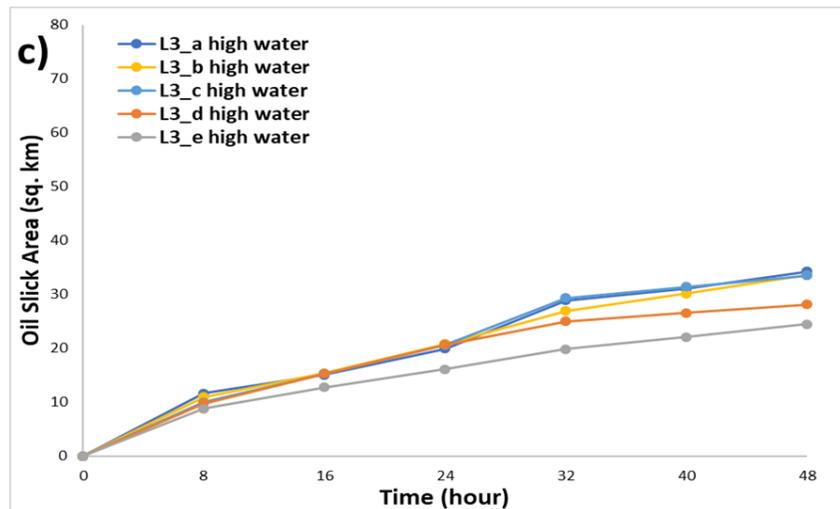
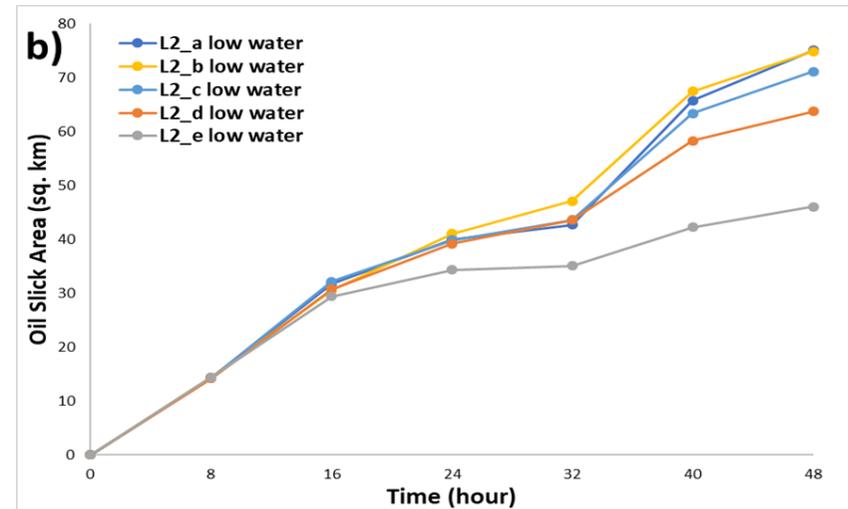
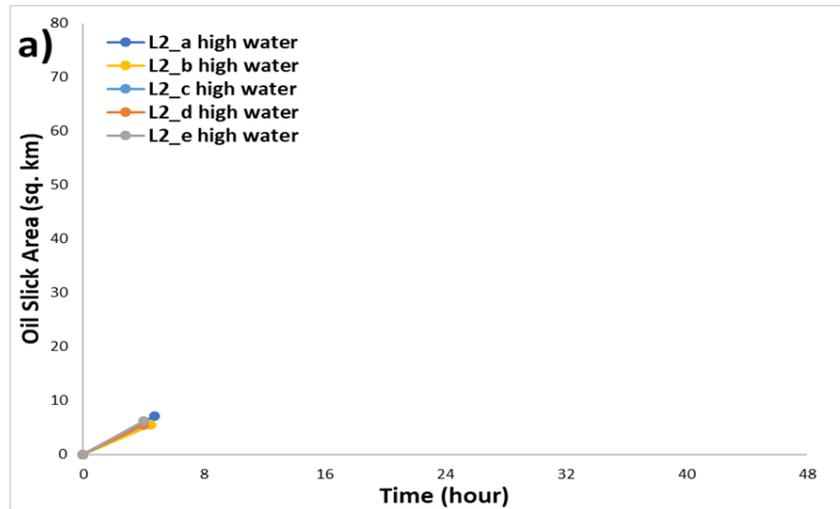


Figure 7: Area covered by simulated oil slick released from varying lateral points a) at L2 high water; b) at L2 low water; c) at L3 high water; d) at L3 low water.

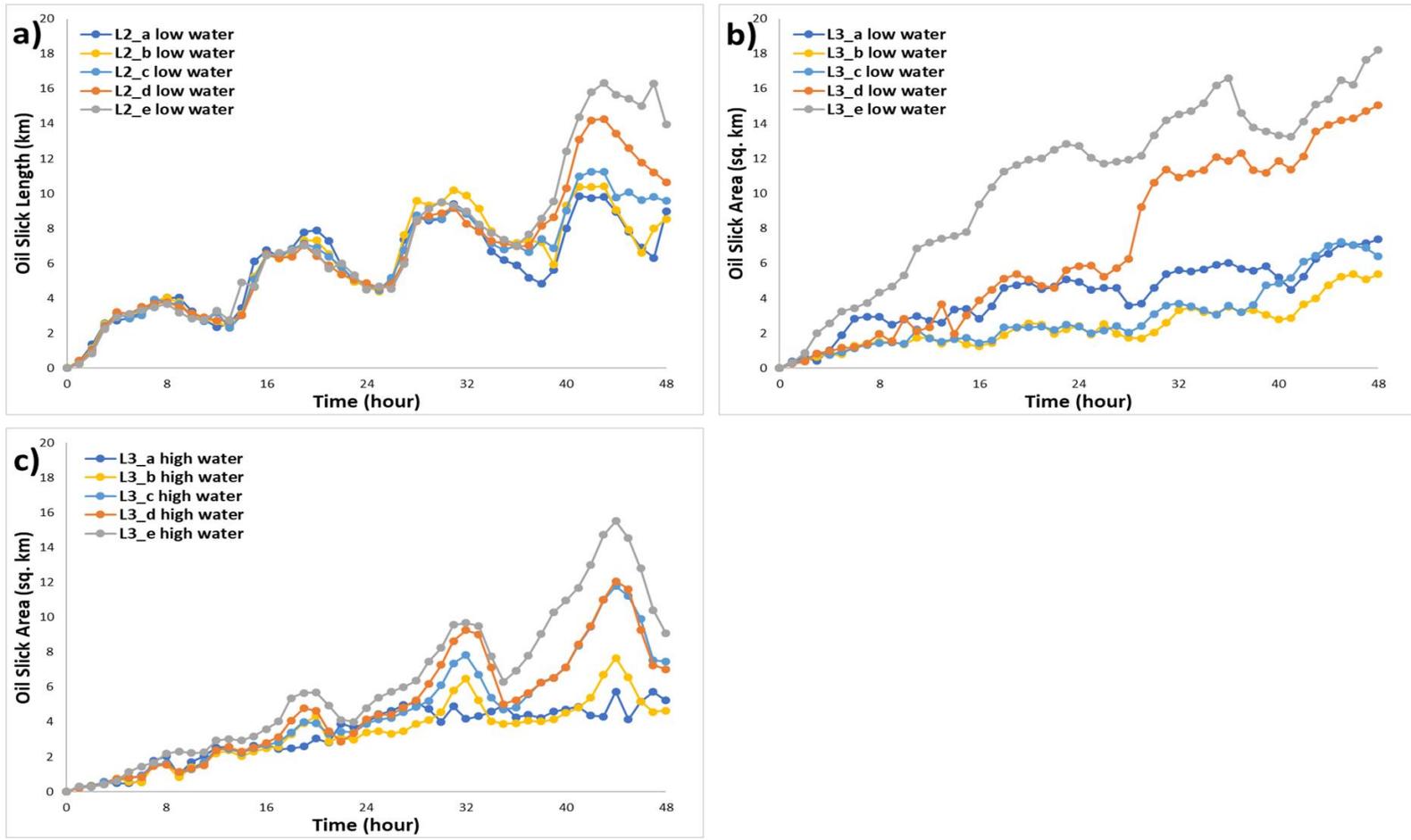


Figure 8: Oil slick length over time for simulated oil slick released from varying lateral points a) at L2 low water; b) at L3 high water; c) at L3 low water.

Table 3: Average current speed and direction measured from the 5 lateral release locations along L2 and L3 within the oil slick. (see Figure S4 and S5 to explain these)

Oil release location	Average current speed (m/s)	Average flood direction	Average ebb direction
L2_a	0.58	290.50	127.99
L2_b	0.62	296.21	107.46
L2_c	0.65	302.43	109.82
L2_d	0.67	306.57	114.41
L2_e	0.68	308.02	119.28
L2	0.64	300.75	115.79
L3_a	0.64	269.05	92.92
L3_b	0.56	267.36	90.41
L3_c	0.54	267.98	89.65
L3_d	0.53	269.52	89.87
L3_e	0.55	271.31	90.56
L3	0.56	269.04	90.68

4.4 Cross-sectional width

Oil slicks released near the mouth of the estuary was observed to travel towards the south bank with the ebb tides (Figures S3.2a; S3.2b; S3.2c; S3.2d; S3.2e). To understand the oil slick transport, current speed and direction were measured from the 5 lateral oil release locations along L2 and L3 (Figure S4). Results reveal a lateral variation in current speed and direction (Figure S4; Table 3). Lateral variation of current speed and direction is common in estuaries and is influenced by estuary shape, length, depth, friction factor, Coriolis acceleration and river flow (Prandle 2009; Pietrzak et al. 2011). Considering the influence of current on oil slick transport, the varying current speed (Table 3) will be a contributor to the difference in distance travelled by oil slicks (Table S9). In the lower half of the estuary, flood currents travelled at 301° upstream, while ebb currents travelled at 116° towards the mouth of the estuary (Table 3). Along L3, flood and ebb currents travelled at 269° and 91° respectively (Table 3). The direction of flood currents towards the head of the estuary and ebb currents towards its mouth highlights the influence of estuary geometry on the estuarine current direction which in turn affects oil slick transport. In the lower half of the estuary (i.e. considering oil slicks released from L2),

the current direction towards the estuary mouth resulted in oil slicks spreading towards the south bank. The difference in current direction across the estuary cross-sectional width (Table 3) can possibly explain the difference in oil slick impacted area (Figure 7b). Consequently, the area impacted by the oil slicks can possibly be explained by the southwards direction of ebb currents and proximity of the release location to the south bank as oil slicks were restricted from spreading any further upon reaching the south bank (Figures S3.2d; S3.2e). After 48 hours, the area covered by oil slick released at L2_a was 63% larger than oil slick released from L2_e (Figures 7b; S3.2a; S3.2e). Analysis of the dynamics of oil slicks released further upstream along L3 also suggest that current direction and proximity to estuary bank influences the oil slick impacted area and travel distance. It was observed that the direction of flood and ebb currents along the estuary followed the change in estuary geometry. This might present a challenge for understanding oil slick transport in non-uniform shaped estuaries. To fully understand the difference in oil slick transport, responders will need to be aware of the axial and lateral variations of current speed and direction in different segments of the estuary and how it affects oil slicks from a particular release location.

Under the various release conditions, maximum oil slick length was greater for slicks released close to the south bank (L2_e LW; L3_e_HW; L3_e_LW) (Figure 8; Table S9). Observation of oil slick transport showed that movement of oil slicks close to the edge of the grid (i.e. riverbank) was distorted, resulting in the formation of longer slicks. For example, movement of part of the oil slicks was observed to be restricted near the edge of the grid possibly due to the lower flow velocities at riverbanks. This elongated the oil slicks. Currents in the opposite direction were then observed to move the entire oil slick, further elongating the oil slick. It is worth noting that lower flow velocities were not consistently observed along riverbank. This is possibly due to the shape of the estuary, which further complicates the estuarine current dynamics. Oil slicks farther away from the south bank expanded southwards, forming wider

slicks, oil slicks close to the south bank formed longer slicks, because of the proximity to the riverbank. The interaction between oil slicks and the riverbank resulted in an increase in overall distance (Table S9). To effectively deal with oil slicks, oil spill modellers will need to take cognisance of the interaction between oil slicks and the edge of the computational grid (riverbank). In a real-life scenario, the influence of estuary banks will depend on the characteristics of oil slicks and on the type of shoreline (Tri et al. 2015).

4.5 Interaction with the edge of the computational grid (oil beaching)

Here, oil beaching is defined as when oil interacts with the edge of the computational grid. It was observed that the risk of beaching increases as the estuary becomes narrower. However, the results depict the complexity in predicting the likelihood of beaching in a large macro-tidal estuary (Table S10). It is clear that the likelihood of beaching is dependent on the oil release location, the geometry of the estuary and current magnitude and direction. These factors also determine the time of first contact with the bank. Oil spill responders will need to be aware of these factors to effectively deal with oil spills in an estuarine environment.

5. Conclusion

Until now, the influence of projected climatic conditions (particularly projected sea level and river flow magnitude) as well as lateral oil release locations on oil slick transport in a large macro-tidal estuary has never been explicitly investigated. The following findings were made, some of which have not been demonstrated until now:

- a. the overall influence of sea level rise on oil slick impacted area, length and overall distance travelled is relatively insignificant.
- b. the influence of short-term sea level rise on oil slick displacement varies from the influence of long-term sea level rise under summer conditions. However, the influence of sea level

- rise on oil slick displacement is consistent under winter conditions, suggesting that the influence of sea level rise on oil slicks displacement is influenced by seasonal variations;
- c. an 80% decrease in summer river flow leads to oil slicks displacement of 0.6 km further upstream and reduced downstream displacement by 0.14 km;
 - d. a 25% increase in winter river flows leads to oil slicks displacement of 0.68 km further downstream;
 - e. oil slicks remain thicker (more concentrated) as the point of release is further upstream.
 - f. projected changes in river discharge have relatively insignificant influence on oil slick impacted area, length and overall distance travelled;
 - g. considering sea level rise and projected river flow (SLR + Flow) scenario, oil slicks were further displaced upstream by 0.35 km and downstream displacement was reduced by 1.33 km in summer while winter slicks were further displaced by 0.4 km. In comparison to the projected flow scenarios, long-term sea level rise mitigates the impact of projected river flow on oil slick spreading;
 - h. difference in current magnitude is the key determinant of difference in dynamics between oil slicks released along the estuary length as current velocities decrease as we travel further upstream;
 - i. while differences in lateral current speed and direction are key determinants of the differences in the dynamics of oil slick released along the estuary width; and
 - j. proximity to the riverbank influences oil slick transport, as lower flow velocities distort oil slick movement resulting in the formation of longer slicks. However, in a real-life scenario, the influence of estuary bank will depend on the characteristics of oil slicks and on the type of shoreline.

These findings suggest that the overall impact of sea level rise and changes in river discharge is rather limited. Hence, the implications of these findings for operational oil spill response

planning are: (a) the need to be aware of current direction in different segments of the estuary and how it affects oil slicks from a particular release location; (b) need to take cognisance of the interaction between oil slicks and estuary bank and how it influences overall distance travelled by oil slicks; (c) the risk of beaching increases as the estuary becomes narrower; and (d) the need to understand the interaction between oil release location, the geometry of the estuary and current magnitude and direction to effectively deal with oil slicks in a tide-dominated estuary.

This hydrodynamic model employed in this study solves the Navier-Stokes equations with or without hydrostatic pressure approximation as a result, consequently the effect of vertical stratification is not considered. Also, we do not consider extreme sea levels and river discharge such as flooding and storm events; and the effect of dams and reservoir on river discharge. Further studies can be undertaken to understand how these events will influence oil slick transport in an estuarine environment.

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quality (temperature and salinity) data; and the Met Office Hadley Centre for provision of the UKCP18 sea level data. The data was provided on a non-commercial license.

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